Probabilistische Erdbeben-Gefährdungs-Analyse für KKW-StandOrte in der Schweiz (PEGASOS)

Probabilistic Seismic Hazard Analysis for Swiss Nuclear Power Plant Sites (PEGASOS Project)

Final Report
Volume 1
Text

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PEGASOS

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by
Norman A. Abrahamson
Kevin J. Coppersmith
Martin Koller
Philippe Roth
Christian Sprecher
Gabriel R.Toro
Robert Youngs

TABLE OF CONTENTS

EXECUTIVE SUMMARY

Purpose and Motivation for Study

In 1998, HSK, the Swiss Nuclear Safety Inspectorate, identified the need to update the seismic hazard assessments for the Swiss nuclear power plants. A probabilistic seismic hazard analysis (PSHA) according to the rules first established by the 'Senior Seismic Hazard Analysis Committee' (SSHAC) on behalf of the US-NRC, Department of Energy, and EPRI, was considered by HSK to best represent the current state-of-the-art. It was decided that the study should be carried out in its most elaborate form, a Level 4 analysis, with the entire input based on evaluations by multiple experts and the systematic, quantitative assessment of the uncertainties. Accordingly, the Swiss nuclear power plant operators ('licensees') were requested to envisage and prepare for a new hazard study that would satisfy SSHAC Level 4 criteria.

The licensees, organised as the 'Association of Swiss Nuclear Power Plant Operators' (UAK), agreed to commission the study and approached Nagra, the Swiss National Cooperative for the Disposal of Radioactive Waste, to help them plan, organise and perform the new seismic hazard assessment for all four power plant sites. The study has since become known under the name of the 'PEGASOS Project' (Probabilistische Erdbeben-Gefährdungs-Analyse für KKW-StandOrte in der Schweiz).

The objectives of the PEGASOS Project are to:

1. Evaluate earthquake-induced ground motion hazards and their uncertainty at the four sites of the Swiss nuclear power plants Mühleberg, Beznau, Gösgen and Leibstadt and
2. Provide documentation of the technical basis for determining these hazards.

Project Organisation and Work Activities

The main components of the project organisation included the project representative of UAK, the project manager, the project management team, three technical subprojects for source (SP1), ground motion (SP2) and site effect (SP3) characterisation, with their respective expert groups and TFI-teams, and a seismic hazard computation group (SP4). Data Procurement and Compilation (DPC) and the Computing, Modelling and Database Centre (CMD) were the major tech support units, designated to help the experts in their evaluations. Administrative support was provided by Nagra and the role of project QA representative was taken on by an external consultant.

HSK monitored the project work through a peer review committee, the 'HSK Review Team' (HSK-RT), conducting a 'Participatory Peer Review' (see SSHAC 1997: NUREG/CR-6372; Vol.1, p. 48-49). Composed of recognised experts, the HSK-RT had to provide assurance that the PSHA process, as described in the PEGASOS Project plan, was properly implemented, that the study incorporated the diversity of views in the technical community, that uncertainties were properly considered in the analysis, and that the documentation of the study was clear and complete.

Hazard Results and Sensitivities

State-of-the-art seismic hazard studies calculate ground motion exceedence probabilities using earth science hypotheses about the causes and characteristics of earthquakes in the region being studied. Scientific uncertainty about the causes of earthquakes in the PEGASOS study region, and about the physical characteristics of potentially active tectonic features, lead to uncertainties in the inputs to the seismic hazard calculations. Similarly, seismologists and earthquake engineers develop equations estimating strong ground shaking in the region, expressing uncertainties in scientific understanding with alternative hypotheses on magnitude and distance scaling, as well as the response of soils at individual sites to ground motions.

Both aleatory variability and epistemic uncertainty are captured and are treated differently in advanced PSHA studies, such as the PEGASOS Project. Integration is carried out over aleatory variabilities to obtain a single hazard curve, whereas epistemic uncertainties are expressed by multiple assumptions, hypotheses, models, or parameter values. These multiple interpretations are propagated through the analysis, resulting in a suite of hazard curves and their associated weights. Results are presented as curves showing statistical summaries (e.g. mean, median, fractiles) of the exceedence probability for each ground motion amplitude.

The hazard results have the form of annual probabilities of exceedence of various levels of vibratory ground motion (peak and spectral accelerations). Probabilities down to 10^{-7} are considered. The integrated hazard results provide a representation of seismic rock hazard and its uncertainty at the four sites, based on the four SP1 expert teams' and five SP2 experts' models. Separate rock hazard results are obtained for PGA and for spectral accelerations at 0.5, 1, 2.5, 5, 10, 20, 33, and 50 Hz. These rock hazard results, combined with the site-specific SP3 expert models, provide a representation of seismic soil hazard and its uncertainty at the four sites. For each site, soil hazard results are obtained for the aforementioned ground motion measures and, in addition, for spectral accelerations at one or two site-specific resonance frequencies.

Comparison of the PEGASOS hazard results to the results from the old site-specific studies performed during the past two decades indicate that the differences between the two sets of results are primarily due to the failure of the older studies to properly account for aleatory variability in ground motions. If the old calculations are revised to include the effect of aleatory variability in ground motions (following current practice), the results are comparable to the PEGASOS results.

An extensive set of sensitivity and deaggregation analyses have been conducted and are included in the report. At ground motion levels corresponding to low probability levels (e.g. PGA = 0.7 g), the hazard at all four sites is dominated by M6 – M7 earthquakes at short distances (0 – 20 km). This is a common result for hazard analyses conducted within stable continental regions lacking active faults. The more active distant sources, which contribute to the hazard at low frequencies and low ground motion levels, are not important sources at the low probability levels.

Sensitivity analyses show that the hazard results are driven by a few key uncertainties. The highest contribution to the total uncertainty arises from the median ground motion models, while the source charcterisation variables show much less epistemic uncertainty. This large uncertainty from the median ground motion models is an expected result and reflects the key issue that faced the SP2 experts: Do the low ground motions observed for small magnitude earthquakes in Switzerland imply that the ground motions from large magnitude earthquakes in Switzerland will also be lower than in other parts of Europe? Until progress is made on this issue, there will remain a large epistemic uncertainty in the rock motions, which will dominate the epistemic uncertainty in the rock hazard.

Another key uncertainty is that associated with the site response models. At low ground motion levels (e.g. 0.15 g for 1 Hz), the largest uncertainty results from the median amplification factor. For the high ground motion levels, the maximum soil motion model is also a signficant contributor to the uncertainty.

The size of the uncertainty in the rock hazard is also fairly typical for sites with significant ground motion model uncertainty. For example, the 15th to 85th fractile range of the PGA hazard on rock at a mean probability level of 1E-4 corresponds to a factor of 20. For comparison, the 15th to 85th fractile from the Yucca Mountain study corresponds to a factor of 30.

Analysis shows that the uncertainties expressed by an individual expert ("within-expert" component of uncertainty) are dominant contributors to the total hazard uncertainties, rather than the uncertainties among multiple experts ("expert-to-expert" component). This is a positive result and supports the conclusion that each expert has made a concerted attempt to consider the views of the larger technical community in their expressions of uncertainty.

Conclusions

As stipulated by HSK, explicit procedural guidance for a SSHAC Level 4 study was followed concerning the approach to be used by the licensees to conduct the PEGASOS study. The assessments were based on evaluations by multiple experts or expert panels. The experts were selected to represent the state of knowledge of the scientific community in their field and were to be asked to evaluate and present the whole range of credible interpretations of the data available to address hazard issues, such as seismic sources, ground motion attenuation and site response. The experts provided their assessments of the uncertainties associated with their models and parameters. The hazard calculations were conducted using qualified software and incorporated the expert assessments. All of the procedural and technical aspects of the study have been documented in this report.

In addition to following the SSHAC Level 4 procedural guidance, the PEGASOS study incorporated new procedural and technical aspects. The assessment of site response models and uncertainties by the use of expert elicitation has not been conducted in previous studies. Likewise, the explicit assessment of maximum ground motions is an innovative aspect and is commonly not addressed. Procedurally, the development and use of hazard input documents (HIDs) served to formalise the interface between the expert assessments and the hazard calculations.

In all aspects, the PEGASOS Project represents a fulfilment of HSK's requirement for the conduct of a SSHAC Level 4 expert elicitation. Since issuance of the SSHAC guidelines, the PEGASOS project represents only the second Level 4 seismic hazard analysis that has been conducted, following the Yucca Mountain PSHA. The project was structured to ensure the proper training, data development and dissemination, expert interactions, technical facilitation, model development, uncertainty treatment, and documentation. Using a participatory peer review process, HSK monitored all important aspects of the project and provided their feedback to the project management and technical facilitation team. Although the structured expert elicitation approach required by Level 4 has not previously been conducted in Europe, it does have precedence in studies for NRC regulated facilities in the US. The results of the study, documented in this report, incorporate fully the assessments of the experts of the three subprojects.

ACKNOWLEDGEMENTS

The project and the present report could not have been completed successfully without the hard work and whole-hearted commitment of the many individuals who were involved in the project work over the past three and a half years. First and foremost, we would like to acknowledge the contributions of the PEGASOS experts who came together from all over Europe to determine the input elements for this study in open discussions and friendly debates. The professional conscientiousness, dedication and enthusiasm of the experts never failed to impress all those who had the opportunity to be present at workshops and elicitation meetings. Three of the six volumes of this report series bear witness to the outstanding quality of their work. It is probably safe to say, that the novel expert elicitations and SSHAC methodology might not have been so well received in Europe without the skilled and convincing implementation by the two TFIs, Norm Abrahamson and Kevin Coppersmith. With their professional stature and experience, they both brought to the job the human qualities required to fulfil their TFI roles in an admirable manner and they have earned our most sincere gratitude and appreciation. Among the indispensable elements for the success of this project, Proseis AG holds a prominent position. The team provided impeccable support and services to the experts and lived up to all the challenges of the huge and complex hazard computation task. We would like to express our gratitude to René Graf, Philippe Roth, Jim Farrington and Andreas Hoelker from Proseis and

Ulli Kuhlmann from TK-Consult for their excellent work. We are equally indebted to Gabriel Toro and Robin McGuire from Risk Engineering for providing the essential software and for their backing of the project with their tremendous know-how and experience. Risk Engineering and Proseis formed a strong team, they never admitted defeat and their dedication and unrelenting efforts enabled us to overcome all the difficulties that were encountered. The list of individuals who greatly contributed to the project results is by no means complete; it also has to include our Swiss consultants, in particular Dieter Mayer-Rosa, the resource experts, the staff and management of Nagra and many others.

Special thanks are due to the review team of HSK, which accompanied and supervised the project from the beginning. With their comments, critisism and (occasional) praise, the members of review team provided not only procedural guidance but also made an important contribution to the robustness of the project results.

This project was performed under the auspices and sponsorship of the UAK, the Association of Swiss Nuclear Power Plant Operators. We are grateful for their support and funding; special thanks go to [redacted] who always lent us his ear and ensured smooth interactions with the clients.

On behalf of the Project Management Team:

Christian Sprecher

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

AF	Project Document Archiving Form
CMD	Computing, Modelling and Database Centre
DB	Database
EMT	Extended Management Team
EPRI	Electric Power Research Institute (USA)
ES	Elicitation Summary
EXA	Expert Assessment
EXM	Expert Model
GIS	Geographic Information System
GM	Ground Motion
HID	Hazard Input Document
HSK	Swiss Nuclear Safety Inspectorate (Hauptabteilung für die Sicherheit der Kernanlagen)
HSK-RT	HSK's PEGASOS Project (participatory) Review Team
ITR	Independent Technical Rewiev
LF	Fault Length
LLNL	Lawrence Livermore National Laboratory (USA)
M_w	Moment Magnitude
NPP	Nuclear Power Plant
NRC	U.S. Nuclear Regulatory Commission
PF	Project Data Archiving Form
PGA	Peak Ground Acceleration
PMT	Project Management Team
PSA	Probabilistic Safety Assessment
PSHA	Probabilistic Seismic Hazard Analysis
REI	Risk Engineering Inc., Denver / CO, USA
RF	Rupture Length
RIF	Rock Hazard Input File
SED	Swiss Seismological Service
SIF	Soil Hazard Input File
SP1	Source Characterisation Subproject
SP2	Ground Motion Characterisation Subproject
SP3	Site Response Characterisation Subproject
SP4	Seismic Hazard Calculation Subproject

SSHAC	Senior Seismic Hazard Analysis Committee (s. SSHAC 1997: NUREG/CR-6372 Report)
TFI	Technical Facilitator/Integrator
UAK	'Unterausschuss Kernenergie der Ueberlandwerke': Association of Swiss Nuclear Power Plant Operators; sponsor of the PEGASOS Project
UHS	Uniform Hazard (Response) Spectrum
WP	Work Package (clearing unit for expert work)
WS-1 / …	Workshop type 1, 2, 3, 4, 5

GLOSSARY OF TERMS

Acceleration (Ground)	Acceleration at the ground surface produced by seismic waves. Typically expressed in units of g (1 g = 9.80665 m/s^2).
Acceleration (Spectral)	Pseudo-absolute response spectral acceleration, given as a function of frequency and damping ratio (typically 5 %). It is equal to the peak relative displacement of a linear oscillator of frequency f attached to the ground, times the quantity (2πf)2. It is expressed in units of g or cm/s^2.
Active Fault, Active Source	A fault or area source that, on the basis of historical, seismological or geological evidence, is considered to have a non-zero probability of producing an earthquake in the present tectonic environment.
Activity Rate	See 'Recurrence'
Aleatory Variability	Uncertainty inherent in a non-deterministic (stochastic, random) phenomenon. Aleatory uncertainty is reflected by modelling the phenomenon in terms of a probabilistic model. In principle, aleatory uncertainty cannot be reduced by the accumulation of more data or additional information. Sometimes called randomness.
Area Source	A region of the earth's crust that is assumed for PSHA to have relatively uniform seismic source characteristics (see also 'Seismic Source Zone').
Attenuation, Ground Motion	Decrease in severity (or amplitude) of ground shaking with increasing distance from the earthquake source.
Background Source	Regional scale area source.
Bandwidth	Range of frequencies or periods.
Basic Data	Outside data as they were originally accepted and entered into the PEGASOS Project data DB
Branch Tip Model	Model resulting from a single path through a logic tree.
b-value	Parameter of the Gutenberg-Richter earthquake recurrence model describing the decrease in the relative frequency of occurrence of earthquakes of increasing sizes. It is the slope of a straight line relating the common logarithm (base 10) of absolute or relative frequency to earthquake magnitude.
Classified Document	Important document that is entered into the PEGASOS Project document DB under an Identifier Code and accompanied by an AF
Clustering (Temporal)	Occurrences of multiple, closely timed earthquakes separated by longer periods of quiescence. Events that tend to cluster represent a deviation from the standard assumption of a stationary Poisson process.
Clustering (Spatial)	Occurrences of multiple earthquakes in close proximity, separated from other earthquakes by longer distances.

Controlling Earthquake	Controlling earthquakes are characterised as mean magnitudes and distances derived from a deaggregation analysis of the mean estimates of the PSHA.
Convolution	Complex multiplication in the frequency domain. Used in site response analysis to take the ground motion at a given depth and 'propagate' it upwards through the soil column. Also used in probability calculations to obtain the distribution of the sum of two or more random variables.
Design Earthquake	The magnitude, distance, and other parameters representing the design ground motion.
Design Ground Motion	A specification of the seismic ground motion at a site used for the earthquake-resistant design of a structure.
Design Spectrum	A set of curves for design purposes that gives spectral acceleration, velocity or displacement (usually absolute acceleration, pseudo-relative velocity, and relative displacement) of a single degree of freedom oscillator as a function of natural period of vibration and damping. (Alternative: The spectral representation of design ground motion).
Distance, Epicentral	Distance from the epicentre of an earthquake to a specific location (site).
Distance, Fault	Shortest distance from the fault to a location (site).
Distance, Hypocentral	Distance from the hypocentre of an eathquake to a specific location (site).
Distance, JB	Shortest distance from a point immediately above the ruptured portion of the fault to a specific location (site) (after Joyner & Boore 1981).
Document Administration DB	Listing of all classified PEGASOS Project documents
Document Archiving Form (AF)	Form used to archive PEGASOS classified documents (see *Sprecher 2003, QA-TN-0402*)
Duration (of ground motion or earthquake rupture)	The length of time during which ground motion at a site shows certain characteristics (e.g. perceptibility, large amplitudes) (see " Frequency (Corner)")
Earthquake	A sudden motion or trembling of the earth caused by the abrupt release of slowly accumulated strain. The ground motion may range from violent at some locations to imperceptible at others (Alternative: Naturally occurring shear failure of rock masses within the earth that gives rise to propagating seismic waves).
Elicitation Summary (ES)	Detailed description of a PEGASOS expert model (includes the technical basis for decisions made)
Epistemic Uncertainty	Uncertainty attributable to incomplete knowledge about a phenomenon which affects our ability to model it. Epistemic uncertainty is reflected in a range of viable models, multiple expert interpretations, and statistical uncertainty. In principle, epistemic uncertainty can be reduced by the accumulation of additional information. (See 'Modelling Uncertainty').

Exceedence Probability	Probability that a specific amplitude of ground motion for at least one earthquake will be exceeded at least once at a site or in a region during a specific exposure time.
Expected Occurrence Rate	Expected value of the number of occurences of an event (e.g. earthquakes) per unit time; generally denoted as ν. Sometimes expressed in units of events / unit time / unit area.
Expected Value	Average or mean value, taken with respect to its probability distribution, of an aleatory (random) or uncertain (epistemic) variable.
Expert Assessment (EXA)	Preliminary and / or incomplete description of a PEGASOS expert model or any other PEGASOS expert elicitation product.
Expert Model (EXM)	Complete subproject-specific PSHA input contribution by one PEGASOS expert (SP2 / 3) or one PEGASOS expert group (SP1).
Extended Management Team (EMT)	PEGASOS PMT plus the TFIs.
Fault	Planar or gently curved fracture surface or zone in the earth across which there has been relative displacement.
Fault, Dip-Slip	Fault in which the relative displacement is along the direction of the dip of the fault plane; either down-dip (normal fault) or up-dip (reverse fault).
Fault, Normal	Dip-slip fault in which the block above the fault has moved downward relative to the block below. This type of fault represents crustal extension.
Fault, Reverse	Dip-slip fault in which the block above the fault has moved upward relative to the block below and the fault dip > 45°.
Fault, Strike-Slip	Fault in which the relative displacement is along the strike of the fault plane, either right- or left-lateral. May occur due to crustal extension or crustal compression.
Fault, Thrust	Dip-slip fault in which the block above the fault has moved upward relative to the block below and the fault dip < 45°. This type of fault represents crustal compression.
Fault Zone	Zone of deformation comprising a fault.
Final (Project) Data	Project data used as input for the PEGASOS final hazard computations.
Final Hazard Computation	Final computation of PEGASOS site-dependent rock and soil hazard (final project results).
Focal Mechanism	Combination of the dip angle of the fault and the direction of slip across the fault; faults are classified as strike-slip, normal or reverse (see 'Fault'). (Alternative: Geometrical representation of earthquake faulting expressed in terms of the strike and dip of the fault plane and the rake angle of the slip vector with respect to the fault plane).
Frequency (Corner)	Frequency at which the amplitude spectrum of an earthquake transitions from a low-frequency level controlled by the

	seismic moment to a high-frequency level controlled by the stress drop. l/fc is approximately the duration of the earthquake rupture.
Global Logic Tree	PEGASOS logic tree containing variables which affect multiple sources.
Ground Motion Attenuation Model	Analytical model used to relate some measure of ground motion (e.g. peak ground acceleration or spectral acceleration) magnitude, distance, source and path parameters. A variety of such models exists. A simple, commonly used form is g(m,r) = C1 + C2M + C3 log R + C4 R. The ground motion model is part of a model for observed ground motion measures, e.g. log A = g(m,r) + ε , where ε denotes aleatory uncertainty. Inherent in the model of the observed ground motion measure is a model of the aleatory uncertainty, often taken to be a normal (Gaussian) probability distribution, i.e. ε ~ Normal (0, σ), where σ, the standard deviation of ε , quantifies the aleatory variability of the ground motion measure. If more complex models are considered, including source and path parameters, e.g. stress drop, and if any of these parameters are aleatory uncertain parameters, the model should include their (aleatory) probability distribution similar to that given for ε above.
Gutenberg-Richter Relation	Model of the relationship between frequency and magnitude of earthquakes (in some specified region), expressed as log N = a – bM, where N is the number of earthquakes with magnitude greater than M and b is the b-value.
Hazard Input Document (HID)	PEGASOS expert model description in terms of inputs required for the hazard computation.
Hazard Software Specialist	PEGASOS TFI-team member with specialist knowledge of the rock (FRISK88MP) and soil (SOILHAZP) hazard software packages and their input requirements.
HSK Review Team (HSK-RT)	(Participatory) review team established by HSK to supervise the PEGASOS Project.
Hypocentre, Focus	The point in the earth at which an earthquake is initiated.
Identifier Code	PEGASOS three-key alphanumeric code that uniquely identifies a classified project document or an item in the project data DB.
Independent Technical Review (ITR)	Review of a PEGASOS data set or computation by a person, other than the originator, who is competent in the relevant technical area.
Intensity	Measure of the effects of an earthquake at a particular place. Commonly used scales to specify intensity are the Rossi-Forel, Mercalli and Modified Mercalli.
Lower Bound Magnitude	Lowest earthquake magnitude considered in deriving the seismic hazard curve for a site (The choice of the lower bound magnitude is based on arguments that smaller earthquakes will not cause structural damage to well-engineered structures).

Magnitude	Measure of earthquake size, determined by taking the common logarithm (base 10) of the largest ground motion observed during the arrival of a certain wave train (e.g. P waves or surface waves) and applying a standard correction for distance to the epicentre.
Magnitude, Body-Wave	Magnitude derived from the largest displacement amplitude of body waves (P or S).
Magnitude, Coda-Wave	Magnitude derived from the amplitude and duration of the seismic coda.
Magnitude Distribution	(Conditional) aleatory probability distribution of earthquake magnitude, given the occurrence of an earthquake, assumed to be homogeneous at all locations throughout a source/ subsource/seismic area. The probability distribution (given a sufficient number of earthquake events) is estimated as $$f_M(m)\,\Delta m = \frac{number\ of\ earthquakes\ with\ magnitude\ in\ \Delta m}{total\ number\ of\ observed\ earthquakes}$$ where f_M (m) is the probability density function. Due to lack of sufficient historical data, this distribution is often taken to be the Gutenberg-Richter relation.
Magnitude, Lg	Magnitude derived from the displacement amplitude of Lg waves; often used in Eastern North America because it can be accurately measured from typical low-gain seismographs at long distances from the source.
Magnitude, Moment (M_w or M)	Earthquake magnitude derived from the seismic moment. Approximately equal to local magnitude for moderate earthquakes, and to surface-wave magnitude for large earthquakes. Magnitude scale M_w differs from M by a small constant (0.033).
Magnitude, Richter or Local (1935)	Common logarithm of the trace amplitude (in microns) of a standard Wood-Anderson seismograph located on firm ground 100 km from the epicentre. Correction tables are used to account for other distances and ground conditions.
Magnitude, Surface-Wave	Earthquake magnitude determined from the maximum amplitude of 20 s period surface waves.
Maximum Credible	The phrase used to specify the largest value of a variable, e.g. the magnitude of an earthquake, which might reasonably be expected to occur. A confusing term with no quantifiable definition. Not recommended for use in PSHA.
Maximum Magnitude	The largest earthquake that a seismic source is capable of generating. The maximum magnitude is the upper bound to recurrence curves or magnitude distributions. It is assumed that all points within an area source have the same maximum magnitude.
Mean	Average (or expected) value of a set of data.
Median (sample median)	Fiftieth fractile of the probability distribution of a variable (middle value of an ordered list of a set of data).

Memo Administration DB	Listing of all non-classified PEGASOS Project documents (PEGASOS MEMO designation).
Model Logic Tree	Logic tree description of the full set of weighted alternatives included in a PEGASOS expert model.
Modelling Uncertainty	Variability of a model-predicted value from the value of the quantity being predicted. In principle, it can be reduced or eliminated by further testing, data accumulation, or more detailed modelling. It is one source of epistemic uncertainty (Often called systematic uncertainty).
Non-classified Documents	Documents that are not considered to be essential for the traceability of PEGASOS Project results or project decisions
Outcrop Motion	Motion specified at the free surface of either a real or hypothetical bedrock outcrop at the ground surface. This motion thus represents the earthquake motion unaltered by surface soft soil layers.
Peak Acceleration	Maximum value of acceleration displayed on an accelerogram.
Peak Displacement	Maximum value of displacement obtained or calculated from a record of ground motion.
Peak Ground Acceleration (PGA)	Maximum absolute amplitude of a ground acceleration time series; controlled by the highest frequency content in the spectrum.
Peak Velocity	Maximum value of velocity obtained or calculated from a record of ground motion.
Pinch Point	Point in the logic tree where a number of branch tip models are grouped into a smaller representative subsets with the appropriate weights.
Preliminary (Project) Data	Non-final PEGASOS Project data; can be used for preliminary hazard computations by the originator subproject or, if released, throughout the Project.
Preliminary Hazard Computations	Hazard input sensitivity tests on behalf of the PEGASOS experts.
Project	The PEGASOS Project.
Project Data	Data that are known to have, or may have, a direct influence on the numerical results of the PEGASOS Project.
Project Data Archiving Form (PF)	Form used to archive PEGASOS Project data (see *Sprecher 2003, QA-TN-0402*); indicates QA and data release status.
Project Database	Includes PEGASOS Project documents and the project data DB.
Project Document Archiving Form (AF)	Form used to archive PEGASOS Project documents (see *Sprecher 2003, QA-TN-0402*).
Project Document	Any form of written record that is likely to be needed to reconstruct history, results or the background of important PEGASOS Project decisions.

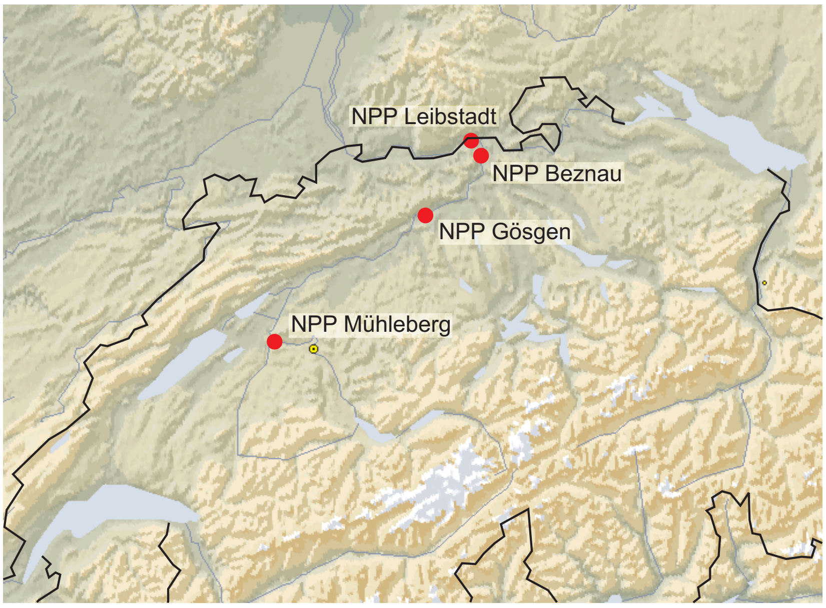
Project Management Team (PMT)	PEGASOS project manager, subproject managers and two project consultants.
QA Certification	Process of filling in and signing of a dedicated PEGASOS QA form (see *Sprecher 2003, QA-TN-0402*) to provide proof that the compulsory QA procedures have been followed.
Randomness	See 'Aleatory Uncertainty'.
Rate of Seismicity	Rate of occurrence of earthquakes above some specified magnitude for a specified region.
Recurrence Interval	The mean time period between earthquakes of a given magnitude.
Recurrence Model	A model to express the relative number or frequency of earthquakes having different magnitudes. A common recurrence model is the exponential magnitude distribution developed by Gutenberg and Richter.
Recurrence, Recurrence Rate, Recurrence Curve	The frequency of earthquake occurrence of various magnitudes, often expressed by the Gutenberg-Richter relation.
Repeat Time	See 'Recurrence Interval'.
Response Spectrum	A set of curves that gives spectral acceleration, velocity or displacement as a function of period of vibration and damping.
Return Period	Commonly used to express the mean time period (in years) between ground motions of a particular amplitude (inverse of exceedence probability).
Rock Hazard Input File (RIF)	Input file for the PEGASOS rock site hazard code (FRISK88MP) prepared for one or more sites by SP4 on the basis of source and ground motion HIDs.
Seismic Hazard Curve	A plot of an estimate of the expected frequency of exceedence (over some specified time interval) of various levels of some characteristic measure of an earthquake (often peak ground acceleration). The time period of interest is often taken as one year, in which case the curve is called the annual frequency of exceedence.
Seismic Moment	A measure of the size of an earthquake based on interpretations of how much stress was relieved over the area of the fault or rupture surface. It is defined by the product of the rupture area, the average slip, and the crustal shear modulus.
Seismic Source	General term used to define faults or area sources.
Seismic Source Characteristics	The parameters that characterise a seismic source for PSHA, including source geometry, probability of activity, maximum magnitude, and earthquake recurrence.
Seismic Source Zone	See 'Area Source'
Seismic Zone	A region showing relatively elevated levels of observed seismicity.

Seismicity	Denotes the propensity for earthquakes to occur in a region and the possible magnitudes, locations and depths of these earthquakes.
Seismogenic	Capable of generating tectonically significant earthquakes.
Seismotectonic Province	A region of the earth's crust having similar seismicity and tectonic characteristics.
Site Response (amplification)	The amplification (increase or decrease) of earthquake ground motion by rock and soil near the earth's surface in the vicinity of the site of interest. Topographic effects, the effects of the water table, and basin edge wave-propagation effects are sometimes included under site response.
Soil Hazard Input File (SIF)	Input file for the PEGASOS soil site hazard code (SOILHAZP) prepared for one or more sites by SP4 on the basis of rock site hazard computations and site response HIDs.
Source Logic Tree	Logic tree with variables affecting a single seismic source (e.g. activity, max. magnitude, recurrence).
Source Zone	See 'Area Source'.
Stationary Poisson Process	A probabilistic model of the occurrence of an event over time (space) characterised by the following properties: (1) the occurrence of the event in a small interval is constant over time (space), (2) the occurrence of two (or more) events in a small interval is 'negligible' and (3) the occurrence of the event in non-overlapping intervals is independent. The model is often used to model the temporal and spatial occurrence of earthquakes within a source zone/seismic area.
Stress Drop	The average shear stress released across a rupture surface during an earthquake, usually expressed in units of bars (1 bar = 1.013 × 106 dyne/cm^2).
Supporting Computations	Computations requested by, and carried out on behalf of, PEGASOS experts by the CMD or outside contractors (e.g. num. site response simulations).
Uncertainty	See "Epistemic Uncertainty" and "Aleatory Uncertainty".
Uniform Hazard Spectrum	A spectrum that is created by calculating the spectral acceleration or velocity associated with a specified annual probability of exceedence and a specified level of damping (% of critical) for many frequencies.
Upper Bound Magnitude	See "Maximum Magnitude".
Variance	The expected value, taken with respect to its probability distribution, of the squared deviation of an aleatory variable from its mean value.
Zonation	The process of developing seismic source maps (or a set of seismic zones) and their associated parameters.

1 INTRODUCTION

In 1998, HSK, the Swiss Nuclear Safety Inspectorate, identified the need to update the seismic hazard assessments for the Swiss nuclear power plants (NPPs). This was partly due to advances in the seismic hazard analysis methodology achieved in the United States in the eighties and early nineties. A Probabilistic Seismic Hazard Analysis (PSHA) according to the rules first established by the 'Senior Seismic Hazard Analysis Committee' (SSHAC) on behalf of the US-NRC, US-DOE, and EPRI was considered by HSK to best represent the current state-of-the-art. It was decided that the study should be carried out in its most elaborate form, with the entire input based on evaluations by multiple experts and the systematic, quantitative assessment of the uncertainties. Accordingly, the Swiss nuclear power plant operators ('licensees') were requested to envisage, and prepare for, a new hazard study that would satisfy SSHAC Level 4 criteria (see below).

The licensees, organised as the 'Association of Swiss Nuclear Power Plant Operators' (UAK), agreed to commission the study and approached Nagra, the Swiss National Cooperative for the Disposal of Radioactive Waste, to help them plan, organise and perform the new seismic hazard assessment for all four power plant sites. The study has since become known under the name of the 'PEGASOS Project' (Probabilistische Erdbeben-Gefährdungs-Analyse für KKW-StandOrte in der Schweiz).



Coordinates:

NPP Leibstadt	8° 11' 04"	47° 36' 08"
NPP Beznau	8° 13' 46"	47° 33' 12"
NPP Gösgen	7° 58' 04"	47° 22' 02"
NPP Mühleberg	7° 16' 09"	46° 58' 13"

Fig.1-1: Map showing the locations of the four Swiss nuclear power plants

A PSHA project plan was submitted to HSK before the end of 1999. Following its approval, the study was initiated early in 2001 and successfully completed according to plan within the originally allocated schedule in July 2004. With this report, we are presenting the results which, according to HSK, will be used to 'quantify risks in PSA studies and to develop updated seismic design criteria for Swiss nuclear power plants' (*HSK 2001f, PMT-RF-0039*).

The project is, to our knowledge, one of the most comprehensive seismic hazard studies carried out anywhere in the world to date, rivalled only by the pioneering USGS Level 4 PSHA for the Yucca Mountain site.

1.1 Project Objectives and Scope of Work

The objectives of the PEGASOS Project are as follows:

1. To evaluate earthquake-induced ground motion hazards and their uncertainty at the four sites of the Swiss nuclear power plants: Mühleberg, Beznau, Gösgen, and Leibstadt; and
2. To provide documentation of the technical basis for determining these hazards.

The hazard results have the form of annual probabilities of exceedence of various levels of vibratory ground motion (peak and spectral accelerations). Probabilities down to 10^{-7} are considered. The ground motions at each plant are given for a reference rock site condition at the surface and for the site-specific soil condition at the surface and at two specified building foundation levels. A comprehensive list of the project objectives (result specifications) is given in section 7.2 of this volume.

HSK stipulated explicit guidance concerning the overall approach that had to be used by the licensees to achieve these objectives. Seismic hazard assessments were to be based on evaluations by multiple experts or expert panels. The experts were to be selected to represent the state of knowledge of the scientific community in their field and were to be asked to evaluate and present the whole range of credible interpretations of the data available to resolve hazard issues. They were also expected to assess the uncertainties associated with these interpretations and hypotheses.

Inputs for a PSHA involve a multitude of issues, such as seismic source identification, seismicity parameters, ground motion models, uncertainties, etc. With regard to all these inputs, the SSHAC has formulated the fundamental principles that *'the underlying basis for inputs related to any of these issues must be the composite distribution of views represented in the appropriate scientific community '* and that *'expert judgement is used to represent the informed scientific community's state of knowledge'.* This originates from the acknowledgement that we still have only an incomplete understanding of earthquake generating mechanisms and processes that govern seismic energy propagation. The database available for the statistical treatment of earthquake occurrence is limited and often not satisfactory for the purpose. The data that exist are, as a rule, interpreted differently by different experts and these divergent interpretations translate into significant uncertainties in the results from a PSHA. These uncertainties, originating from two distinguishable sources, our incomplete knowledge base on the one hand and the random nature of the earthquake process on the other, have to be accepted if the objective of a seismic hazard analysis to be attained. SSHAC's answer to the question of how we should best fill these gaps in our knowledge and, at the same time, quantify the unavoidable uncertainties is by carefully structured expert judgement.

The roles of the experts on one side and the analysts of the project team on the other are clearly defined. While the experts are asked to act as representatives of the 'informed technical community', determining the input for the hazard study, it is the task of the analysts to facilitate the experts' work, provide data, general support and procedural guidance and – in the end – condense the range of expert opinions into an unbiased analytical result that captures in the best possible way the current state of knowledge. The SSHAC describes this last item as '*properly representing the center, the body and the range of technical interpretations that the larger informed technical community would have if they were to conduct the study*' and considers it to be the most difficult challenge of a PSHA. For the analyst entrusted with this important responsibility, the term 'Technical Facilitator/Integrator' or TFI has been introduced. In this study, we acknowledged and accepted the above basic understanding of the respective roles of experts and analysts in the PSHA process, including the key position held by the TFI. It is reflected in the way the project organisation was set up and the way the project work has been conducted.

The seismic hazards presented as a result of this study are exclusively based on input that has been developed by the appointed and recognised experts and expert panels of the project. Four expert panels or groups (EG1a-d), each comprising three experts, contributed models of the seismic sources. Five individual experts, making up expert group EG2, evaluated ground motion attenuation and provided the models used to compute the site specific rock hazard. The soil site conditions at each of the power plant sites were investigated and characterised by the four experts of expert group EG3, who supplied the input models for the soil hazard computations.

Evaluating the available data and the range of credible interpretations was the common task of all experts and expert groups. These evaluations were carried out in a structured and formal manner under the leadership of two TFIs, one assuming responsibility for the seismic source characterisation and the other for the ground motion and site response characterisation process. Another role of the TFIs was to ensure adequate communication and interaction between the subprojects. The important parts of the 'expert elicitation' process were open, face-to-face discussions of key technical issues and alternative hypotheses and interpretations during the project workshops and elicitation meetings. These interactions had the purpose for all experts to develop a common level of understanding of technical issues, available data and current scientific thinking and to minimise misunderstandings. While 'resource experts' were invited to illustrate proponents’ views, the experts themselves were asked to serve as evaluators of the current state of knowledge of the scientific community and not as promoters of their own favourite hypotheses or models. The process culminated in the elicitation of the PSHA input in the form of multiple expert models. The uncertainty in these models is expressed in a logic tree structure as weighted alternatives.

The assessments and the associated uncertainties were propagated through a two-step hazard computation process, both of these steps relying on well established seismic hazard codes. The first step produced rock site condition results for all four power plant locations. The second step used the site response expert models to establish the soil site condition hazard, using the rock hazard as input. The basic hazard results are presented as mean, median and fractile curves, reflecting the total aleatory and epistemic uncertainty attributed by the experts to their input models.

1.2 Background

1.2.1 Earthquake Hazard in Switzerland

Earthquakes are considered an important natural hazard in Switzerland. They are basically a manifestation of the ongoing tectonic activity including the Alps in the south and the Rhine Graben in the north. Historical earthquakes reached magnitudes larger than $M_S = 6$ in the alpine as well as in the pre-alpine areas. However, on a worldwide scale this level of seismicity may be considered low to medium. In the past, earthquakes originated in practically all areas of Switzerland with varying recurrence rates. In combination with the rather dense distribution of sensitive structures (lifelines and power facilities), the severity of damage scenarios (risk assessment) has become a matter of major concern for the Swiss Government, as well as for the private industrial sector.

1.2.2 Previous Seismic Hazard Studies for Swiss NPPs

The first homogeneous countrywide earthquake hazard map was prepared in 1977, with special emphasis on the requirements of the nuclear power plants. New earthquake design spectra were developed in 1980 at the request of the Swiss Federal Nuclear Safety Inspectorate (HSK). Different but fairly generalised geological ground conditions were taken into account. A number of specific seismic studies were performed between 1984 and 1996 for each of the existing

NPPs, calculating seismic hazard for annual probabilities of exceedence down to 10^{-7} (Basler & Hofmann 1984 / 1989 / 1991 / 1996).

1.2.3 Motivation for the PEGASOS Project

Probabilistic safety assessments (PSAs) performed for Swiss and foreign nuclear power plants have shown that earthquakes are a significant contributor to the estimated frequency of core damage. The Swiss nuclear regulatory authority therefore places considerable emphasis on the evaluation of the seismic hazard. Based on their review of older studies, HSK concluded in 1998 that existing seismic hazard assessments were no longer state-of-the-art and required updating. As a result, HSK made an effort to initiate a new evaluation of the seismic hazard at the four nuclear power plant sites Mühleberg (KKM), Gösgen (KKG), Beznau (KKB) and Leibstadt (KKL). This evaluation was to be based on up-to-date data and what was considered to be the best available methodological approach that would also explicitly consider uncertainty. HSK issued a set of methodological guidelines to help the power plant operators to plan the new study and specify its scope and requirements. The guidelines closely resemble the study Level 4 methodology recommendations issued by the 'Senior Seismic Hazard Analysis Committee' (SSHAC 1997: NUREG/CR-6372).

The concept of sampling the state of knowledge of the informed scientific community by expert elicitation and then using the aggregated views and opinions with their assessed uncertainty as input for the PSHA goes back to two landmark studies in the US in the mid 1980s (EPRI 1989 and Bernreuter et al. 1989). Although successful, some of the results of these studies showed differences that could not be easily explained. This induced the US-NRC and other interested parties to establish the SSHAC to investigate the cause of these differences and provide methodological guidance on the subject. The SSHAC concluded that the main reasons for the differences in the PSHA results were procedural rather than technical, highlighting the need for a formalised process that could improve the stability of future studies. The final report (SSHAC 1997) provides technical advice and procedural guidance at 4 different 'levels of complexity' of a PSHA study. Each of these study levels from 1 – 4 has a higher degree of sophistication, requiring an increasing effort and additional means and resources. The SSHAC recommends that the choice of the level should consider factors such as the importance of the study (as perceived by the public and other stakeholders), the degree of complexity and the amount of contention about the technical issues, the available resources, etc. For the PEGASOS Project, HSK had specifically asked for a 'procedural implementation structure equivalent to a SSHAC Level 4 PSHA' (*HSK 2001f, PMT-RF-0039*).

These recommendations were addressed to the Association of Swiss Nuclear Power Plant Operators UAK ('Unterausschuss Kernenergie der Ueberlandwerke'), who in turn decided to ask Nagra to plan and eventually execute a PSHA project in accordance with the new HSK regulations. In December 1999, Nagra's planning team submitted a first project plan (in German) under the name of PEGASOS ('Probabilistische Erdbeben-Gefährdungs-Analyse für die KKW-StandOrte in der Schweiz'). This draft plan was extensively reviewed by HSK throughout most of the following year. Discussions among the regulator, the utilities and the planning team led to some modifications which UAK agreed to incorporate (see section 1.2.5). The last version dated 20th September 2000 met all requirements and was finally accepted by HSK without reservations. On 24th November 2000, UAK took the decision to sponsor the study and to have it executed by a project team under the overall contractual responsibility of Nagra (a corresponding contract between UAK and Nagra became effective on 24 November 2000).

1.2.4 Project Plan

The PEGASOS Project plan (*Pegasos, PMT 2000 PMT-TB-0001*) was largely based on the SSHAC's recommendations for the implementation of a Level 4 seismic hazard study. It is worth mentioning, however, that experience with the practical application of the Level 4

SSHAC rules is still very limited. This not only applies to Europe but worldwide. To our knowledge, the only known application on a similar scale, after the publication of the guidelines, was the PSHA for the Yucca Mountain high-level nuclear waste repository project in Nevada (CRWMS M&O 1998).

An unprecedented feature of the present study was the Level-4 treatment of site effects. It was decided early on to treat site response in the same manner as all the other PSHA input components and develop site models by multiple expert elicitation, based on the existing site-specific geotechnical information. This geotechnical database for the NPP sites was not unequivocal in all cases, but the constraints of the project schedule did not allow it to be significantly improved. This meant that there was much room for interpretation and a large judgement component to consider. On the other hand, it was expected that the impact on hazard would be significant, which led to the conclusion that it was not justified to treat site effects differently from other key issues and that a full Level 4 expert elicitation approach was warranted.

From the beginning, it had been the intention to use previous US experience with this methodology to the best effect by engaging a consultant who had actively participated in one of the earlier landmark studies. On the other hand, it was a declared aim to use the available local European expertise to the greatest possible extent. Since all the required geological, seismological and hazard analysis expertise could be found in Switzerland and other European countries, it was decided to restrict the selection of experts to Europe. The concept of a strong local base was fully endorsed by the project sponsors, who went one step further by adding the requirement of a local 'PSHA know-how centre' to the list of project objectives. This local centre of competence was intended to accommodate and later maintain a permanent PSHA database with archives, software tools and trained staff, in order to be in a position to carry out hazard computations and update the project results if the need arose. Full autonomy was to be achieved by the time the study ended.

It was found necessary to make minor changes to the implementation of the methodology in order to respond to some characteristics of the European working environment. The lack of a seismological consulting industry comparable to that in the US meant that there were fewer potential experts to choose from. Candidates could not be expected to have any experience with expert elicitation and, since most of them were likely to come from university institutes and government agencies, it was anticipated that they would not in all cases be backed up by adequate in-house support. Training and technical assistance therefore had to be provided by the project. The plan was to have the experts propose and direct data acquisition and processing, supervise its execution and then do the interpretation of the results, up to and including the development of the final PSHA input models. They were expected to provide concepts and instructions rather than the finished products. This project-biased distribution of the workload was quite different from previous studies. It was hoped that there would be benefits in this approach, such as less redundancy of the work that had to be carried out, a more comprehensive and homogeneous project database and equal accessibility of this database for all the experts.

With *Proseis AG* in Zürich-Oerlikon, a local company was identified and chosen to provide computational and drafting services, host the database and archives and act as centre and focal point of the technical project work. As the 'Computing, Modelling and Database Centre' (CMD), Proseis was to be equipped with the necessary PSHA software licences and had to hire and train additional staff to to cope with the assignment. The intention was to have Proseis AG develop the means and skills required to eventually take over the role of the aforementioned 'PSHA know-how centre'. The project headquarters, with management and administration services, was to be located at Nagra's Wettingen premises.

The plan was to develop the PSHA input by 3 groups of experts, each group working under the supervision and guidance of a TFI in an organisational and administrative unit called a subproject. Subprojects were planned for the charcterisation of *seismic sources* (SP1, 5 – 7 experts), *ground motion* (SP2, 3 – 5 experts) and *site response* (SP3, 3 – 5 experts). The 4th subproject had the task of processing and aggregating the expert-developed input and deriving the seismic hazard. Since SP4 (*seismic hazard computations*) was conceived purely as a computation centre, with analysts receiving the experts' input already in a form that was compatible with the mathematical model used by the PSHA software, without being allowed to introduce any of their own judgement, it was not deemed necessary to provide this subproject with its own experts. SP4 was to be physically located at the CMD.

Three workshops were originally planned to allow the experts to establish their databases and evaluate their inputs in each of the subprojects. The three workshops were to be complemented by individual interpretation work and an as yet undetermined number of elicitation meetings. It was planned to structure and subdivide the project work into work packages, each with subproject-specific objectives and predetermined chargeable time allotments for the experts. The first activities that were anticipated included the selection of TFIs with their teams, the selection of experts, the evaluation and choice of PSHA software and the gathering and compilation of preliminary data sets. Critical processes which had a direct impact either on project results or the reproducibility of these results, including the underlying reasons and decisions, were to be subjected to project-specific QA procedures.

In a process basically driven by expert decisions, it was difficult to foresee how the project would develop in detail. For scheduling and budget planning purposes, a probable scenario had to serve as a starting point. Care was taken not to constrain either the methodological approaches or the databases in their nature, content or size, so that full freedom was preserved for the experts to choose their factual basis and address and resolve the issues in question in any way they wanted. The management had to remain flexible throughout the project to address additional needs as they arose, to allow the project goals to be met.

The review of the project plan by HSK concluded that the plan was comprehensive, technically complete, well structured and organised and generally consistent with the key elements of a Level 4 PSHA. However, HSK criticised the lack of experience in the project team and strongly recommended to engage a 'high level person' with broad PSHA experience to fill this gap. Furthermore, it was recommended to shift the relative weight of the expert elicitation effort from an almost equal distribution over the subprojects to a clear emphasis on SP1, arguing that source characterisation involved the most complex interpretations and required the widest range of scientific expertise. A minimum of 4 independent and multidisciplinary teams of 3 experts each was thought to be necessary to accomplish the SP1 objectives. On the other side, it was felt that the planned expert elicitation effort for the characterisation of site response went beyond HSK's expectations and was not warranted. With regard to workshops, it was recommended to include a fourth workshop in all subprojects to review preliminary seismic hazard and sensitivity results. An early selection of a state-of-the-art PSHA software package was strongly emphasised. Preprocessing software needed to capture epistemic uncertainty in the form of alternative expert interpretations and modern postprocessing routines to display the sensitivity of the hazard to input parameters and interpretations were considered to be mandatory. The project plan review report (*HSK 2001b, EXT-AN-0093*) triggered some discussion between HSK, the UAK and the project planning team. In the end, most of the recommendations of the HSK review team were followed and incorporated in a revised and final version of the project plan (*Pegasos PMT 2000, PMT-TB-0001*).

Project activities went largely according to this plan for the whole of the project duration. The original time schedule and budget could be maintained, in spite of inevitable uncertainties due to the experts' possibility to direct the course of work in their respective areas of responsibility as they saw fit. The one exception to this, and the only significant revision that became necessary, was a consequence of the project sponsors' decision to change the project result specifications (*UAK 2002, UAK-TN-0155*). These changes, which became effective more than two years after the project had started, asked for new evaluations and new products to be calculated. To meet the requirements, an additional workshop and elicitation session of SP3 had to be planned and the project duration and budget had to be extended.

1.3 Project Organisation

1.3.1 Project Stucture

The main components of the project organisation included the project representative of UAK, the project manager, the project management team, three technical subprojects for source (SP1), ground motion (SP2) and site effect (SP3) characterisation, with their respective expert groups and TFI-teams, and a seismic hazard computation group (SP4). Data Procurement and Compilation (DPC) and the Computing, Modelling and Database Centre (CMD) were the major technical support units, designated to help the experts in their evaluations. Adminstrative support was provided by Nagra's secretarial services and a designated project accountant. The role of project QA representative was taken on by an external conultant who assumed responsiblility for implementing and supervising the PEGASOS quality assurance procedures. All team members are shown and mentioned by name on Figure 1-1 and in Tables 1-1 to 1-5 below.

Not part of the project organisation, but shown on the project's organisational scheme, are HSK's review team and the group of representatives of the power plants who contributed to the study. There was frequent interaction between the project management and both of these groups, on special occasions such as workshops as well as on a routine basis, by meetings and progress reports throughout the project's duration. A third group who, without being part of the project organisation, nevertheless played an important role in the PSHA process were technical specialists known by the SSHAC term 'resource experts'. Resource experts were invited on many occasions to familiarise the evaluators with specific data sets, models or interpretations or to discuss particulars of special data processing or modelling work that was about to be commissioned by the evaluator experts. All resource experts who took part in workshops are listed in the workshop summaries (see Vol. 3 of the project report).

The nature of the work that would be required and the partitioning into specialised seismological disciplines led to the fairly obvious division into three thematic subprojects. Work was planned to run in parallel in all three subprojects in order to save time. This meant that adequate interaction on a technical level had to be guaranteed to identify possible interface problems and address and resolve them in time. To ensure good communication between the subprojects was part of the responsibilities of the TFIs. SP2 and SP3 had a common TFI-team, partly because it was recognised that a close cooperation between these two subprojects was particularly important.

All the technical work in each of the subprojects was handled by the attached TFI and his team. The TFI's responsibilities included the guidance and supervision of the experts’ work, as well as the elicitation of the subproject-specific components of the PSHA input. The subproject manager's responsibilities covered mainly non-technical, organisational and administrative aspects that had to be organised from the operations centre in Switzerland. This split of responsibilities was in part a consequence of the high demands that were made on the key positions of the TFIs. It allowed the project to choose the personalities with the best professional reputation and the most relevant record of experience that could be found, regardless of other criteria such as home country or spatial separation from the operations centre in Switzerland. If needed, the subproject managers received technical support from local consultants. These technical consultants were at the same time members of the TFI-teams.

While the Nagra offices in Wettingen played the role of 'project management headquarters' and administrative base, the CMD was the centre of most of the technical project work The CMD was an important asset, not only as a provider of computer installations and skilled staff, but as a permanent 'technical headquarters' which ensured a necessary degree of continuity and provided a physical focal point in a working situation that was otherwise very fluid and thinly spread out over half the globe and a long time period.

1.3.2 Project Management Team

The project management team (PMT) provided overall management of the project. Within the allocated budget and time frame, the team decided all issues with an important impact on the project's course and progress and assumed responsibility for achieving the project's ultimate goals. This involved overseeing the technical work in the subprojects, identifying project needs and dealing with the various expert requests. On a non-technical level, it involved the organisation of workshops, elicitation meetings and expert or expert group working sessions and the preparation and review of reports. The PMT did the detailed planning of all project activities and regularly reviewed the work progress, the schedule and the budget situation. It ensured compliance with the legitimate interests of the clients on the one side and consistency with regulatory requirements on the other. It did its best to support HSK's review effort by regularly briefing the review team, responding to review comments and reports and implementing recommendations. The team consisted of [redacted], the project manager and PMT chairman, [redacted], the manager of SP2 and deputy project manager, [redacted], manager of SP3, [redacted], manager of SP4, and the two permanent project consultants [redacted] and [redacted]. Meetings were held at regular intervals or if justified by special agenda issues.

On several occasions, the PMT was complemented by the TFIs and additional representatives of the hazard computation group. These meetings of the extended management team (EMT) were usually convened to discuss matters of overriding general importance or matters that needed special inter-subproject coordination, such as resolving interface problems or adapting hazard software tools to the expert-generated input.

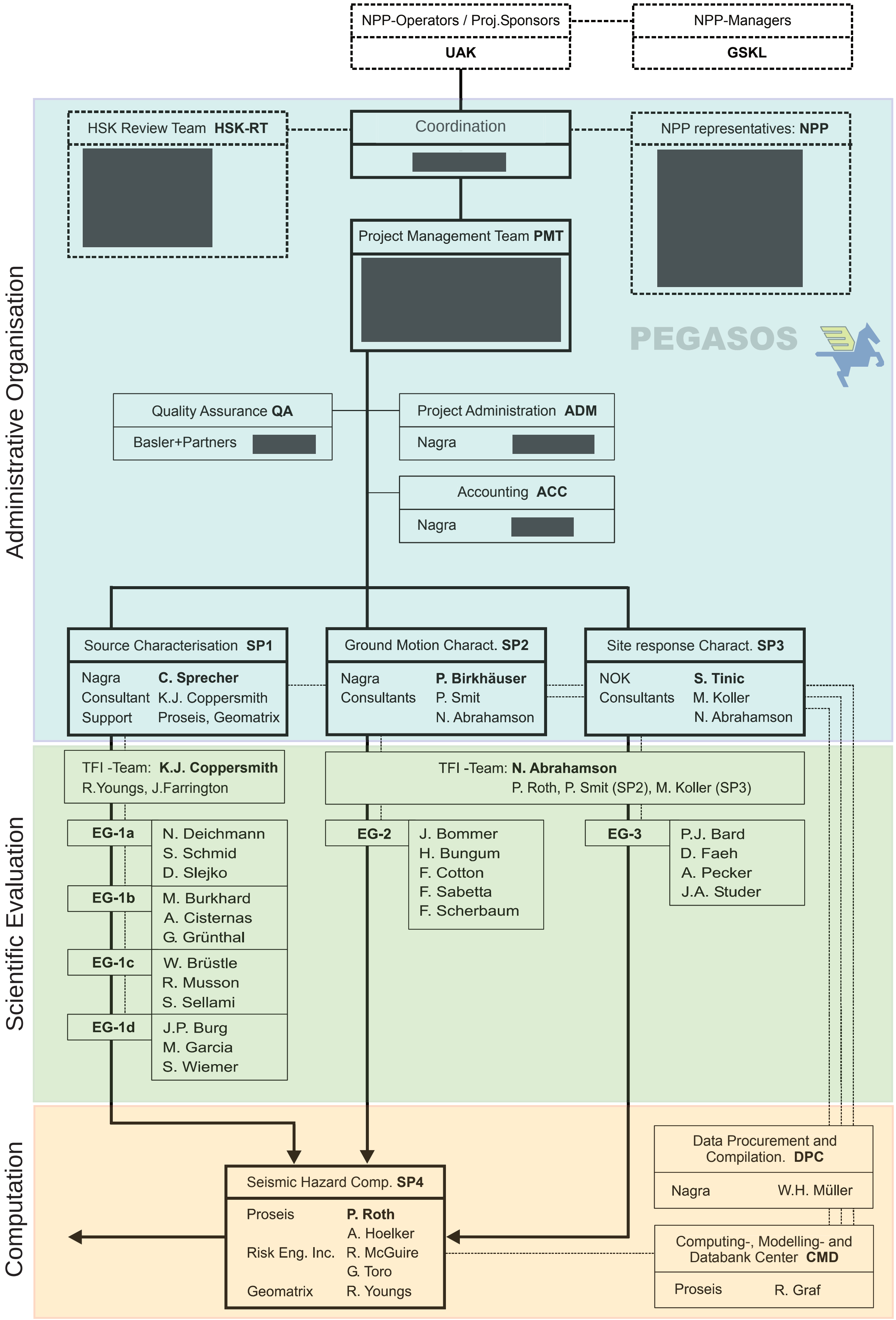


Fig.1-2: Project organisational scheme

Tab.1-1: Project Management Team

Name	Affiliation	Project Responsibilities
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]

1.3.3 Subprojects and TFI-Teams

The main responsibility of subprojects SP1-SP3 was to provide their specific contributions to the PSHA input ('expert models'), within the allocated time and budget frame in a parameterised and software-compatible form, as specified by the SP4 hazard computation group. This task was split between the subproject managers, who oversaw all activities and represented the subproject in the PMT, and the allocated TFIs, who assumed the principal responsibility for the technical work with the experts and the elicitation of the subproject-specific inputs. Subproject SP1 was headed by [redacted] Christian Sprecher, subproject SP2 by Philip Birkhäuser, subproject SP3 by Mrs. Sener Tinic and the hazard computation subproject SP4 by Philippe Roth.

Two TFI-teams were formed: Team 1, headed by *Kevin Coppersmith* and assisted by *Robert Youngs* and *Jim Farrington*, took responsibility for the seismic source characterisation by the 12 experts of the 4 SP1 expert groups (EG1a-c). In this TFI-team, Robert Youngs acted as 'hazard software specialist' (see section 1.5) and Jim Farrington was the team's local representative, maintaining close contact with all the European SP1 experts.

Team 2 was headed by *Norman Abrahamson,* who was assisted by *Philippe Roth*, *Patrick Smit* (SP2) and *Martin Koller* (SP3). This team covered both the ground motion characterisation work by the 5 SP2 experts (EG2) and the site response characterisation by the 4 SP3 experts. Philippe Roth acted as 'hazard software specialist' and Patrick Smit (SP2) and Martin Koller (SP3) were local representatives of the TFI and the prime contact persons for the European-based SP2 and SP3 experts.

Tab.1-2: Subprojects and TFI-teams

Subproject	Name	Affiliation	Project responsibilities
SP1 / TFI-team	Dr. Christian Sprecher	Nagra	Subproject manager SP1
	Dr. Kevin Coppersmith	Coppersmith Consult. Inc. Walnut Creek, CA, USA	SP1-TFI, consultant
SP1 / TFI-team	Dr. Robert Youngs	Geomatrix Consultants Inc. Oakland, CA, USA	Member SP1 TFI-team Hazard software specialist
	Mr. Jim Farrington	ProSeis AG, Zürich-Oerlikon, Switzerland	Member SP1 TFI-team

SP2 / TFI-team	Mr. Philip Birkhäuser	Nagra	Subproject manager SP2
	Dr. Norman Abrahamson	Norman A. Abrahamson Inc. Piedmont, CA, USA	SP2-TFI, consultant
	Dr. Philippe Roth	ProSeis AG, Zürich-Oerlikon, Switzerland	Member SP2 TFI-team Hazard software specialist
	Dr. Patrick Smit		Member SP2 TFI-team Technical consultant

SP3 / TFI-team	Mrs. Sener Tinic	Nordostschweizerische Kraftwerke AG (NOK), Baden, Switzerland	Subproject manager SP3
	Dr. Norman A. Abrahamson	Norman A. Abrahamson Inc. Piedmont, CA, USA	SP3-TFI, consultant
	Dr. Philippe Roth	ProSeis AG, Zürich-Oerlikon, Switzerland	Member SP3 TFI-team Hazard software specialist
	Dr. Martin Koller	Résonance Ingénieurs-Conseils SA, Carouge, Switzerland	Member SP3 TFI-team Technical consultant

SP4	Dr. Philippe Roth	ProSeis AG, Zürich-Oerlikon, Switzerland	Subproject manager SP4 Hazard computations
	Dr. Gabriel R. Toro	Risk Engineering Inc. Acton, MA, USA	Consultant, Rock hazard computations
	Dr. Robin K. McGuire	Risk Engineering Inc. Boulder, CO, USA	Consultant, Soil hazard computations
	Dr. Andreas Hölker	ProSeis AG, Zürich-Oerlikon, Switzerland	Soil hazard computations

1.3.4 Expert Panels

Expert candidates were identified based on a list of criteria that had been established by the PMT in conjunction with the TFIs and based on the recommendations of a number of acknowledged members of the technical community ('nomination experts'). The criteria had the purpose of ensuring a very high level of scientific competence and, on the other hand, interpersonal skills and sufficient motivation and commitment to complete the work in time. Different ways of actually selecting the candidates in an impartial and unbiased manner have been proposed in the past. The approach chosen in this project assumed that the peers of the expert candidates were in the best position to evaluate the relevant developments in their respective fields and assess the suitability of candidates, provided that the general expert role and the specific background needed were adequately explained. The survey among the nomination experts resulted in a pool of 109 (European) candidates. From this long list, the extended management team (EMT) chose 21 candidates for the different expert groups. In the case of SP1, the expert teams were chosen with consideration of an adequate and balanced representation of all relevant disciplines. All expert candidates that were approached accepted, with the exception of one individual who could not free enough of his time to participate in the project. The final list (including a replacement for the candidate who had declined) was submitted to HSK for approval. This approval was granted without any reservations, modifications or amendments (*HSK 2001d, EXT-KS-0070 / HSK 2001e, EXT-KS-0128*).

For a comprehensive treatment of the expert selection process, see section 3.3. Table 1-3 lists names, affiliations, special expertise (without any claim to completeness) and expert group attachments of all candidates that were finally selected.

Tab.1-3: Expert panels

Sub-proj.	Expert Group	Name	Affiliation	Special Expertise
SP1	EG1a	Dr. Nicolas Deichmann	Schweizerischer Erdbebendienst, ETHZ, Zürich, Switzerland	Seismology / Geophysics, Seismotectonics
		Prof. Dr. Stefan Schmid	Geologisch-Paläontologisches Institut der Universität Basel, Basel, Switzerland	Geology, Seismotectonics
		Dr. Dario Slejko	Istituto Nazionale di Oceanografia e di Geofisica Sperimentale, Trieste, Italy	Seismology / Geophysics, Seismic Hazard Analysis
	EG1b	Prof. Dr. Martin Burkhard	Université de Neuchâtel Institut de Géologie, Neuchâtel, Switzerland	Geology, Seismotectonics
		Dr. Armando Cisternas	Université Louis Pasteur Inst. Physique du Globe, Strasbourg, France	Seismotectonics, Seismic Hazard Analysis
		Dr. Gottfried Grünthal	Nauen, Germany	Seismology / Seismotectonics, Seismic Hazard Analysis
	EG1c	Dr. Wolfgang Brüstle	Landesamt für Geologie, Rohstoffe und Bergbau Baden-Württemberg, Freib. i. Brsg., Germany	Seismology, Geology, Seismotectonics
		Dr. Roger Musson	British Geological Survey, Edinburgh, United Kingdom	Seismology / Seismotectonics, Seismic Hazard Analysis
		Dr. Souad Sellami	Schweizerischer Erdbebendienst, ETHZ, Zürich, Switzerland	Seismology, Seismotectonics, Seismic Hazard Analysis
	EG1d	Prof. Dr. Jean Pierre Burg	Geol. Institut der ETHZ, Zürich, Switzerland	Geology, Seismotectonics
		Dr. M. Garcia-Fernandez	Instituto de Ciencias de la Tierra 'Jaume Almera' CSIC, Barcelona, Spain	Seismology / Geophysics, Seismotectonics
		Dr. Stefan Wiemer	Geologisches Institut der ETHZ, Zürich, Switzerland	Seismology, Seismotectonics, Seismic Hazard Analysis

SP2	EG2	Dr. Julian Bommer	IC Consultants Ltd., Imperial College, London, UK	Seismology, Ground Motion
		Dr. Hilmar Bungum	NORSAR, Kjeller, Norway	Seismology, Ground Motion, Seismic Hazard Analysis
		Dr. Fabrice Cotton	Laboratoire de Géophysique Interne et Tectonophysique LGIT, Univ. Louis Fournier, Grenoble, France	Seismology, Ground Motion
		Dr. Fabio Sabetta	Rome, Italy	Seismology, Ground Motion
		Prof. Dr.Frank Scherbaum	Universität Potsdam, Institut für Geowissenschaften, Potsdam, Germany	Seismology, Ground Motion Seismic Hazard Analysis

SP3	EG3	Dr. Pierre Yves Bard	Laboratoire de Géophysique Interne et Tectonophysique LGIT, Univ. Louis Fournier, Grenoble, France	Geotechnical Engineering, Site Effect Modelling
		Dr. Donat Fäh	Schweizerischer Erdbebendienst, ETHZ, Zürich Switzerland	Seismology, Site Effect Modelling
		Dr. Alain Pecker	Géodynamique et Structure, Bagneux, France	Seismology, Geotechnical Engineering
		Dr. Jost Studer	Studer Engineering, Zürich, Switzerland	Geotechnical Engineering

1.3.5 Computing, Modelling and Database Centre

The CMD was headed and managed by René Graf, who oversaw and quality assured all the work of ProSeis that was connected to the project. This work covered a wide range of activities, including the establishment of the project database with its GIS (geographical information) display system, the maintenance of archives, the dissemination of data, special data processing tasks and supporting computations on behalf of the experts, input model parameterisations, the development of HIDs and, as a final step, the computation of the seismic hazard results.

In the evaluation and input model development phase, it was the aim to provide all experts with common data sets which were processed and displayed according to their specifications. Usually these data needs were identified by the experts during the workshops of their subprojects, but requests for data or derivative data products were also accepted by the CMD at any other time. If complementary data sets (not just special displays) were procured on request of one particular expert or expert team, the CMD made this known to all the experts in the same subproject to give them the possibility of including the data in their own evaluations. This crossfeeding of information eliminated differences in interpretation that could solely be attributed to a different knowledge- or database.

In general, the level and volume of services provided by the CMD to the experts was much more extensive than it had been in earlier comparable PSHA projects. This was partly due to fact that most experts came from academic institutions that were usually less well equipped to provide services than commercial contractors. From a project management point of view, the centralised but flexible handling of data procurement, processing and representation helped to reduce redundancy and keep the database homogeneous and generally accessible. The experts appreciated the ease and comfort of ordering and obtaining data, data processing and drafting products. They looked upon, and used, the CMD as a general supply, support and information centre. Among the many services provided was a PEGASOS web homepage which displayed regularly updated lists of all archived data sets and project documents, as well as general project information, news and notices.

Different members of the ProSeis staff have made contributions to the CMD service package, which itself gradually changed in character over the years as the project work evolved. Those who had a particularly important part in the proceedings and were instrumental in the CMD's performance are listed in Table 1-4 below.

Tab.1-4: Computing and Database Centre

Unit	Name	Principal Responsibilities
CMD	Mr. René Graf	General management of CMD, QA, project consultant
	Dr. Philippe Roth	Project database and archives, QA, SP2 (GM model) parameterisation, SP2 HID development, final rock hazard computations, management of SP4, Project Report Vol.2
	Dr. Andreas Hölker	SP3 (site effect model) parameterisation, SP3 HID development, final soil hazard computations, QA
	Mr. Jim Farrington	Project database and archives, dissemination of GIS products, QA, SP1 workshop organisation and support, SP1 (source model) parameterisations, SP1 supporting computations, SP1 HID development
	Dr. Ulli Kuhlmann (TK-Consult)	SP2 (GM model) Parameterisation, SP2 HID development
	Mr. Roland Helbling	Drafting services

1.3.6 Resource Experts

Resource experts from a variety of organisations were invited to workshops to present pertinent data sets or explain and advocate specific hypotheses and interpretations. Most of these invitations were initiated by the experts. Outside specialists acting as proponents of a particular technical position helped clarify its weight and relevance and the alternatives being presented stimulated an open scientific debate.

Resource experts were not considered to be part of the project team and their position and role should not be confused with that of expert panel members asked to temporarily act as a proponent of particular data set or hypothesis. The specialists invited from the outside are listed in the workshop section of each subproject chapter (see sections 4.2, 5.2 and 6.2), together with their affiliations and the issues on which they were interviewed.

1.3.7 Contractors

To satisfy all expert requests for special studies and supporting computations, a considerable volume of work had to be assigned to outside contractors other than the CMD. The following Table 1-5 lists the most important of these contractors in European countries and the US.

Tab.1-5: Outside contractors

Sub-project	Name / Company	Scope of work
SP1	Swiss Seismological Service, ETHZ, Zürich, Switzerland	PEGASOS earthquake catalogue, catalogue declustering
	Inst.de Radioprot. et de Sûreté Nucleaire (IRSN), Fontenay-aux-Roses, France	Review of moment magnitude conversion in the PEGASOS earthquake catalogue
	British Geological Survey, Keyworth, UK	WIZMAP software development
	Geomatrix Consultants Inc., Oakland / CA, USA	M_u and recurrence computations for source models, incl. EPRI and Kijko approach, etc.
SP2	Istituto Nazionale di Oceanografia e Geofisica Sperimentale (E. Priolo), Trieste, Italy	Estimation of upper limit GMs in Switzerland based on num. simulation of extended sources and full wavefield propagation; estimations of median near-fault GMs
	URS Corporation (A. Pitarka), Pasadena / CA, USA	Numerical simulations for the evaluation of upper bound GMs in Switzerland
	Dep. of Geophysics, Charles University (J. Zahradnik), Prague, Czech Republic	Numerical simulations of GMs for finite extent sources (upper limit GM estimation)
	Laboratoire de Géologie (R. Madariaga), Paris, France	Kinematic fault models as a basis for upper limit GM assessments (feasibility study)
	Universität Potsdam, Institut für Geowissenschaften (F. Scherbaum, A. Rietbrock), Potsdam, Germany	Input parameters for the stochastic simulation of strong GMs for Switzerland; Joyner-Boore distance metric conversions (conversion coeff.) for SP1 source models
	A.M. Becker, Lawrence, KS / USA	Evaluation of point source parameters; Brune stress drops for small magn. CA data at hard rock sites
	Francesca Bay, Zürich, Switzerland	Numerical simulations to check Swiss point source param., QA and DB comparisons
	BRGM French Geological Survey, Marseille (H. Zeegers), France	Computation of H/V ratios
	P. Smit, Zürich, Switzerland	Computation of residuals for candidate GM models; computation of spectra (WAF DB)
	Albert-Donié Geo-Consult GmbH, Wettingen, Switzerland	Support SP2
SP3	Golder Associates Inc. (A.J. Augello, B. Hamershock), Irvine / CA, USA	1-D numerical site effect modelling using time histories and SHAKE
	Pacific Engineering and Analysis, EL Cerrito / CA, USA (W. Silva, N. Gregor)	1-D numerical site effect modelling using RVT (Random Vibration Theory) and the soil profile randomisation option
	Institute of Geopysics (D. Fäh), ETHZ, Zürich, Switzerland	2-D modelling of S_H-wave amplification; spectral amplification for S_H and P_{SV} waves at Beznau, Gösgen and Leibstadt
	Laboratoire de Geophysique Interne et Tectonophysique LGIT (P.Y. Bard, M. Bouchon), Grenoble, France	2-D S_H site amplification factors for Leibstadt considering high and low strain cases

Sub-project	Name / Company	Scope of work
SP3	Geodeco S.p.A (F. Pelli), Bogliasco, (Genova), Italy	Non-linear site response considering cyclic mobility effects for Beznau and Gösgen
	Géodynamique & Structure (A. Pecker), Bagneux, France	Non-linear site response analysis for Gösgen, evaluation of max. GMs on soil
	Résonance Ingénieurs-Conseils SA Carouge, Switzerland	Scaling of time histories, SHAKE computation of GM scaling factors; upper limit GMs on soil from a simplified analytical model; sensitivity studies, etc.
	University of California, Berkeley / CA, USA	Visualising of SHAKE num. simulations, comparisons of SHAKE and RVT runs
	GeoExpert AG, Schwerzenbach, Switzerland	Geophysical processing, SAWS survey Gösgen site
	Studer Engineering (J. Studer), Zürich, Switzerland	Evaluation of the geotechnical databases at each of the four NPP sites
SP4	Risk Engineering Inc., Boulder / CO, USA	FRISK88M software licence, SOILHAZP software development, software modifications, prov. hazard computations, pinching guidelines, pinching support, QA final hazard computations
	TK Consult (U. Kullmann), Zürich-Oerlikon, Switzerland	SP2 (GM) model parameterisation
	Risk Management Associates Inc (F. Torri), Leucadia / CA, USA	Evaluation of PSHA software
PMT	E. Basler + Partner AG, Zollikon, Switzerland	QA audits [redacted]
	Bundesamt für Landestopographie, Wabern, Switzerland	Digital maps, satellite pictures for GIS database
	Landeshydrologie und –geologie, Bern, Switzerland	Geological maps for GIS database
	Math Works, Gümligen, Switzerland	Matlab software
	Ravenholm Computing, Baden, Switzerland	Fortran compiler
	Petraconsult, Arni, Switzerland	Report editing

1.4 Project Activities

1.4.1 Establishment of Project Team

Project work was officially initiated with the first PMT meeting on 13 December 2000 after a 3-month project planning phase late in 1999 and about one year of regulatory review and contractual negotiations (see section 1.2.3) with the licencees (UAK). In the autumn of the year 2000, representatives of the project planning team had visited the US on a scouting trip to survey available PSHA software packages and establish first contacts with US consultant companies and TFI candidates. As a result of this evaluation, K. Coppersmith and N. Abrahamson were invited to Switzerland mid-March 2001 to discuss the assignment. Final contracts were signed in early April. In connection with the PSHA software evaluation (section 1.4.2 below), Risk Engineering Inc. of Boulder, CO, was chosen as a consultant / contractor for the seismic hazard computations and as main supplier of software.

The evaluation of experts started in January 2001, when senior members of the seismological community in Europe were invited to nominate suitable candidates. By mid-March, their recommendations had arrived and a selection was submitted for approval to the HSK-RT. After HSK's approval of the proposed candidates and the expert teams' composition on 2 May 2001 (*HSK 2001d, EXT-KS-0070* / *HSK 2001e, EXT-KS-0128*), all experts were personally interviewed by the project manager and the TFI, either in Switzerland or near the experts' home base. During these interviews, all aspects of the project were explained, with particular emphasis on the role and importance of experts in this type of study. By 19 July 2001, verbal agreements with the 21 designated experts had been reached and the project team was fully established and operational, even though the discussion of contractual details went on until the last of the contracts was signed on 27 November 2001.

1.4.2 Database and PSHA Software

As recommended by HSK, the project endeavoured to make an early decision on the hazard computation software. From the software packages that were on the market in the US or could be obtained from university institutes or government agencies, seven were included in a first evaluation. All of these codes were based on the basic Cornell-McGuire PSHA model (see section 2.1). It soon became clear that the major differences concerned the availability of pre- and postprocessing routines, level of support, modelling capabilities and user-friendliness.

Preprocessing software that allowed capture of alternative expert interpretations and postprocessing routines with a capability to condition hazard results on input parameters and interpretations and display sensitivities were indispensable for the implementation of the SSHAC Level 4 methodology. Since site effect depends on earthquake magnitude and the level of ground motion, the possibility to deaggregate hazard on magnitude, distance and ground motion variability was a prerequisite for the site response analysis in SP3. Taking these requirements into account, and adding QA certification as a desirable feature, it turned out that only Risk Engineering Inc. (REI) had, with FRISK88M, a software package that satisfied all specifications and had a QA certificate. REI agreed to grant a licence for the use of FRISK88M to the CMD, to provide ongoing support and, if necessary, to modify the software so that it could handle all the yet unknown features of the experts' input models. Since the choice of software had been made subject to approval by HSK's review team, the evaluation result was presented to HSK, together with the proposal to acquire a licence from REI. HSK supported the choice and formally agreed that FRISK88M was the hazard software package to be used for the project work (*HSK 2001b, EXT-AN-0093* and e-mail message of 02.03.2001). Following the signing of a licence agreement, the software package was installed at the CMD in August 2001 and all its components were carefully tested under the supervision of a REI representative.

The establishment of a Project data database (DB) at the CMD (see section 3.4) was another task that started early, based first on assumptions on what was likely to be needed by the experts for their work and then, in a second phase after the first workshop, on the basis of explicit expert requests. Conceptual and planning work began in January 2001, with the design of a practical structure and data mangement scheme (see Figure 3-1) This included 'Geographical Information Systems' (GISs) with a variety of map and other display options, set up to operate at large scales for source characterisation purposes and at very small scales for the site-specific requirements of SP3. It also included procedures for implementing expert requests, for the acceptance of the data sets into the system, for the requisition of data and their disseminaton to the experts.

Some major components of the database, such as the PEGASOS earthquake catalogue (*SED 2002, EXT-TB-0043*), the SP2 ground motion and wave form (WAF) DB (*Smit et al. 2002, TP2-TN-0276*) and the paleoseismic (PALEOSEIS) DB (*SED 2001, EXT-TB-0034*) took such a long time to develop that a head start was essential to avoid delays. The development of these data sets started in some cases years before the project began, sponsored by a variety of organisations, including the European Union (EU), the Swiss National Science Foundation (SNF), HSK and the Swiss Federal Institute of Technology in Zürich (ETHZ). Discussions with principal investigators were initiated early in 2001 to find out if the results of ongoing research projects could be supplemented or further developed to fit the specific needs of the PEGASOS Project. This resulted in a major development contract with the Swiss Seismological Service (SED) for a project-specific earthquake catalogue and contracts for modifications, supplements and continuous updates of the WAF collection of European earthquake recordings. Work on these contracts started on 30 April 2001 and was scheduled for completion by the end of the year 2001.

Efforts to support the future work of the experts were not confined to the basic data inventory. They also included the provision of software tools that were meant to facilitate the use of huge data collections and catalogues and simplify the development of seismic source models. The most notable of these tools was the WIZMAP program, which originated from the British Geological Survey (BGS) and was further developed into a PEGASOS database compatible version by Roger Musson, one of the authors of the software. It was intended to put these tools at the disposal of the experts, for them to use if they wanted, or – as an alternative – have the work carried out by the CMD under their direction. For a complete list of the 'auxiliary software', see Table 3-2.

By the end of September 2001, the project database existed in its initial development stage and was ready for scrutiny and amendments by the experts who convened for the first time on October 15 for WS-1. From then on, the development was continuous. Expert requests for the addition of new data sets, compilations and processing jobs went on for most of the remainder of the project and ended only shortly before final input models were finalised.

1.4.3 Organisation of Expert Work (WPs)

The experts’ work was broken down into individual 'work packages' (WPs), each with a description of scope and objective and a predefined time budget (in working days) attached to it. Work was reimbursed corresponding to the time allocated, independent of the time that was actually spent to complete the task. There were nine WPs defined to cover the whole of the experts’ work in each of the subprojects (in the case of SP3 later extended to 14). The work packages served as a system for structuring expert work and defining deliverables for remuneration. They were a generally agreed part of the experts’ contracts.

1.4.4 Workshops and Elicitation Meetings

Workshops and elicitation meetings are essential constituents of the expert elicitation process and the general scope and objectives of the different types of workshops are therefore described in detail in chapter 3, as part of the PSHA methodology. An account of the actual proceedings, with the conclusions reached and the results achieved, can be found in the subproject-specific chapters, sections 4.2 (SP1), 5.2 (SP2) and 6.2 (SP3). All workshop dates were planned at a very early stage, when the EMT first met on 16 March 2001. Apart from one exception, these dates could be maintained throughout the project and all workshops took place as scheduled.

The sequence of project workshops started on 15 October 2001 with WS-1 in Regensdorf near Zürich and ended with the end-of-project workshop (WS-5) on 27 February 2004 in Davos (for all the workshop dates see section 1.4.8 below). Most of the workshops and individual workshop sessions were subproject-specific, but some were intentionally scheduled with an overlap to allow common sessions between two or all three subprojects. Workshops usually lasted three working days. Comprehensive minutes in the form of 'workshop summaries' were issued and then distributed to all PEGASOS experts, irrespective of team affiliation or attendance, as part of the information flow between the subprojects (see Vol. 3).

Elicitation meetings were organised throughout the project to guide the experts in developing their models. The experts (or expert groups in SP1) met individually with the TFI and a member of the TFI-team. These meetings lasted between half a day and three days. The TFI familiarised the experts with a few key concepts of SSHAC Level 4 studies (such as the difference between epistemic and aleatory uncertainty). The experts typically explained the approach they intended to use to develop their models. They had the opportunity to ask questions of the TFI, whether procedural or technical in nature. Requests for additional data or supporting computations (see next section) were also collated during these meetings.

1.4.5 Supporting Computations and Special Studies

Apart from accessing existing data in the project database and asking for the procurement and inclusion of new data sets, the experts frequently asked for further processing work, numerical simulations or modelling jobs to be carried out to their specifications. At times, when confronted with a novel and poorly understood problem such as maximum ground motion assessments, the experts went beyond specifying computations. They invited renowned specialists to propose research and modelling work with the potential of helping to better understand the key phenomena and processes. For both these types of expert-commissioned work, the term 'supporting computations' is used (see sections 3.5.1 and 3.5.2). Supporting computations started with WS-1, in October 2001, and went on for most of the project's duration, until WS-3a of SP3 in the autumn of 2003. Usually applications were submitted and listed at the end of workshops or elicitation meetings, but they were also accepted at any other time if handed in with a justification in writing. The PMT decided if they could be carried out within the limits of schedule and budget. No other criteria were applied and only very few, if any, of these requests had to be turned down. In total, 57 separate supporting computation projects were executed, quality assured, documented and archived. For a complete list, see Tables 3-3 through 3-5.

1.4.6 Model Implementation Support

Supporting computations were commissioned by the experts and carried out by the project on their behalf. In these cases, the project assumed responsibility for quality assurance and the correctness of the results. The situation was looked at differently, however, in the case of an expert (or SP1 expert group) who asked for project assistance to complete his / its own input model ('expert model'). The expert model was the true contribution of the individual expert, of which he had to take ownership and for which he could not share responsibility. As a consequence, the experts or expert groups received the necessary means and computation support but the full responsibility for their model stayed with them. Working orders were their own and they were asked to supervise the work carried out by the CMD or outside contractors themselves, up to and including the QA checks. The term 'model implementation support' was used for this type of expert-directed work, to point out the difference and set it apart from supporting computations which were supervised by the project (see section 2.5 of the QA

Guidelines, Rev 03, App. 1). A large volume of model implementation computations were commissioned in the second half of 2002 when, after the type 3 workshops, most of the PSHA input was finalised.

1.4.7 Hazard Computations

The last link in the chain of activities was the computation of the seismic hazard. It proceeded in two separate phases: preliminary hazard computations first, immediately after the experts' input models had been handed in, and later the final hazard computations, after the experts were given an opportunity to review the hazard effect of their inputs and could choose to revise their initial assessments. Most of the expert models were completed by the end of the year 2002. The next step was the translation of these models into mathematical models that are compatible with the software, in the form of 'hazard input documents' (HIDs). Once this was done, and the proposed HID parameterisation had been approved by the experts, the preliminary hazard computations could start in late January 2003. These computations were performed by combining a complete SP2 expert model with a simplified SP1 model (the so called TFI model) and vice versa. The results were ready for inspection by the experts at WS-4 in late February 2003. Based on this hazard feedback, extensive discussions with their peers and careful reconsideration of the most hazard-sensitive aspects of their models, the experts finalised their input in the course of spring and summer 2003. The final hazard computations started on first October 2003, with the CMD (Proseis) in the role as leading contractor and Risk Engineering Inc. (REI) acting as consultant and reviewer. A particularly important part of this consulting was advice on algorithmic pinching. The volume of the computations turned out to be so great that simplifying (without introducing significant errors) was not an option, but an absolute requirement if the task was to be completed within a reasonable timeframe. At the end of February 2004, the final results (horizontal component) were ready for presentation and inspection at the end-of-project Workshop (WS-5) in Davos. The QA checks by REI took another two months to complete.

1.4.8 Schedule and Project Milestones

Date	Activity / Milestone	Section in Vol.1 of Project Report
13.12.00	First PMT meeting	1.3.2
03.01.01	Start of project work	1.4.1
09.01.01	Decision on PSHA software (evaluation since 06.11.00)	1.4.2
10.01.01	Development of a concept / plan for a project database	3.4.1
29.01.01	Senior European seismologists invited to nominate expert candidates	3.3
09.02.01	US consultants and TFIs invited to participate in the project	1.4.1
15.03.01	Expert candidate proposals from 'nomination experts'	3.3
16.03.-17.03.01	First EMT meeting with K. Coppersmith & N. Abrahamson attending	1.3.2
17.03.01	All workshops scheduled; exp. and exp. team composition proposed	1.4.1
09.04.01	FRISK88M software licence agreement signed	1.4.2
30.04.01	Establishment of project database started at CMD (test data)	1.4.2
30.04.01	Contract with SED on development of PEGASOS earthq.catalogue	3.4.1
02.05.01	HSK approval of proposed expert candidates and team composition	3.3
18.05.01	Installation / test runs of FRISK88M hazard software at the CMD	1.4.2
05.07.01	Development of database and 3-D structural (NPP) site models started	3.4.3
06.06.-19.07.01	Interviews with expert candidates	3.3
19.07.01	Verbal agreements with all 21 experts reached, contract discussions	3.3
26.07.01	Inventory and takeover of geol./ geotechn. data available at NPP sites	3.4.3
30.07.01	GIS system with SP1 test data available at the CMD	1.4.2
12.10.01	First developm. stage of GM and wave form (WAF) database compl.	3.4.2
15.10.-17.10.01	WS-1 on 'Key Issues and Data Needs' (all subprojects)	3.6.1
15.10.01	Start of expert-directed development stage of database / GIS system	3.4.2
17.10.01	Complementary geophysical site investigations at NPP sites initiated	3.4.5
27.11.01	All expert contracts signed	3.3
31.12.01	First version of PEGASOS earthq catalogue available	3.4.1
31.12.01	SP1 database report / user manual issued to experts	3.4.1
30.01.02	Additional geophysical site investigations at NPP sites concluded	3.4.5
04.02.02	Presentation of NPP site databases and site models to SP3 experts	3.4.3
04.02.02	SP3 expert group meeting on 'Validation of Soil Profiles' in Baden	6.2.2
12.02.-14.02.02	WS-2 / SP1 on 'Methodologies for Defining Seismic Sources and ….'	4.2.2
25.02.02	SP2 database report / user manual issued to experts	3.4.2
10.03.02	Empirical attenuation models (EAT) DB completed	3.4.2
31.03.02	QA Guidelines (Rev.0) become effective	1.5
31.03.02	Final version of PEGASOS EC (TP1-CAT-0004) available to SP1	3.4.1
10.04.02	Start of numerical site response simulations (RVT, SHAKE, TNL)	6.1
13.04.02	Final development GM and wave form (WAF) database completed	3.4.2
16.04.-18.04.02	WS-2 / SP2 on 'Evaluation of Models'	5.2.2
09.05.-16.05.02	First series of SP1 interactive elicitation meetings EG1a-d (4×3 days)	4.2.3
14.05.-16.05.02	WS-2 / SP3 on 'Evaluation of Models'	6.2.3

17.05.02	QA Guidelines handed over to HSK	1.5.2
31.05.02	SP3 database report / user manual issued to experts	3.4.3
18.06.-20.06.02	WS-3 / SP1 'Feedback on .., Method. for Max Magn. and Recurrence'	4.2.4
20.06.02	Ext. review of EC magn. conversion concluded: 'No further action'	3.4.1
03.07.02	Final development of geol./geotechn.databases for NPP sites compl.	3.4.3
04.07.-10.07.02	SP2 experts' elicitation interviews (1 day / expert)	5.3.3
24.07.-26.07.02	Second SP1 interactive elicitation meeting EG1d (3 days)	4.2.5
27.08.02	1. dispatch of numerical site effect simulation results to SP3 experts	6.1
03.09.02	2. dispatch of numerical site effect simulation results to SP3 experts	6.1
27.09.-03.10.02	Second series of SP1 interactive elicit. meetings EG1a-c (3 × 3 days)	4.2.5
01.10.-03.10.02	WS-3 / SP2 on 'Initial Feedback on Experts' Estimates'	5.2.4
04.10.-05.10.02	Planning software modifications / preliminary hazard comp. (EMT)	
08.10.02	3. and final dispatch of site effect simulation results to SP3 experts	6.1
08.10-10.10.02	SP3 experts' elicitation interviews (surface level); first 3 experts	6.2.4
29.10.02	SP3 expert elicitation interview (surface level); fourth expert	6.2.4
31.10.02	Final report of 'PALEOSEIS' study handed out to the SP1 experts	3.4.1
19.11.-21.11.02	WS-3 / SP3 on 'Initial Feedback on Experts' Estimates' (surface level)	6.2.5
15.12.02	Rev.02 of QA Guidelines issued	1.5
08.02.03	SP1 sensitivity source models for preliminary hazard computations	4.3.5
15.02.03	SP3 sensitivity site effect models for preliminary haz. computations	6.3.2
20.02.03	SP2 sensitivity GM atten. models for preliminary haz. computations	5.3.2
24.02.-28.02.03	WS-4 on 'Expert and Hazard Sensitivity Feedback' (all subprojects)	3.6.4
02.03.-03.03.03	WS-4 / SP2 extension Davos (new project result specifications)	5.2.5
12.04.03	SP3 WS meeting on 'Maximum Ground Motion' in Nice	6.2.7
13.04.03	SP2 WS meeting in London on 'Scaling Factors for Style of Faulting'	5.2.6
30.06.-03.07.03	Outline / org. final project report agreed, writing assignments (EMT)	
12.08.03	SP1 source models for final hazard computations (HIDs signed off)	4.3.7
03.10.03	SP2 GM atten. models for final haz.computations (HIDs signed off)	5.3.5
03.10.03	Start of final (rock) hazard computations by SP4	7.4
15.09.-17.09.03	SP3 experts' elicitation interviews (max GM, embedded levels)	6.2.8
20.10.-21.10.03	WS-3a / SP3 on 'Max. GM and Embedded Level Motions'	6.2.9
10.12.03	SP1 elicitation summaries (ESs) available (released for printing)	4.3.8
09.01.04	SP2 elicitation summaries (ESs) available (released for printing)	5.3.6
14.01.04	Rev.03 of QA Guidelines issued	1.5
27.02.04	WS-5 'end-of-project' workshop in Davos (all subprojects)	3.6.5
15.03.04	SP3 site effect models (all levels) for final comp. (HIDs signed off)	6.3.5
13.04.04	Final hazard computations completed (horiz. component)	7.5
04.06.04	Final hazard computations completed (incl. vertical component)	7.5
25.06.04	QA checks of final hazard computations completed, results available	7.5
28.06.04	First draft of final project report completed; start of peer review	
26.07.-30.07.04	Final report review meeting San Francisco; end of peer review	
23.08.04	SP3 elicitation summaries (ESs) reviewed (released for printing)	6.3.1
30.08.2004	Final project report completed; hand-over to clients (sponsors)	

1.5 Quality Assurance

1.5.1 Scope

Quality assurance in this project had three major goals: to minimise the possibility of errors occurring (or remaining undetected), to enforce important SSHAC rules by putting them into the concrete form of working instructions and to guarantee the reproducibility and traceability of all project results. Traceability extended to the reasoning behind decisions if these decisions had an impact on the results. The intention was not to cover all aspects of the project work but to restrict QA to critical areas. The procedures were to be simple and practical without unduly impeding the normal flow of work. On the other hand, the project expected rigorous adherence to the streamlined rules and procedures that were finally adopted.

The following processes were subjected to QA procedures (for details see the Appendix to this document: QA Guidelines, Rev.03, *Sprecher 2003, QA-TN-0402*):

- Management of project documents
- Management of project data
- Acceptance and entry of basic data into the project database
- Supporting computations on behalf of the experts
- Development of expert models
- Conversion of expert models into hazard computation input
- Software verifications
- Preparation of hazard software input files
- Hazard computations
- Algorithmic pinching

1.5.2 QA Guidelines

An initial set of QA rules, dealing with the documentation and archiving of project documents, was introduced as part of the project plan and covered the early stages of the project work. As work and planning progressed and gradually became more tangible, many additional requirements and procedures were specified. The first comprehensive set of guidelines was issued on 31 March 2002 (*Sprecher 2002a, QA-TN-0156*). They regulated most of the above activities by defining requirements in a series of short and concise paragraphs. The requirements were of a widely different nature, depending on the subject, ranging from registration on archiving forms, mandatory checks and tests to independent technical reviews (ITRs) or, in other cases, the demonstration that predefined accuracy criteria had been met.

In general, it was necessary to have processes clearly defined as a prerequiste for introducing QA requirements. Sometimes, however, the opposite was also true, when the need to cover a critical process by a new QA procedure helped to better understand and define the process. One such example is the transformation of expert models into software-compatible inputs. In former SSHAC-type studies, this was a source of concern, because judgements on the part of the analysts in the hazard computation team (SP4) were often needed to convert expert models into files that could be accessed by the PSHA software. These judgements were generally beyond the control of the experts. PEGASOS changed that by introducing the HID concept, a proposal worked out by the TFI-team that described in detail how the expert's model was to be quantified ('parameterised') to a stage where it was fit for a 'hands-off' translation into a hazard software input file. The 'hazard input documents' (HIDs) were scrutinised by the experts who could turn them down, approve or amend them. Only after their formal approval could the HIDs be used as hazard input. Another example is algorithmic 'pinching', an unavoidable simplification of expert logic trees or their combination, which can result in billions of branch tip models. Such computation volumes can no longer be handled even by state-of-the-art computer equipment.

While pinching was applied in the past more on the basis of informed guesswork and experience than hard evidence, an effort has been made in this project to make this process more transparent and traceable. Software modifications and 'pinching guidelines' (*Toro 2004a, TP4-TN-0394*) allowed for the first time to quantify the pinching error, define accuracy criteria and set up the operational rules that were entered into the second revision of the QA Guidelines (*Sprecher 2002b, QA-TN-0292*). This addition turned out to be a practical tool, putting pinching decisions on a firm basis and allowing SP4 analysts to trace pinching errors in a transparent manner that was understandable to all concerned and acceptable to the experts.

A Level 4 PSHA is still far from being a routine process and the QA Guidelines had therefore to be conceived as a dynamic document that could easily be adapted to new requirements, experiences and insights. Three revisions were issued over the project's duration, the last of which carries the date of December 2003 and contains minor amendments and modifications related to the documentation of the final hazard computations (*Sprecher 2003, QA-TN-0402*). This final version of the QA Guidelines is attached as an Appendix to Vol. 1.

1.5.3 QA Evidence

Evidence that a specific QA requirement had been met is provided according to the provisions in the QA manual. This evidence ranges from simple electronic archiving forms that accompany classified project documents and classified project database items, to 'QA certificates' and (QA) technical reports. QA certificates (six different types, see App.1) are paper forms that had to be filled out and signed by at least two parties to give proof of a successful QA check (e.g. an 'Independent Technical Review') or the agreement reached to use a certain input data set (e.g. the release of a 'hazard input ocument'). QA certificates are an important part of the QA documentation; they exist only as a single signed original (for examples see the HID QA certificates included in Vols. 4, 5 and 6 of this report). In rare cases, the proof of compliance with a QA requirement had to be more elaborate, e.g. when a pinching error was outside the operational criteria but it could still be demonstrated that the primary accuracy criteria were met. In such cases, the evidence was presented in the form of a technical note.

1.5.4 QA Audits

The QA Guidelines provided for independent audits of their implementation by a professional auditor. Several of these audits were carried out by the project's QA representative [redacted] who verified strict adherence to the rules and provisions of the guidelines on behalf of the PMT. In addition, HSK was invited to carry out or commission QA audits of their own.

1.6 Project Review by the Regulatory Authority (HSK)

HSK monitored the project work through a peer review committee, the 'HSK Review Team' (HSK-RT), conducting a 'Participatory Peer Review' (see SSHAC: NUREG/CR-6372, Vol. 1, 48-49). Composed of recognised experts, the HSK-RT had to provide assurance that the PSHA process as described in the PEGASOS Project plan was properly implemented, that the study incorporated the diversity of views in the technical community, that uncertainties were properly considered in the analysis and that the documentation of the study was clear and complete. The participatory nature of this review allowed HSK to observe and comment on all aspects of the proceedings. It incorporated the possibility of spot checks of data, methods and calculations, as deemed warranted, and provided HSK with input to form an opinion on the quality of the project work. However, the participatory peer review' character meant that: *'HSK's review involvement had to be designed to specifically avoid and help verify that there existed no exogenous influences on experts as they developed their interpretations'* (quote from *HSK 2001c, EXT-AN-0125*).

HSK's review activities included the observation of all workshops and many of the elicitation meetings, followed by meetings with the project management to critically assess strengths and weaknesses. These preliminary assessments were followed by comprehensive review reports to the licencees and the project management. The project management in turn answered the review report in writing, presenting its position and / or promising corrective action if it was deemed necessary. Even though some issues were vividly debated between HSK-RT and the project organisation, final agreement could be reached in every case and the constructive criticism and intellectual stimulus of the review team made an important contribution to project quality and the development of robust assessments.

1.7 Project Products and Report Organisation

This final PEGASOS Project report (*Sprecher et al. 2004*) comprises six volumes. Volume 1 is the text part that describes and summarises all project activities and presents illustrative examples of project results. The complete compendium of hazard results for all four NPP sites is represented in Volume 2 as figures and tabulated numerical values (CD-ROM). Volume 3 includes all workshop summaries. Volume 4 contains the elicitation summaries and expert biographies of the SP1 seismic source characterisation teams, together with the corresponding HIDs and HID QA certificates. The corresponding elicitation summaries and supplementary information of the SP2 ground motion and SP3 site response experts are contained in Volumes 5 and 6 respectively.

The present Volume 1 was prepared by a team of 7 authors (Norman A. Abrahamson, Kevin J. Coppersmith, Martin Koller, Philippe Roth, Christian Sprecher, Gabriel R.Toro and Robert Youngs) under the overall direction of Christian Sprecher.

Volume 1 is made up of eight main chapters. Following this introduction, the PSHA methodology is described in chapter 2, firstly in a more general way, with mention of alternatives, and then, in the second part, how the methodology was actually implemented in the present study. Chapter 3 describes the expert elicitation process and the development of PSHA input in a generic sense, without consideration of thematic subprojects or the proceedings of the actual workshops. The subproject-specific activity reports follow in chapters 4, 5 and 6. These chapters start with a brief methodological introduction (e.g. seismic source characterisation methodology) and then proceed to a summary of the subproject's workshops and elicitation meetings, emphasising highlights and course-setting decisions. The development of the expert models is reported in chronological order, followed by a more comparative discussion of the salient features and, finally, by a subproject-specific summary of the assessments. Chapter 7 covers the hazard computations. It includes the list of result specifications, the software tools, detailed accounts of how the rock and soil hazard computations were performed and a special paragraph about algorithmic simplifications ('pinching'). Volume 1 concludes with chapter 8, a sample presentation of hazard results.

The different project products correspond to the site-specific content of Volume 2 and include (for the horizontal GM component): rock hazard curves and rock hazard spectra for a number of specified frequencies, soil hazard curves and soil hazard spectra for the specified frequencies and three elevation levels (incl. surface), deaggregations and a selection of other sensitivity products, such as sensitivities to upper ground motion estimates, seismic sources and expert models. These sensitivity results and the contributions to hazard and the epistemic and aleatory uncertainties are discussed in the second part of chapter 8.

2 PSHA METHODOLOGY

This chapter describes the methodology used to perform the probabilistic seismic hazard calculations for ground motion at the four PEGASOS sites. Section 2.1 provides a broad overview of the probabilistic seismic hazard analysis for horizontal motions on rock and introduces some key terms. Section 2.2 introduces the distinction between aleatory variability and epistemic uncertainty. Sections 2.3 and 2.4 describe how the horizontal rock results are transformed into soil results and vertical results by introducing site effects and the V/H (vertical to horizontal) transfer function. Section 2.5 describes the treatment of maximum ground motions. Section 2.6 provides details about the implementation of the PSHA methodology for the particular conditions in this study.

State-of-the-art seismic hazard studies calculate ground motion exceedence probabilities using earth science hypotheses about the causes and characteristics of earthquakes in the region being studied. Scientific uncertainty about the causes and effects of earthquakes in the study region and about the physical characteristics of potentially active tectonic features lead to uncertainties in the inputs to the seismic hazard calculations.

These uncertainties are propagated through the entire analysis. The result is a suite of alternative results (in the form of hazard curves[1]), where each hazard curve is associated with one set of hypotheses and is assigned a weight that represents the relative merit or credibility of that set of hypotheses. These curves quantify the seismic hazard and its uncertainty at the site, and can be used to make decisions regarding seismic design or retrofit. In addition, this suite of hazard curves implicitly contains information about the sensitivity of the hazard results to the various assumptions or parameters and about the contributions of these assumptions and parameters to the total uncertainty in seismic hazard.

2.1 The Basic PSHA Model (Rock)

The methodology used to calculate seismic hazard at a site is well established in the literature (Cornell 1968, 1971, Der Kiureghian & Ang 1975, McGuire 1976, 1978). Calculation of the hazard requires specification of the following three inputs:

1. Source geometry: the geographic description of the seismic source. A seismic source is a portion of the earth's crust associated with a fault with a concentration of historic seismicity or with a general region of the earth's crust having similar geological characteristics that may be capable of producing earthquakes. The geometry of a seismic source (say source 1) relative to the site and a relationship between rupture size and magnitude determine the conditional probability distribution of the distance, r, from the earthquake rupture to the site for a given magnitude: $f_{R(i)|M(i)}(r;m)$.
2. Recurrence: the mean annual rate of occurrence, ν_i, and magnitude distribution, $f_{M(i)}(m)$, of earthquakes occurring in each source i. This characterisation includes the maximum magnitude that a source can produce. Magnitude is characterised by the moment magnitude scale in this study.
3. Ground motion equation (sometimes called attenuation function or attenuation equation): an algorithm that allows the estimation of ground motion amplitude (e.g. peak ground acceleration or spectral acceleration) at the site as a function of earthquake magnitude and distance. This characterisation consists of the following three elements: (1) an algorithm for

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[1] To be defined below.

the median amplitude, (2) an algorithm for the standard deviation, σ, that describes the site-to-site and event-to-event scatter in log[amplitude] observations for the same magnitude and distance, and (3) an algorithm for the maximum ground motion that can occur (i.e. an amplitude that has zero probability of being exceeded, given that magnitude and distance).

These inputs are illustrated in Figure 2-1, parts a through c. Figure 2-1a shows the geometry of a seismic source and the distance distribution for a given value of magnitude. The distribution of magnitude, $f_{M(i)}(m)$, for an area source is typically specified as the doubly truncated exponential distribution (Figure 2-1b). Seismicity for a source with the exponential magnitude distribution is completely specified by the minimum magnitude, m_0, maximum magnitude $m_{\max}$, and recurrence parameters a and b. Parameter a is a measure of seismic activity and parameter b is a measure of relative frequency of large versus small events. The log of the annual rate of events with magnitude m, $\log[\ _i f_{M(i)}(m)]$, is proportional to bm for $m \le m_{\max}$

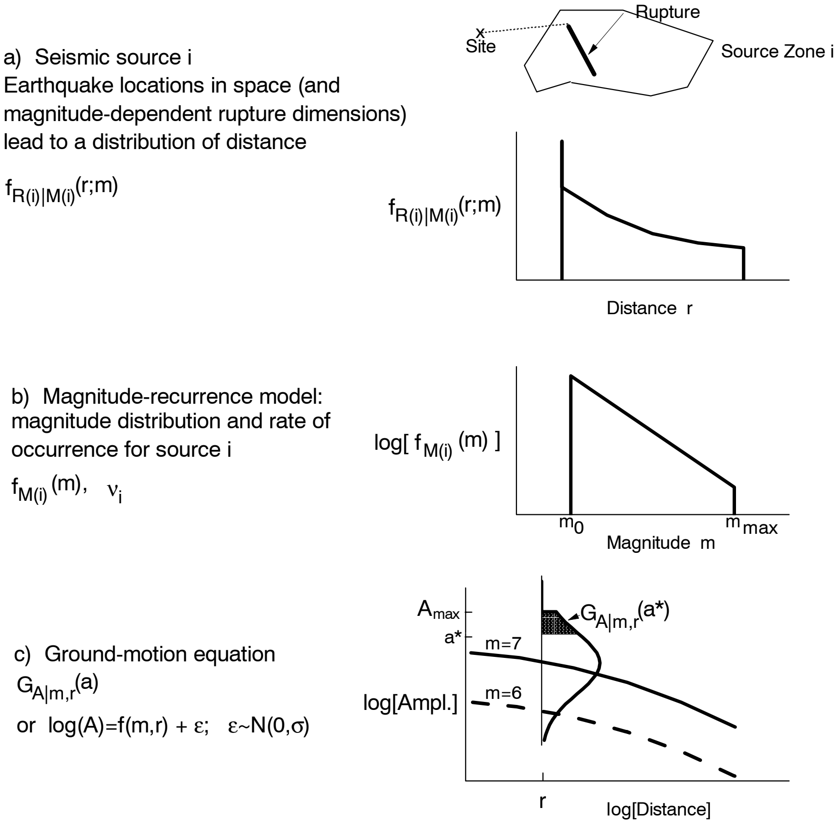

Fig.2-1: Inputs for the calculation of seismic hazard: a) geometry of seismic source and distribution of distance; b) magnitude recurrence model; c) ground motion attenuation equation

The ground motion is modelled by a ground motion function, as illustrated in Figure 2-1c. The attenuation equation is usually expressed in the form $\log[A] = \log[A_{median}(M,R)] + \varepsilon$, where A is ground motion amplitude, M is magnitude, R is distance, and ε is a normally distributed random variable with mean zero and standard deviation $\sigma(M,R)$, that represents variability in $\log[A]$ for a given magnitude and distance. The maximum ground motion, $\log[A_{\max}(M,R)]$, modifies the upper tail of the distribution of ε. For the purpose of the calculations, it is useful to express the attenuation function as the probability $G_{A|M,R}(a^*;m,r) = P[A > a^* \mid m,r]$; namely the probability that the ground-motion amplitude A is larger than a^*, for a given m and r.

These three elements (i.e. source geometry, recurrence and attenuation equation) can be used to calculate the annual probability of exceeding amplitude a^* at the site, which is expressed as the following summation:

$$\mathrm{Haz}(a^*) = \sum_i \nu_i \int_r \int_m G_{A|m,r}(a^*;m,r)\, f_{M(i)}(m) f_{R(i)|M(i)}(r;m)\, dm\, dr \qquad (2\text{-}1)$$

in which $Haz(a^*)$ is the annual rate of earthquakes that produce amplitudes $A > a^*$ at the site, and the summation is performed over all seismic sources i. The integration on magnitude in Equation 2-1 considers only earthquakes with magnitudes greater than a minimum magnitude m_o, typically taken as moment magnitude 5. Smaller earthquakes are assumed to produce no damage to engineered structures, regardless of the ground motion amplitudes they generate. Both ν_i and $f_{M(i)}(m)$ are typically defined in terms of magnitudes greater than m_0, although lower magnitudes are considered in the determination of the rate and magnitude distribution.

Equation 2-1 is formulated using the assumption that earthquakes (most particularly successive earthquakes) are independent in size and location. In most seismic hazard applications, primary interest is focused on computing probabilities for high (rare) ground motions for which the probability of two or more exceedences of a^* in one year is negligible. Thus, the quantity on the right side of Equation 2-1, which strictly speaking is the annual rate of earthquakes with amplitude $A > a^*$, is a very good approximation to the probability of exceeding amplitude a^* in one year[2].

The calculation in Equation 2-1 is performed for multiple values of a^*. The result is a hazard curve, which gives the annual probability of exceedence as a function of a^*. This calculation can be performed for multiple measures of ground motion amplitude (i.e. peak ground acceleration, peak ground velocity, and spectral acceleration at multiple frequencies).

It is useful to understand Equation 2-1 using a deterministic perspective as the starting point. Suppose we want to determine the ground motion amplitude for an earthquake of known magnitude occurring within a certain seismic source and at a certain distance to the site. We know that we cannot determine this amplitude exactly, even for fixed magnitude and distance, because the earthquake source cannot be fully described by a single parameter (magnitude) and wave propagation through the earth's crust cannot be fully described by a single parameter (distance). To represent the resulting variability in ground motion, we use a probability distribution in the form of $G_{A|M,R}(a^*;m,r) = P[A > a^* \,|\, m,r]$; (i.e. the attenuation equation written as a complementary cumulative probability distribution). This is simply a method for sorting out which of the earthquakes lead to ground motions above the target value a*.

Suppose now that we want to consider all potentially damaging earthquakes in a certain seismic source. The integral over magnitude and distance in Equation 2-1 is just a mechanism for sampling all possible earthquakes that may occur in the given source, while weighting each earthquake by how frequently it occurs, given the regional seismicity and geology (this weight is expressed by the joint probability $f_{M(i)}(m) f_{R(i)|M(i)}(r;m)\, dm\, dr$). Multiplication of this integral by the rate ν_i transforms this probability into units of occurrence per year, as required for design decisions and for comparison with other natural and man-made hazards. Finally, the summation samples the earthquakes from all of the seismic sources in the region.

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[2] It is commonly assumed that earthquake occurrences in time represent a Poisson random process (Parzen 1962). In fact, this assumption is not necessary, provided the probability of two or more exceedences of a^* in one year is negligible.

Another useful result is obtained if we use separate "bins" to accumulate the weights from earthquakes in different magnitude ranges (e.g. using one bin for magnitudes 5.0 to 5.5, another bin for 5.5 to 6.0, etc.), and then divide these accumulated weights by the total hazard. The result, which is called the magnitude deaggregation of seismic hazard (McGuire 1995, Bazzurro & Cornell 1999) indicates which magnitude ranges contribute significantly to seismic hazard. We can obtain similar deaggregation results for distance and for ε. Furthermore, we can obtain joint deaggregation results, where we use separate bins for different combinations of magnitude, distance, and ε.

2.2 Treatment of Uncertainty

2.2.1 Aleatory Variability vs. Epistemic Uncertainty

Advanced PSHA studies distinguish between two types of uncertainty, namely epistemic uncertainty and aleatory variability. Aleatory variability (sometimes called randomness) is probabilistic variability that results from natural physical processes. The size, location, and time of the next earthquake on a fault and the resulting ground motion are examples of elements considered to be aleatory. In current practice, these elements cannot be predicted, even with collection of additional data. Thus, the aleatory variability is irreducible without the inclusion of additional predictive parameters. On the other hand, epistemic uncertainty (sometimes simply called uncertainty) results from imperfect knowledge about earthquakes and their effects. In principle, epistemic uncertainty can be reduced with advances in knowledge and the collection of additional data.

Aleatory variability and epistemic uncertainty are treated differently in advanced PSHA studies. Integration is carried out over aleatory variabilities to obtain a single hazard curve (see section 2.1, particularly Equation 2-1), whereas epistemic uncertainties result in a suite of hazard curves based on multiple assumptions, hypotheses, models or parameter values. Results are presented as curves showing statistical summaries (e.g. mean, median, fractiles) of the exceedence probability for each ground motion amplitude. The mean and median hazard curves convey the central tendency of the calculated exceedence probabilities. The separation among fractile curves conveys the net effect of epistemic uncertainty in the source characteristics and ground motion prediction on the calculated exceedence probability.

There are epistemic uncertainties associated with each of the three inputs to the seismic hazard evaluation, as follows:

- Uncertainty about the seismogenic potential of faults and other geological features, as a result of (1) uncertainty about the tectonic regime operating in the region and (2) incomplete knowledge of these geological features. There is also uncertainty about the geometry of these geological features.
- Uncertainty in recurrence is generally divided into uncertainty in maximum magnitude, uncertainty in the rate ν_i, and uncertainty in parameter *b.*
- Uncertainty in the ground motion equations arises from uncertainty about the dynamic characteristics of the earthquake source and wave propagation in the vicinity of the site. This uncertainty is usually large in regions where few strong motion recordings are available.

Further discussion on the philosophical and practical issues regarding the distinction between epistemic uncertainty and aleatory variability in PSHA is provided by SSHAC (1997) and by Veneziano (2003).

2.2.2 Logic Tree Methodology

The epistemic uncertainty about the various inputs that affect seismic hazard is organised and displayed by means of logic trees (Kulkarni et al. 1984, SSHAC 1995). This technique is used for seismic source, ground motion and site effects characterisation, but this discussion will refer only to source characterisation where the use of logic trees is more visible. Each node of a logic tree represents a key seismic source characteristic affecting seismic hazard. This characteristic may be a discrete state of nature (e.g. are the Permo-Carboniferous troughs seismically active?) or a numerical parameter (e.g. maximum magnitude on the Basel seismic source). In the latter case, the continuous range of values is approximated by a discrete set of values. Each branch emanating from a node represents one alternative interpretation of the source characteristic represented by that node. The collection of all branches emanating from a node are assumed to be a mutually exclusive and collectively exhaustive set of alternative interpretations. The weight assigned to each branch indicates the expert or expert team's assessment of the likelihood that this branch represents the true state of nature, given existing knowledge and data. These weights are conditional on the values of preceding (i.e. lower) branches in the logic tree.

Each end branch of the logic tree ('branch tip model') represents a complete description of the inputs to the PSHA model presented in section 2.1, for all seismic sources affecting the site. Associated with each branch tip, there are a weight, calculated as the product of the weights of all branches followed, and a hazard curve, calculated using Equation 2-1. These hazard curves, together with the associated probabilities, are used to calculate statistical summaries of the seismic hazard (e.g. mean, median, and fractile hazard curves), as well as sensitivity results.

2.3 PSHA for Soil

2.3.1 Site Response

The unconsolidated material (soil) beneath a site affects the amplitude, frequency content, and duration of earthquake ground motion at the surface or in embedded layers. From a first-order, engineering perspective, the three most important physical phenomena that affect the amplitude of ground motions at the site are (1) impedance contrasts between the reference rock used for the rock calculations and the soil medium, (2) resonance effects from energy that is trapped between the surface and the bedrock, and (3) increased damping. In addition, two- and three-dimensional effects are sometimes considered. At high amplitudes of motion, non-linearity may have a significant effect on the elastic properties and damping of the soil.

2.3.3 Alternative Methods for Implementing Site Response Effects

The most common approach is to perform the PSHA only for rock conditions and then modify the rock amplitudes to introduce the effects of site response. The key disadvantage of this approach is that it does not incorporate the effects of the aleatory variability and epistemic uncertainty in the amplification factors.

Conceptually, the most straightforward approach for incorporating aleatory variability and epistemic uncertainty in the site response effects in a PSHA is to start with a site-specific ground motion equation, which may be obtained empirically or via modelling. Then Equation 2-1 can be implemented directly for site-specific amplitudes, using these site-specific ground motion equations. Alternatively, the rock ground motion model and site amplification model can be treated separately. The advantages of the latter approach are that the required expertise and project workload are decoupled and more combinations of rock motion and site response models are allowed. The disadvantage is that some of the source information available to the rock ground motion model is not available to the site response model (e.g. source location and depth).

Bazzurro & Cornell (see Bazzurro 1998, Bazzurro et al. 1999) and McGuire et al. (2002) have investigated the accuracy of a number of approximate approaches for the introduction of site response effects in hazard results. McGuire et al. (2002) compared several approximate approaches to the straightforward approach and recommended one (denoted as approach 2A/3) that explicitly includes epistemic and aleatory uncertainty in site amplification, as well as the dependence of site amplification on the rock input motion and on the the dominant earthquake magnitude.

This approach integrates over all rock amplitudes, calculating the frequency of exceedence of specific soil amplitudes, using means and (log) standard deviations that are functions of magnitude. The resulting equation is:

$$P[A_s > a^*] = \iint P[A_s > a^* \mid m,a] f_{M|A}(m;a) f_A(a)\, dm\, da \qquad (2\text{-}2)$$

where $P[A_s>a^*]$ is the probability that soil amplitude A_s exceeds a*, m is earthquake magnitude, $f_A(a)$ is the probability that the rock amplitude equals a, $P[A_s>a^*\backslash m,a]$ is the probability that soil amplitude A_s exceeds a^* given m and a, and $f_{M|A}(m;a)$ is the probability distribution of m given a. The approach recommended by McGuire et al. (2002) modified Equation 2-2 slightly by approximating $f_{M|A}(m;a)$ with a delta function at the mean value of m given a (this is the "2A" part of the approach), so that the dominant magnitude for each ground motion amplitude a is used to assess $P[A_s > a^*\backslash m,a]$. This approach was found to give accurate estimates of $P[A_s > a^*]$, in comparison to the straightforward approach.

To evaluate Equation 2-2, the median site amplification factor (SAF) and the standard deviation of log (SAF) are required. The function $f_A(a)$ is obtained as the negative derivative of the rock hazard curve, and the dominant earthquake magnitude is calculated by deaggregating the seismic hazard.

Epistemic uncertainty in soil amplification is treated by including multiple soil amplification models, with weights. For calculation of soil hazard, all possible soil models ($P[A_s > a^*\backslash m,a]$ in Equation 2-2) are combined with all possible rock hazard models ($f_A(a)$ in Equation 2-2) to calculate a family of soil hazard curves, each curve with its own weight. Statistics on the soil hazard (mean, fractiles) are determined from this family of soil hazard curves.

There are several advantages to using Equation 2-2 over the other alternatives. First, the rock hazard curves can be calculated using region-wide ground motion equations, rather than developing a set of equations for each site. Second, site-specific amplification models can be derived independently of the seismic hazard study, in the context of soil properties and input motions only. This is how such models are generally applied. Third, this approach allows explicit evaluation of the impact of epistemic uncertainty in soil amplification, which may point to the need for additional data or modelling, rather than combining epistemic uncertainties in soil response with epistemic uncertainties in ground motion attenuation and dependence on earthquake magnitude. Finally, if site-specific amplification models are updated at a later date, for example with additional site data, the soil hazard can be derived (through Equation 2-2) without repeating the entire seismic hazard calculation.

2.4 Vertical Ground Motion Component

There are two approaches that are commonly used for computing vertical ground motions in a PSHA. In the first approach, the vertical component is computed independently of the horizontal motion using vertical component ground motion equations in place of the horizontal component ground motion equations in the PSHA calculation. In the second approach, the vertical ground motion is computed conditional on the horizontal ground motion from the PSHA; the vertical ground motion amplitude is the vertical amplitude that is expected to occur given the occurrence of the horizontal amplitude associated with the exceedence probability of interest.

If the first approach is used (independent vertical component), then the vertical component may correspond to a different earthquake than the horizontal component, so that the combination of the loads from the horizontal and vertical components would be physically unrealistic. Because the horizontal motion is generally more damaging than the vertical component, the main impact of the vertical component is to modify the amount of damage from the horizontal component. Therefore, the preferred approach is to develop the vertical component conditional on the horizontal component (approach 2).

2.5 Maximum Ground Motions

The assumption of an unbounded normal distribution for the rock ground motion residual ε implies that arbitrarily high values of ground motion amplitude are possible for any given magnitude and distance[3]. This simplifying assumption is used frequently in practice, although it is understood that it contradicts physical intuition about earthquakes and their effects. Experience has shown that limiting the distribution of ε – using typical values of the upper bound ground motion – has a moderate effect on seismic hazard for the exceedence probabilities considered in design, but may have a large effect for lower probabilities.

The maximum ground motion on rock may be specified in either of these two forms:

- In terms of the distribution of ε (e.g. ε cannot exceed 3.5 standard deviations). We refer to this form as 'upper-tail truncation'.
- In terms of ground motion amplitude (e.g. the amplitude for a certain magnitude and distance cannot exceed the Ambraseys et al. median attenuation equation times a factor of 2.8). We refer to this form as 'maximum ground motion'.

Both forms may be specified simultaneously, in which case the lower of the two (for each magnitude – distance combination) controls the calculation.

2.6 Implementation of Methodology in this Study

2.6.1 Source Characterisation

Seismic source characterisation consists of probability models for: (1) spatial location of future earthquakes, (2) geometry of earthquake ruptures, (3) frequency and size distribution of earthquakes, and (4) maximum earthquake magnitude. The treatment of earthquake recurrence and maximum magnitude followed standard approaches. The treatment of the spatial distribution and rupture geometry of earthquakes is described below.

2.6.1.1 Area Sources

Most of the seismicity in the PEGASOS study region is represented using area sources (sometimes called source zones). The geometry of an area source is defined by a polygon (in latitude-longitude space). The geometry of earthquake ruptures within that source is defined by

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[3] This assumption implies a log-normal aleatory distribution of ground motion amplitudes for given magnitude and distance. See section 2.1 for the definition of ε .

the strike or azimuth and dip angle of the underlying faults and the hypocentral depth distribution. All these parameters may have associated epistemic uncertainties.

In most past PSHA studies, earthquakes occurring in area sources have been treated as point sources for the purpose of computing distance from the event to the site. As a response to the complex SP1 expert models, this study uses a more realistic representation of the earthquake ruptures for area source events, by explicitly considering their size, depth, and orientation. This allows the use of arbitrary distance metrics for area sources.

The following sections provide further details on how area sources are modeled in this study.

Treatment of Spatial Distribution of Rate

Traditionally, the maximum magnitude, b-value, and annual rate of hypocentres per unit area have been assumed to be the same for all points within an area source. In this study, some SP1 expert teams specified spatial variability of rates within an area source with the maximum magnitude and the b-value kept constant. The variable seismicity option is often used in the context of broad, regional-scale source zones.

In the case of variable seismicity, the hazard software divides the source into multiple sub-sources by superimposing a longitude-latitude grid over the perimeter of the source. The size of this grid was specified by the SP1 TFI. The input to the hazard software indicates what fraction of the source's total rate is associated with each sub-source.

Treatment of Horizontal Extent of Ruptures

For the sake of simplicity, the horizontal and vertical geometric calculations are decoupled. This simplification introduces no error for vertical faults and introduces negligible error for typical dipping faults. This is not an issue for PEGASOS, because the only distance metric specified by the SP2 experts is the Joyner-Boore distance[4], which is a horizontal distance measure.

For the purpose of computing the horizontal distance from the site to the rupture, the hazard software takes into account the length and azimuth of the rupture, as well as the relationship between the rupture and the source boundary for hypocentres that are located near that boundary.

The logarithm of the mean rupture length is treated as a linear function of magnitude and the rupture width is calculated as length times a constant aspect ratio. If the rupture width exceeds the fault width, these calculations are modified as follows:

- The rupture width is made equal to the fault width.
- Optionally, the rupture length may be increased from the value calculated above, so as to conserve a linear relationship between magnitude and log[rupture area]. All PEGASOS SP1 teams chose this option.

The azimuth (or strike) of the rupture may be specified as a deterministic value, a uniform distribution, or an arbitrary discrete distribution.

If the entire rupture is located within the source, the rupture is assumed to extend symmetrically from the hypocentre. Two approaches are available for the case where the hypocentre is within the source but the closest point from the rupture to the site is not within the source (see Figure 2-2). In the 'strict' approach, the rupture is truncated at the boundary and no shifting of the rupture or adjustment of the width is performed. In the 'loose' approach, the rupture is not truncated and distance to the rupture is computed in the usual manner. The SP1 teams used both

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[4] When the Joyner-Boore distance metric is used, this decoupling introduces no errors because this metric considers only horizontal distances. A very small error is introduced near the source boundary if the "strict boundary" approach has been specified (see section 2.6.1.2). This error is particularly small because seismic hazard is dominated by low magnitudes (which are associated with small rupture dimensions).

approaches, some choosing the strict approach for certain sources and the loose approach for others.

Treatment of Depth and Vertical Extent of Ruptures

The distribution of hypocentral depth is specified by the SP1 expert groups for each individual source[5]. This distribution is assumed to apply to small events (with negligible source dimensions) and is modified for the effect of magnitude-dependent rupture dimensions. The approach followed is based on Appendix J of CRWMS M&O (1998) and on EPRI (1993), and is identified as the *Weighted Approach* in *Toro* (*2003b, TP1-TN-0373*). This approach is based on the following two assumptions: (1) hypocentres occur on the lowest fraction T of the earthquake rupture, and (2) the normalised distance from the bottom of the rupture to the hypocentre is uniformly distributed between 0 and T. These assumptions are used to calculate a weighting function that represents the probability that a certain combination of hypocentral depth and magnitude is realisable (i.e. the probability that the top of the rupture is located at or below the ground surface). The magnitude-dependent depth distribution is then obtained by multiplying the low-magnitude distribution specified by the SP1 group by the weighting function, and then normalising the probability so that the sum of probabilities is unity. Figure 2-3 illustrates the weighting functions and resulting magnitude-dependent depth distributions.

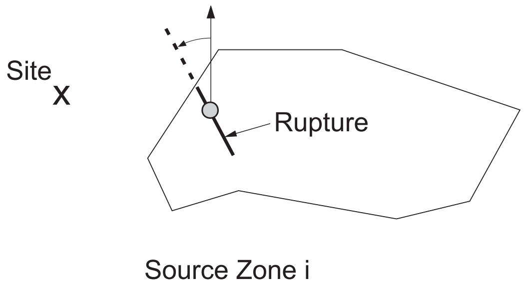

Fig.2-2: Treatment of rupture-site-zone geometry when the earthquake is located near a source boundary.

In the "loose" approach, the rupture is allowed to extend past the source boundary for the purposes of computing the minumum distance to the site. In the "strict" approach, the rupture is truncated at the source boundary.

2.6.1.2 Fault Sources

The geometry of fault sources is represented in three dimensions by a fault trace, a dip angle, and minimum and maximum seismogenic depths. The PEGASOS SP1 teams specified only two fault sources: the Reinach fault and the Fribourg fault.

Treatment of Along-fault Distribution of Rate

Earthquake ruptures are assumed to be uniformly distributed along the fault strike. More precisely, if *LF* is the fault length and *RF* is the rupture length for magnitude M (see section 2.6.2.2 below), the along-fault horizontal distance from the southern end of the fault to the southern end of the rupture is uniformly distributed between 0 and $LF - LR$.

Treatment of Horizontal Extent of Ruptures

Earthquakes occurring on faults are treated as having magnitude-dependent length, which is calculated using a linear relationship between magnitude and the logarithm of rupture length. If the calculated rupture length exceeds the fault length, it is truncated.

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[5] This distribution may be normal, uniform, trapezoidal, or specified by an arbitrary discrete distribution

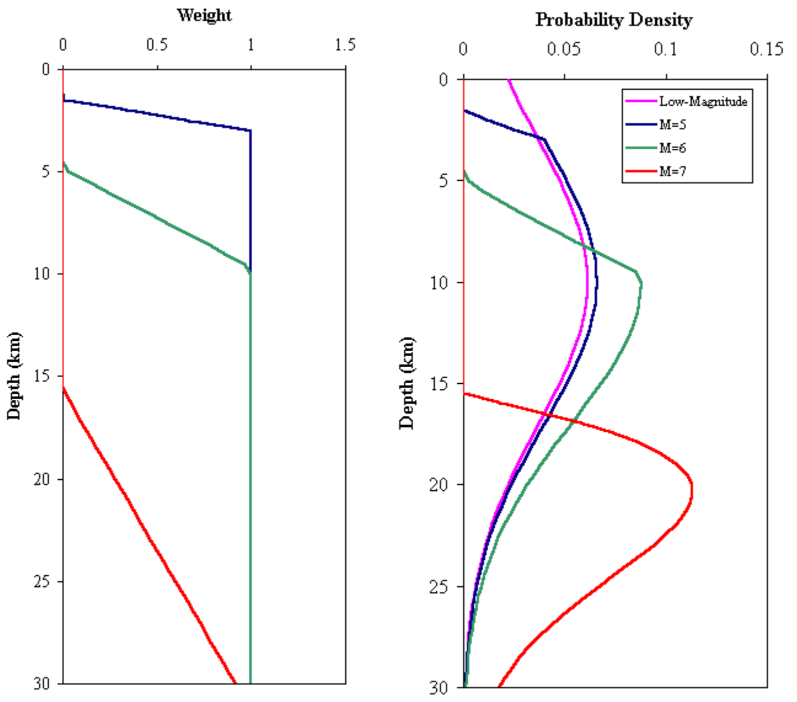

Fig.2-3: Weighting functions and magnitude-dependent depth distributions for T = 0.5 (weighted approach).

Treatment of Depth and Vertical Extent of Ruptures

Earthquakes occurring on faults are treated as having magnitude-dependent width, which is calculated using the relationship between magnitude and the logarithm of rupture length specified by the expert groups, together with a constant aspect ratio. If the calculated rupture width exceeds the width of the seismogenic zone, it is truncated.

The top of the rupture is assumed to be uniformly distributed over the seismogenic width of the fault, in a manner analogous to that described in section 2.6.1.1. A normal depth distribution is available in the software, but was not used. One team specified trapezoidal depth distributions for its two faults. These distributions were replaced by uniform distributions having the same mean and minimum depth.

2.6.1.3 Treatment of Faulting Style

For most seismic sources, the SP1 expert groups specified multiple styles of faulting, with their associated probabilities. According to the expert groups, these probabilities represent fractions of the total number of events in the seismic source, not weights on alternative hypotheses. Therefore, faulting style constitutes aleatory variability, not epistemic uncertainty. Each faulting style has an associated dip angle[6] and is associated with an attenuation equation (see section 2.6.5).

2.6.1.4 Epistemic Uncertainty in Seismic Source Characterisation

The PSHA methodology and software employed in the PEGASOS study allows each SP1 team to define its own source characterisation logic tree. The following discussion illustrates the common features of these logic trees. Further details are contained in sections 4.3 through 4.5.

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[6] One expert group specified multiple dip angles with associated weights for each faulting style, also representing aleatory variability.

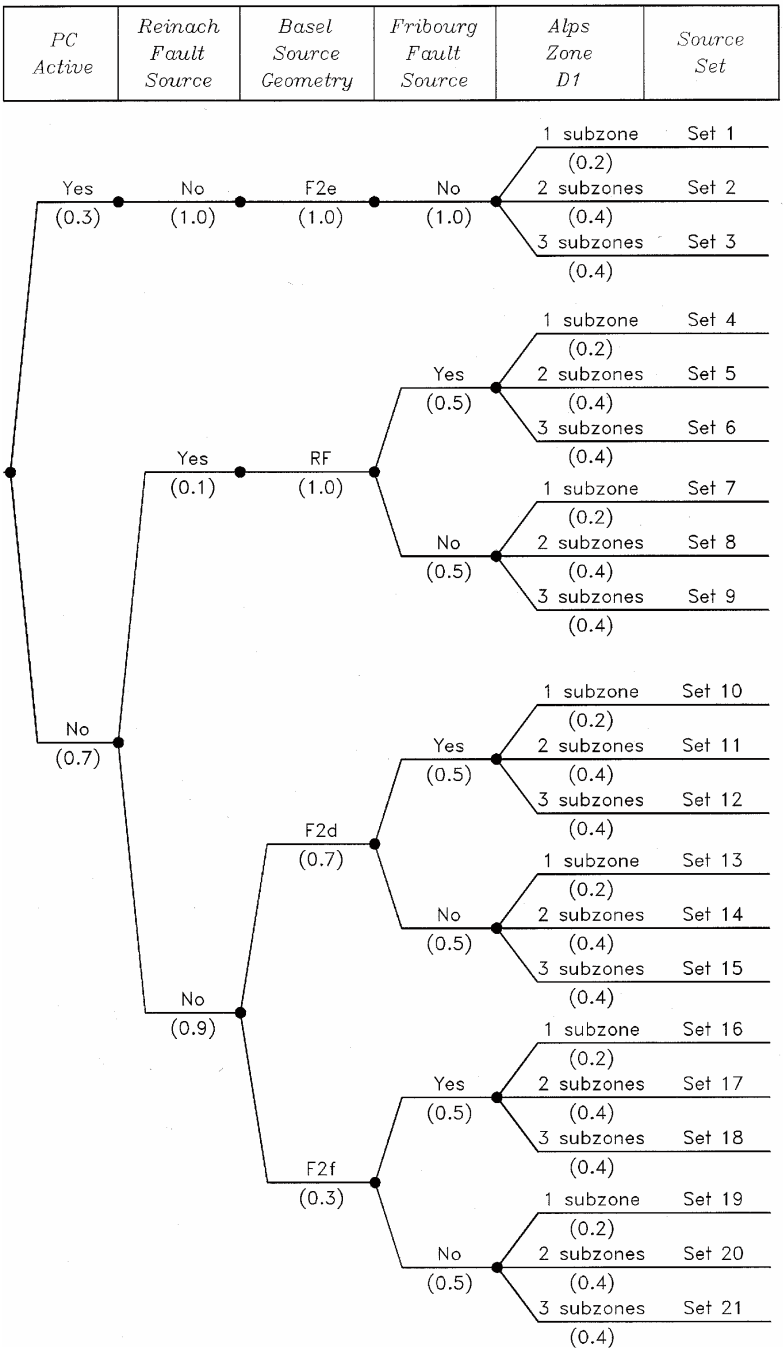

Fig.2-4: Logic tree for EG1a seismic source zonation

The first group of logic tree variables, called global variables, are those that affect multiple seismic sources[7]. The choice of logic tree variables, dependence relations among these variables, number of branches and their probabilities and how these variables affect the source parameters (i.e. horizontal and vertical source geometries, activity rates, b-values, maximum magnitudes, etc.) are quite flexible. Global variables may be subdivided into two main categories, as follows:

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[7] Variables that affect multiple characteristics of a given source (e.g. geometry and maximum magnitude) also fall within this category.

- Variables related to alternative global zonation approaches and the existence of sources. The geographic scope of these variables may range from those covering the entire study region (e.g. EG1b's alternative zonation approaches: large-scale with smoothing vs. small-scale with homogeneous seismicity), to those covering small perturbations of a source's boundary. These variables typically control the existence and geometry[8] of the various seismic sources. Figure 2-4 illustrates this portion of the logic tree.
- Variables related to the calculation of source parameters. Examples of these include the catalogue to use, catalogue completeness model, regional b-values, and approaches to use for calculating recurrence parameters (e.g. maximum likelihood vs. Bayesian vs. regression for the calculation of rates and b-values, EPRI vs. Kijko for the calculation of maximum magnitude, truncation of maximum magnitude distribution at M 7.5 vs. 8.0).

The second group of logic tree variables, called local or source variables, are those that affect only one set of parameters (i.e. geometry, recurrence, or maximum magnitude) for only one source. Note that these are the quantities that actually enter the hazard calculations in Equation 2-1. The dependence of these variables on the global variables is specified by the SP1 team. Multiple, alternative values of these variables represent the conditional epistemic uncertainty (often statistical uncertainty) in the source parameters, given the values of the global variables. There are two[9] of these variables, as follows:

- Recurrence. This is a vector-valued variable, consisting of the rate (ν) and the b-value. These two quantities are specified as pairs because they are highly correlated.
- Maximum magnitude.

2.6.2 Rock Ground Motion Characterisation

2.6.2.1 Horizontal Ground Motion

Based on the discussions in sections 2.1 and 2.5, we note that the complete specification of a ground motion model (i.e. all the ground motion information needed for the evaluation of Equation 2-1) consists of four separate algorithms, which calculate the following quantities as a function of magnitude and distance: (1) median ground motion amplitude, (2) standard deviation σ, (3) upper-tail truncation (in units of σ), and (4) maximum ground motion (in units of amplitude).

This complete specification is vector-valued, in the sense that it contains separate algorithms for each style of faulting and for each ground motion frequency. For the sake of flexibility, all these algorithms are implemented using tables in magnitude-distance space for each style of faulting in the PEGASOS Project. Interpolation is used to compute the ground motion parameters at magnitude and distance pairs not specified in the tables.

Epistemic uncertainty in ground motions is characterised by expert-to-expert differences in the models and by within-expert estimates of epistemic uncertainty. Regarding the latter, each SP2 expert defined a logic tree (in a manner similar to that described in section 2.6.4). This process is documented in sections 5.3 through 5.5. Prior to the hazard calculations, the SP2 TFI-team transformed the expert logic trees from their original (physical space) variables into the four (hazard space) quantities described above. This parameterisation of the SP2 expert models is described in section 5.3.3. Figure 2-5 summarises the final ground motion logic tree used in the

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[8] Note that the source geometry usually affects the recurrence parameters and maximum magnitude of a seismic source, because it may affect which events in the catalogue are treated as occurring within that source.

[9] There is a third source variable, which is used in the PEGASOS study to characterise aleatory variability in faulting style (see section 2.6.3).

hazard computations. The assignment of weights to the within-expert median and σ branches and subsequent steps prior to the hazard runs are documented in *Toro* (*2004b, TP4-TN-0395*).

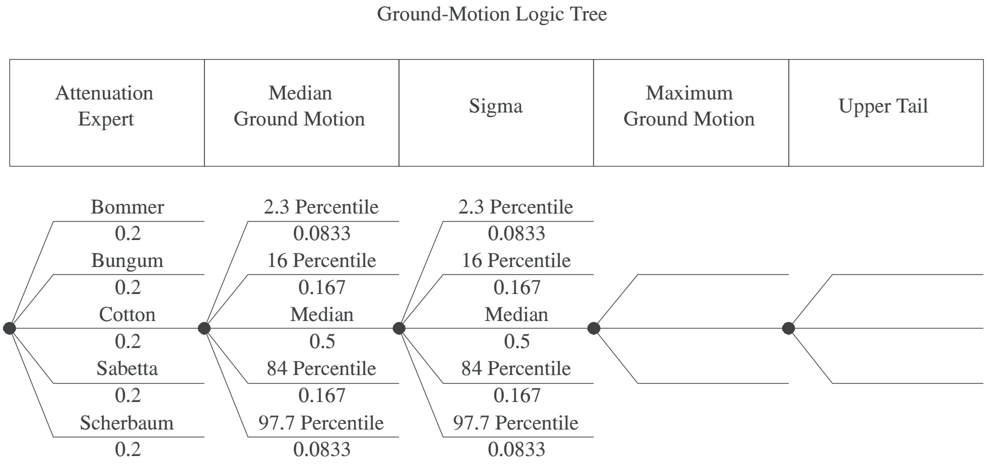

Fig.2-5: Rock ground motion logic tree (in generalised form)

The last two levels of the tree (see section 2.6.2.3) are expert-dependent and are only schematically drawn here. The SP2 experts considered up to six alternative branches for the maximum ground motion and up to three branches for the upper-tail truncation.

2.6.2.2 Vertical Ground Motion

Based on the results of the PSHA for the horizontal component, suites of hazard curves and uniform hazard spectra are available, which represent the epistemic uncertainty in the hazard for the horizontal component of motion. The corresponding vertical-component uniform hazard (response) spectrum (UHS) is computed by scaling the horizontal-component UHS at each fractile by the appropriate V/H ratio. Because the V/H ratio assessed by the SP2 experts depends on magnitude, distance and faulting style, the results of the deaggregation are needed to define the contribution of the magnitude-distance pairs for computing the V/H ratio. For each ground motion amplitude and each spectral frequency, the weighted average of the V/H ratio is computed with the weights given by the deaggregation.

The SP2 experts provided logic trees for the V/H ratio and for the maximum vertical ground motion, so there are alternative values of the ratio and of the upper limit representing the epistemic uncertainty. However, because the approach for the vertical component seeks to calculate the anticipated vertical motions given the horizontal motions represented by the horizontal UHS, the upper-limit corrected mean value from the logic tree for the V/H ratio is applied to all of the horizontal UHS fractiles for a given ground motion amplitude and spectral frequency. That is, for a given expert, the same corrected V/H ratio is applied to all fractiles for a given ground motion amplitude and spectral frequency.

The vertical-component hazard curves are computed in the same way by scaling the horizontal component ground motion (values on the x-axis of the hazard curves) by the mean V/H ratio for the given ground motion amplitude and spectral frequency.

The vertical-component UHS is computed using the horizontal-component UHS and the median V/H ratio (corrected for the vertical ground motion upper limit):

$$UHS_{vert}\left(freq, Frac, Amp\right) = UHS_{horiz}\left(freq, Frac, amp\right)\cdot \overline{V/H_{corr}\left(freq, {\max}\, GM_V\right)} \tag{2-3}$$

where $\overline{V/H_{corr}}$ is the corrected mean value of the median V/H ratio from the logic tree for each SP2 expert. The uncorrected V/H ratio for a given combination of amplitude, frequency and faulting style is given by

$$\overline{V/H}\left(Amp, freq\right) = \sum_i \sum_j deagg\left(Amp, freq, m_i, r_j\right)\sum_k P_k V/H\left(freq, m_i, r_j, style_k\right) \tag{2-4}$$

To calculate the mean V/H ratio over all faulting styles specified by the four expert groups (see section 2.6.3), one considers the probabilities assigned to the different faulting styles for the controlling source zones[10] (P_k) averaged over the four expert groups. It is sufficient to consider only the controlling source zones because the hazard is dominated by distances within 20 km for peak accelerations greater than 0.05 g.

The deaggregation of the hazard for the horizontal component, from which one derives the deaggregation contributions that appear in Equation 2-4, is calculated only for selected ground motion amplitudes and spectral frequencies. The deaggregation at the other amplitudes and frequencies needs to be estimated. The deaggregation changes in a smooth manner, so the computed values can be interpolated to estimate the deaggregation at each of the magnitude-distance pairs for the other cases. Therefore, linear interpolation and nearest neighbour extrapolation were judged to be appropriate.

The corrected V/H ratio accounts for the maximum vertical ground motions specified by the SP2 experts. The vertical ground motion upper limit (${}_{max}GM_V$) is the mean value of the maximum ground motion estimates from the logic tree for each SP2 expert. The V/H_{corr} ratio is computed by applying the maximum ground motion truncation to the product of the uncorrected ratio and the horizontal rock hazard and rebuilding the V/H ratio.

$$\overline{V/H}_{corr}\ freq, Amp, {}_{max}GM_V \qquad \min \ \frac{\overline{V/H}\ freq, Amp}{{}_{max}GM_V\ /UHS_{horiz}(freq, Frac, Amp)} \tag{2-5}$$

2.6.2.3 Maximum Ground Motion

The SP2 experts specified maximum ground motion on rock, in terms of ε, in terms of a maximum amplitude that depends on magnitude and distance, or in terms of both. In addition, two alternative mathematical forms were specified for the associated truncation. Typically, the distribution of ε is assumed to follow a truncated normal distribution. Another option is introduced in this study, where the normal probability density function is multiplied by a taper function and then normalised (Figure 2-6).

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[10] Each SP1 model has a different site and zonation scenario-specific probability scheme of the three styles of faulting in the host zones. These probabilities vary little from site to site and from scenario to scenario, therefore the mean value is considered. The SP1 models are equally weighted.

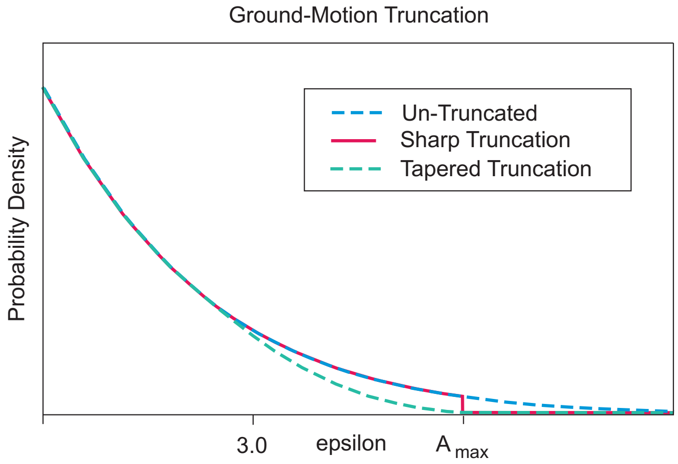


Fig.2-6: Distribution of ε and implementation of maximum ground motions on rock

In the un-truncated case, the distribution of ε extends to infinity. In the sharp truncation, case, amplitudes greater than $A_{\max}$ are not allowed. In the tapered truncation case, the probability density is multiplied by a taper function that is equal to 0 at the value of ε associated with $A_{\max}$ and is equal to unity at $\varepsilon = 3$.

Epistemic uncertainty in the rock maximum ground motion is specified by means of logic trees, along with the other epistemic uncertainties affecting rock ground motions and site amplification, respectively.

2.6.3 Site Response Characterisation

2.6.3.1 Reference Rock Condition

The SP2 experts developed ground motion attenuation models for a rock site condition. The SP3 experts developed soil / rock amplification factors that are used to scale the response spectral values on rock to compute the response spectral values for the type of soil found at the four sites. This approach allowed the regional rock site ground motions to be evaulated separately from the site-specific site response.

A consistent definition of 'rock' needs to be used by SP2 and SP3. The selection of the reference rock site condition is not critical as long as it is consistent beween SP2 and SP3. For PEGASOS, the experts defined a reference rock site as a site with a surface shear-wave velocity of 2000 m/s (see Vol. 3, *Koller et al. 2002, PMT-TN-0206*, minutes EG3 Meeting 04.02.2002) This shear-wave velocity corresponds to a hard-rock site. It was selected because the site shear-wave profiles at all four NPP sites have velocities less than 2000 m/s at the deepest embedment level.

The candidate rock attenuation relations considered by the SP2 experts correspond to different shear-wave velocities ranging from 500 m/s to 2800 m/s. Most of the models are applicable to velocities less than the reference 2000 m/s. To account for the different reference v_s values, the ground motions predicted by the candidate models were adjusted to the 2000 m/s PEGASOS reference rock site condition using response spectral factors based on generic velocity profiles applicable to the region for which the attenuation relation was developed. On average, these factors reduce the ground motion as compared to the published models because most of the models are applicable to sites with $v_s < 2000$ m/s.

The resulting soil hazard curves are not dependent on selected reference rock condition. For example, if a reference rock velocity of 1000 m/s had been selected rather than 2000 m/s, the rock hazard would give higher ground motions, but the soil / rock amplification factors would be reduced so the soil hazard would be unchanged. This is not only valid for the mean hazard but also applies to the associated uncertainty.The selection of the reference rock site velocity is not an uncertainty, it is a definition that is consistent between SP2 and SP3.

2.6.3.2 Horizontal Amplification Factors

As with the horizontal ground motion, the complete specification of the horizontal amplification model consists of four separate algorithms, which calculate the following quantities as a function of magnitude and rock motion amplitude: (1) median amplification, (2) standard deviation of the amplification, $_{\ln AMP}$, (3) maximum soil ground motion.

This complete specification is vector-valued, in the sense that it contains separate algorithms for each style of faulting and for each ground motion frequency. For the sake of flexibility, all these algorithms are implemented as tables in magnitude-rock motion space in the PEGASOS Project.

Epistemic uncertainty in site amplification is characterised by expert-to-expert differences in the models of the median amplification and the aleatory variability of the amplification and by within-expert estimates of epistemic uncertainty. An example of an SP3 logic tree is shown in Figure 2-7. The alternative models represent the uncertainty in the soil properties (velocity profile and non-linear behaviour), 1-D site response estimation methodology, and potential 2-D and / or 3-D effects on the site response.

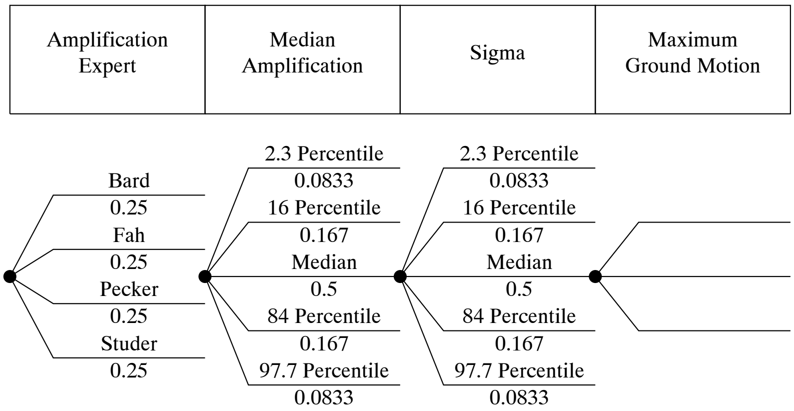


Fig.2-7: Site response logic tree (in generalised form). The last levels of the tree (see section 2.6.3.4) are expert-dependent and are only schematically drawn here.

Epistemic uncertainties in the maximum ground motion on soil (at the surface and at the embedded levels) are also characterised by the SP3 experts. The epistemic uncertainty represents the alternative methods for computing the maximum ground motion based on soil strengths and using empirical observations of the largest ground motions recorded on soil sites.

The soil hazard software tracks the epistemic uncertainties in the site amplification using the experts' logic trees in the same way they are treated for the source characterisation and ground motion characterisation. The soil hazard program combines the epistemic uncertainty from the rock motion (in terms of fractiles of the hazard curves) with the epistemic uncertainty of the amplification factors to compute the total epistemic uncertainty of the soil motion at the surface and at the embedded levels.

2.6.3.3 Vertical Amplification Factors

For the vertical component soil ground motion, two approaches were used. In the first approach, a separate amplification model was constructed, and the soil hazard was computed using the vertical component hazard curves for rock, developed as described above for the horizontal component (section 2.6.3.2). In the second approach, the vertical motion was computed by multiplying the horizontal motion by a V/H ratio. The second approach had two variants: either multiplying the rock horizontal motion by the V/H ratio, or multiplying the soil horizontal motion by the V/H ratio.

2.6.3.4 Maximum Ground Motion

The SP3 experts specified maximum horizontal ground motions on soil. This was done in terms of ground motion amplitude (which may be a function of magnitude). Epistemic uncertainty in the soil maximum ground motion was specified by means of logic trees based on alternative models of the soil strength.

2.6.4 Display of Sensitivity to Quantities Having Epistemic Uncertainty

In the PEGASOS Project, epistemic uncertainties in seismic source characterisation, ground motion equations and site effects were quantified by considering inputs from the four SP1 source characterisation teams, the five SP2 ground motion experts, the four SP3 site effects experts and by each team's and expert's own assessment of uncertainty. That is, each SP1 team formulated multiple alternative interpretations about the seismogenic characteristics of potential seismic sources and assigned weights to these hypotheses according to their credibility given the current state of knowledge and the degree to which they are supported by data. Each SP2 ground motion expert applies a similar procedure to alternative interpretations about the source and path characteristics affecting rock ground motions. Finally, each SP3 expert uses the same approach to characterise the amplification or deamplification of the rock motion at the four sites. The development of these seismic source, ground motion and site effects interpretations is documented in chapters 4, 5, and 6 of this report.

This study displays sensitivity to a variable or hypothesis in the logic tree by calculating and displaying the results associated with each separate instance of that variable or hypothesis. Consider a situation where an SP2 expert specifies five alternative values (with associated weights) for the median ground motion equation. To display sensitivity to the expert's median ground motion equation, the software identifies all hazard curves arising from branch tip models that consider the expert's first ground motion model, and then computes the average of these hazard curves. The software repeats the procedure for the second through fifth ground motion equation, resulting in five (conditional) hazard curves. By comparing these five hazard curves (and considering their associated weights), we obtain a measure of how much this uncertainty contributes to total uncertainty in seismic hazard.

3 EXPERT INPUT

This chapter describes the process followed to elicit and incorporate expert judgements in the key inputs to the PSHA. Described in this chapter are the criteria for being an expert, the expert selection process, and the general process followed in eliciting the evaluations of experts. Experience has shown that, to be credible and useful, technical analyses such as those performed for the seismic characterisation, ground motion attenuation and site response must: (1) be based on sound technical information and interpretations, (2) follow a structured process that considers all available data, and (3) incorporate uncertainties (SSHAC 1997). A key mechanism for quantifying uncertainties is the use of formal expert elicitation.

In the PEGASOS PSHA, the term 'elicitation' is used in a broad sense to include all of the processes involved in obtaining the technical evaluations of multiple experts. These processes include reviewing available data, debating technical views with colleagues, evaluating the credibility of alternative views, expressing interpretations and uncertainties in elicitation interviews, and documenting interpretations. In this sense, the elicitation process began with the first workshop and ended with the finalisation of the elicitation summaries.

3.1 Guidance Regarding Expert Elicitations

Comprehensive guidance on processes to be followed for expert elicitations has been set forth in the document *Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and Use of Experts* by the Senior Seismic Hazard Analysis Committee (SSHAC 1997). The guidance was developed under sponsorship of the US Nuclear Regulatory Commission (US-NRC), the Electric Power Research Institute (EPRI), and the US Department of Energy (US-DOE). The study was conducted with the purpose of drawing on the experience gained from expert elicitation projects, particularly those conducted for nuclear power plants in the central and eastern United States, and developing a consensus position regarding acceptable methodologies. In reviewing the differences in PSHA estimates conducted by different groups for individual sites, the SSHAC study concluded that the differences were largely due to *procedural* differences in the manner in which the PSHA was conducted. Hence, it is concluded that the procedural steps are as important as the technical analyses that comprise a PSHA. Accordingly, the PEGASOS Project fully implements the SSHAC procedural guidance, duly adjusting detailed process steps to accommodate the specific data and technical issues of importance to the Swiss nuclear power plant sites.

A basic principle defined by SSHAC (1997, p. 21) is that:

'The underlying basis for the inputs [to a PSHA]… must be the composite distribution of views represented in the appropriate scientific community. Expert judgement is used to represent the informed scientific community's state of knowledge.'

As noted in SSHAC (1997, p. 21), the goal of any formal expert elicitation process is:

'To represent the center, the body, and the range of technical interpretations that the larger informed technical community would have if they were to conduct the study'.

In this context, 'informed' signifies, hypothetically, that all in the community have a full understanding of the site-specific technical details. The SSHAC guidance specifies four 'study levels', ranging from a Level 1 study conducted by a single Technical Integrator (TI) and based on data from the available literature, to a Level 4 study involving the formal elicitation of multiple experts by a Technical Facilitator/Integrator (TFI). The PEGASOS PSHA is a SSHAC Level 4 study and the methodology is consistent with the structured elicitation formalism associated with that study level, including the integration of the assessments of multiple experts.

In addition to procedural guidance, the PEGASOS expert elicitation methodology is consistent with the experience gained from past PSHAs of a similar scale. Two examples are the PSHAs conducted by the Electric Power Research Institute (EPRI-SOG 1986, EPRI 1989) and for the Yucca Mountain, Nevada, high-level nuclear waste repository. In the EPRI study, which provided an assessment of the seismic hazard at 37 commercial nuclear power plant sites in the central and eastern US, experts were arranged into six earth science teams. Each team had a range of expertise required for characterising seismic sources, including seismology, geophysics, and geology/tectonics. Multiple workshops were held to evaluate technical issues, and each team developed seismic source characterisations including their associated uncertainties. The technical basis for the assessments was documented in a final report (EPRI-SOG 1986) and the study underwent extensive review by the US Nuclear Regulatory Commission (EPRI-SOG 1986, vol.11).

As in the EPRI-SOG study, the seismic source characterisation experts in the Yucca Mountain PSHA (CRWMS M&O 1998, Stepp et al. 2001) were arranged into teams and each team was expected to function as a 'virtual expert', expressing its evaluations and uncertainties as an individual expert. The Yucca Mountain PSHA methodology also included a number of structured workshops in which data were presented, alternative models and interpretations were debated, and feedback was given. In both studies, uniform databases were provided, interaction among the experts was encouraged, elicitations were conducted in interviews, and documentation was developed in elicitation summaries for each expert or expert team. Experience gained from these previous studies, as well as others that have occurred over the past fifteen years, provide a firm basis for developing and implementing the methodology for the PEGASOS PSHA.

3.2 General Approach

The PEGASOS PSHA followed the procedural guidance set forth in the SSHAC (1997) study, both in spirit (e.g. recognition of the importance of facilitated expert interactions) and, as applicable, in details of implementation (e.g. suggestions for conducting workshops and elicitation interviews). For example, the seismic source characterisation, ground motion attenuation and site response experts were all provided with training to help them express their uncertainties in probabilistic terms. The distinction between aleatory variability and epistemic uncertainty was discussed in terms of applicable examples. The experts were also made aware of the possible motivational and cognitive biases that are common to all forms of expert judgement, such that these biases could be mitigated. The experts were informed early in the project, and reminded throughout, of the need to express full ranges of uncertainty; that is, they were asked to express alternative interpretations permitted by the available data weighted by the degree that each was supported by the data.

3.2.1 Experts and Expert Groups

The SSHAC defines the roles of expert *proponents, evaluators,* and *integrators.* An expert proponent advocates a particular technical hypothesis or interpretation, an expert evaluator considers the support for alternative hypotheses and interpretations in the available data and evaluates the credibility or weight to assign to the alternatives, and an expert integrator combines the evaluators' alternative interpretations into a composite distribution that includes uncertainties. The fundamental role of the experts on the project is that of evaluators. The expert evaluators are expected to forego the role of proponents in making their interpretations and evaluating uncertainties. Proponents of specific hypotheses or interpretations participated in the project at workshops and presented their points of view to the experts. Alternative proponent interpretations were presented to the experts and open scientific debate was encouraged. In some cases, individual experts on the panel were asked to 'change hats' and to serve as proponents of particular models or interpretations at the workshops. The experts were also asked to assist the technical facilitator/integrator (TFI) in the process of integrating the evaluations across all experts and in ensuring that the composite distribution of evaluations is representative of the larger informed technical community.

In the case of subproject SP1, the expert evaluations were conducted by four expert groups or teams that acted as a single virtual expert. Similarly to the EPRI study and the Yucca Mountain PSHA, seismic source characterisation requires a range of technical expertise, which is best accomplished through the use of a multidisciplinary expert group. Each expert group included an expert in seismology, geology, and seismotectonics. Further, each group included at least one member with experience in providing input to a PSHA. Working as a team, the SP1 experts addressed the various components of the seismic source models. Evaluations and assessments of uncertainty by each team reflected the multidisciplinary nature of each team and all team members agreed to the assessments given in the final elicitation summary for their team.

3.2.2 TFI and TFI-Teams

Expert interactions are a central component of the elicitation process and must be properly facilitated. Experience from numerous seismic hazard studies has shown that experts interact frequently in their professional activities, and that workshops serve to provide information and interaction that encourage their consideration of hypotheses and data. Expert interactions on the PEGASOS Project were facilitated through multiple workshops. Presentation, technical challenge, and debate of alternative interpretations was the focus of these meetings, which included discussions of preliminary interpretations made by the experts.

For a Level 4 PSHA, the SSHAC guidance defines the role of a 'Technical Facilitator/Integrator' or TFI. A technical *facilitator* is an individual – or a small group of individuals acting as a team – who has acknowledged technical expertise as well as expertise in probability and uncertainty treatment. In the case of the PEGASOS Project, the TFI-team for each of the subprojects consisted of a technical facilitator, an individual with expertise in uncertainty quantification, and an individual skilled in translating the SP inputs into hazard inputs.

In addition to facilitation, the TFI is also an *integrator*, integration being defined as 'the process of combining multiple experts' evaluations into an aggregate assessment across all experts'. The SSHAC (1997) process emphasises the need to consider at the outset of a project the strategy for integration of the experts' evaluations. From the beginning of the PEGASOS Project, a strategy was defined to combine the evaluations of the experts using equal weights. The key procedural components of the project, ranging from the selection of the experts to the dissemination of data, were designed to allow the equal-weights strategy to be implemented in a defensible manner. As noted by the SSHAC (1997), the goal of a multi-expert evaluation of inputs to a PSHA is to capture and express the range of uncertainty such that the aggregated hazard represents reasonably the uncertainty of the informed technical community. The final integration of the experts' evaluations was done using equal weights, and the experts provided their concurrence that the result – aggregated across all of the experts on the panel – provides a reasonable expression of uncertainty and would not be systematically different from the larger technical community if they had performed the evaluations.

3.2.3 Principal Steps

The general approach implemented by the PEGASOS Project for eliciting the evaluations of the experts is described in this section. The specific steps for each subproject are given in chapters 4, 5, and 6.

- Development of a Project Plan. The project management team (PMT) developed a project plan that outlined the goals and key elements of the project, the scheduling of significant activities such as workshops and work packages, and the organisation and management of the entire project. The project plan was submitted to HSK and accepted prior to the initiation of the project. Throughout the project, flexibility was maintained to address additional needs as they arose in order to ensure that the project goals were achieved (see section 1.2.4).

- Selection of Experts. The PMT established criteria for the selection of experts (see section 3.3). These criteria were intended to ensure that all experts had proper professional stature within the technical community, technical expertise and experience to perform the required tasks, and sufficient motivation and commitment to complete the tasks in a timely manner. A list of 109 candidates was developed by the PMT, which was broken down by subproject, with input from the TFIs. From this list of candidates, 12 experts (four teams of three) were selected for SP1, five experts for SP2, and four experts for SP3.
- Data Compilation and Dissemination. The compilation and distribution of pertinent data, including published reference material, began early and continued throughout the project (section 3.4). A fundamental goal of the project was to provide to all experts a consistent, uniform database for their evaluations. Further, the process for identifying data to enter into the database was designed to be responsive to experts' requests, and database materials requested by the experts were to be provided in an expeditious manner. Before the first workshop, a number of anticipated references and databases were entered into the PEGASOS database. The first workshop was focused on identifying the key technical issues and provided a forum for the experts to define the data that they would need for their subsequent evaluations. This provided the basis for the first data delivery to the experts. At various times during the course of the project, the project honoured 134 data requests.
- Meetings of the Experts. Structured, facilitated interaction among the experts took place during the workshops and working meetings. The workshops were designed to identify significant issues, review available data, debate alternative models, and review methods to quantify uncertainties in the seismic source, ground motion, and site response inputs to the PSHA. Proponents of particular technical positions provided their interpretations to the experts. Debate and technical challenge of alternative interpretations were facilitated to understand differences and identify uncertainties. At these meetings, resource experts participated from a variety of organisations, presented pertinent data sets, and discussed alternative models and methods. All of the experts from all four subprojects were in attendance at the first workshop, to participate in discussions of the project goals and expectations, overviews of the tasks to be undertaken, and elicitation training in uncertainty and probability. All of the experts also participated in a joint session at workshop WS-4 to receive feedback regarding the relative importance of various inputs to the seismic hazard results. Finally, a joint session of all experts was held at the end of project workshop WS-5, which provided an opportunity to review the entire project, the hazard results, and sensitivity analyses. In addition to the workshops, small meetings were held among the expert teams in SP1 for discussion within each team, and among the SP2 and SP3 experts to discuss specialised topics.
- Elicitation Interactive Meetings. Elicitation interviews or interactive meetings were held, lasting one to three days depending on the subproject, with individual experts and representatives of the TFI-teams. The interview sessions provided an opportunity to review the inputs required for the seismic hazard analysis, to discuss the preferred and alternative evaluations, to express and quantify uncertainties, and to specify the technical bases for the assessments. Based on experience gained in other elicitations, the TFI-team did not require the experts to conduct all of their evaluations during the interview sessions. Rather, the overall assessments were discussed, the approaches and methodologies were defined, and example detailed evaluations were given during the elicitation interview sessions. Agreements were also reached regarding the level of detail for the documentation of the expert assessments. Following the sessions, the experts completed their evaluations independently (or as a group, in the case of SP1), drawing on support from the TFI-teams as needed.

- Requests for Supporting Calculations. The workshops and elicitation interviews provided an opportunity for the experts to identify methods and approaches to their evaluations. In many cases, implementation of those methods and approaches required calculations based on the approaches, algorithms, and input data requested by the experts. The project provided calculation support for these requests. In many cases, the supporting computations conducted provided a basis for the experts to examine the sensitivity of various approaches or the relative importance of different inputs to the calculated results (see section 3.5).
- Feedback of Preliminary Results. Following the elicitation interactive meetings and the completion of preliminary evaluations, feedback workshops were held for each subproject. The objectives of these workshops were to review, discuss, and debate the evaluations of each of the experts or expert teams, allowing them to understand the alternative approaches used by others as well as to technically defend their preliminary interpretations. Debate and technical challenge of the interpretations, conducted in a facilitated and structured environment, were encouraged to make sure that alternatives were understood and uncertainties were being appropriately addressed. In addition, preliminary calculations of interim results (e.g. calculations of earthquake recurrence rates, ground motion amplitudes or soil amplification factors) and of hazard results were presented by the TFI-teams and discussed. This calculated feedback provided a mechanism for focusing the subsequent work of the experts toward those models and parameters of most significance to the results.
- Preparation of Hazard Input Documents. Once the experts had finished their evaluations, a hazard input document (HID) was developed by the TFI-team. The HID defines the components of the experts' assessments in a form that is directly useable in the PSHA (see section 3.8). The draft HID was reviewed by each expert to ensure that it was accurate, signed by the expert, and then passed on to the SP4 hazard calculation team. This process ensured that the expert assessments were properly and accurately passed along to the hazard calculation team.
- Finalisation of Expert Evaluations. Following the elicitation interview and feedback workshops, the experts revised and refined their evaluations. Documentation of the experts' assessments was developed in the elicitation summaries (ESs). The outline for the summaries was provided to the experts early in the project so that they would be aware of the documentation requirements throughout the course of the elicitation. Immediately following the completion of the final HIDs, the draft elicitation summaries were developed. Reviews of the draft ESs were conducted by the TFI-teams to ensure that the explanation of the models, components, parameters, and associated uncertainties was clearly provided. The final elicitation summaries provided in this report (Volumes 3, 4 and 5) are the fundamental input to the PEGASOS PSHA.

3.3 Selection of Experts

The selection of experts involved four steps: (1) developing selection criteria, (2) obtaining a pool of candidates, (3) selecting and inviting candidates to participate, and (4) obtaining approval by HSK of the list of chosen experts. A selection panel, formed from members of the PMT and the TFI-teams, was responsible for the expert selection process.

Expert selection was based on the following criteria:

- Having sound technical expertise in their respective fields, as demonstrated by professional reputation, academic training, and peer-reviewed publications
- Having specific knowledge of conditions related to seismic hazard in Switzerland and the study region in general
- Being willing to commit the time required for the project

- Being willing to participate in a series of open workshops, diligently prepare the required evaluations, and openly explain and defend technical positions with other experts on the project
- Being prepared to foresake the role of a proponent and perform as an evaluator, including independence from any organisational positions
- Being capable of making firm commitments and expressing judgements in quantitative terms for use in PSHA
- Having personal attributes of strong communication skills, interpersonal skills, flexibility, impartiality, and an ability to simplify and explain technical positions.

With input from a few acknowledged members of the technical community, the selection panel compiled a pool of candidates for each of the three subprojects. A total of 109 candidates were identified in the pool.

Starting with the candidate pool, the experts were selected based on the considerations for each subproject. For the seismic source characterisation SP1, multidisciplinary expert teams were required, with each team having expertise in geology, seismotectonics, and seismology / geophysics. Experts were selected and placed into teams based on these considerations. An additional consideration was that each team should have at least one member with experience in seismic hazard analysis. For ground motions SP2, five experts were chosen with consideration of a panel that included individuals knowledgeable in both empirical approaches and numerical approaches to ground motions. In addition, experience in near-field source effects and crustal attenuation in Europe was also considered. For site response SP3, the four experts were selected with consideration of experience in geology, geotechnical engineering, and site response modelling.

The curriculum vitae for the experts in each of the subprojects are given in the Appendices to Volumes 3, 4 and 5 of this report. The list of experts chosen by the selection panel was submitted to HSK and approval was obtained.

3.4 Project Database / Compilation and Dissemination of Data

Data compilation and dissemination was an important aspect in all subprojects. The goal was to ensure that the experts could base their evaluation and models on all available data and existing interpretations, whether or not they were published, and that all experts were informed about, and had equal access to, the same data sets and information. All the collated data were centralised at the Computing, Modelling and Database Centre (CMD) at Proseis AG.

Before the first workshop, a first selection of anticipated references and data sets had been collated and formed the starting point of the PEGASOS database. One of the main purposes of Workshop 1 was to present the existing data and to identify the key technical issues and associated additional data sets that the experts would need to perform their assessments and develop their models. The additional data layers and reference materials were collated by the project and presented at the following workshops or expert elicitation meetings, during which requests for new data were systematically gathered and, whenever possible, subsequently met. To ensure that all experts were equally informed, data sets were either disseminated to all the experts within a subproject (whether or not they all had solicited the data) or the availability of a data set, together with a short description, was announced to all subproject experts.

Two categories of data were identified: *documents* and p*roject data*. Documents were typically written documents such as reports, memoranda, technical notes or minutes of meetings. *Project data* referred to all data that could have a direct influence on the numerical results of the project. Both categories of data were administrated in separate databases: the *document DB* and the *project data DB.* A unique identifier code was assigned to each individual record in the databases, thus to each of the approximately 2000 data sets. Listings extracted from these databases (with highlighted new entries) were regularly published on the PEGASOS web site, to which each expert and project member had access. The CMD was responsible for the administration of the databases, for receiving the written data requests from the experts and other project participants, for compiling and disseminating the data to the experts and for maintaining the PEGASOS web site and the project-specific ftp site.

In addition, the CMD received copies of all e-mail messages of general importance to the project, archived these messages with their attachments and maintained listings.

3.4.1 Structure of the Project Data DB

Figure 3-1 shows the general structure of the project data DB and delineates the flow of information. The database was conceived in such a way that the entirety of the project data is comprehensive enough to allow a reconstruction of all numerical results arising from the project and guarantees traceability and reproducibility of all computations back to the level of basic data (see below).

Individual database subunits (boxes in Figure 3-1) were designed to hold different types of data, each type with its own three-letter designation. A formal procedure for quality assuring, registering and archiving project data is described in the QA Guidelines (*Sprecher 2003, QA-TN-0402*, see Appendix to this volume) and briefly sketched in section 3.4.6. It was applied throughout the project.

Another formal data release procedure (also described in *Sprecher 2003, QA-TN-0402*) ensured that the project data DB items were used only within the subproject from which they originated, as long as they were considered preliminary. Project data DB items were released by the project manager at the request of a subproject leader, after all verifications regarding QA checks and the future use of the data set had been made.

The uppermost level in the project data DB structure is the *basic data* level, with the different, subproject-specific external data as they were originally accepted and entered into the project data DB (see sections 3.4.3 through 3.4.5). The flows continue with the supporting computations made on behalf of the experts (see sction 3.5) which, together with the basic data, form the project support entity and which led first to experts' assessments (individual elements of the expert models) and eventually, after a few iterations, to the complete expert models. The next level in the flow is a highly important interface level between the expert elicitation block (see Figure 3-1) and subproject 4, in which the TFI-teams, based on the expert's elicitation summary, develop the *hazard input documents* (HIDs, see section 3.2.3): descriptions of translations and parameterisations of the expert models in terms of the inputs required for the seismic hazard computations. With the approval of the HID by the experts, the expert elicitation block ends, while the SP4 part of the database structure starts. Based on the HIDs, SP4 developed the *rock hazard input files* (RIFs) and the *soil hazard input files* (SIFs, see sections 7.4.1 and 7.5.1). The use of the *hazard software* (HSW) then led sequentially to the *rock hazard calculations* (RHZ) and the *soil hazard calculations* (SHZ).

3.4.2 Data Requisition and Dissemination

During the entire phase of expert elicitation, about once a month the PEGASOS web site was updated and new listings of database entries were published. Each update was announced to the experts and the new datasets were highlighted and, where needed, briefly described. When a critical data set was made available to the project, the experts were informed immediately by e-mail.

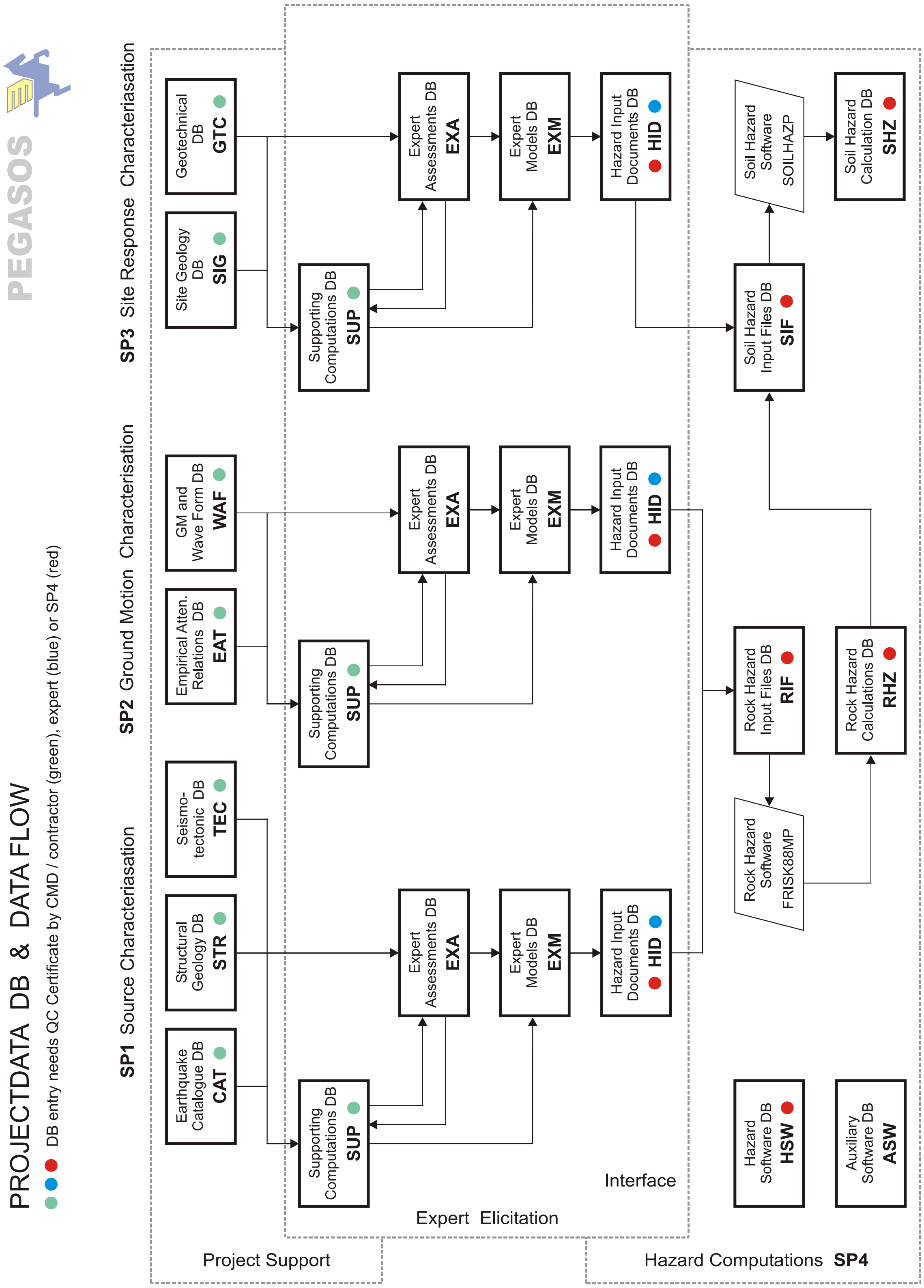


Fig.3-1: Structure of the PEGASOS Project data DB and the flow of data

If a database data set had not been requested by all the experts of a subproject – in which case the dataset was distributed voluntarily – the individual experts had to follow a precise procedure to receive the data. An e-mail had to be sent to the CMD with the identifier codes of the requested data sets, extracted from the web site listings. The CMD operator would then collate the data (possibly digitising it if needed) and send an e-mail to the requesting expert, either with the data attached or with instructions on how to download it from the project ftp site. Typically, the reaction time was a only few hours.

3.4.3 SP1: Source Characterisation DB

The identification and characterisation of seismic sources involves a large range of data types. Since most of these data types have a geographic reference, a Geographic Information System (GIS) was built up and made available to the SP1 experts in the form of any possible combination of data layers. It was tried as far as possible to extend the coverage of the GIS layers to a distance of up to 300 km from the four investigated sites. The SP1 experts made extensive use of this tool; they ordered a large number of maps extracted from the GIS. They could choose between A0-format hardcopy maps on a series of predefined scales and map frames on one side and digital raster datasets to use as backdrops for the WIZMAP source characterisation tool (see section 3.4.7) on the other. Table 3-1 summarises all SP1-specific project data DB layers, their database identifier code and specifies whether or not they were part of the GIS. The individual data sets are described in *Roth* (*2002a, RDZ-TB-0003*) and *Roth* (*2002b, RDZ-TN-0139*).

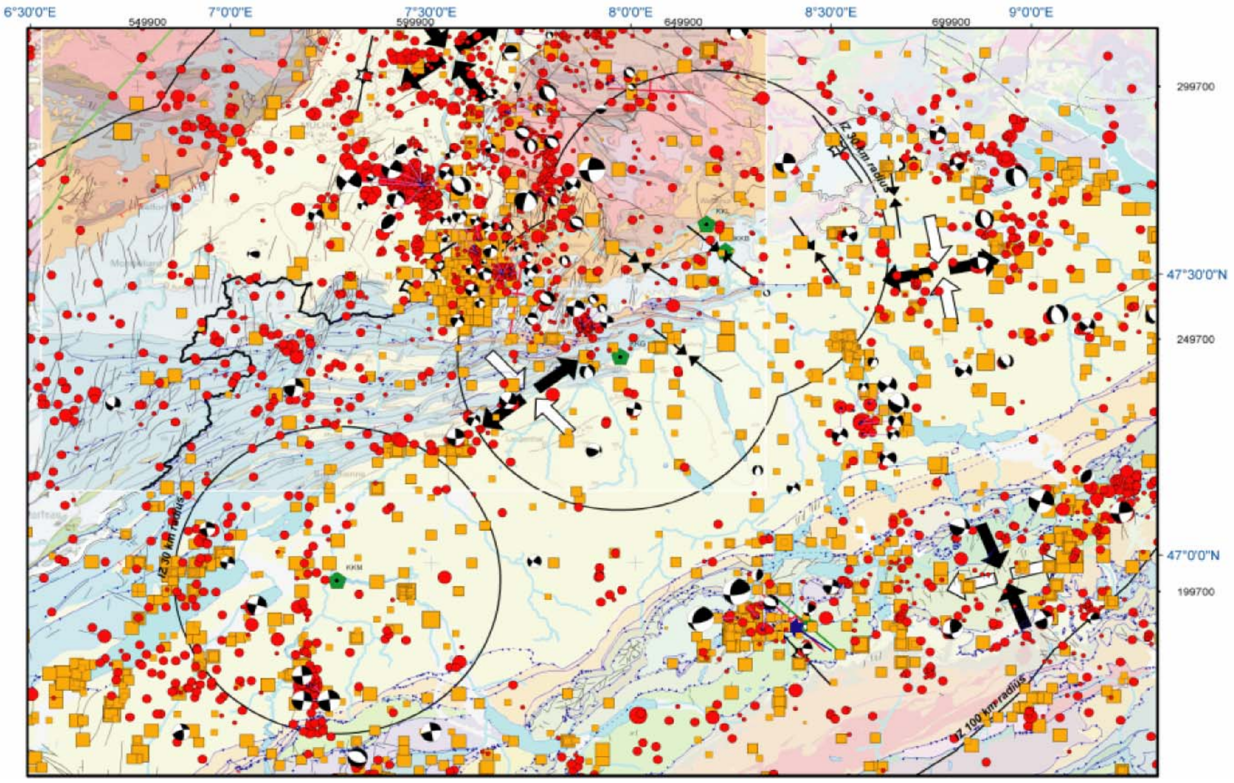


Fig.3-2: Example of a combination of different GIS layers

The four sites are marked as green pentagons. Circular black lines indicate distance ranges from the sites.

Tab.3-1: SP1 (source characterisation) project data DB items and their availability as mappable GIS layers

PD Identifier	Name	GIS?
TP1-CAT-0004	Pegasos Earthquake Catalogue	Yes
TP1-STR-0001	…with GTÜ350 for Baden-Württemberg	Yes
TP1-STR-0002	…with GTÜ500 for Baden-Württemberg	Yes
TP1-STR-0003	Faults	Yes
TP1-STR-0004	Moho Isolines	Yes
TP1-STR-0005	Digital Elevation Model	Yes
TP1-STR-0006	Distribution of Reflection Seismic Lines	Yes
TP1-STR-0007	Topographic Layer (rivers, lakes, cities, etc.)	Yes
TP1-STR-0008-0012	Isohypse Maps of given Seismic Reflectors	No
TP1-STR-0013	Information on the Mettau and Mandach faults	No
TP1-STR-0014	Heat Flow Map of Switzerland	No
TP1-STR-0015	Thermal Springs	Yes
TP1-STR-0015-0016	Aeromagnetic Total and Residual Fields	Yes
TP1-STR-0018-0019	Bouguer Anomaly Maps	Yes
TP1-STR-0020	Faults at the Base Mesozoic in Northern Switzerland	Yes
TP1-TEC-0002	In-situ Stress Measurements	Yes
TP1-TEC-0003	Stress Inversions	Yes
TP1-TEC-0004	National Uplift and Subsidence	Yes
TP1-TEC-0005	Nagra Uplift and Subsidence	Yes
TP1-TEC-0006	Macroseismic Field Data in Baden-Württemberg	No
TP1-TEC-0007-0008	Maximum Intensity Maps	No
TP1-TEC-0010	Fault Plane Solutions	Yes

The PEGASOS earthquake catalogue (*SED 2002, EXT-TB-0043*) is probably the most important data set in this list. It is the result of a PEGASOS-founded, complete reassessment of the macroseismic databases and of the historical and instrumental Swiss earthquake catalogues. All earthquakes located within or outside Switzerland that produced significant effects (intensity larger than V/VI) in Switzerland were re-evaluated. A combination of historical, macroseismic and seismological investigations was conducted, depending on the size and location of the events. However, since Switzerland is a small country and the region of interest reaches 300 km away from the investigated sites, catalogues from neighbouring countries had to be used. A total of 15 different foreign instrumental and macroseismic catalogues were merged into the new PEGASOS catalogue, identifying and flagging duplicate events. A reference moment magnitude M_W for all earthquakes was determined, while the original magnitudes were preserved. Details about the PEGASOS catalogue can be found in *SED* (*2002, EXT-TB-0043*).

3.4.4 SP2: Ground Motion Characterisation DB

The characterisation of ground motion is a critical part of seismic hazard analysis and involves different data types. Besides the content of the document DB, two categories of project data were made available to the SP2 experts. At Workshop 1 (WS-1), it was decided to use a series of scaled existing ground motion models rather than to develop a new project-specific model. The coefficients and parameters of all candidate ground motion models selected by the experts were stored as empirical attenuation relations (EAT) in the project data DB and made available to them.

The second important type of data is the ground motion and wave form database, the WAF database (TP2-WAF-0009). This is a collection of about 2000 mostly European earthquake recordings (strong motion, short period and broadband data). The data used by Bay (2002a) to develop her ground motion model of Switzerland were added to TP2-WAF-0009. The database contains the uncorrected and corrected time histories as well as the elastic response spectra. The earthquake and recording station parameters (such as style of faulting, site geology, velocity profile if available) are also part of this database. In the course of the project, the experts expressed the wish to add new data, either from new, recent earthquakes (like the St. Dié, February 2003 event) or from the strongest ever recorded earthquakes, to help them in developing their assessment of maximum ground motion. These requests were all satisfied. See *Smit et al.* (*2002, TP2-TB-0036*) and *Smit* (*2002, TP2-TN-0276*) for a description of the WAF database.

The WAF database was not used to derive new attenuation relations. It was a tool used to perform comparisons with simulation results (e.g. comparing the largest recorded ground motion as a function of distance and magnitude with the simulated maximum ground motions) or to develop scaling relationships (e.g. accounting for different definitions of horizontal component in the candidate models).

3.4.5 SP3: Site Effect Characterisation DB

The characterisation of site effects involves geological and geotechnical data. A constraint of the project was that new field data would not be acquired at the four power plant sites for the purpose of the site characterisation. All available geological and geotechnical data were collected, presented at WS-1, completed with new geological cross-sections and maps, distributed to the experts, and archived in the project data DB as site geology (SIG) and geotechnical (GTC) data sets. Refer to *Farrington* (*2002, TP3-TB-0044*) for a description of these two entities of the project data DB.

A major part of both the site geology (SIG) and geotechnical (GTC) data sets took the form of large database tables, with a table generated for each data type and for each power plant site. The tables listed physical parameters (whether measured in the laboratory or *in-situ*) and geological observations extracted from site survey boreholes located within a radius of approximately 2 km around the power plants. Not all parameters were available for every borehole; however, the tabulated parameters were standardised to the extent possible and the source reference of the borehole was also listed in the database tables, together with quality ratings.

These two data sets were combined in four small-scale GIS projects (one per site) with scanned geological maps, compiled lithological surface grids, and high resolution digital elevation models (DEMs). They were used as the basis for the creation of a number of supplementary products (like velocity maps or 1-D SHAKE modelling) designed to assist the experts' investigations.

3.4.6 Acceptance and Entry of Basic Data into the Project DB

All the project data DB data sets mentioned in the last three sections, that together form the *basic data,* were submitted to an independent technical review by a qualified reviewer determined by the PMT. The review was not intended to check the numerical accuracy of the external data sets, but to establish their general acceptability. Furthermore, an independent check was performed by another person, after the data sets had been integrated into the database, to control their numerical integrity after integration. Both reviews were documented in a specific QA certificate (see *Sprecher 2003, QA-TN-0402* appended to this volume).

3.4.7 Software Tools for Use by the Experts

On a few occasions, software tools were made available to the experts to assist them in developing their models. These software tools entered the project data DB as auxiliary software (AUX) items. Not all the software tools were distributed among the experts since they sometimes preferred to have the CMD running the software and to receive the results only. Table 3-2 lists only the latest version of the software tools that were actually distributed either to all or to individual experts. In all cases, and as for the other types of project data DB items, all experts of a subproject were informed about the availability of auxiliary codes (see section 3.4.2).

Tab.3-2: Auxiliary software given to the experts

PD Identifier	Name	Author	Description
RDZ-ASW-0016	WIZMAP	Musson	Program to plot epicentre maps, draw seismic sources, compute recurrence parameters. The program was further enhanced for the PEGASOS project to accept GIS raster maps as backdrops and to allow more complicated earthquake recurrence analyses to be performed.
TP2-ASW-0006	-	Abrahamson	Excel sheet to help the SP2 experts in developing their models and guiding them through the different questions.
TP2-ASW-0009	-	Smit et al.	Fortran code to compute and Matlab script to plot residuals for empirical attenuation models. Was distributed with the WAF database to the SP2 experts.
EG2-ASW-0011	-	Sabetta	Excel worksheet to allow comparison of spectral attenuation models.
TP1-ASW-0013	Eprimax	Youngs & Toro	Fortran M_{max} calculation software.
TP1-ASW-0015	-	Youngs	Least-squares fitting software for recurrence calculations, including errors provided to EG1c in response to a request from Brüstle.
TP1-ASW-0021	PLABD	Youngs	Fortran code used to compute relative likelihood distributions for recurrence parameters; provided in response to an EG1b request.
TP1-ASW-0022	PLFBAD	Youngs	Fortran code used to compute recurrence parameter distribution; provided in response to an EG1b request.

3.5 Supporting Computations and Special Studies

3.5.1 Supporting Computations commissioned by the Experts

During discussions at the workshops and elicitation meetings, the experts requested not only access to existing data sets, but to create new ones, either by further processing existing data or by performing numerical simulations. At the end of the workshops and elicitation meetings, lists of expert requests were compiled by the TFI-teams and submitted to the project management team, which decided whether or not they could be met within the existing schedule and budget constraints. The experts made extensive use of this resource. These requests ranged from the simple duplication and dissemination of reports to time-consuming, complex modelling computations. These supporting computations (SUPs) were performed either by external contractors, by the CMD or by individual experts who then acted as resource experts. All these requests for supporting computations were either met or, in rare instances, turned down following further discussions between the experts and TFI.

The next three tables list the supporting computations performed on behalf of the experts in the three subprojects SP1, SP2 and SP3 (only the non-superseded SUPs are listed here).

Tab.3-3: Model development supporting computations carried out in SP1

PD Identifier	Author	Description
TP1-SUP-0045	Farrington	EG1d: Kernel smoothing. Gaussian smoothed 'a' values incorporating uncertainty, 6 filter radii
TP1-SUP-0046	Farrington	EG1b: Kernel smoothing. Gaussian smoothed 'a' values by zone, 3 filter radii
TP1-SUP-0049	Farrington	EG1b: EPRI μ distributions using 8 large zones and 23 smaller zones
TP1-SUP-0051	Youngs	EG1d: Revised regional b-value calculations
TP1-SUP-0053	Youngs	EG1c: Results of least-squares fitting recurrence modelling
TP1-SUP-0054	Youngs	EG1c: N & β distributions computed using least-squares fitting
TP1-SUP-0055	Youngs	EG1a: M_{max} and recurrence computation
TP1-SUP-0056	Youngs	EG1d: Source model recurrence computations
TP1-SUP-0057	Youngs	EG1d: EPRIMax computations

Tab.3-4: Model development supporting computations carried out in SP2

PD Identifier	Author	Description
TP2-SUP-0001	Zahradnik	Numerical simulations of GM for finite extent sources – EXT-TN-0144
TP2-SUP-0002	*Priolo et al.*	*Superseded estimation of the GM upper limit in Switzerland based on numerical simulations of extended sources and full wavefield propagation (EXWIM)*
TP2-SUP-0003	*Pitarka*	*Superseded estimation of the GM upper limit in Switzerland, based on the empirical source time function method*
TP2-SUP-0031	Bertrand	H/V ratio computation for 20 European sites: implications for soil quality – EXT-TN-0217

PD Identifier	Author	Description
TP2-SUP-0036	Rietbrock	Determination of input parameters for the stochastic simulation of strong GM for Switzerland – EXT-TN-0306
TP2-SUP-0037	Madariaga	Assessment of feasibility of kinematic fault models used for upper limit ground motion evaluations for the PEGASOS Project – EXT-TN-0308 (no real computation is associated with this assessment)
TP2-SUP-0038	Bay	Forward modelling, PSS inversion, DB comparison – EXT-TN-0251, EXT-TN-0216, EXT-TN-0209, resp.
TP2-SUP-0039	Hölker et al.	Residual computations for the candidate GM models – TP2-TN-0232
TP2-SUP-0040	Roth	Residuals as a function of epicentral distance for GMs recorded at short JB distances – TP2-TN-0249
TP2-SUP-0041	Hölker	Normal probability plots of residuals of selected empirical GM models with more than 1000 recordings – RDZ-TN-0214
TP2-SUP-0042	Hölker	Derivation of coefficients for the missing frequencies of the candidate GM models – TP2-TN-0270
TP2-SUP-0043	Pitarka et al.	Supersedes TP2-SUP-0003: M5.5 & M7 numerical simulations for evaluation of median and upper limit GM in Switzerland – EXT-TN-0277
TP2-SUP-0044	Priolo et al.	Estimation of the GM upper limit in Switzerland: EXWIM numerical simulations – EXT-TN-0278 – EXT-TN-0303
TP2-SUP-0048	Smit	Computation of spectra in TP2-WAF-0008 – TP2-TN-0276
TP2-SUP-0050	Toro	Sensitivity analysis on upper tail modification of the GM distribution for Switzerland – EXT-TN-0293
TP2-SUP-0052	Cotton & Farrington	KNET and Berge magnitudes and distances for each data point used by Lussou et al. (2000) – TP2-TN-0361
TP2-SUP-0058	Becker	Brune stress drops for small magnitude California data recorded at hard rock sites – EXT-TN-0218
TP2-SUP-0061	Lacave et al.	Computation of scaling factors for 20 generic "rock" profiles – TP2-TN-0363
TP2-SUP-0064	Lacave et al.	Computation of scaling factors for three "realistic" rock profiles – TP2-TN-0350
TP2-SUP-0067	Priolo	Estimation of the median near-fault ground motion in Switzerland – TP2-TN-0384

Tab.3-5: Model development supporting computations carried out in SP3

PD Identifier	Author	Description
TP3-SUP-0008	EG3	Shear wave velocity profiles for the four sites – TP3-SP-0043
TP3-SUP-0011	Lacave	Scaling of 15 time histories for the determination of site amplification factors for M6 using 1-D TH-Method – TP3-TN-0151
TP3-SUP-0012	*Augello*	*Superseded 1-D numerical models of site effects using time histories and SHAKE*
TP3-SUP-0013	*Silva*	*Superseded 1-D numerical models of site effects using the Random Vibration Theory (RVT)*

PD Identifier	Author	Description
TP3-SUP-0014	*Travasarou*	*Superseded comparison between TP3-SUP-0013 (RVT) and TP3-SUP-0012 (SHAKE) runs*
TP3-SUP-0015	*Silva*	*Superseded comparison of amplification factors at the four NPP sites, different material sets, shaking levels*
TP3-SUP-0018	Augello	M5 and M7 SHAKE time histories for the 4 NPPs – TP3-TB-0047
TP3-SUP-0019	Silva	Amplification factors for surface, outcropping and total motions computed using the RVT method – TP3-TN-0204
TP3-SUP-0020	*Silva*	*Superseded amplification factors computed using the RVT method with soil randomisation*
TP3-SUP-0021	*Augello*	*Superseded one-dimensional site response analysis with soil profiles as defined in TP3-TN-0166*
TP3-SUP-0022	Pelli	Non-linear site response analyses for Beznau, Gösgen and Leibstadt – TP3-TB-0048
TP3-SUP-0023	Bard	2-D S_H computations for the Leibstadt nuclear power plant site: Amplification factors in the low and high strain cases – TP3-TN-0186
TP3-SUP-0024	Fäh	Spectral amplification for S_H and PS_V waves at sites Beznau Gösgen and Leibstadt – TP3-TN-0167
TP3-SUP-0025	*Fäh*	*Superseded two-dimensional modeling of* S_H *wave amplification*
TP3-SUP-0026	Pecker	Gösgen NPP, true non-linear site response analysis – TP3-TN-0205
TP3-SUP-0027	*Travasarou*	*Superseded visualisation and comparison of RVT and SHAKE results – TP3-TN-0212*
TP3-SUP-0028	Augello	Additional 1-D site response analysis for M5 and 7 earthquakes – TP3-TB-0049
TP3-SUP-0032	Fäh	2-D modelling of S_H wave amplification – TP3-TN-0240
TP3-SUP-0033	Augello	1-D site response analysis with soil profiles as defined in TP3-TN-0166 – TP3-TB-0049
TP3-SUP-0034	Silva	Amplification factors computed using the RVT method with soil randomisation – TP3-TB-0046, TP3-TN-0204
TP3-SUP-0035	Travasarou	Visualisation and comparison of RVT and SHAKE results – TP3-TN-0212
TP3-SUP-0047	Pelli	Site response analyses considering cyclic mobility effects for 2 sites (Beznau and Gösgen) in Switzerland – TP3-TB-0051
TP3-SUP-0059	Lacave	Development of scaling factors to account for the differences in definitions of reference rock between SP2 and SP3 – TP3-TN-XXXX
TP3-SUP-0060	*Pecker*	*Superseded evaluation of maximum GM for each of the 4 sites*
TP3-SUP-0062	Pelli	Additional non-linear site response analyses for Beznau and Gösgen at a high shaking level considering cyclic mobility effects – TP3-TN-0353
TP3-SUP-0063	Pecker	Evaluation of maximum GM levels – TP3-TN-0354
TP3-SUP-0069	Augello	Additional SHAKE computations at depth – TP3-TB-0052

3.5.2 Special Studies on behalf of the Experts

The supporting computations may have been complex and time-consuming but they were straightforward most of the time, as the procedures to be followed by the commissioners were well established. On a few occasions, however, special studies were commissioned that partly broke new ground. This was particularly the case for the assessment of ground motion upper limits in SP2 and SP3. For these studies, the experts, together with the commissioner, developed sets of modelling input parameters, which usually had to be revised after the first results had been obtained. In other cases, a well known resource expert specialised in a field not covered by the PEGASOS experts was invited to assess alternative scenarios. This latter type of study typically did not generate any computational results. From a conceptual and database technical point of view, however, all the special studies were treated as supporting computations and are listed in Tables 3-3 through 3-5.

3.6 Workshops

An essential component of the PEGASOS PSHA was the conduct of workshops, and significant activities and milestones were tied to the workshops. Furthermore, the workshops provided a fundamental opportunity for the experts to share data, provide their interpretations, and receive feedback from their colleagues. Although the timing and topics varied somewhat among the three subprojects, the major goals and purposes of the workshops were similar and are described briefly below. Detailed discussions of the workshops are given in the respective subproject chapters 4, 5, and 6.

3.6.1 WS-1: Key Issues and Data Needs

Workshop-1 (WS-1) on key issues and data needs, held on 15 – 17 October 2001, was the first of several workshops that were conducted for the PEGASOS Project. The purposes of this workshop were to introduce members of the expert panel to the goals and context of the project, to train the experts in expressing uncertainties through an elicitation process, to identify the key issues that must be addressed by the experts and to review available data, identifying those data sets the experts would use in their evaluations. The first day of the workshop was a joint session for all of the subprojects. During the second and third days of the workshop, individual sessions were held for each subproject.

During the joint session of the workshop, the expectations of the regulator (HSK) were summarised and a historical context for the PEGASOS Project was discussed in terms of previous seismic hazard studies. The TFIs summarised the basic elements of probabilistic seismic hazard analysis, including definitions of epistemic uncertainty and aleatory variability. The expert selection criteria were reviewed and ground rules were established for all workshops to ensure open discussion and a focus on the important technical issues. It was noted that the goal of the project is to integrate the assessments across each expert panel using equal weights. Many elements of the project, ranging from the expert selection process to the accessibility of a common database, have been designed to support an equal-weighting integration scheme. The work packages to be conducted by each expert and the associated schedule were also laid out, along with the expectations for the contributions to be made by the experts toward the final documentation of their elicitations.

The second half of the common session was devoted to elicitation training conducted by a normative expert, Dr. Karen Jenni. Dr. Jenni reviewed the terminology and probability calculations used in probabilistic analysis, providing examples of probability distributions and ways in which discrete uncertain events are represented in probability trees. She discussed independent and dependent uncertainties, ordering of events in a logic tree, representation of continuous uncertain variables, and the parameters commonly used to characterise a probability distribution. Common cognitive and motivational biases of experts were also reviewed, as well as ways to avoid these potential problems.

The second and third days of the workshop were conducted in separate sessions for the three subprojects. In general, the subprojects identified key issues, summarised available data and analyses, and developed a list of data and analyses needed to conduct their evaluations.

The SP1 group began with a summary of key issues of importance to seismic source characterisation, including the geographical region to be considered. This was followed by a series of presentations on the data available to the SP1 experts, including the PEGASOS database, seismicity catalogues, paleoseismic data, and seismotectonic studies. In the light of the key issues and the available data, the experts then identified the data needed to conduct their subsequent evaluations. The list of identified data needs was then made a priority for the PEGASOS database contractor in the weeks following the workshop.

The SP2 and SP3 groups began with a joint session to review the issues associated with conducting a site-specific PSHA with site response, including definition of a reference rock site condition. This session also included a summary of deaggregation of previous hazard results, to identify issues of importance to hazard. In separate sessions, the SP2 group then discussed key issues in the light of various methodological approaches. This was followed by a description of the ground motion database, and empirical and analytical ground motion approaches were discussed. The result of the workshop was a list of documentation needs and data analysis needs required by the experts for their evaluations. The SP3 group reviewed the key issues based on prior experience and pilot computations. The result of the workshop was a list of general data needs as well as site-specific data needs for each of the four power plant sites.

3.6.2 WS-2: Methodologies and Evaluation of Models

The general purpose of the WS-2 workshop was to discuss alternative methodologies and the advantages and disadvantages of various models. These discussions were designed to ensure familiarity with all methodological tools and potential alternative models. In turn, the workshop served to prepare the experts for the subsequent elicitation sessions. The manner in which these goals were achieved varied somewhat with each subproject.

SP1 divided the expert evaluations into two parts: 1) characterising the seismotectonic setting and defining the spatial configuration of seismic sources, and 2) evaluating maximum earthquake magnitude and earthquake recurrence. Therefore, WS-2 was an opportunity to review the seismotectonic setting and the methods for seismic source definition. The elicitation interactive meeting followed. At the beginning of WS-3, preliminary assessments were presented and methods for evaluating maximum magnitudes and recurrence were reviewed, followed by the second round of elicitation interviews.

At SP1 WS-2, the databases were reviewed that had been developed as a result of expert requests at WS-1, and the PEGASOS seismicity catalogue was discussed along with the methods used to process the data. Methodologies available to define the spatial configuration of seismic sources, and for evaluating the probability that particular geological structures are seismogenic, were reviewed and discussed. As part of that discussion, seismic source interpretations made in previous pertinent seismic hazard studies were presented. Site-specific technical issues that could have implications for defining sources for the SP1 project were identified and preparations were made for the first round of elicitations.

For SP2, the empirical ground motion models already existed, so WS-2 went straight into an evaluation of the available alternative models, rather than discussing methodologies for developing new models as was the case for SP1. The activities of SP2 WS-2 included: a) reviewing the ground motion databases that have been developed and completed as a result of expert requests at WS-1; b) discussing the strengths and weaknesses of the alternative empirical and numerically simulated ground motion attenuation relationships identified at WS-1 in terms of their applicability to accurately characterise ground motions in Switzerland; c) defining additional plots and/or analyses that are needed by the experts for the evaluation of the empirical and numerically simulated attenuation relationships; d) selecting approaches for estimating the vertical component ground motion; e) evaluating preliminary numerical simulations of ground motions for constraining the upper limit of the ground motion; f) defining additional numerical simulations of ground motions for constraining the upper limit of the ground motion; and g) preparing for the first round of elicitations.

For SP3, the alternative computational methods for site response were well known by the experts, so WS-2 went straight to evaluation of the results from the initial application of alternative methodologies. The activities of SP3 WS-2 included: a) evaluating the differences between equivalent-linear and non-linear approaches and determining how to best use the results from the sensitivity studies using the non-linear approach; b) discussing the strengths and weaknesses of the alternative methods for computing the site amplification factors using the equivalent-linear approach in a probabilistic hazard analysis (RVT vs. time history); c) reviewing the approaches for estimating the vertical component ground motion; d) defining additional plots and or analyses needed by the experts for the evaluation of the amplification functions; and e) preparing for the first round of elicitations.

3.6.3 WS-3: Peer Feedback on Preliminary Expert Assessments

The purpose of the third workshop was to provide an opportunity for the experts to present their preliminary models and assessments, and to receive feedback from their colleagues on the expert panel. The spirit of these workshops was open, collegial debate of the preliminary assessments, acknowledging that revisions or clarifications would likely result from the interaction. This type of peer feedback is different from the hazard sensitivity feedback that occurred in WS-4.

The SP1 workshop included two peer feedback loops to accommodate the two parts of the assessment: evaluations of seismotectonic framework and seismic source definition, and assessments of maximum earthquake magnitude and earthquake recurrence. WS-3 entailed presentations by the expert teams of their preliminary seismotectonic frameworks and the preliminary identification of seismic sources. Each presentation was followed by structured debate and discussion. The second half of WS-3 was devoted to outlining alternative methodologies for assessing the maximum magnitudes and earthquake recurrence for seismic sources. The methdology discussion included identifying the types of data required to implement the methods and the associated uncertainties.

The SP2 workshop included each expert presenting the framework of his initial logic tree and the technical basis for his initial evaluation of branch weights to the other experts. WS-3 for SP2 consisted of the following activities: a) reviewing the status and results of the various experts' requests formulated during WS-2 / SP2; b) evaluating empirical data for constraining the tails of the statistical distribution of the ground motion; c) evaluating the results of numerical simulations for constraining the upper limit of the amplitude of the ground motion in Switzerland; d) presenting each expert's chosen approach and reasons for the preliminary weighting of the models; e) comparing the experts' preliminary estimates, and f) preparing for the first revision of the experts' estimates, which took place following the workshop.

The SP3 workshop included each expert presenting the framework of his initial logic tree and the technical basis for his initial evaluation of branch weights to the other experts. Comparisons of the amplification functions resulting from the experts' estimates (weights of the models) were shown. The discussion was focused on understanding the differences between the experts' models. The goal was to make sure that the differences were intentional and not the result of misunderstandings by the experts. The first day was for the experts to present their initial models. The second day was for the experts to discuss the site response calculations in detail. The last day was for discussion of maximum ground motions on soil and to prepare the experts for the first revision of the experts' estimates for use in hazard sensitivity calculations. The new and extended project output specifications which had recently been agreed between the licensees and the regulatory authority (HSK) implied that the future work of SP3 (after WS-4) had to be rescheduled. The TFI and the experts therefore discussed the technical implications, the extra effort required, and planned the additional workshop (WS-3a) and elicitation meetings.

3.6.4 WS-4: Expert and Hazard Sensitivity Feedback

Workshop WS-4, held on 25 – 28 February 2003, provided an opportunity for the experts within each subproject to receive feedback from their colleagues on the panel regarding their assessments. In addition, as a group including all subprojects, the experts received feedback regarding the sensitivity of various inputs to the seismic hazard.

WS-4 for SP1 focused on feedback regarding preliminary assessments of maximum earthquake magnitudes and earthquake recurrence for their seismic sources. Each team presented and discussed its logic tree, identifying seismic sources and establishing the dependencies among source interpretations and their subsequent characterisation in terms of maximum magnitudes and recurrence. They then presented their preliminary evaluations of maximum earthquake magnitudes and earthquake recurrence for their seismic sources, including the manner in which uncertainties had been quantified. Active discussion and debate was encouraged, with an emphasis on understanding interpretations, their technical bases, and expression of uncertainties. Discussion took place regarding how, in aggregate, all teams' evaluations represent the views of the larger informed scientific community. During the common session, the SP1 experts received feedback and discussed sensitivity analyses quantifying the relative importance of various evaluations made by each team regarding maximum magnitude and earthquake recurrence, and regarding their importance for site-specific seismic hazard estimates. The common session also provided an opportunity for discussion and coordination among the subprojects. The final SP1 session covered the future schedule and milestones required for finalisation of the PEGASOS Project.

During SP2 WS-4, each expert explained revisions to his weights and the reasoning behind the revisions to the other experts. Comparisons of the ground motions resulting from the experts' estimates (weights of the models) were shown. The discussion was focused on understanding the differences between the experts' models. As in WS-3 / SP2, the goal of this comparison was to make sure that the differences were intentional and not the result of misunderstandings by the experts. The afternoon of the first day was devoted to the presentation of experts' revisions following WS-3 / SP2. The second day was devoted to comparisons between ground motions and preliminary hazard resulting from the experts' sensitivity models. The morning of the third day was reserved for a joint session with SP3 to discuss the reference rock scaling between SP2 and SP3 and the afternoon for a joint session with SP1, SP2 and SP3. The morning of the last day was used to discuss expected revisions by the experts following the workshop and to prepare for the finalisation of the experts' models. Approaches to evaluating style of faulting scale factors for horizontal and vertical ground motions were discussed.

A follow-up SP2 meeting was held on 13 April 2003 on scaling factors for different styles of faulting. The discussions included comparison of the effect of fault style for proponent attenuation relations and scaling factors between normal and strike-slip faulting. The scaling factors used in the Yucca Mountain study were also reviewed.

During SP3 WS-4, comparisons of the site amplification factors resulting from the experts' estimates (weights of the models) were shown. Each expert explained revisions to his weights and the reasoning behind the revisions to the other experts. The discussion was focused on understanding the differences between the experts' models. As in WS-3, the goal of this comparison was to make sure that the differences were intentional and not the result of misunderstandings by the experts. The first day was reserved for a joint session with SP2 (morning) to discuss the reference rock scaling between SP2 and SP3 and for a joint session with SP1, SP2, and SP3 (afternoon). The second day was devoted to the presentation of experts' revisions following WS-3 and to comparisons between amplification factors resulting from the experts' models. The third day was for feedback on preliminary hazard calculations, discussion of expected revisions by the experts following the workshop, and preparation for revision 2 of the experts' estimates.

A follow-up SP3 meeting was held on 12 April 2003 on maximum ground motions on soil. The meeting included a discussion of the details of the maximum horizontal ground motion evaluations of A. Pecker. Methods for estimating the maximum ground motion spectra on soil were discussed, as well as methods for estimating the maximum vertical ground motions on soil. Preparations were made for the implementation of maximum ground motions to experts' models, which occurred following the meeting.

3.6.5 WS-5: End-of-Project Workshop; Project Results

The WS-5 end-of-project workshop brought together all members of the PEGASOS Project team, with the fundamental purpose of reviewing the final seismic hazard results. The workshop provided an opportunity for all experts to discuss the hazard results and the sensitivity of those results to the various inputs.

3.7 Expert Elicitations

The elicitation of the experts involved a series of activities, including preparation for the elicitation, elicitation interviews, feedback and sensitivity analyses, documentation and review, and aggregation of expert assessments. Each of these activities is summarised below.

3.7.1 Preparation for the Elicitation

At a common session during the first workshop WS-1, the experts received elicitation training from a normative expert. The objectives of the training were to demonstrate how to quantify uncertainties using probabilities, to recognise common cognitive biases and compensate for them, and to present examples of the types of assessments that would be made at the elicitation interviews (e.g. continuous variables, alternative discrete hypotheses and associated weights). The training was designed to help the experts be comfortable with the *process* of elicitation, so that the elicitation interviews themselves could focus on the *technical issues* of importance to the seismic source, ground motion and site response characterisation.

Besides the elicitation training, the experts prepared for the elicitation by identifying data needs in WS-1, fulfillment of those data requests following WS-1 (as well as throughout the project), and presentation and discussion of alternative models and methods at WS-2. In general, the elicitation of the experts followed two rounds of assessment, characterised by 1) presentation of methods and models, 2) elicitation interviews, 3) presentation of preliminary assessments for peer feedback, and 4) finalisation of assessments. This process ensures that all experts are familiar with the tools that they need to conduct their assessments, that they are assisted as needed in expressing their judgements and the associated uncertainties, that they understand the assessments made by other experts on the panel, and that they receive sufficient feedback from their colleagues prior to finalising their assessments. The documentation of the elicitation is the elicitation summary.

3.7.2 Elicitation Interactive Meetings

Elicitation interviews, termed "interactive meetings" to emphasise the interactive nature of the exchange between the experts and the TFI, were an important part of the elicitation process. The meetings, which were 2 – 3 days in length, were conducted by members of the TFI-teams. To maximise the efficiency of the meetings, the experts were informed of the focus of the discussions prior to the sessions, any analyses that they should have completed upon arrival at the meeting, and any materials that they should bring with them to the session. Applicable parts of the PEGASOS Project database were made available to the experts for their use during the interview sessions, and representatives from the database contractor were 'on-call' to honour requests for data, maps, plots, etc.

The elicitation interactive meetings followed a logical sequence from general to more specific assessments. Typically, the experts would first outline their overall logic structure and logic tree. Alternative conceptual models and approaches were considered, as well as the relative weights expressing the expert's degree of belief in the alternatives. For particular models and approaches, the parameter values and associated uncertainties were then discussed and assessed. In SP1, the interviews were structured over a three-day period. Each team met with the TFI-team on the first day to establish the logic structure and assessments to be made. The second day, the team worked independently on the assessments, focusing on a range of assessments and identifying any questions or difficulties. The third day was spent with another meeting of the expert team with the TFI-team to work through the assessments and resolve any problems or questions that had arisen the previous day. The session also included discussion of the documentation that was expected following the sessions.

The elicitation interactive meetings provided the opportunity for the experts to work with the TFI-team in a one-on-one environment. This served to ensure a common understanding of the methods and models, the logic structure for the assessments, and the manner in which uncertainties should be expressed and quantified. Further, a number of assessments were worked through during the interview sessions to serve as examples of the subsequent assessments that the experts would conduct on their own following the interview sessions. In the case of SP1, the individual teams held working meetings as a team to work through the remaining assessments. Subsequent to the elicitation meetings, the TFI-teams were available to provide support to the experts as needed.

3.7.3 Documentation and Review

The fundamental documentation of the expert elicitations is the elicitation summary and all expert assessments were made part of these documents. The TFI-team provided the experts with an outline of essential elements of the elicitation summaries early in the project. Hence, all text written by the experts explaining the expert assessments, the associated technical bases, and the uncertainties was made part of the draft elicitation summary. By following the same outline, all experts were aware of the topics to be covered and their sequence.

Draft elicitation summaries prepared by the experts were reviewed by the TFI-teams to ensure completeness, clarity, and adequate discussion of all assessments. The summaries were also reviewed from the standpoint of accuracy and consistency with the HID, to ensure that the HID properly reflected the expert assessments. The experts responded to the TFI review comments and finalised their elicitation summaries, which are included in Vols. 4, 5 and 6 of this document.

The peer review process followed in the PEGASOS Project was a participatory peer review (SSHAC 1997), which was conducted by the project management team (PMT). The PMT provided 'real-time' reviews of ongoing workshops during meetings conducted following each day of the workshop sessions. In addition, the PMT held periodic meetings to review the progress of the project, key issues, and potential difficulties. They provided feedback to the TFI-teams regarding suggestions for improvement and helped set priorities for carrying out various tasks (e.g. database development).

To a large extent, the HSK-RT also provided a participatory peer review of the project. Periodic meetings were held following each workshop, with the aim of providing the HSK-RT's preliminary views of the progress being made on the project and questions regarding the path forward. These preliminary comments were then compiled in terms of formal written comments to the project, which were responded to in writing.

3.7.4 Feedback and Sensitivity Analyses

As indicated in the SSHAC (1997) guidance, feedback to experts is a fundamental component of an expert elicitation and occurred in the PEGASOS project through a number of means. Informally, the experts received feedback from their colleagues during the structured discussions and debates during all of the workshops. Part of the role of the TFI is to encourage the technical interaction among the experts such that the experts' preliminary assessments are presented and discussed. Part of this process includes discussions of the technical bases for the assessments and the associated uncertainties.

More formally, feedback was provided to the experts in the following:

- At WS-3, the experts presented their preliminary assessments to their peers with the express purpose of providing a forum for the interchange of ideas. The experts were encouraged to understand alternative views, their technical bases, and uncertainties.
- At Workshop WS-4, which occurred after the elicitation interviews, discussion focused on the expert preliminary assessments. Facilitated discussions included the technical basis for the interpretations, the weights assigned to alternative models, and expressions of uncertainty in parameter values.
- Calculations conducted at the subproject level also were presented at WS-4 to provide insight into the implications of the preliminary assessments. The implications of alternative methodologies or conceptual models specified by the experts were presented by the TFI-team and helped the experts understand the potential implications of these alternatives.
- Hazard sensitivity calculations were presented as feedback to the experts in WS-4. These calculations showed the relative impact of various assessments within each subproject on the hazard results, as well as the impacts across the subprojects. Importantly, the hazard sensitivity feedback provided a basis for prioritising the subsequent refinement of the expert assessments towards those aspects of most importance to the hazard results.
- The experts submitted written drafts of their elicitation summaries to the TFI-team for review and feedback to ensure clarity and completeness of documentation.

The feedback-revision process required the experts to defend/revise their assessments as appropriate and to provide adequate documentation in their elicitation summaries. In all cases, the experts responded positively to the feedback and reviews of their assessments. The resulting finalised elicitation summaries reflect the significant effort expended by each expert and expert team.

3.7.5 Integration of Expert Assessments

Integration is the process of combining the expert assessments into a composite assessment across the subproject for input to the hazard calculation. The approach taken in the PEGASOS Project is to integrate the expert evaluations using equal weights. In the case of SP1, this means assigning equal weights to each of the teams. The equal-weights approach was not a default but a goal from the start of the project, a goal the experts were apprised of throughout the project. Accordingly, the proper conditions were created throughout the project to allow for the use of equal weights (SSHAC 1997). The actions taken to provide these conditions included:

- Conducting a careful expert selection process resulting in the identification of highly qualified experts coming from diverse disciplines and experience

- Establishing and confirming throughout the project the commitment of each expert to providing the required effort
- Identifying data needs and developing a comprehensive database, and providing equal access of all experts to the data
- Training the experts in elicitation methodologies, including ways to quantify uncertainties
- Establishing the roles of the experts as evaluators responsible for representing the views of the larger informed technical community, and drawing a distinction between evaluators and proponents
- Providing structured, facilitated interaction among the experts and other resource experts in workshops to foster a free exchange of data and interpretations, including scientific debate with respect to alternative interpretations
- Providing feedback and sensitivity analyses to the experts, such that all experts were aware of the implications of their assessments
- Providing an opportunity for experts to revise their assessments in the light of feedback

It should be noted that, in accordance with the guidance provided by SSHAC (1997), conditions could have been such that different weights would have been necessary. For example, if an expert had been unwilling or unable to devote the required time and effort to develop a complete assessment and documentation, that expert would have been removed from the project.

3.8 Quantitative Parameterisation of Expert Models (HID Development)

3.8.1 Implementation of Expert Models

As defined in the QA Guidelines (*Sprecher 2003, QA-TN-0402*), an 'expert model' consists of a set of alternative quantitative models of the parameters considered by each subproject. The model logic tree, which is an integral part of the expert model, describes the structure of this set of alternatives, the relationship between the models and the weight assigned to each of them. In developing their models, the experts in some cases made computations of their own or requested computations be conducted for them by the CMD. These calculations were conducted under the supervision of the experts and, ultimately, are incorporated into the expert's model as deemed appropriate by the expert.

3.8.2 Hazard Input Document (HID)

An important link between the expert models and the seismic hazard calculations are the HIDs, which were developed for all of the expert models. The HID is based on the expert elicitations, the elicitation Ssmmary, or a draft of the ES and was prepared by the TFI-team. HIDs parameterise the expert models in term of the inputs required for the hazard computation. Responsibility for the HID lies with the TFI-team, but the HID needs to be approved by the experts. The process of developing the HIDs is outlined in the QA Guidelines (see *Sprecher 2003, QA-TN-0402*, appended to this volume). The first drafts were developed by the TFI-teams and were reviewed by the hazard software specialists within the TFI-teams to be sure that the HID contained all of the subproject-specific computation input required by the hazard software. It was also reviewed to see if any changes in the existing hazard software were required to accommodate the expert models. In those cases, the project manager was notified of the need for these revisions to the software.

Following completion of the initial draft HIDs, these were reviewed by the experts to ensure that they were compatible with the expert models. In some cases, the experts identified changes to the HID that were required and, following final review, indicated their approval by signing the HID QA certification. The HID was then sent to the hazard calculation contractor (SP4) for use in the hazard computations. All approved HIDs, together with the signed QA certificates, are included in the elicitation summary volumes of this report (see Vols. 4, 5 and 6).

3.8.3 Elicitation Summary (ES)

The fundamental documentation of the expert models is the elicitation summary (ES). It is the principal product of the experts on the project. The overall outline for the ES was presented to the experts by the TFI-teams early in the project and the experts were encouraged to consider all documentation of the assessments to be made part of the draft ES. Guidelines for the development of the ES were discussed with the TFI-teams at workshops to ensure a common knowledge of the expectation regarding the items to be documented, as well as the degree of detail needed. An important expectation is that the ES contains not only the fundamental elements of the expert model, including the alternatives identified in the logic tree, but also a discussion of the technical bases for the assessments on the tree. This includes technical reasons for the alternative models/branches, as well as the reasons for ascribing the relative weights given to the alternatives. Following review by the TFI-teams, the ESs were finalised by the experts and approved (i.e. they are the owners of the assessments contained within them). The summaries, together with the corresponding HIDs, are included in Vols. 4, 5 and 6 of this report.

4 SEISMIC SOURCE CHARACTERISATION

4.1 Seismic Source Characterisation Methodology

Seismic source characterisation for PSHA is the process of specifying probability models describing the aleatory variability in the location, timing and size of future earthquakes within a region. The three principal aspects of seismic source characterisation are the definition of seismic sources, the assessment of maximum magnitude, and the assessment of earthquake recurrence. The definition of seismic sources addresses the spatial aspects of the problem, e.g. where do earthquakes occur within the crust. The assessment of earthquake recurrence addresses the timing and size distribution of future earthquakes. The assessment of maximum magnitude addressed the limits on the size of earthquakes that may occur. Strictly speaking, the assessment of maximum magnitude is part of earthquake recurrence assessment, but it is discussed separately because it is often evaluated using different tools.

4.1.1 Seismic Sources and the Spatial Distribution of Seismicity

In the context of PSHA, a seismic source is a volume of the earth's crust that has an earthquake recurrence rate, maximum magnitude and / or spatial distribution of seismicity that is distinct from the adjacent crust. Thus, a seismic source defines the volume to which a specific set of probability models for the spatial distribution, frequency, and size distribution of future earthquakes is applied.

There are two general classes of seismic sources: feature-specific and areal source zones. Feature-specific or fault-specific sources are used when a specific geological feature (i.e. a fault) is identified as localising seismicity at a rate distinct (higher and/or larger) from the surrounding crust. A clear example would be the North Anatolian fault in Turkey. Fault-specific sources would be identified on the basis of historical ruptures or paleoseismic evidence.

Areal source zones are used to represent blocks of crust where discrete earthquake sources are not readily identified or identifiable. Often they may be used to characterise regions where there is diffuse seismicity without clear patterns and where there is a poorly understood relationship between observed seismicity and geological structures. They may vary greatly in scale from a zone encompassing a cluster of persistent seismicity, such as in the Swabian Jura, to continent-wide regions with spatially variable seismicity rates, such as used by the US Geological Survey to map seismic hazards in the United States. A variety of bases may be used to define these zones, including patterns of seismicity, geological and tectonic history, and contemporary stress fields.

The key aspect of seismic source definition is specification of the models for the spatial distribution of earthquakes and the geometry of earthquake ruptures. The following sections summarise the general methods used in the PEGASOS Project to address these aspects of seismic source characterisation.

4.1.1.1 Spatial Distribution Modelling

Areal Source Zones

There is a wide range of spatial distribution models that are applied to model earthquake locations within areal source zones. The 'classic' approach is to assume that earthquake locations are uniformly distributed within the area of the source zone. This model was used in the initial development of the PSHA methodology (Cornell 1968, 1971) and is employed in many PSHA analyses performed today. This approach was used in the recently published European-Mediterranean seismic hazard map (Giardini et al. 2003). An alternative approach is the so-called 'zoneless' approach, in which the spatial distribution of earthquakes is modelled using kernel density estimation over the entire region of interest (e.g. Frankel 1995, Woo 1996). This approach is currently used by the US Geological Survey to map seismic hazard in the United States (Frankel et al. 2002). In practice, the two approaches can be combined in a model where large regional zones are defined on the basis of geology and tectonics to represent regions where similar types of earthquakes occur and the maximum magnitude is expected to be the same. Local variations in the seismicity rate are then modelled using spatial smoothing. An approach of this type was used in the EPRI-SOG (1986) assessment of seismic hazard at nuclear power plant sites in the central and eastern United States.

The kernel density estimate of the spatial distribution of earthquakes, $f(x,y)$, is given by the expression:

$$f(x,y) = \frac{\sum_{i=1}^{N} K(d_i,h)}{\iint_Z K(d_i,h) \cdot dx \cdot dy} \qquad (4\text{-}1)$$

where $K(d_i,h)$ is a kernel density function with characteristic dimension h, and d_i is the distance from the i^{th} earthquake to point x,y. The denominator of Equation 4-1 is the integral of the kernel density estimates over the region or source zone of interest, normalising the kernel density to a proper probability density. There are a variety of kernel functions that may be employed. A very common form is the two-dimensional Gaussian kernel (Silverman 1986) defined as:

$$K(d_i,h) = \frac{e^{-(d_i/h)^2/2}}{2\pi h^2} \qquad (4\text{-}2)$$

This kernel function was adopted by the SP1 expert teams to develop kernel density estimates of spatial seismicity patterns. The controlling factors are the selection of the characteristic dimension h and the selection of the seismicity data set to use in the spatial density estimation. The parameter h can be considered to control the degree of spatial stationarity in the seismicity. The objective of the spatial density model is to estimate the relative frequency spatially of potentially damaging earthquakes (e.g. $M \geq 5$). Typically, this is based on the spatial pattern of a catalogue of predominantly smaller earthquakes (e.g. $3 \geq M > 5$). Use of a small value of h implies a high degree of spatial stationarity – damaging earthquakes are much more likely to occur near concentrations of smaller earthquakes that elsewhere in the region. Increasing the values of h weakens this assumption to the point that use of an infinite h produces a uniform spatial distribution within the characterised region or zone.

The SP1 expert teams used a variety of source zone models in combination with kernel density estimation to model the spatial distribution of earthquakes within the study region. Their set of weighted alternative source zones and alternative kernel smoothing parameters captures the epistemic uncertainty in the spatial distribution of future potentially damaging earthquakes in the region.

Fault-Specific Sources

The geometry of the fault or feature is used to control the spatial distribution of earthquakes. Fault-specific sources are represented by planar surfaces with earthquake ruptures constrained to occur on these planar surfaces. Typically, the location of rupture is modelled with a uniform distribution along the length of the fault. This approach was used by the SP1 expert teams to model fault-specific sources.

4.1.1.2 Rupture Dimensions and Rupture Orientation

Areal Source Zones

Earthquakes are modelled in the PSHA as having finite rupture dimensions. The size of the rupture is specified as a function of earthquake magnitude. The aleatory variability in rupture size for a given magnitude is not explicitly incorporated into the PSHA. Studies by Bender (1984) have shown that the use of mean estimates of rupture size in the computation of hazard yields results nearly equal to those obtained when the aleatory variability in the size of individual ruptures is incorporated in the analysis.

The preferred orientation of earthquake ruptures may be specified for each source zone on the basis of the local geology, tectonics, and stress field. For example, the earthquakes may be considered a mixture of normal, strike-slip and reverse faulting, with each style of faulting having its own preferred orientation (strike). This mixture of faulting types and orientation represents aleatory variability.

Fault-Specific Sources

For fault-specific sources, earthquakes also are modelled with magnitude-dependent finite rupture dimensions. The orientation of rupture is defined by the fault plane. Earthquakes occurring on fault-specific sources also may consist of a mixture of faulting styles.

4.1.1.3 Depth Distribution

Areal Source Zones

The third dimension of the spatial distribution of earthquakes is their depth distribution. The recorded seismicity in the region provided data that the SP1 expert teams used to estimate the depth distribution of earthquake hypocentres. The hypocentral depth data are only reliable for the more recent instrumental seismicity and provide data principally for small-magnitude ($M < 5$) earthquakes. Because earthquakes are modelled in the PSHA as having magnitude-dependent finite rupture dimensions, what is needed is the depth distribution of the rupture surface for larger ($M \geq 5$) earthquakes. *Toro* (*2003b, TP1-TN-0373*) describes approaches that can be used to develop magnitude-dependent rupture depth distributions by adjusting the small-magnitude hypocentral depth distributions to limit the upper edge of the rupture surface to the earth's surface. These adjustments can incorporate information on the likely location of hypocentral depth within the width of large-magnitude ruptures. The SP1 expert teams provided source-specific assessments of hypocentral depth distribution and the appropriate approach for developing magnitude-dependent rupture depth distributions.

Fault-Specific Sources

For fault-specific sources, earthquake ruptures are modelled by a uniform distribution over the fault width, maintaining the same lower bound (i.e. same shallowest depth) and the same mean depth that was specified by the team for the source zone in which the fault is located.

4.1.1.4 Source Boundaries

Areal Source Zones

The method described above in section 4.1.1.1 is used to specify the spatial distribution of earthquake epicentres. Magnitude-dependent extended earthquake ruptures are located symmetrically at each epicentre location (the epicentre is placed at the midpoint of the rupture length).

For those epicentres located near a source zone boundary, the SP1 expert teams were provided the flexibility to treat the boundary as a barrier to rupture or to allow ruptures to extend through the boundary (see *Toro 2003b, TP1-TN-0373*). The first approach (the boundary as a barrier to rupture) corresponds to the interpretation that the zone boundary represents a physical structure or change in structure that would prevent the occurrence of through-going ruptures. The alternative (ruptures may extend through the boundary) corresponds to the interpretation that the zone boundary only marks a change in seismicity rate density.

Fault-Specific Sources

Earthquake ruptures on fault-specific sources are confined to the defined fault plane.

4.1.1.5 Epistemic Uncertainty in Seismic Source Definition

The epistemic uncertainty in defining seismic sources and the spatial distribution of seismicity is represented in the PSHA by the development of a weighted set of alternative models in a logic tree framework (see section 2.2). Each of the SP1 expert teams developed their own representation of the epistemic uncertainty using the generalised logic tree structure shown on Figure 4-1. These logic trees first address global alternatives for source characterisation that affected the assessments for the entire study region. The logic tree shown on Figure 4-1 indicates this by the first assessment on the left for two alternative approaches, large regional source zones versus small source zones. Hypothetical examples of these alternative interpretations are shown on Figure 4-2.

The next level of the source definition logic tree addresses alternative assessments of spatial density of future seismicity obtained using different earthquake catalogue minimum magnitudes and the characteristic dimension *h*. Figure 4-3 shows examples of spatial density estimates for the study region obtained using the parameters specified in the logic tree shown on Figure 4-1. These spatial density estimates may be computed on a zone-by-zone basis (i.e. limited to the spatial extent of a single source zone and computed using only the earthquakes within the source) or computed for the entire region (as shown on Fig. 4-3) and then normalised within each source zone for use in the PSHA calculation. Following the regional zonation branch all the way to the right in the example logic tree (Fig. 4-1) leads to a single set of regional source zones with four alternative spatial density models.

The next three levels of the example logic tree address alternative zone boundaries that may exist in the local zonation model. For the example shown in the lower plot on Figure 4-2, these alternatives are: separating or including the Basel area in the lower Rhine Graben source, representing Northern Switzerland by either one or two source zones, and representing Eastern France by either one or two zones. These three levels of assessment lead to eight alternative sets of local source zones for the PSHA calculation, as indicated on the right hand side of Figure 4-1.

4.1.2 Assessment of Maximum Magnitude

In the context of PSHA, maximum earthquake magnitude, m^u, represents the upper truncation of the earthquake recurrence relationship for a seismic source. The source maximum magnitude is the largest possible earthquake that can occur on the source. The existence of a maximum magnitude is based on the concept that there is a physical limit to the size of an earthquake that a seismic source can produce in the current tectonic regime. Relating maximum magnitude to a physical limit on the size of an earthquake rupture provides a basis for assessing its value. When the source is an identified fault, then identification of a physical limit on the maximum size of earthquake rupture is a relatively clear concept. However, when the seismic source is an area (volume) of the earth's crust (a source zone), then identification of the potential physical limits of earthquake ruptures becomes more problematic. In both cases, there is uncertainty in defining the value of the limiting earthquake size.

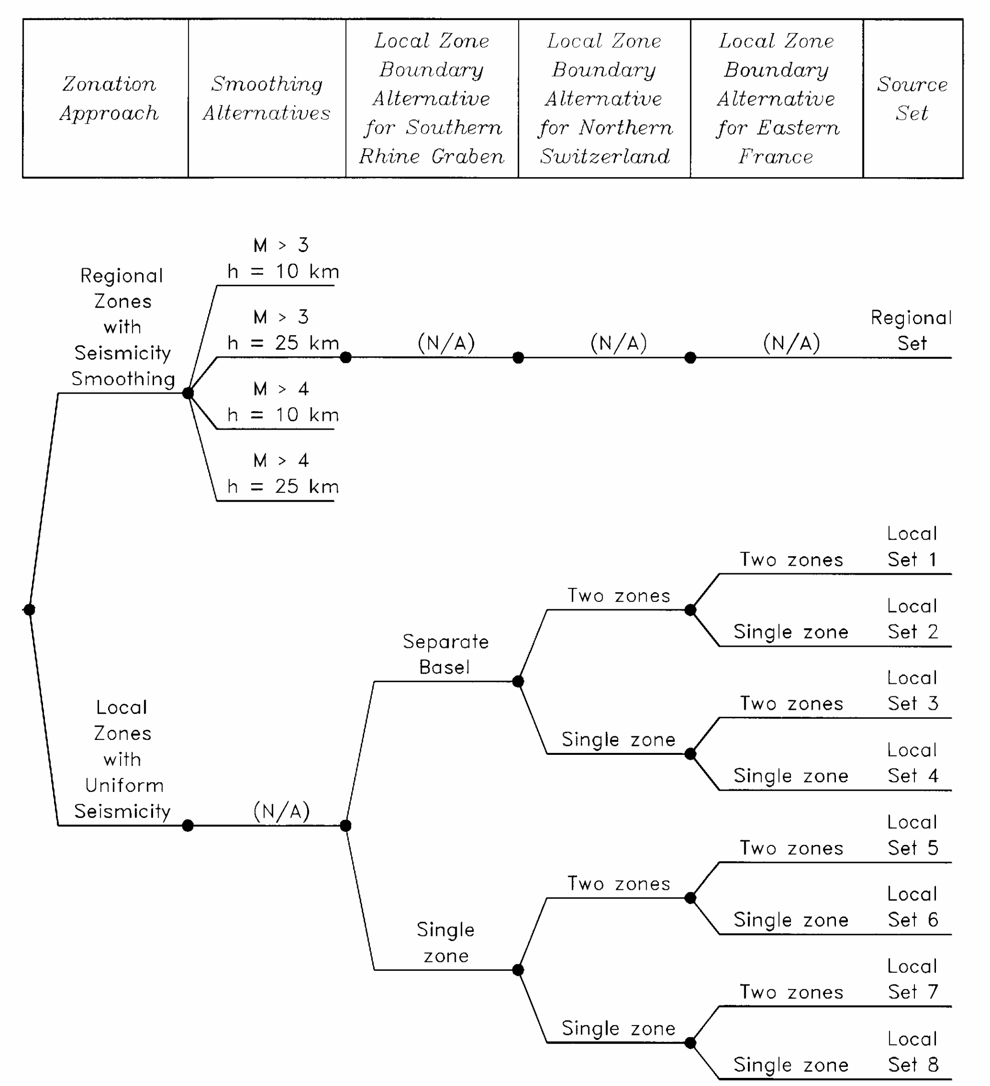
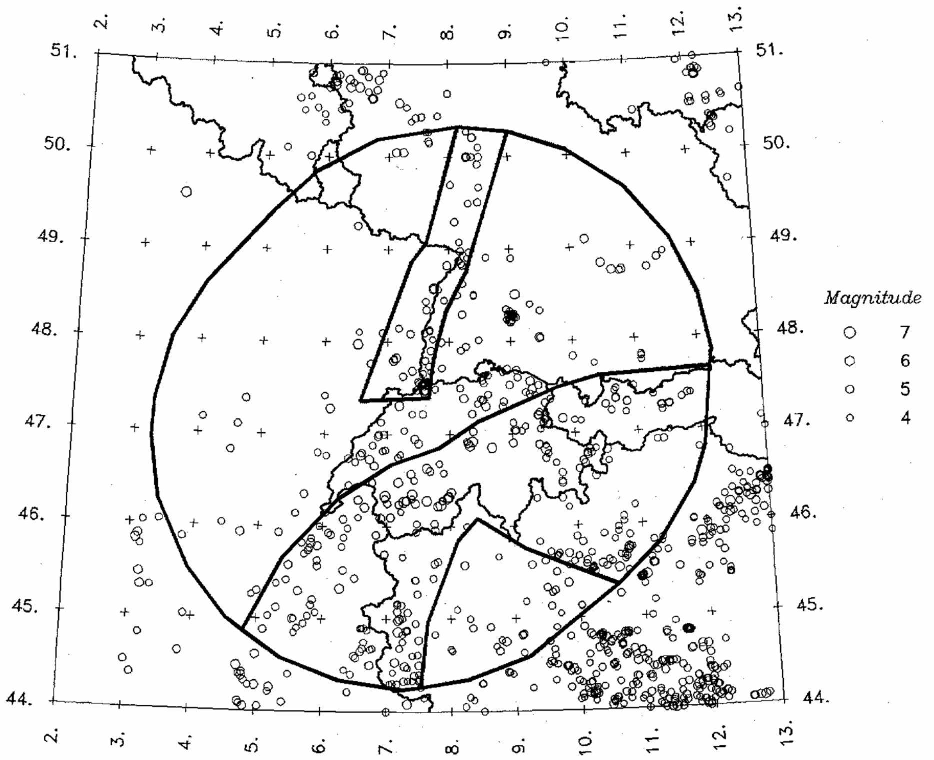


Fig.4-1: Example seismic source definition logic tree

4.1.2.1 Maximum Magnitude for Areal Sources

Areal seismic source zones are used to model the earthquake potential of regions of the earth's crust where fault-specific sources cannot be identified, or where seismicity may be distributed among a number of faults of generally similar characteristics. Typically, the assessment of maximum magnitude is more uncertain for such sources. The dimensions of the source zone are often much larger than what might be considered as reasonable maximum rupture dimensions for rupture on an individual fault. If the characteristics of faulting within the source zone can be readily identified and described, then their typical dimensions might be used to constrain estimates of maximum rupture dimensions and the procedures described in section 4.1.2.2 can be used to assess the source maximum magnitude.

Regional Zones



Local Zones

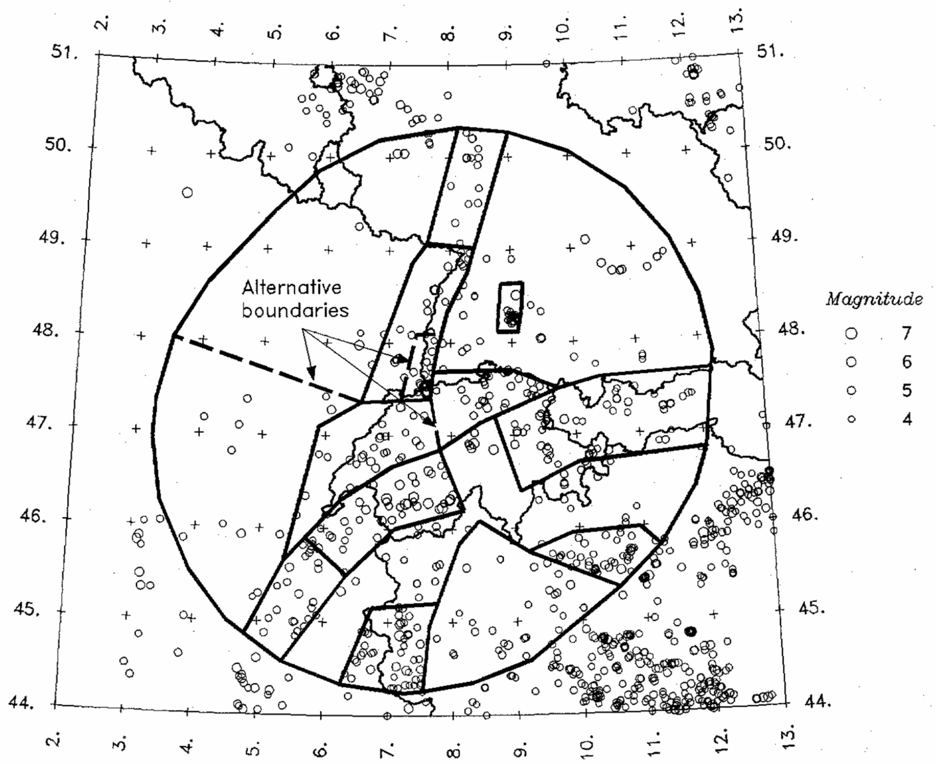


Fig.4-2: Example alternative seismic source definition approaches

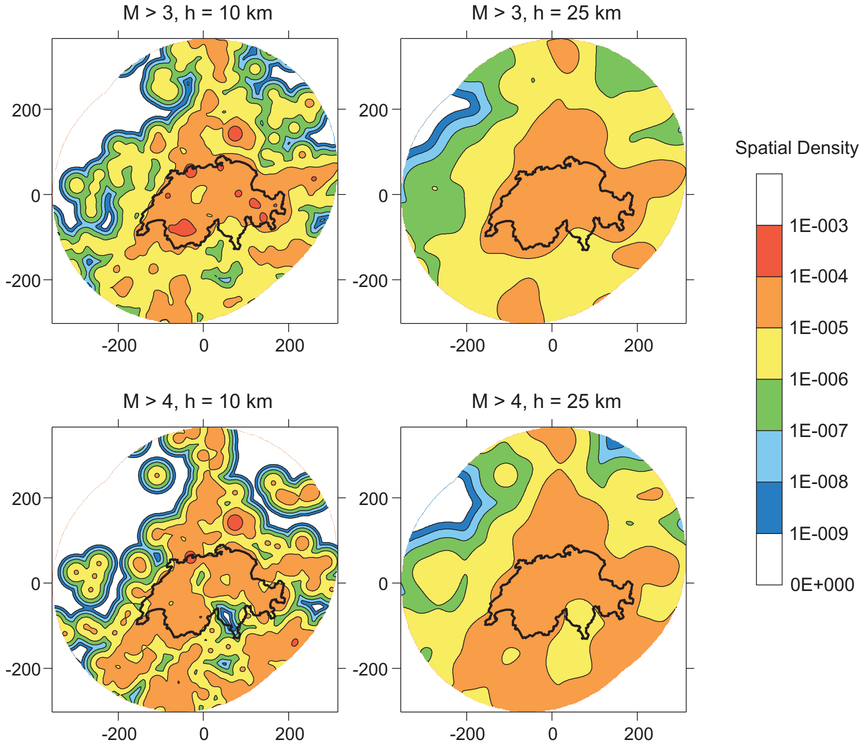


Fig.4-3: Example spatial density estimates for study region

Alternatively, the maximum magnitude assessment may be based on the recorded earthquake record alone, or in combination with the general characteristics of the crust within the areal source zones. Two quantitative methods are available to use this type of information to assess the maximum magnitude for an areal source zone.

The "EPRI" Approach

The largest earthquake recorded in a seismic source provides an estimate of the minimum value of the maximum magnitude (assuming that the event is not considered to be unique and not repeatable). Given the form of the earthquake recurrence relationship that applies to the source, one can define a likelihood function for various values of maximum magnitude given the historical earthquake record. The most common form of the earthquake recurrence relationship applied to seismic source zones is the truncated exponential distribution (Cornell & Van Marke 1969) based on Gutenberg & Richter's (1954) recurrence law. Using this recurrence relationship, the likelihood function for the upper limit magnitude, m^u, is:

$$L[m^u] = \begin{array}{ll} 0 & \text{for } m^u < m_{\max}^{observed} \\ \left[1 - \exp\left\{-b\ln(10)(m^u - m_0)\right\}\right]^{-N} & \text{for } m^u \geq m_{\max}^{observed} \end{array} \tag{4-3}$$

where b is the Gutenberg-Richter b-value, N is the number of recorded earthquakes with magnitudes larger than a minimum value m_0, and $m_{\max}^{observed}$ is the largest recorded earthquake. Figure 4-4 shows examples of this likelihood function for various values of N and m_0 given $m_{\max}^{observed} = 6$ in the source. The maximum likelihood estimate of m^u is $m_{\max}^{observed}$, the maximum observed value. However, unless N is large and m_0 is near $m_{\max}^{observed}$, the likelihood function is very flat, indicating that the likelihood is nearly the same for a large range of values of m^u. Because the likelihood function has a minimum value of 1 at $m^u = \infty$, it cannot be used as a probability distribution because it has an unbounded integral. By imposing an upper limit on m^u, however, the likelihood function can be used to construct a distribution for m^u (e.g. McGuire 1977).

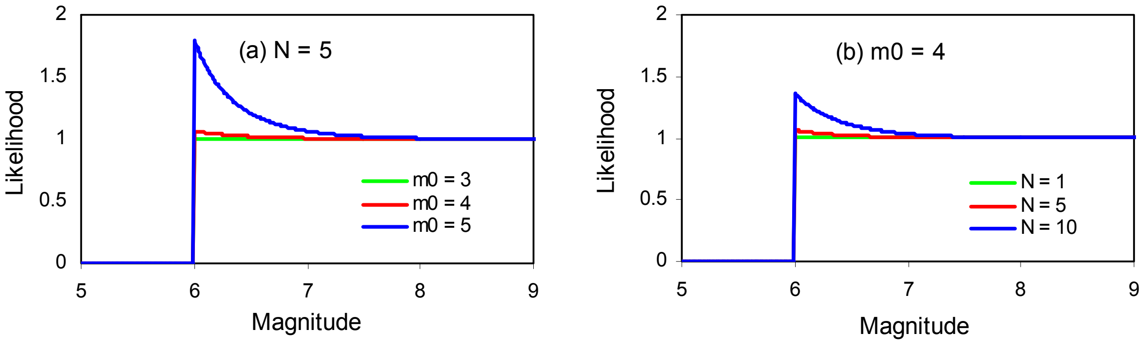


Fig.4-4: Example likelihood functions for upper limit magnitude m^u computed using Equation (4-3) and $b = 1.0$: (a) Effect of m_0 for $N = 5$; (b) Effect of N for $m_0 = 4$

The utility of the historical record for assessing the maximum magnitude distribution for a source is greatly improved if one combines it with a prior distribution for m^u. This is the basis of the Bayesian approach developed in a study of large earthquakes in stable continental regions (SCR) sponsored by the Electric Power Research Institute (Johnston et al. 1994). This study developed a worldwide database of large SCR earthquakes. The SCR crust was subdivided into domains on the basis of crustal characteristics (such as age, type of crust, stress state and tectonic history). By pooling domains with similar characteristics, the investigators were able to obtain sufficient numbers of earthquakes within each "super domain" such that estimates of the maximum magnitude for each domain type could be made with confidence. From these data, Johnston et al. (1994) developed two types of general prior distributions for m^u. The first is based on a simple division of the SCR into extended and non-extended crust. The statistics of the values of m^u for the super (pooled) domains in each group were used to define a normal distribution for m^u. The second approach was to develop a regression model relating m^u to the characteristics of the super domains.

The application of this methodology is illustrated in Figure 4-5. A prior distribution for m^u is selected by either identifying the source zone as consisting of extended or non-extended crust, or by applying the regression model given in Johnston et al. (1994). In the top-left panel of Figure 4-5, the prior distribution for extended crust is used, a normal distribution with a mean of 6.4 and a standard deviation of 0.84. The recorded earthquake history for the example source zone contains five earthquakes with magnitudes between 4.5 and 5.3. Equation 4-3 is used to construct the likelihood function shown on the lower-left panel of Figure 4-5. The prior distribution is then multiplied by the likelihood function and the resulting posterior distribution renormalised to give unit area under the probability density curve. The result is a continuous probability distribution for m^u, shown on the upper-right panel. This can be discretised for use in a logic tree, as illustrated in the lower-right panel of Figure 4-5.

It is important to note that the Bayesian updating approach described above is not limited to using the prior distributions developed by Johnston et al. (1994). One could use any justifiable bases for establishing a prior distribution for the maximum magnitude for a source and then use the earthquake history to update the prior. For example, truncating the likelihood function at an upper limit for m^u is equivalent to using a uniform prior distribution for m^u over a specified range. Alternatively, the prior distributions defined by Johnston et al. (1994) can be truncated at an upper limit based on an assessment of the maximum possible rupture dimensions permissible within a seismic source.

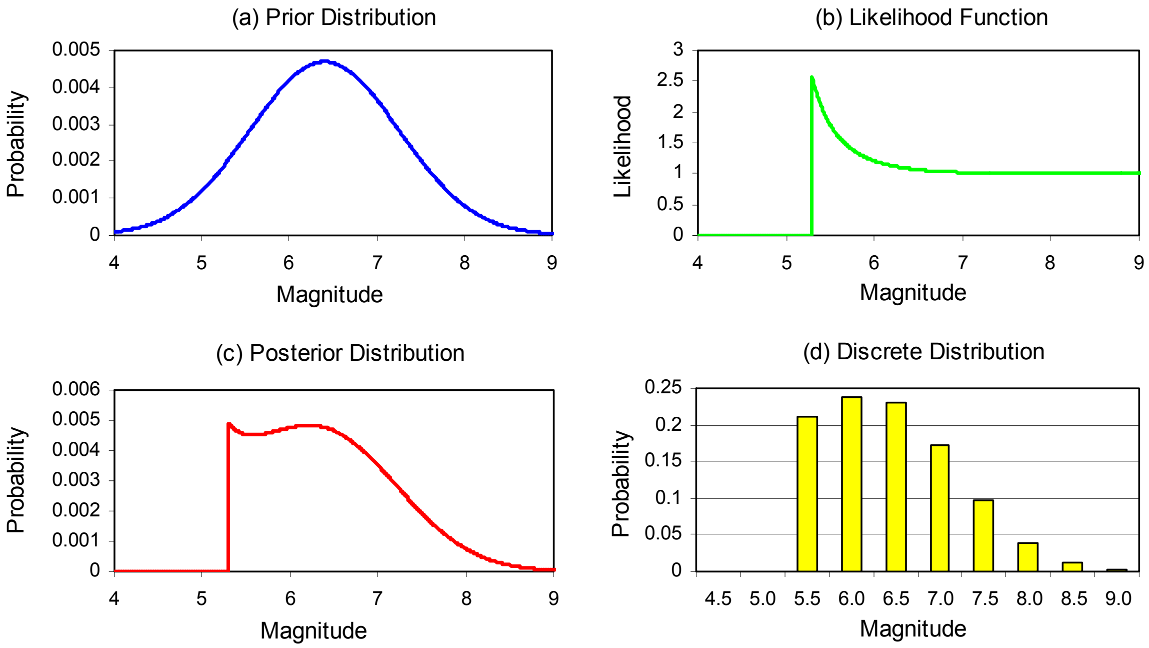


Fig.4-5: Example application of the "EPRI" Bayesian approach for assessing maximum magnitude

The "Kijko" Approach

Kijko & Graham (1998) present an approach for estimating the maximum magnitude in a region based solely on the recorded seismicity within the region. Where the “EPRI” approach uses a prior distribution to construct a distribution for maximum magnitude, Kijko and Graham use the "order statistics" of earthquake magnitudes in a set of independent earthquakes. Assuming that earthquake magnitudes follow a doubly-truncated exponential distribution between m_0 and m^u, Kijko & Graham (1998) present two specific relationships for estimating m^u as a function of $\beta = b \times \ln(10)$, N = number of earthquakes with magnitudes $\geq m_0$ in the period of complete reporting, and $m_{\max}^{observed}$, the largest observed earthquake. The general form of the estimators is $\mathrm{E}[m^u] = m_{\max}^{observed} + \Delta$, and $Var[m^u] \approx {\sigma_m}^2 + \Delta^2$, where Δ is a bias correction to the maximum likelihood estimate of m^u, $m_{\max}^{observed}$, and σ_m is the uncertainty in magnitude determination. Their T-P estimator takes the form:

$$\mathrm{E}[m^u] = m_{\max}^{observed} + \frac{1 - e^{-\beta(m_{\max}^{observed} - m_0)}}{N\beta e^{-\beta(m_{\max}^{observed} - m_0)}}$$

$$Var[m^u] \cong \sigma_m^2 + \frac{(N+1)}{N}\left[\frac{1 - e^{-\beta(m_{\max}^{observed} - m_0)}}{N\beta e^{-\beta(m_{\max}^{observed} - m_0)}}\right]^2 \tag{4-4}$$

and their K-S estimator has the form:

$$\mathrm{E}[m^u] = m_{\max}^{observed} + \frac{E_1(Tz_2) - E_1(Tz_1)}{\beta e^{-Tz_2}} + m_0 e^{-\lambda T}$$

$$Var[m^u] \cong \sigma_m^2 + \left[\frac{E_1(Tz_2) - E_1(Tz_1)}{\beta e^{-Tz_2}} + m_0 e^{-\lambda T}\right]^2 \tag{4-5}$$

where λ is the rate of earthquakes with magnitudes ≥ m_0 in the time period of complete reporting, T (note that assuming complete recording over time T, N is essentially equivalent to λT), $z_1 = -\lambda\ A_1/(A_2-A_1)$, $z_2 = -\lambda\ A_2/(A_2-A_1)$, $A_1 = \exp(-\beta\, m_0)$, $A_2 = \exp(-\beta\, m_{\max}^{observed})$, $E_1(z)$ is an exponential integral function that can be approximated by:

$$E_1(z) = \frac{1}{z} e^{-z} \frac{z^2 + 2.334733z + 0.250621}{z^2 + 3.330657z + 1.68134} \tag{4-6}$$

Kijko & Graham (1998) also develop Bayesian estimators that include the effect of uncertainty in β (the b-value). Their Bayesian T-P estimator (T-P-B) is given by:

$$\begin{aligned} \mathrm{E}[m^u] &= m_{\max}^{observed} + \frac{1}{NC_\beta(q/p)} r^{-(q+1)} \\ Var[m^u] &\cong \sigma_m^2 + \frac{(N+1)}{N}\left[\frac{1}{NC_\beta(q/p)} r^{-(q+1)}\right]^2 \end{aligned} \tag{4-7}$$

where $p = \hat{\beta}/\sigma_\beta^2$, $q = \left(\hat{\beta}/\sigma_\beta\right)^2$, $r = p/(p + m_{\max}^{observed} - m_0)$, and C_β is given by:

$$C_\beta = \left[1 - r^{-q}\right]^{-1} \tag{4-8}$$

Their Bayesian K-S estimator (K-S-B) is obtained by numerically integrating:

$$\begin{aligned} \mathrm{E}[m^u] &= m_{\max}^{observed} + (C_\beta)^N \int_{m_0}^{m_{\max}^{observed}} \left[1 - \left(\frac{p}{p + m - m_0}\right)^q\right]^N dm \\ Var[m^u] &\cong \sigma_m^2 + \left[(C_\beta)^N \int_{m_0}^{m_{\max}^{observed}} \left[1 - \left(\frac{p}{p + m - m_0}\right)^q\right]^N dm\right]^2 \end{aligned} \tag{4-9}$$

Figure 4-6 compares the four estimates of m^u a function of the estimator and N for $m_0 = 4$ and $m_{\max}^{observed} = 6$.

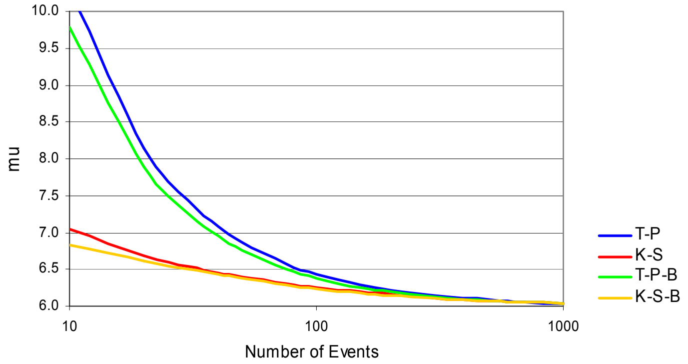


Fig.4-6: Example maximum magnitude estimates using the Kijko & Graham (1998) estimators for $m_0 = 4$ and $m_{\max}^{observed} = 6$

Kijko & Graham (1998) do not indicate the form of the distribution for m^u. However, given the fact that it is derived from an exponential base form and the fact that the standard deviation for Δ is approximately equal to the mean (assuming a small value for σ_m), it is likely that the distribution can be approximated by a shifted exponential (i.e. the distribution for Δ is approximately exponential). This assumption could be used to construct a distribution for m^u given an estimate of Δ.

4.1.2.2 Maximum Magnitude for Fault-Specific Sources

For fault-specific seismic sources, maximum magnitudes are typically assessed using estimates of the maximum dimensions of future earthquake ruptures and empirical relationships between rupture dimensions and earthquake magnitude. The rupture dimensions used typically include rupture length, rupture area, maximum displacement, and average displacement. One also can combine estimates of rupture area with average displacement to obtain an assessment of the maximum seismic moment. A number of empirical relationships between rupture dimensions and earthquake magnitude have been published (e.g. Wells & Coppersmith 1994). The process of maximum magnitude estimation becomes one of assessing the limits of rupture and, given these values, selecting appropriate relationships to translate the dimension estimates into magnitude estimates.

Figure 4-7 illustrates the process with an example from a PSHA study conducted for a site in the Basin and Range province of the western United States. The seismic source in question is a large, basin-bounding normal fault. The rupture dimensions used to estimate maximum magnitude are maximum rupture length and maximum rupture area. The fault in question displayed evidence for rupture segmentation, including differences in the timing of past ruptures along its length as well as significant changes in geometry. The locations of these changes suggest possible fault segmentation points. The assessment of the maximum rupture length consisted of evaluations of the relative merits of the various segmentation points as limits to future ruptures.

Assessment of maximum rupture area required evaluation of the maximum rupture width. For large faults, it is typically assumed that maximum ruptures extend from the surface to the base of the seismogenic crust. The thickness of the seismogenic crust is typically assessed using the depth distribution of observed hypocentres, although other information such as heat flow measurements can be used. Downdip rupture width is obtained using the crustal thickness and fault dip.

Figure 4-7 shows a logic tree constructed to represent the uncertainties in the assessment of the maximum rupture parameters. The first three levels of the logic tree define the uncertainty in the thickness of the seismogenic crust, the fault dip, and the maximum rupture length. The next level of the logic tree addresses the use of alternative empirical relationships between rupture dimensions and earthquake magnitude. One of the relationships considered (Anderson et al. 1996) incorporates the effect of slip rate in the relationship between rupture length and magnitude. Shown at the right of the logic tree is the uncertainty estimate for the fault slip rate.

Each path through the logic tree shown on Figure 4-7 results in an estimate of maximum magnitude for the seismic source. The probability assigned to the assessment is equal to the product of the probabilities assigned to each of the branches along the path. Enumerating all of the paths through the logic tree produces the discrete probability distribution for maximum magnitude shown in the lower part of Figure 4-7.

4.1.3 Assessment of Earthquake Recurrence

Recurrence relationships define the frequency of occurrence of earthquakes of various magnitudes within a seismic source. Figure 4-8 shows examples of earthquake recurrence curves, expressed as the cumulative annual frequency for earthquakes of magnitude m or larger (top plot) and as the rate density of earthquakes of a particular magnitude m (bottom row of plots).

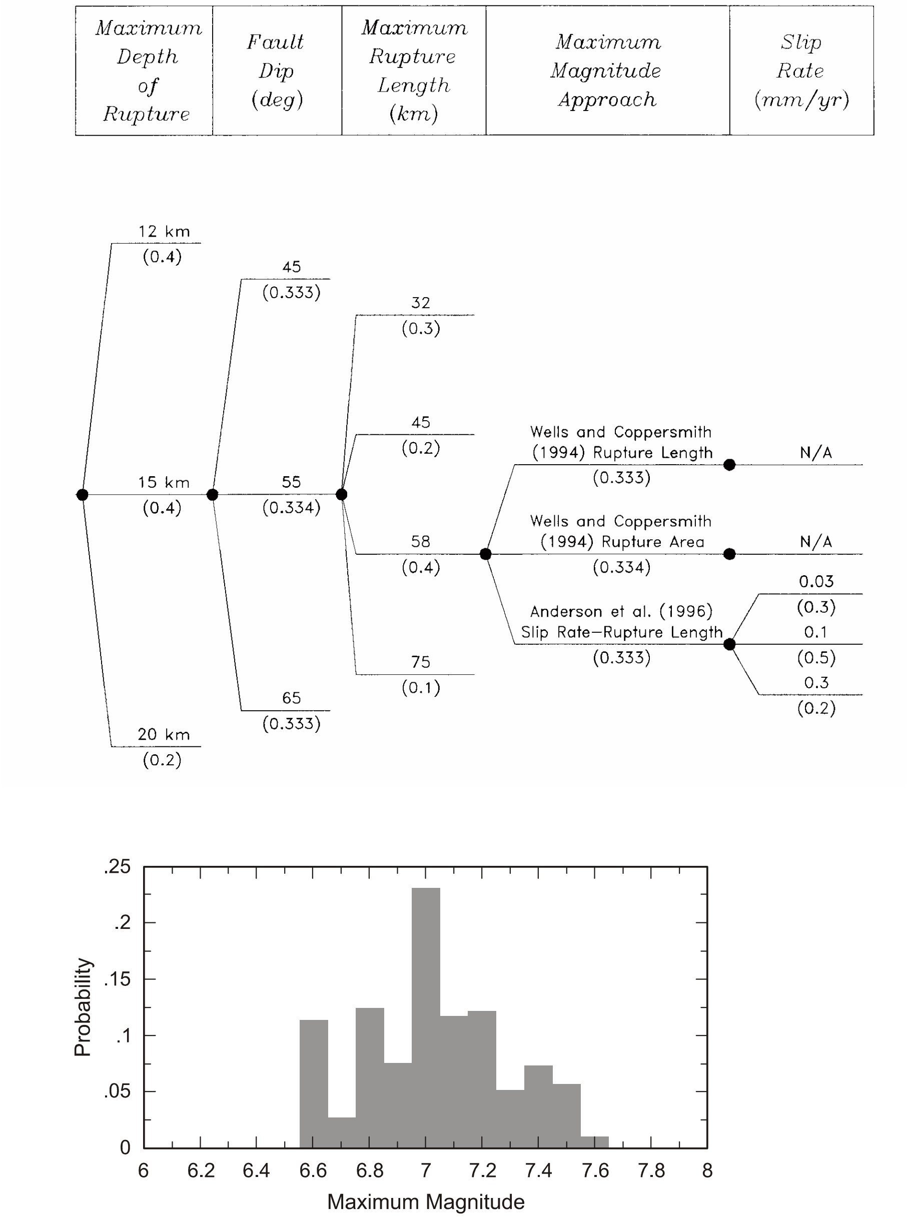


Fig.4-7: An example maximum magnitude assessment for a fault-specific seismic source using relationships between rupture dimensions and earthquake magnitude

The earthquake recurrence relationship most commonly used in PSHA is the truncated exponential distribution (Cornell & Van Marke 1969). It is derived from the Gutenberg & Richter (1954) recurrence model by truncating the rate density of earthquakes at a maximum magnitude, m^u (see bottom-left plot in Figure 4-8). The truncated exponential model is given by the expression:

$$N(m) = N(m_0)\frac{e^{-\beta(m-m_0)} - e^{-\beta(m^u-m_0)}}{1-e^{-\beta(m^u-m_0)}} \tag{4-10}$$

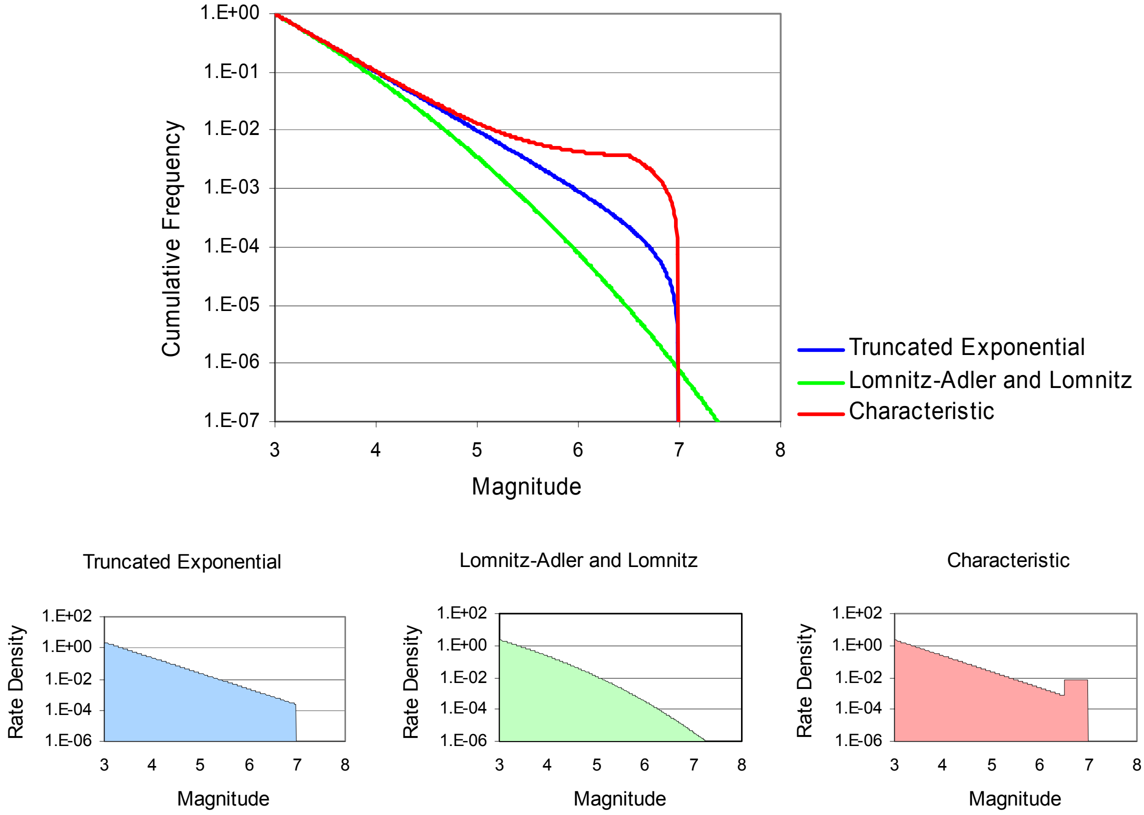


Fig.4-8: Example earthquake recurrence relationships: truncated exponential (Cornell & Van Marke 1969), Lomnitz-Adler & Lomnitz's (1979) modified Gutenberg-Richter, and the characteristic earthquake model of Youngs & Coppersmith (1985)

where $N(m_0)$ is the annual frequency of earthquakes larger than magnitude m_0, and $\beta = b\ln(10)$, the Gutenberg-Richter b-value. This form of recurrence relationship is typically applied to regions and areal source zones representing multiple individual faults. The abrupt truncation of the rate density of earthquakes causes the cumulative curve to deviate smoothly from the straight log-linear Gutenberg-Richter line towards zero at m^u.

Lomnitz-Adler & Lomnitz (1979) also proposed a modification to the Gutenberg-Richter relationship to account for limiting energy release in a region. Their relationship does not impose a specific value of maximum magnitude, but rather an increasing deviation from the log-linear rate density as magnitude increases (see bottom middle plot of Figure 4-8). The Lomnitz-Adler & Lomnitz relationship can be expressed by the relationship:

$$N(m) = N(m_0)\exp[B'(1 - e^{\alpha(m-m_0)})] \qquad (4\text{-}11)$$

where $B' = b\ln(10)/\alpha$, and b is again the Gutenberg-Richter b-value. The parameter α controls the deviation from the Gutenberg-Richter relationship; the larger the value of α, the greater the deviation. A value of α of 0.2 was used to generate the curve shown on Figure 4-8.

The third recurrence relationship shown on Figure 4-8 is an example of the type of recurrence models now commonly being applied to individual faults. The model shown is the "characteristic" earthquake recurrence model developed by Youngs & Coppersmith (1985). The model is based on the concept that individual faults tend to produce a characteristic size of earthquake near the upper size the fault can produce. These characteristic earthquakes occur more frequently than somewhat smaller earthquakes and occur more frequently than would be predicted by extrapolating the exponential distribution of small-magnitude earthquakes. The Youngs & Coppersmith model includes an exponential distribution of smaller magnitude events (see bottom right plot of Figure 4-8). Other forms of this model may consist of only the characteristic event (e.g. Wesnousky et al. 1983) or Gaussian distributions for the characteristic magnitude rather than the uniform distribution shown on Figure 4-8. This type of model has been shown to work well in modelling earthquake recurrence associated with moderate to high activity faults (Youngs & Coppersmith 1985, Youngs et al. 1992).

4.1.3.1 Earthquake Recurrence for Areal Source Zones

Earthquake recurrence parameters for areal source zones are typically based on analysis of the earthquake catalogue. There are two principal steps needed to prepare an earthquake catalogue for assessment of earthquake recurrence parameters: (1) identification of dependent events and (2) evaluation of catalogue completeness.

Identification of Dependent Events

The PSHA formulation developed by Cornell (1968, 1971) is based on the assumption that the occurrence of earthquakes is a Poisson process. Studies such as Gardener & Knopoff (1974) have shown that when foreshocks and aftershocks are removed from an earthquake catalogue, the remaining events can be considered to conform to a Poisson process in time. It has also been shown that the Poisson model provides a reasonable representation for the combined effects of the contributions from multiple independent processes, even when the individual processes are more cyclic in nature (Brillinger 1982).

There are several approaches for catalogue declustering (identification of foreshocks and aftershocks). The approach developed by Gardener & Knopoff (1974) uses magnitude-dependent fixed time and distance windows to identify dependent events. Other researchers have developed region-specific assessments of these magnitude-dependent time and distance windows (e.g. Uhrhammer 1986 for central California; Grünthal 1985 for central Europe). An alternative approach developed by Reasenberg (1985) defines interaction space-time windows for individual clusters on a statistical basis. The parameters of Reasenberg's algorithm have been optimised for northern California. *Wiemer* (*2002, EXT-TN-0244*) developed four declustered versions of the PEGASOS catalogue *(SED 2002, EXT-TB-0043*), three using the Gardener & Knopoff (1974) approach with space-time windows developed by Gardener & Knopoff (1974), Uhrhammer (1986) and an updated version of Grünthal (1985) (Grünthal personal communication 2002). One uses the Reasenberg algorithm modified to incorporate spatially variable catalogue completeness and individual earthquake uncertainties. *Wiemer & Woessner (2002, TP1-TN-0266*) showed that the resulting catalogues of independent events are consistent with a Poisson process in time, while the original catalogue is not. Table 4.1 summarises the results of the catalogue declustering performed by Wiemer.

Tab.4.1: Summary of PEGASOS catalogue declustering by *Wiemer* (*2002, EXT-TN-0244*).

Declustering Approach	Number of dependent events	Percent of catalogue represented by dependent events	Percent of total seismic moment represented by dependent events
Gardener & Knopoff (1974)	8792	43.2	1.65
Grünthal (pers. communication 2002)	9459	46.5	1.88
Uhrhammer (1986)	4927	24.2	0.74
Reasenberg (1985) modified by *Wiemer* (*2002, EXT-TN-0244*)	7891	38.8	0.94

Assessment of Catalogue Completeness

In its simplest form, the process of estimating earthquake recurrence rate for a Poisson process involves dividing the number of earthquakes, *N*, that has occurred in time period *T* by the length of the time period. This calculation assumes that all of the earthquakes that occurred in time period *T* have been reported in the catalogue. Thus, one needs to evaluate the time periods over which the earthquake catalogue can be considered complete. One approach to evaluating catalogue completeness was presented by Stepp (1972). The basic concept is to plot the rate of earthquakes as a function of time, starting at the present and moving back towards the beginning of the catalogue. Assuming that the rate of earthquakes represents a stationary Poisson process (homogeneous in time within the catalogue region), this rate should remain fairly constant during the period of complete reporting. As one moves back into the period of incomplete reporting, the rate should begin to steadily decline. This process can be used to assess the time period of complete reporting for earthquakes within a specific magnitude interval $m_i \le m < m_{i+1}$. The rate of earthquakes as a function of time before the end of the catalogue $\lambda(m, T)$ is defined as:

$$\lambda(m_i \le m < m_{i+1}, T) = \frac{N(m_i \le m < m_{i+1})}{T} \tag{4-12}$$

where $N(m_i \le m < m_{i+1})$ is the number of independent earthquakes in the magnitude interval $m_i \le m < m_{i+1}$ counted from the end of the catalogue back *T* years. Figure 4-9 shows such a "Stepp" plot for the PEGASOS catalogue declustered using the Reasenberg (1985) algorithm (*Wiemer 2002, EXT-TN-0244*).

These types of plots can be used together with an evaluation of earthquake recording history to assess the periods of complete catalogue reporting.

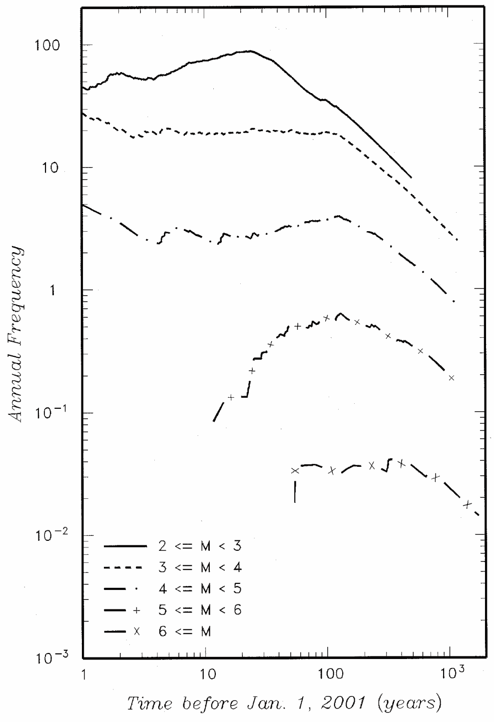


Fig.4-9: Catalogue completeness plot for the PEGASOS catalogue declustered using the Reasenberg approach

Estimation of Recurrence Parameters

The parameters of the earthquake recurrence relationships may be estimated by a variety of techniques. One common technique for estimating the parameters of the truncated exponential recurrence relationship is the maximum likelihood technique developed by Weichert (1980). Veneziano & Van Dyck (1985) have extended Weichert's technique to include the use of a prior estimate for the *b*-value to stabilise the assessments in zones with limited seismicity. They presented the following penalised likelihood formulation for the truncated exponential model:

$$
\begin{aligned}
L &= \prod_i \frac{(\lambda_i t_i)^{n_i}\, e^{-\lambda_i t_i}}{n_i!} \times e^{-W(\beta-\beta_p)^2/2} \\
\lambda_i &= \text{rate for } m_i - m_{i-1} = N(m_0)\frac{e^{\beta(m_t - m_0)} - e^{\beta(m_{t+1}-m_0)}}{1-e^{\beta(m^u - m_0)}}
\end{aligned}
\qquad (4\text{-}13)
$$

where $N(m_0)$ = rate for $m \geq m_0$, $\beta = b\ln(10)$, n_1 = number of earthquakes in magnitude range $m_i - m_{i-1}$, t_i = completeness period for $m_i - m_{i-1}$, β_p = prior, and W = weight controlling strength of prior.

The penalty term in Equation 4-13, $e^{-W(\beta-\beta_p)^2/2}$, acts to reduce the likelihood as β (the *b*-value) deviates from the prior β_p. The weight parameter, *W*, can be considered equivalent to the inverse of the variance on β_p.

The likelihood function can be used to develop a joint distribution for the rate of earthquake activity, $N(m_0)$, and the *b*-value. The process involves setting up a grid of pairs of $N(m_0)$ and *b*, computing the likelihood that the observed seismicity in a zone was produced by each pair, and then normalising these likelihoods to form a discrete joint distribution for $N(m_0)$ and *b*. This process captures the correlation between $N(m_0)$ and *b*.

The likelihood formulation of Equation 4-13 was extended to allow for variable catalogue completeness within a source zone and for a change in rate over the time period covered by the catalogue. The extended likelihood function is given by:

$$
\begin{aligned}
L &= \prod_k \prod_j \prod_i \frac{(\lambda_{i,j,k} t_{i,j,k})^{n_{i,j,k}}\, e^{-\lambda_{i,j,k} t_{i,j,k}}}{n_{i,j,k}!} \times e^{-W(\beta-\beta_p)^2/2} \\
\lambda_{i,j,k} &= \frac{A_j}{\sum_j A_j} N_k(m_0)\frac{e^{\beta(m_t - m_0)} - e^{\beta(m_{t+1}-m_0)}}{1-e^{\beta(m^u - m_0)}}
\end{aligned}
\qquad (4\text{-}14)
$$

where the index *j* refers to the different completeness regions within a source zone, each with area A_j, and the index *k* refers to the time periods with different rates of activity, $N_k(m_0)$.

An alternative method of fitting the recurrence parameters is least-squares. The fitted relationship is $y_i = \alpha + \beta x_i$, with $x_i = m_i - m_0$ and $y_i = \ln(n_i/t_i)$ when fitting interval earthquake frequencies, or $y_i = \ln(\sum_{j=i}^{I} n_j / t_j)$ when fitting cumulative earthquake frequencies (*I* is the largest magnitude interval). An uncertainty distribution for the parameter of the regression fit can be obtained using a normal distribution approximation for the data point distribution. The relative likelihood of obtaining the observed data set with a range of values of α and β is given by:

$$L(\alpha,\beta) \propto \prod_{i=1}^{n} \exp\left[-\frac{1}{2}\left\{ \frac{y_i-(\alpha+\beta x_i)}{\sigma} \right\}^2 \right] \tag{4-15}$$

where σ is the standard error in the fitted linear regression. These relative likelihoods can be normalised into a joint discrete distribution for the recurrence parameters.

4.1.3.2 Fault-Specific Sources

Earthquake recurrence parameters for fault-specific sources may be developed in two ways. One approach is to identify a region in which the observed seismicity is interpreted to be associated with the fault-specific source. This seismicity can then be used to develop earthquake recurrence parameters for the source using the techniques described in section 4.1.3.1. Alternatively, geological and paleoseismic data may be used to develop earthquake recurrence parameters. If the fault slip rate can be assessed, it can be used to develop earthquake recurrence relationships using formulations such as that of Anderson (1979) for the truncated exponential recurrence model and Youngs & Coppersmith (1985) for the characteristic recurrence model. If paleoseismic data on the timing of past ruptures is available, it can be used to assess the frequency of large-magnitude earthquakes on the source. The frequency of smaller earthquakes is then estimated by fitting the appropriate earthquake recurrence model to the estimated rate for the larger earthquakes.

4.2 SP1 Workshops and Elicitation Meetings

This section summarises the significant activities and major topics covered at the workshops and elicitation interviews for SP1. The general flow and principal focus of the workshops was discussed for all subprojects in section 3.6, and the general process followed during the elicitation interviews was described in section 3.7. For a detailed account of the technical content of the SP1 workshops, the reader is referred to the workshop summaries provided in Volume 3.

4.2.1 WS-1 / SP1: Key Issues and Data Needs

The first workshop WS-1 was held on 15-17 October 2001. The first day of WS-1 was devoted to a common session with the other subprojects, which is described in section 3.6.1. In a separate SP1 session, the second day began the process of identifying key issues and data needs for the remainder of the project. Key issues were identified based on consideration of the seismic source characterisation efforts conducted for other PSHAs in comparable tectonic environments. The experts then considered how the seismotectonic framework for the Swiss power plant sites compares with the analogue sites and what this might mean in terms of the important issues. For example, site-specific hazard studies within stable continental regions such as the eastern United States have shown that the characteristics (e.g. recurrence rate) of the host seismic source zone are often a dominant contributor to the site hazard. This is in contrast with sites within plate boundary tectonic settings, where characteristics of nearby active faults are often a dominant technical issue. An important constraint in the SP1 experts' assessments was the region within which seismic sources need to be characterised. Dr. Gabriel Toro from SP4 summarised preliminary hazard calculations conducted for the four sites and presented his recommendations for the distances from the sites requiring source characterisation. These constraints were used by the experts throughout their subsequent source characterisations.

Following the discussion of issues, the workshop then focused on the available data that had already been developed, either as part of the PEGASOS database or for other purposes. The structure and access to the PEGASOS database was identified, as well as the mechanisms for adding new data to the database. As witnessed throughout the project, the experts made numerous requests for data from the database, provided their own contributions, and received strong support from the database contractor. The first key data set discussed at the workshop was the seismicity catalogue, particularly the catalogue developed by the Swiss Seismological Service (SED) for the PEGASOS Project. Other data discussed included paleoseismic data for Switzerland, regional seismicity catalogues, seismicity studies in Germany and the Rhine Graben, and seismotectonic studies in Switzerland based on the characteristics of seismicity (e.g. depths and focal mechanisms). To the extent that geological structures might be considered potential seismic sources, the local geological structures proximal to the sites were also summarised.

In the light of the key issues for seismic source characterisation and the available data, the experts then identified the data that they would need to conduct their evaluations. The resulting list of data needs, which is given in the WS-1 summary in Volume 3, includes a wide range of data types ranging from professional publications to unpublished data. The PEGASOS Project database contractor was successful in honouring these data requests in a timely manner prior to WS-2. Data requests occurring later in the project were also honoured.

4.2.2 WS-2 / SP1: Methodologies for Defining Seismic Sources and Probability of Activity

WS-2, held on 12 – 14 February 2002, provided the SP1 experts with an opportunity to begin the technical work required for their seismic source characterisations. In particular, the workshop focused on the technical issues associated with defining seismic sources, their spatial configuration, and their seismotectonic framework. Most of these issues had been identified as important in the first workshop. A key dataset involved in the assessment of seismic sources is the earthquake catalogue and the workshop began with a discussion of the PEGASOS catalogue by representatives from the Swiss Seismological Service (SED). The PEGASOS catalogue has been compiled specifically for the project, based on specifications that provide for its intended use in seismic source characterisation. For example, all earthquakes in the catalogue are assigned a single, unified magnitude (moment magnitude M), which is compatible with the eventual usage in recurrence and ground motion calculations for the hazard analysis. In addition, each event is associated with estimates of uncertainty in the location and magnitude. Historical (macroseismic) events as well as instrumental events are included in the catalogue, with an algorithm developed for the combination of intensity and magnitude measures to arrive at M. Discussion at the workshop centred around the approach taken by SED to estimate moment magnitude using intensity data, including alternative approaches that have been used elsewhere. In anticipation of future use of the catalogue for defining seismic sources spatially, as well as recurrence calculations, the experts also discussed catalogue completeness spatially and temporally. Such discussions would recur during subsequent workshops as the experts conducted their own evaluations of the catalogue and recurrence characteristics.

Consideration of approaches to defining the spatial configuration of seismic sources was the next topic of the workshop. This began with the TFI-team presenting the "tools in the toolbox", which, in this case, are the various approaches that have been employed in other PSHAs as well as approaches to expressing the epistemic uncertainty in source definition using logic trees. Alternative approaches include areal seismic source zones, spatial smoothing of seismicity, tectonic feature-based source zonation, and fault sources. Subsequent talks were designed to amplify on these various approaches and to allow proponents thereof to provide examples of their application. In the course of these presentations, the experts discussed the types of data needed to apply to various approaches and the pros and cons of their application for source characterisation for the PEGASOS Project.

Presentations and discussions of pertinent experience regarding seismic source definition began with examples from Italy and France for previous hazard studies. This was followed by consideration of seismotectonic features as potential controls on the location and spatial configuretion of sources. Uncertainties of using tectonic features, including faults, within stable continental regions were key parts of these discussions. A formalised approach for incorporating these uncertainties into a "probability of activity" assessment for tectonic feature-based source assessments was reviewed, using the EPRI-SOG (1986) methodology as an example. Mindful of the need to deal with the potential seismic source responsible for the 1356 Basel earthquake, discussions also included approaches for characterising the alternative seismic sources responsible for individual large earthquakes. Following a different approach to source definition, discussions then turned to the approach of spatially smoothing observed seismicity – in particular the rate density or a-values – and examples of this approach. In addition to alternative ways to implement this approach (e.g. using alternative smoothing operators), the experts discussed the basic issue faced by smoothing as well as the alternative source zone approach: spatial stationary of seismicity. That is, the degree to which the spatial distribution of *observed* seismicity can or should provide a constraint on the spatial distribution of *future* seismicity is a function of one's degree of belief in spatial stationarity. It was recognised by the experts that this is a fundamental, although uncertain, issue and will have to be addressed explicitly by the experts in their assessments.

The next session of the workshop was designed to spark discussion related to two fundamental source definition issues: the degree to which the spatial pattern of small-magnitude earthquakes provides information about the future pattern of large-magnitude earthquakes and the potential use of the location of tectonic domains to define seismic sources. Proponents for various points of view began with presentations, followed by open discussion by all experts. The presentations were particularly focused on data and examples from Switzerland and the surrounding region. This allowed the experts to debate the alternative approaches not only from a generic perspective, but also from the perspective of the ease or difficulty in applying the approach in the region of interest for the PEGASOS study. An additional session dealt with the potential for geological structures – particularly faults – as seismic sources identified for the hazard study. A detailed summary was given of the studies conducted in the vicinity of the power plant sites (e.g. the faults bounding the Permo-Carboniferous troughs), as well as the recent and ongoing paleoseismic studies of the Reinach fault. As in other stable continental regions, the uncertainties are considerable regarding the potential for specific identified faults to generate earthquakes. The discussion at the workshop and the range of views expressed highlighted the fact that these uncertainties will need to be incorporated into the seismic source definitions coming from the expert teams.

It should be noted that the ground rules for the workshops allowed the invited resource experts and proponent experts to participate in the general discussions at the workshops. This proved to enliven the discussions and to provide additional perspectives.

The workshop then included a demonstration of the WIZMAP seismic hazard program (*Musson 2002, RDZ-ASW-0016*), particularly emphasising the aspects of the program that had been augmented to support the PEGASOS Project. Additional improvements were made subsequent to the workshop, based on suggestions from the experts. The WIZMAP program, mounted with the base maps specified by the experts, would become a key tool used by the SP1 experts throughout the project to assist in their deliberations. For example, the program provides for the rapid evaluation of recurrence parameters for a given expert team's source zones. It is therefore relatively easy to see the effect of changes to recurrence parameters as a function of changes in the geometry of seismic source configurations.

The last discussion of the workshop consisted of a presentation by the TFI-team regarding the role of the expert teams to act as a single 'virtual expert', thus necessitating the development of an internal consensus within each team. It was noted that, based on experience in similar elicitations, the best way to achieve that consensus was to agree to an uncertainty representation that is sufficiently broad to incorporate the range of views within the team. Discussion also ensued concerning how one "represents the views of the larger informed technical community", particularly when many of the site-specific issues have not been addressed by others in the community. It was indicated that, for most such issues, as noted in SSHAC (1997), the exercise is a hypothetical one, particularly inasmuch as one must imagine that the larger community is equally "informed" by having gone through the same process as have the experts on the panel. The final test of this concept is whether or not the TFI is able to conclude at the end of the project that the range of assessments across the panel of experts is not systematically different from that which could be developed by the larger informed technical community.

The final session also discussed the need to provide sufficient and adequate technical support for expert assessments, including complete documentation in the elicitation summaries. It was indicated that, although the fundamental basis for the experts' assessments is their professional judgement, they must provide clear and supportable technical bases for their assessments, such that other experts on the panel, as well as reviewers of the project, can understand the technical support for the assessments.

Subsequent to the workshop, a memo was sent to the experts containing the outline for their elicitation summaries. It was stated that the purposes of the elicitation summaries include: 1) to provide a *transparent* record of expert evaluations that is *traceable* back to the technical basis for the assessments; 2) to provide the tectonic framework for all seismic source evaluations; 3) to provide the models and parameters that provide input to PSHA as well as the technical basis for all assessments; and 4) to provide quantification of uncertainties, such as logic trees and probability distributions. The outline included all of the major elements of the seismic source characterisation that would be required by a third party to understand the assessments made by the expert teams including: the seismotectonic framework, seismic source definition, maximum earthquake magnitudes, and earthquake recurrence. The first two of these topics would be covered in the first group of elicitation interactive meetings and the second two topics would be covered in the second set of elicitation meetings.

4.2.3 EG1a–d: First Elicitation Interactive Meetings on Defining Seismic Sources and Probability of Activity

The first set of elicitation interactive meetings was held in mid-May 2002. Each meeting lasted three days and was scheduled such that the expert team would meet with the TFI-team on the first and third days, and work independently on the second day. The first day included a review of the purpose of the session, followed by a development of the logic structure of the entire assessment. Typically, the first day also included going through a number of assessments with the experts working with the TFI-team to identify alternative models (branches of the logic tree), weights associated with the models, and uncertainties in parameter values. The second day entailed the expert team members working through their assessments independently from the TFI. Applicable data and reference materials were provided to the team, as needed, and the database contractor was available to honour requests, such as plots or maps. The third day, the expert team once again met with the TFI-team, with the purpose of reviewing progress and resolving questions. Having worked through several assessments, the teams would often have questions by the third day regarding the manner in which their assessments should be conducted (e.g. the logic structure for relating seismotectonic information to alternative conceptual models for the configuration of seismic sources) or suggestions regarding approaches to expressing uncertainties (e.g. the incorporation of earthquake location uncertainty into the shape of a smoothing kernel).

The goal of the interactive meetings was to establish the overall logic structure for the assessment of the seismotectonic framework, the relationship of the framework to the definition of seismic sources, the alternative approaches to defining seismic sources (e.g. source zones versus spatial smoothing), and the approaches to expressing and quantifying uncertainties in the conceptual models and parameters defining the sources. The second goal was to complete a sufficient number of assessments in the presence of the TFI-team such that the expert team would be comfortable conducting the remaining assessments on their own.

The interactive meetings ended with a review of the key milestones of the project, the expectations for presentations of preliminary assessments at WS-3, and the requirements for accurate and complete documentation. The teams were encouraged to begin their draft elicitation summaries as soon as possible and were reminded that, together with the presentation materials they would develop for WS-3, they were expected to produce a draft of the first two chapters of their elicitation summaries – pertaining to seismotectonic framework and seismic source definition – prior to WS-3.

A few weeks prior to WS-3, the TFI-team sent an e-mail to the expert teams reminding them of several important considerations in preparation for the upcoming workshop. These considerations included a reminder to present the technical basis for their preliminary assessments and to discuss the manner in which uncertainties were being characterised and addressed. The guidance also reminded the experts that their assessments would be viewed as preliminary and subject to change in light of feedback during the workshop. In that spirit, the experts were reminded that they were expected to "present, challenge, and defend" their assessments in a positive way, and that they should make their best attempt to represent the views of the larger informed technical community.

4.2.4 WS-3 / SP1: Feedback on Seismotectonic Framework and Source Definition; Methodologies for Assessing Maximum Magnitudes and Earthquake Recurrence

Workshop WS-3, held on 18 – 20 June 2002, had dual purposes, each consuming one and a half days: 1) to provide feedback to the expert teams on their preliminary assessments of seismotectonic framework and seismic source definition, and 2) to discuss alternative methods and approaches to characterising maximum earthquake magnitudes and earthquake recurrence. The elicitation interactive meetings had focused on the seismotectonic framework interpretations and seismic source definition, so this workshop represented the first time that the SP1 experts were presenting and discussing parts of their seismic source characterisation assessments for the PEGASOS Project. Therefore, they were reminded at the outset that the workshop would provide a forum for each expert team to present their preliminary evaluations of seismotectonic frameworks, and that the open discussion and debate of alternative conceptual models and other elements of the seismotectonic frameworks were encouraged. They also were told that the workshop would allow each expert team to present their preliminary interpretations of seismic sources, the technical bases for their interpretations, and the associated uncertainties. The workshop would promote active discussion, challenge, and debate of each team's alternative interpretations, with an emphasis on understanding interpretations, their technical basis, and expression of uncertainties.

Each team presented their preliminary interpretations of seismotectonic frameworks and seismic sources in a session followed by discussion. During the course of the discussion, a list was developed of cross-team seismic source definition issues for focused discussion the following day. Included on this list were thick- and thin-skinned tectonic models, reactivation of existing structures, assessing which structures are potentially seismogenic (e.g. Permo-Carboniferous troughs, Reinach fault), specific regions requiring detailed source definition (e.g. Basel, Swabian Jura), alternative conceptual models for some of the sources, spatial stationarity, and source boundary properties. These topics provided a basis for the forum of discussion that occurred the morning of the second day of the workshop. They would also provide a basis for common consideration across all teams in the finalisation of the seismic source interpretations following the workshop. The experts engaged in lively and constructive discussions during the presentations of their preliminary assessments and clearly fulfilled their roles as evaluator experts.

The second half of the workshop began with a series of talks presenting various approaches to assessing maximum earthquake magnitudes. The discussions centred around the applicability of various approaches – which have been developed and implemented in other seismic hazard analyses – to the seismic sources in the region of importance to the PEGASOS Project. For example, approaches for assessing maximum magnitudes that use fault rupture dimensions were discussed from the standpoint of whether or not such fault rupture information is available for seismic sources in Switzerland. Likewise, approaches such as the EPRI maximum magnitude approach, which was specifically developed for stable continental regions, was considered as a potential tool for use on this project. A key consideration was the availability of pertinent data required to use these alternative approaches and the degree to which the approaches provide for the quantification of uncertainties.

The next session entailed a series of talks related to methods for assessing earthquake recurrence. The earthquake catalogue is an important dataset for recurrence evaluation and the session began with a summary of a review that had been conducted of the PEGASOS catalogue. Topics in this discussion were the conversions of intensity and instrumental magnitudes to achieve a moment magnitude for all events, merging of several catalogues across several countries, stated uncertainties in magnitudes and locations, and comparison with previous catalogue compilation efforts. This was followed by a series of presentations regarding methods and approaches related to recurrence evaluation. As in the case of the maximum magnitude discussion, the discussions related to these presentations surrounded the applicability of the approaches to the PEGASOS Project and the manner in which uncertainties can be quantified. Following the presentations, a general discussion session was held to address key recurrence issues and alternative methods, including declustering of earthquake catalogues, catalogue completeness evaluation, uncertainties in a- and b-values, and incorporation of uncertainties in magnitude estimates in recurrence calculation. Because of the relation of spatial smoothing to recurrence, discussions also considered how a-values might be smoothed and the potential relationship of smoothing options (e.g. smoothing kernels and smoothing distances) with uncertainties in recurrence parameters.

In the final session of the workshop, the TFI-team led a discussion of future activities, including the second round of interactive meetings, documentation, and actions required for WS-4. The expert teams were asked to identify the sensitivity analyses that they would like to have calculated in order to provide additional insight. The TFI-team also addressed questions related to the manner in which the expert teams should regard the assessments made by the other teams, and the distinction between alternative conceptual models (e.g. spatial stationarity of seismicity) and tools for expressing these models (e.g. smoothing versus source zones). The elicitation interactive meetings were scheduled for late July (one team) and early October 2002 (three teams).

The final talk was by [redacted] Christian Sprecher, who presented the QA Guidelines for the project and explained how they would provide a basis for the controlled data flow between the various subprojects. He confirmed that all experts and TFI-team members were in possession of the QA Guidelines document and he answered questions related to it.

Prior to the first elicitation interactive meeting in July 2002, a memo from the TFI-team was distributed to the expert teams to provide additional insight into the role of evaluator experts in a formal SSHAC Level 4 expert elicitation. The memo was motivated by questions asked at the workshop such as: Do all teams need to evaluate all hypotheses? Does evaluating all technical hypotheses also entail considering or using all approaches (i.e. "tools in the toolbox")? How do we implement the notion of "representing the larger informed technical community"? The memo was centred around the definitions and guidance given in SSHAC (1997), including the roles and responsibilities of evaluator experts and the TFI. In particular, the role of "integrator" was noted, which entails "an individual or team who is responsible for providing a representtation of the informed scientific community's view of the important component and issues". "Informed" in this sense assumes, hypothetically, that the "community of experts was provided with the same data and level of interaction as that of the evaluators" (SSHAC 1997).

The relative responsibilities of the evaluators and the TFI for "integration" were described in the memo. The evaluator experts and the TFI are expected to work together as a team to assess the views of the larger technical community. However, according to the SSHAC methodology, the ultimate responsibility for integration lies with the TFI. A key part of that assessment lies with the manner in which the assessments of the expert teams are integrated and, as expressed from the start of the project, the goal for the PEGASOS Project is to create the proper set of conditions to integrate defensibly the expert assessments using equal weights. Advice given to the experts in the memo included the following:

1. Evaluate all technical hypotheses, including those that are assigned zero weight. The list of hypotheses to consider regarding seismic source definition was developed and discussed at WS-3.
2. Distinguish between technical hypotheses and tools for evaluation. Although it is required that all teams consider all hypotheses, there is no requirement that all teams use all available tools to represent the hypotheses. An example is the issue of spatial stationarity, which must be addressed, but it is possible to do so using a variety of tools including areal source zones, tectonic feature-based sources, and spatial smoothing.
3. Consider the views of the larger technical community. Although it is particularly important to consider the larger community's views in identifying the technical issues and hypotheses, it may be difficult to imagine the community's views relative to the specific issues required for a site-specific seismic hazard analysis. This is expected and the teams should consider whether they have reasonably incorporated all pertinent uncertainties and will assist the TFI in assessing whether the uncertainties across all four teams represent an unbiased assessment relative to a larger informed technical community.

4.2.5 EG1a–d: Second Elicitation Interactive Meetings on Maximum Magnitudes and Earthquake Recurrence

The second round of elicitation interactive meetings, held on 24 – 26 July and 27 September through 3 October 2002, followed a similar format to the first round: three days total, with the first and third days spent with the TFI-team and the second day spent with the team working independently. The meetings began with a review of required assessments, including maximum earthquake magnitudes and earthquake recurrence estimates for each seismic source. The first day, the teams identified alternative conceptual models for assessing maximum magnitudes, considering the relative credibility of the alternatives, and defining the logic structure for incorporating the alternatives and associated uncertainties. For example, a team might consider approaches to assessing maximum magnitudes using historical seismicity and alternative conceptual models regarding the degree to which the maximum observed seismicity in the catalogue provides an estimate of the maximum possible magnitudes. In the discussion, alternative approaches such as the "EPRI" maximum magnitude approach and that proposed by Kijko & Graham (1998) were debated and their applicability considered. Given the possible approaches, the teams also considered the parameters that would define the characteristics of each seismic source and associated uncertainties. The TFI-team worked through several examples with each team to ensure an adequate understanding of the approaches so that the teams could work independently on other sources.

On the subject of recurrence, decisions were made regarding treatment of the catalogue that would allow for recurrence evaluations. This included alternative conceptual models for declustering and completeness evaluation, together with the calculations that would implement these models. Consideration was also given to alternative magnitude-frequency models and possible approaches to recurrence curve fitting (e.g. least-squares, maximum likelihood). During the second day, the teams carried out a number of evaluations of the effect of these recurrence models on recurrence parameters for several of their seismic sources.

On the third day of the elicitation interactive meetings, the experts reviewed their preliminary assessments and questions with the TFI-team. A number of exploratory analyses and sensitivity analyses were identified that would be conducted following the meeting, many of which would require computational support from the TFI-team. The teams also explored possible ways to express their uncertainties in recurrence estimates.

At the conclusion of the meeting, each expert team identified the supporting calculations that they required and the milestones and schedule for the calculations and other inputs were established for the team to complete their assessments.

During the course of the elicitation interactive meetings and thereafter, a technical issue was raised by the experts regarding the seismicity data. The issue had potential significance to earthquake recurrence estimates, thus a request was made by the TFI-team, on behalf of the SP1 experts, to the Swiss Seismological Service. The request for information was summarised in a memo sent to the SED in October 2002. Briefly, the memo stated that frequency versus magnitude plots of all earthquakes in Switzerland and Southern Germany show a systematic difference in the rate of occurrence (a-value) of earthquakes for the period prior to about 1975 and the period from 1975 to the present. Despite similarities in b-values, the rate prior to approximately 1975 is systematically higher than the rate after that time. The shift of the frequency-magnitude curve is equivalent to a shift earthquake magnitude of about 0.2 to 0.4 magnitude units. It was noted that the date of 1975 is the approximate date of the start of the instrumental record in Switzerland, hence this apparent change in rate could be due to a difference in magnitudes between the intensity-based magnitudes prior to 1975 and the instrumentally-based magnitudes following that time. Acknowledging that the SED had previously identified this issue and had given it some thought, a request was made for a written SED position to assist the experts in their considerations.

The SED responded with a memo sent in November 2002, which summarised a number of analyses that they had conducted to explore the issue. These analyses included consideration of the spatial distribution of this apparent rate change, the timing of the change (noting that it is not exactly at 1975, but appears to have begun earlier), the nature of the intensity-magnitude conversion and its potential contribution, and an examination of whether the phenomenon exists in intensity data alone. These analyses provided a substantial amount of insight into the issue and demonstrated that the SED had thoroughly evaluated the potential causes. They conclude that their analyses based on catalogue consistency cannot conclusively answer the question of whether or not the rate change around 1965 – 1975 is real or an artifact. The evidence for an artificial rate change is cited as: 1) Stationarity of the frequency-magnitude distribution would be preserved if a shift of 0.2 in magnitude occurred; 2) The rate change influences a large region; and 3) The major transition from a macroseismic catalogue to an instrumentally-based catalogue coincides more or less with the onset of the rate decrease. The SED concluded that a likely scenario is that the observed activity fluctuations are a mixture of natural and artificial changes, and that there are no definitive tests or independent data available that would allow resolving the remaining uncertainty about the nature of the rate change. They therefore recommended that this uncertainty in interpretation is built into the rate computations as one of the numerous uncertainties influencing earthquake recurrence.

All of the SP1 experts were part of the distribution of these memos to deal with this issue and discussions begun in WS-3 continued into WS-4 regarding the nature and significance of the issue. In the end, this potential source of uncertainty was considered by all of the teams in their evaluations of seismicity and earthquake recurrence (see section 4.4.4).

4.2.6 WS-4 / SP1: Feedback on Maximum Magnitudes, Earthquake Recurrence and Seismic Hazard Sensitivity

Workshop WS-4, held on 25 – 27 February 2003, had several purposes: 1) To allow each team to present and discuss its logic tree for identifying seismic sources and for establishing the dependencies among source interpretations and their subsequent characterisation in terms of maximum magnitudes and recurrence; 2) To provide a forum for each expert team to present their preliminary evaluations of maximum earthquake magnitudes and earthquake recurrence for their seismic sources, including the manner in which uncertainties have been quantified; 3) To provide and discuss sensitivity analyses that quantify the relative importance of various evaluations made by each team regarding maximum magnitude and earthquake recurrence; and 4) To discuss in common session with SP2 and SP3 the sensitivity of various assessments to site-specific seismic hazard estimates. A parallel goal in having a common session with the other subprojects was to ensure coordination among the subprojects.

The first session provided a forum for each team to present a summary of its more developed source model logic tree, to receive feedback from their colleagues on the panel, and to evaluate the interpretations made by the other teams. This session was important because the logic trees provide the framework for linking the seismic sources defined previously with the characteristics that would be used to define them for the hazard analysis. For example, the relative credibility of alternative seismic source configurations and source boundary properties were expressed in the logic tree. Likewise, alternative approaches to expressing spatial stationarity (e.g. areal sources versus smoothing) were given. Based on these alternatives, the various parameters that define them – maximum magnitudes and earthquake recurrence – can be assessed conditionally within this logic structure.

The next session of the workshop provided a forum for each team to present a summary of their evaluations of maximum magnitudes for their sources, alternative approaches and their relative credibility, parameter values, and associated uncertainties. Each team received feedback from their colleagues on the panel, and evaluated the interpretations made by the other teams. The experts discussed the significant uncertainties associated with defining an approach that was uniquely and well-suited to estimating maximum magnitudes for the PEGASOS study. Approaches discussed included the "Kijko" and "EPRI" approaches, which consider the observations of seismicity worldwide as well as within the sources of interest. Considerable discussion centred around the proper *prior* distribution to be used in the EPRI approach (e.g. extended or non-extended crust) and the possibilities of modifying the *prior* distribution to make it more appropriate for the source of interest. In addition, discussions considered the degree to which limits on rupture dimensions, such as the maximum rupture length, could serve to limit maximum magnitudes and/or the *prior* distribution for the EPRI approach. By presenting, discussing, and interacting with the other experts on the panel, each team received considerable feedback regarding their maximum magnitude estimates and applicable parameters implementing various approaches.

During the course of the maximum magnitude discussion, the issues of the rupture of large events and the possibility of very large (magnitude larger than M 8) earthquakes were also debated. It was indicated by the TFI-team that each team would need to specify rupture "rules" for the hazard analysis, which would indicate the sense of slip and magnitude-dependent size of ruptures in three-dimensions, including whether or not ruptures would break the surface, the depth dependency of earthquake magnitudes, and the nature of seismic source boundaries relative to rupture. In the consideration of M > 8 earthquakes, the experts debated the geological and seismotectonic signature of sources that are capable of generating these great earthquakes, and debated whether or not such evidence was present for the seismic sources that they were defining. They would return to this discussion later in the workshop following interaction with experts from the other subprojects.

The discussion of earthquake recurrence followed a similar structure to the maximum magnitude part of the workshop, with the expert teams each presenting their approaches and preliminary assessments, followed by feedback and interaction with their colleagues on the panel. The technical issues discussed included approaches to declustering the earthquake catalogue and assessments of catalogue completeness. At the request of the experts, an implementation and evaluation of the effects of alternative declustering algorithms had been conducted by Dr. Stefan Wiemer and the results distributed to the experts for their own evaluations. Assessments of completeness included not only statistical approaches (e.g. Stepp's method), but also consideration of the historical seismicity record as a function of space and time. Development of recurrence frequency-magnitude relationships was also discussed in terms of alternative approaches (e.g. least-squares fitting, penalised maximum likelihood, simulation) and the degree to which a- and b-values would be expected to vary spatially.

The next part of WS-4 was a common session with the other subprojects. The TFI-teams presented a summary of certain key issues of potential interest and importance to the other subprojects. The SP1 TFI discussed the manner in which the seismic source geometries were being expressed, typical seismic source configurations, the nature of source boundaries, styles of faulting, faults and fault-like sources, the modelling of rupture geometries for future events, the relationships between magnitude and rupture dimensions, depth distributions of future earthquakes, and the maximum magnitude distributions across all teams. He noted that the SP1 experts were well aware of the distance measures that the SP2 experts would be using in their attenuation relationships. He noted that earthquakes larger than M 8 were being considered by the experts, but the evaluation process was not yet complete. In the discussion, the SP2 experts indicated that they were not presently using style of faulting as a model parameter, nor were they considering the potential for earthquakes larger than magnitude M 8. Subsequent consideration by the SP1 experts the following day led to the conclusion that there would be no need to consider M > 8 events; however, the need to include style of faulting as a model parameter was confirmed and SP2 held a special workshop for this consideration.

Representatives from SP4 presented seismic hazard results and sensitivity analyses in the common session. These presentations were designed to indicate the dominant contributors to the hazard across the various subprojects and to identify the relative significance of various hazard inputs. The SP4 team also presented a fault rupture model that they would propose be considered by the SP1 teams. Because of the need for the occurrence of earthquakes to be modelled as finite fault sources, a fault rupture model is needed to express the three-dimensional rupture geometry and its magnitude dependence. The proposed model could be varied as desired by the teams to express their belief in the focal depth distribution, boundaries to rupture, and the potential for rupture to the surface. Ultimately, all of the SP1 teams provided such a fault rupture model in their team assessments and documented in their elicitation summaries.

The final session of the workshop was once again held with the SP1 experts separately. This session was designed to provide the expert teams with "intermediate" feedback (i.e. the effect of the expert assessments on seismic source characteristics such as maximum magnitudes and recurrence), as well as hazard feedback. The TFI-team provided several summaries of the characteristics of certain seismic sources common to all or most teams, such as the Basel source, and the impact of alternative approaches and models for assessment of maximum magnitude and recurrence. Plots were also shown comparing the observed rate of seismicity with predicted rates based on the source characterisation provided in the experts' preliminary assessments. This was followed by a presentation from SP4 of the hazard implications of the SP1 assessments. The goal of these presentations and subsequent discussions was to provide feedback to the SP1 expert teams such that they would understand the implications of their preliminary assessments. Importantly, this feedback was also intended to provide a basis for the teams to prioritise their subsequent efforts in finalising their assessments around those technical issues of most importance to the hazard.

At the conclusion of the session on feedback, the expert teams were asked to identify any specific additional sensitivity analyses or feedback that they would like from either the TFI-team or SP4. This would provide additional insight to each team. Following the workshop, each team made its final request for sensitivity analyses and these were provided to each team for their use in finalising their elicitations.

The final discussions at the workshop centred on the consideration of earthquakes larger than magnitude 8 and the need to specify a fault rupture model. All teams provided their justifications for truncating their maximum magnitude distributions at values equal to or less than 8 and discussed the technical bases for doing so. The finalisation of the fault rupture models would occur after the conclusion of the workshop.

Following the workshop, in early May 2003, a memo was sent to the expert teams to provide guidance for the finalisation of their assessments. Certain technical issues were discussed, particularly in light of reviews by the HSK following WS-4. The issues included: 1) truncation of the *prior* distributions in the EPRI maximum magnitude approach; 2) rules for specifying the orientation of ruptures including rupture across source boundaries; 3) specifying the relative frequency of hypocentres with depth and the possibility of magnitude dependence of rupture depth; 4) clarifying the distinction between surface rupture and surface faulting hazard; and 5) the need to consider the hazard sensitivity results, provided to them all, in prioritising their remaining work. A list of the remaining deliverables and deadlines was also provided as part of the memo.

4.2.7 WS-4 / SP1: End-of-Project Workshop

On 27 February 2004, an end-of-project workshop was held with all participants of the PEGASOS Project. The purpose of the project was to summarise the seismic hazard results, including the relative contributions of the various inputs to the hazard assessment. In the context of SP1, discussions included the dominant seismic sources at each of the four sites, the relative importance of various seismic source characteristics, and the contribution to the total hazard uncertainty that is contributed by the total uncertainty across all SP1 assessments. Expert team-to-team comparisons were also presented and discussed. The TFI-team provided its assessment that the four expert team evaluations, in aggregate, are representative of, and would not differ systematically from, the larger informed technical community.

4.3 SP1 Expert Team Model Development

This section describes the general process used by the SP1 expert teams to develop their seismic source models.

4.3.1 Development of Seismotectonic Framework

The first step was the development of a seismotectonic framework for the study region. This framework provided the guiding philosophy that each team uses in identifying seismic sources. The framework addressed the important issues that each team believes influences the identification and characterisation of seismic sources in the region.

Topics addressed include:

- Contemporary tectonic processes that control present and future seismicity.
- Tectonic models that are applicable to contemporary processes, the observed seismicity, and are compatible with seismic sources.

- Spatial distribution of seismicity in three dimensions, and the associated focal mechanisms and their relation to potential seismic sources.
- Implications of contemporary stresses and strains (e.g. earthquake focal mechanisms, geodetics, other kinematic constraints) for defining sources.
- Use of historical and instrumental seismicity to provide a basis for defining the future locations of seismicity.
- Use of preexisting geological structures to provide a basis for defining the future locations of seismicity.

The SP1 expert teams developed their seismotectonic frameworks between SP1 Workshops 2 and 3. Guidance on this effort was provided in WS-2 and in *Coppersmith* (*2002a, TP1-TN-0138*).

4.3.2 Development of Seismic Sources and Source Definition Logic Trees

Using their seismotectonic frameworks as a basis, the SP1 expert teams developed seismic source interpretations for the study region. This work took place between SP1 Workshops 2 and 3. Alternative interpretations of seismic sources (e.g. large regional sources with spatial smoothing of seismicity versus localised source zones) and alternative source zone boundary configurations were incorporated in their seismic source models as weighted alternatives using the logic tree methodology. The teams were assisted in their specification of seismic sources by use of a project-specific version of the program WIZMAP (*Musson 2002, RDZ-ASW-0016*). The PEGASOS project team provided the SP1 expert teams with assistance in digitising seismic source zone maps and performing supporting calculations of seismicity spatial density functions using kernel density estimation. Guidance on this effort was provided in Workshop 2 and in *Coppersmith* (*2002a, TP1-TN-0138*). Interactive meetings between the SP1 TFI-team and the individual SP1 expert teams were held to assist this process (see section 4.2.3).

4.3.3 Review and Revision of Seismotectonic Framework and Seismic Source Definition

The SP1 expert teams presented their seismotectonic frameworks and seismic source definition models in SP1 Workshop 3. Following that workshop, the teams refined their interpretations considering the verbal feedback they received during the workshop. The seismotectonic frameworks and seismic source definition models are documented in the SP1 elicitation summaries. Guidance on the contents of the elicitation summaries was provided in *Coppersmith* (*2002b, TP1-TN-0187*).

4.3.4 Assessment of Maximum Magnitude and Earthquake Recurrence

The SP1 expert teams' next set of tasks was the assessment of maximum magnitudes and earthquake recurrence for their seismic sources. Guidance on this process was provided in SP1 Workshop 3 and in *Coppersmith* (*2002c, TP1-TN-0241*), *Coppersmith* (*2002d, TP1-TN-0252*) and *Youngs* (*2002, TP1-TN-0377*). A second round of interactive meetings was held between the SP1 TFI-team and expert teams (see section 4.2.5). The assessments were performed through a combination of team evaluations/calculations and supporting calculations performed by the project team.

4.3.5 Development and Review of Sensitivity HIDs and Earthquake Recurrence Predictions

The first complete seismic hazard model developed by each team was developed to perform hazard sensitivity analyses. A Hazard Input Document (HID) was developed for each team's seismic hazard model following the requirements specified in the project QA Guidelines (*Sprecher 2003, QA-TN-0402*). The hazard sensitivity model HIDs were prepared by the SP1 TFI-team using initial drafts of the elicitation summaries and the results of supporting calculations. The HIDs were submitted to the expert teams for their approval and to the SP4 team for review for completeness and clarity.

The TFI-team also prepared plots for each SP1 expert team comparing earthquake recurrence for individual seismic sources based on the hazard sensitivity model HID to the observed seismicity rates (*Youngs 2003a, TP1-TN-0334*, *Youngs 2003b, TP1-TN-0335*, *Youngs 2003c, TP1-TN-0336* and *Youngs 2003d, TP1-TN-0339*). Figure 4-10 shows an example of these earthquake recurrence plots.

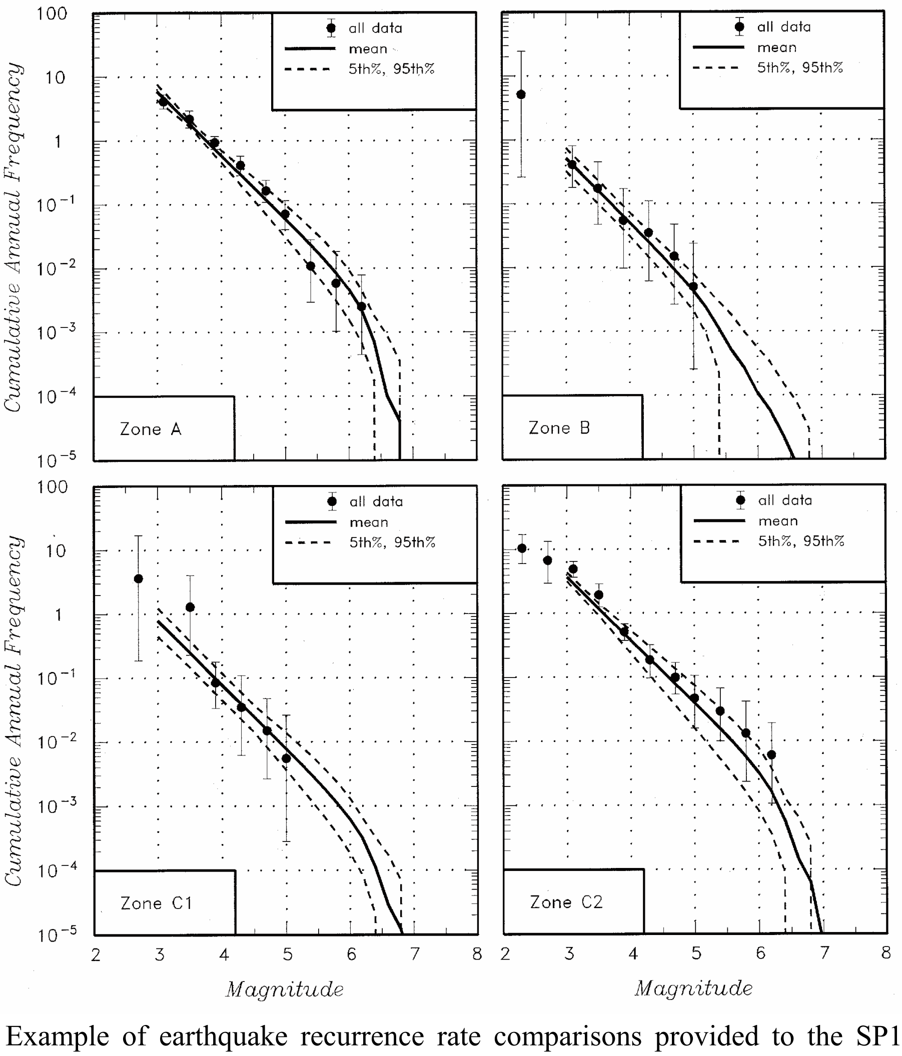


Fig.4-10: Example of earthquake recurrence rate comparisons provided to the SP1 expert teams

Each plot shows the cumulative recurrence rate of earthquakes based on the observed earthquake catalogue data (solid circles with 90 percent error bars) and the distribution of cumulative earthquake recurrence rate obtained using the maximum magnitude and earthquake recurrence parameter distributions specified by the team for an individual seismic source.

4.3.6 Model Revisions

The SP1 expert teams presented their assessment of maximum magnitudes and earthquake recurrence parameters in SP1 WS-4. Following that workshop, the teams refined their interpretations considering the verbal feedback they received during the workshop, the results of the hazard sensitivity calculations presented at the workshop and provided to each team *(Toro, 2003c, TP4-TN-0346)*, and the earthquake recurrence plots for individual sources described in section 4.3.5. The expert teams were encouraged to review their entire seismic hazard model. The finalised seismic hazard model for each team was documented in their elicitation summary.

4.3.7 Development and Review of Final HIDs

Upon completion of the final model revisions by the expert teams, the final HIDs were prepared. These HIDs were based on final drafts of the teams' elicitation summaries and the results of any additional supporting calculations. The final HIDs were submitted to the expert teams for their approval and to the SP4 team for review for completeness and clarity.

4.3.8 Documentation of Final Expert Models (Elicitation Summaries)

Each SP1 expert team prepared an elicitation summary that documented their interpretations for seismotectonic framework, seismic sources, maximum magnitudes, and earthquake recurrence parameters. A critical component of these summaries is a thorough documentation of the bases for the team's assessments. Guidance on the contents of the elicitation summaries was provided in *Coppersmith* (*2002b, TP1-TN-0187*). The elicitation summaries were reviewed by the TFI-team for clarity and completeness before finalisation by the expert teams. The SP1 elicitation summaries are presented in Vol. 4 of this report.

4.4 Features of SP1 Expert Team Models

This section summarises the approaches used by the SP1 expert teams to develop their seismic source models for the PEGASOS Project. The intention of this section of the report is to provide the reader with a general view of the technical content of the SP1 experts' assessments. It is not intended to be comprehensive or complete. For a complete discussion, the reader is referred to the elicitation summaries (Vol. 4). For the information derived from the expert assessments that became inputs to the seismic hazard analysis, the reader is referred to the hazard input documents (appended to the elicitation summaries in Vol. 4).

4.4.1 Seismotectonic Framework

The first step in the development of the seismic source characterisation models was development of a seismotectonic framework for the region. The framework provides the guiding philosophy that each team used in identifying seismic sources. The framework addresses the important issues that each team believes influences the identification and characterisation of seismic sources in the region. The seismotectonic frameworks developed by the four SP1 expert teams are summarised below.

EG1a

Team EG1a started from a large-scale kinematic framework for the region encompassing Switzerland, northern Italy, and southern Germany. The primary element of this framework is the west-northwest motion and counter-clockwise rotation of the Adria microplate. The interaction of this plate with central Europe leads to the identification of six neotectonic and kinematic provinces, labeled A to F in Figure 4-11. Province A, the Apennines, is bounded by the presently active northern front of the Apennines to the north (Adria microplate) and by a sinistrally transpressive western limit (contact with the Western Alps). Province B, the Adria microplate, moves to the WNW relative to a fixed European framework and rotates counter-clockwise around a pole situated in western Liguria. Province C, the Western Alps, is the part of the Alps that is partially displaced towards the WNW, together with the Adria microplate. It also absorbs part of the WNW-directed translation of Adria with respect to Europe. Province D is the Central and Eastern Alps. The southern boundary is defined by the Valais – Simplon – Garda movement zone, which extends into the Friuli active area situated just outside the SE edge of the map. The northern limit is characterised by two features: it corresponds to the southern limit of the zone of deep crustal earthquakes characteristic for the European foreland and to the northern limit of significant present-day thrusting activity. Province E is the proximal European foreland and Province F is the distal European foreland. These provinces are less affected by the movement of the Adria microplate than the provinces to the south and east.

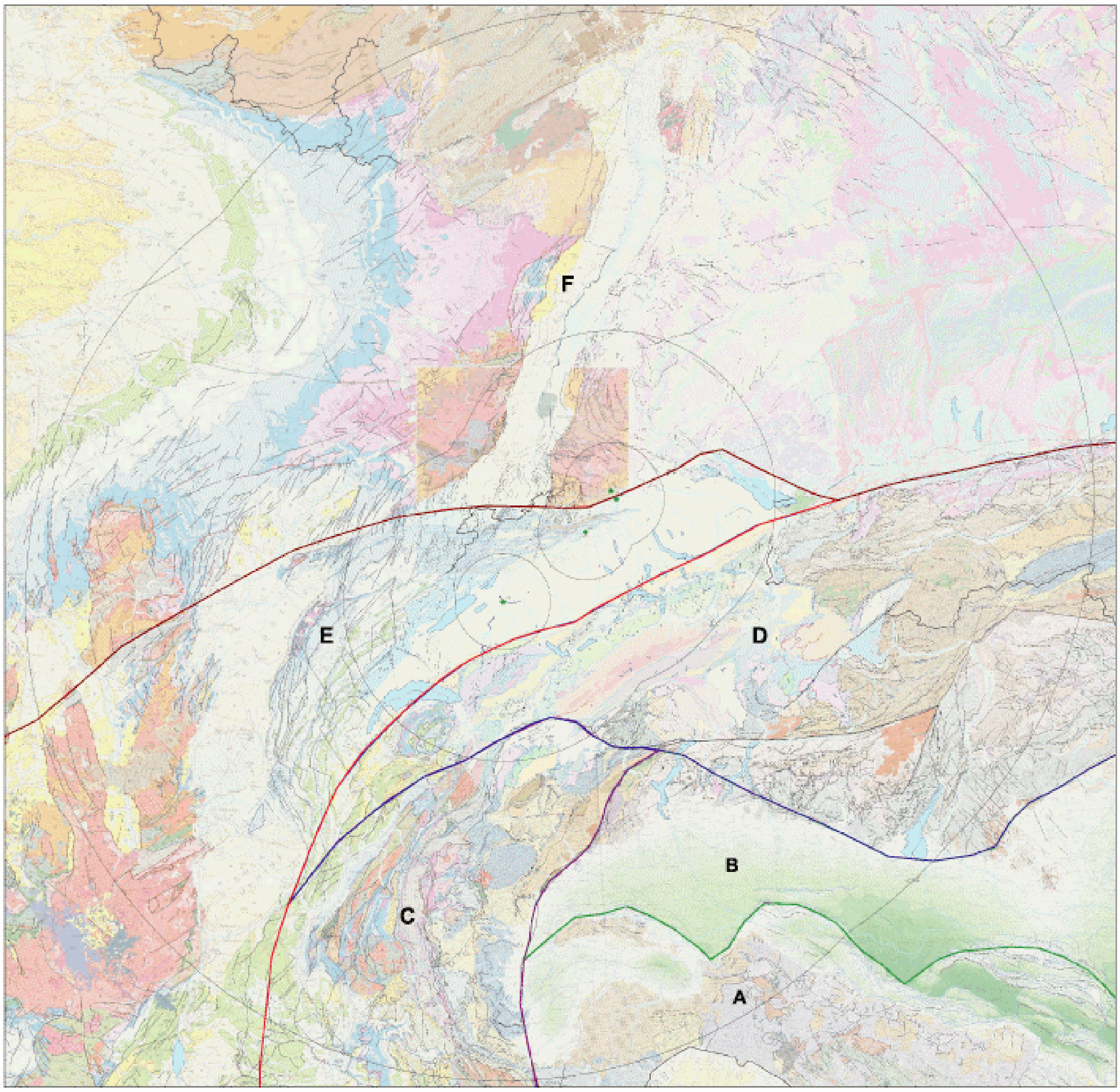


Fig.4-11: Map of neotectonic and kinematic provinces defined by EG1a: A – Apennines, B - Adria plate, C – Western Alps, D – Central and Eastern Alps, E – Proximal Alpine foreland, and F – Distal Alpine foreland

The team concluded that most of the observed seismicity represents reactivation of pre-existing fault systems in the present-day stress regime without clear association of seismicity with any one mapped fault. The three fault systems are:

1. The "Rhinish" system (strike NNE-SSW) essentially formed during Oligocene Rhine and Bresse Graben formation. This system is suitable for sinistral reactivation in the present-day stress field.

2. The "Hercynic" system (strike NW-SE, such as Vorwald or Neuhausen faults) was formed and reactivated during a series of geological periods (i.e. the Variscan orogeny, formation of Permo-Carboniferous troughs, Miocene). This system is suitable for tensile and/or dextrally transtensive reactivation in the present-day stress field.
3. The "Permo-Carboniferous trough" system (strike ENE-WSW) formed during the Variscan orogeny, but predominantly during the Late Carboniferous to Permian graben formation in a dextrally transtensive regime. This system is suitable for thrust reactivation only in the present-day stress field.

The team also addressed the issue of thick- versus thin-skinned present-day tectonic activity in the northern Alpine foreland. They conclude that elements of both thick-skinned and thin-skinned tectonic models are supportable in the data and that the choice of one of the competing theses is not crucial as seismicity is documented to occur both with and below the "thin skin", with no evidence for a higher seismic activity in the upper plate, situated above the "decollement" horizon, compared to within the basement below this horizon.

Using the orientation of faulting and seismotectonic data, team EG1a subdivided the six neotectonic and kinematic provinces shown on Figure 4-11 into the seismotectonic regions shown on Figure 4-12. Provinces A and B were not subdivided primarily because their large distance to the area of interest did not warrant detailed subdivision. Most of province A consists of the Alps-Apennines transfer zones with expected sinistral strike-slip focal mechanisms in the shallow crust and dip-slip mechanisms in the deep crust. Province B includes the Po plain and can be considered as a stable, low seismicity area. Province C was subdivided into C1 – the western "compressional" region (strike-slip to thrusting), C2 – the central extensional area region (normal faulting), and C3 – the eastern "compressional" region (strike-slip to thrusting). Province D was subdivided into D1 – the northern "compressional" region (strike-slip and subordinate thrusting), D2 – the central dome region (no fault plane solutions, stress regime unknown), D3 – the Austroalpine extensional region (normal faulting and subordinate strike-slip), and D4 – the southern "compressional" region (no seismotectonic evidence). Province E was subdivided into E1 – the Massif Central region (reactivation mode unknown), E2 – the Bresse-Jura-Western Molasse basin region (reactivated in strike-slip), and E3 – the Eastern Molasse basin region (reactivated in strike-slip to normal fault motion). Province F was subdivided into F1 – the Paris basin region (reactivated in strike-slip to normal fault mode), F2 – the Rhine Graben region (reactivated in strike-slip mode), and F3 – the Black Forest and Swabian Alb (reactivated in strike-slip to normal fault mode).

EG1b

Team EG1b based their seismotectonic framework on an assessment of the architecture of the north-western Alpine foreland resulting from two geologically recent (last 50 million years), but contrasting, events: Alpine subduction / collision and Oligocene extension and graben formation in the northern Foreland. The Alpine subduction / collision event is responsible for the large-scale architecture of the Alps and a number of thrust systems. Team EG1b identified important alpine thrust system elements at the NW border of the Alps (related primarily to "thin-skinned" tectonics), potential alternative interpretations of these elements related to "thick-skinned" tectonics, and important thrust system elements within the Alps. All of these structures were considered to have complex 3-D geometries at depth, making their use as "zone boundaries" problematic. The Oligocene extension event led to the formation of the Rhine - Bresse Graben system within the European plate, immediately adjacent to the alpine collision zone.

Using the above elements, the EG1b team developed the large-scale seismotectonic subdivision of the region shown on Figure 4-13. The East France (EF) and South Germany (SG) zones are considered as "stable European foreland" to the Alps, with a crustal thickness of approx. 30 km. Reactivation is predominantly in strike-slip mode. The Rhine Graben (RG) and Bresse Graben (BG) zones are characterised by well-marked surface depressions, vast Quaternary alluvial plains, Tertiary graben fills and complex faulted border areas with Mesozoic and Basement outcrops. The principal mode of reactivation is strike-slip. The Alps External (AE) zone comprises areas that have visibly undergone some alpine shortening in the form of folds and thrusts. The principal mode of reactivation is strike-slip. The Alps Central (AC) and Alps Internal (AI) zones represent the main body of the Alps as defined by its topographic expression. The main difference between the Alps Central and Alps Internal zones is the vergence of the latest thrusting: northwest-ward in Alps Central, southeast-ward in Alps Internal. The Po Plain (PP) zone represents the southern foreland basin to the Alps and the northern foreland to the Apennines, covering the vast, Quaternary alluvial lowlands of the Po Plain. This zone also comprises frontal parts of the Apennines, both emergent and hidden below the Latest Miocene, Pliocene and Quaternary sediments of the Po Plain; compare with "Modello Strutturale, Italian map".

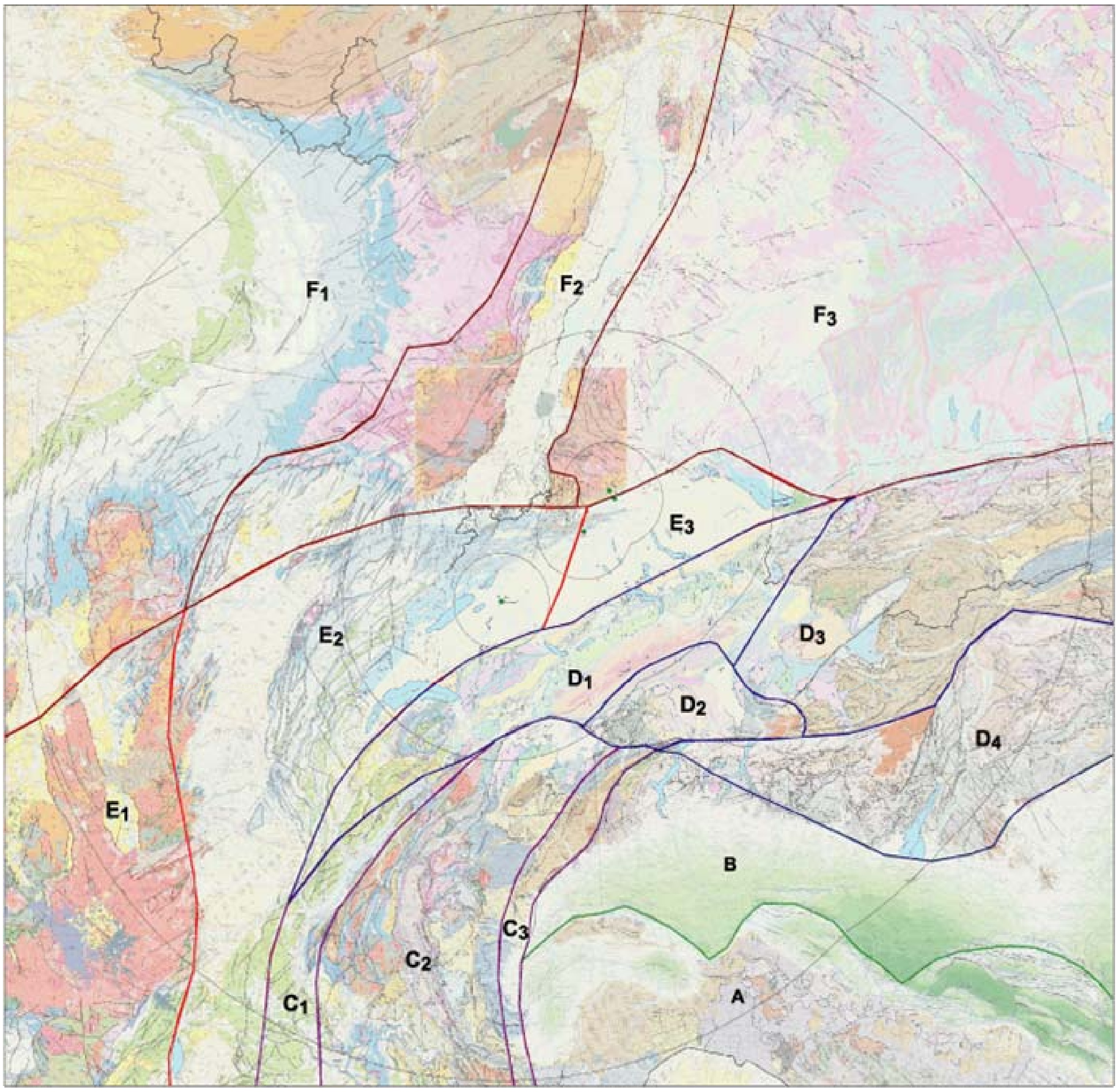


Fig.4-12: Map of seismotectonic regions defined by expert team EG1a

A - Apennines; B - Adria plate; C1 - Western compressional belt of Western Alps, C2 - Central extensional belt of Western Alps; C3 - Eastern compressional belt of Western Alps; D1 - Northern compressional area; D2 - Central dome; D3 - Austroalpine extensional area; D4 - Southern compressional area; E1 - Massif Central; E2 – Bresse / Jura / Western Molasse basin; E3 - Eastern Molasse basin; F1 - Paris basin; F2 - Upper Rhine Graben; F3 - Black Forest - Swabian Alb

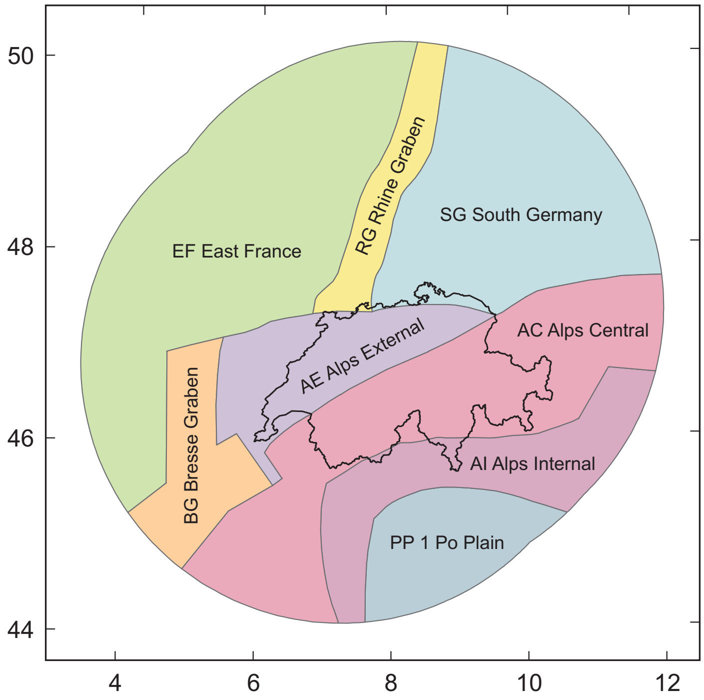


Fig.4-13: Large-scale seismotectonic zonation of the study region developed by the EG1b team

<u>EG1c</u>

Team EG1c started with development of a kinematic model for the region. The team considers the Adriatic Plate to be acting as a rigid indenter into southern Europe. They interpret the stress pattern in the Alpine region to arise from an interaction between the prevailing continental stress direction and the radial pattern resulting from the rotational collision of Adria and Europe. The dominant cause of seismicity is interpreted to be the reactivation of old features in a typical intraplate manner. As a result, the distribution of seismicity is related to the interaction of stress direction and the availability of suitably oriented structures for reactivation.

The team concludes that the weight of contemporary geological opinion generally favours thin-skinned tectonics in the Alpine foreland. However, they indicate that it is clear from the earthquake catalogue that seismicity is far from being concentrated within the upper crustal detachment and appears to be more significantly concentrated within the basement. They indicate that the geographical pattern of seismicity in the basement and the detachment do not seem to be greatly different.

Figure 4-14 shows the mapped pattern of tectonic stress used by the EG1c team in developing their seismotectonic framework. They construct a series of dividing lines following the curve of the Alps, marking major crustal divisions, and a second series of dividing lines perpendicular to the first, following the direction of maximum compressive stress. The resulting pattern was interpreted to contrast most strongly in seismicity rate as one moves from west to east, and contrast most strongly in depth distribution (and possibly *b*-value) when moving from north to south.

The team also identified several important crustal boundaries as being significant in dividing different faulting regimes: in particular, the Helvetic Front (HF) and Penninic Thrust (PT) (Figure 4-14), and to the south of these the Insubric Line (IL) in northern Italy. The significant tectonic boundaries identified in the western and northern portions of the study area are the Bresse Graben and Rhine Graben.

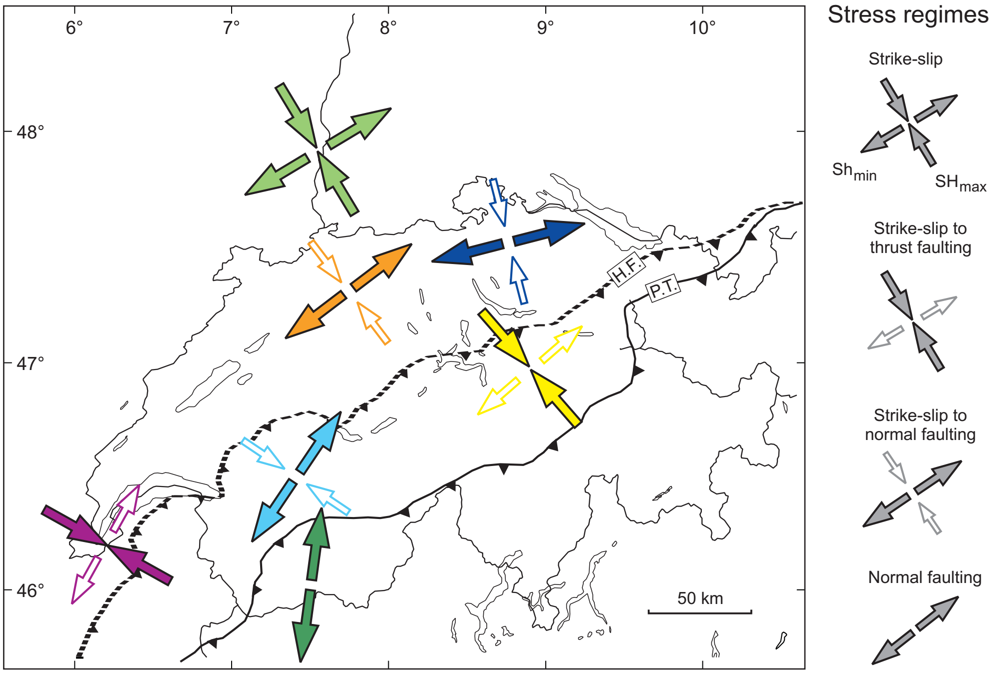


Fig.4-14: Tectonic stress distribution and location of the Helvetic Front (HF) and Penninic Thrust (PT) used in the seismotectonic framework developed by the EG1c team (after Kastrup 2004)

Figure 4-15 shows the major seismotectonic elements defined by the EG1c expert team. The Alpine foreland is divided into the Jura, Molasse, and Graben inversion regions. The Alps are divided into the Helvetic, Penninic, and eastern Alps regions. North of the Alpine foreland, the three major elements are the Rhine Graben, the French transpressional region and the south-western Germany crustal block. The southern background region lies south of the Alps.

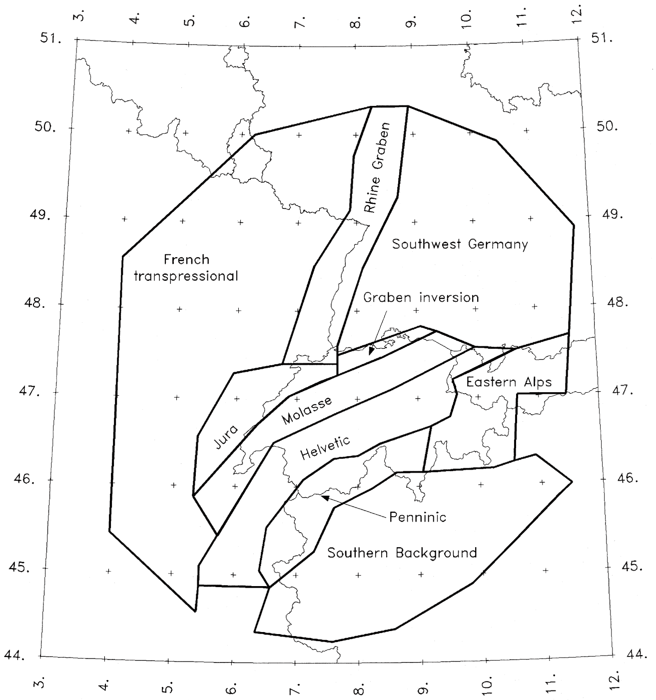


Fig.4-15: Major seismotectonic elements of the study region defined by the EG1c team

EG1d

The basic element of team EG1d's seismotectonic framework is the slow (rates < 10 mm/a) convergence zone between Europe and the Adria microplate. Their conceptual model consists of several distinctive geological and rheological units exposed to a broad regional stress / strain field. Within these large regions, seismic potential is, to a first order approximation, homogeneous and seismicity is diffuse. Localised stress concentrations, fluid interactions, zones of weaknesses etc., give rise to persistent or temporary clusters of activity. They view the issue of thin- versus thick-skinned structural interpretations as having limited importance regarding the present-day deformation linked to seismicity. Their interpretation is based on the recorded seismicity, showing that seismogenic deformation is equally distributed over the whole thickness of the European crust in the foreland area, and within the upper 15 km of the Alpine hinterland.

Figure 4-16 shows the major seismotectonic elements of the study region defined by the EG1d team. The boundaries of these elements are defined by major crustal boundaries. The Helvetic Front defines the boundary between the Alpine Foreland and the Alps proper. The Insubric line separates the Southern Alps from the Crystalline Alps. The Penninic Front separates the Crystalline Alps from the Helvetic Alps. These crustal boundaries define the three elements, the Southern Alps (SA), the Crystalline Alps (XWCA), and the Helvetic Alps (XHHA). The Jura (J) zone is separated from other elements on the basis of rock composition and the existence of a shallow-dipping contact zone between the deformed sedimentary cover and the apparently less deformed basement of pre-Triassic rocks. The South Rhine Graben / Basel (SRGB) element includes the Rhine Graben and its shoulders south of the Variscan suture zone. This across-graben division is consistent with different temperature and composition characteristics of observed hot springs, and with the thermal anomalies. The remaining portion of the study region consists of the European (E) background to the west, north and east of the South Rhine Graben.

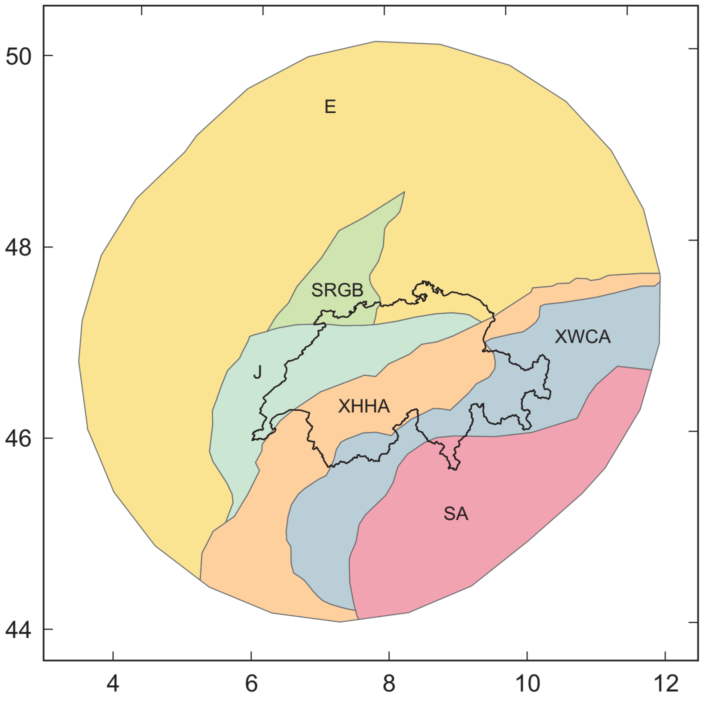


Fig.4-16: Major seismotectonic elements of the study region defined by the EG1d team

SA – Southern Alps, XWCA – Crystalline Alps, XHHA – Helvetic Alps, J – Jura, SRGB – South Rhine Graben/Basel and E – European Background.

The team also identified several additional elements that may affect the identification of seismic sources. Shown on Figure 4-17, these elements are the North Rhine Graben (NRG) being distinct from the European background, the South Rhine Graben Transfer Zone (TZ) representing the northern Jura border active fault system, the Freiburg-Konstanz zone (FKZ) representing a fraction zone inherited from Permian Carboniferous tectonics that may extend relatively deep in the crust, and the Swabian Alb (SWA) representing a zone similar to the FKZ extending through the clustered earthquake activity. In addition, the Helvetic Alps and Crystalline Alps zones are subdivided.

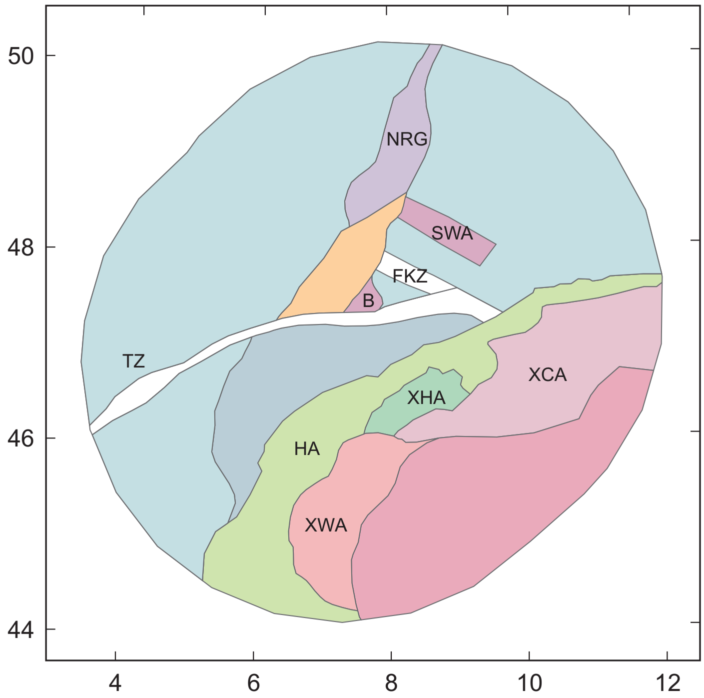


Fig.4-17: Location of additional seismotectonic elements defined by the EG1d team that may affect the identification of seismic sources

NRG – North Rhine Graben, B – Basel area, TZ – South Rhine Graben Transfer Zone, FKZ – Freiburg-Konstanz zone, SWA – the Swabian Alb, HA – Helvetic Alps, XHA = Crystalline Helvetic Alps, XWA – Crystalline Western Alps, and XCA – Crystalline Central Alps.

4.4.2 Seismic Source Definition

Based on the seismotectonic framework for the region, each expert team developed a model for seismic sources. Alternative interpretations of seismic sources were characterised as weighted alternatives within a seismic source logic tree. The seismic source models developed by the four SP1 expert teams are summarised below.

EG1a

Expert Team EG1a considered the following issues in their interpretations of seismic sources. They did not consider the "zoneless" approach to be appropriate because, in their view, the seismicity of the region does not seem to be stationary in time and space, and because they consider the quality of the geological and geophysical data to be high and particularly relevant to assessing the potential locations for low probability events. Seismic source zones with uniform spatial density of seismicity were used to model the spatial distribution of future earthquakes. Within the source zones, the sources of future activity were interpreted to be reactivation of the fault systems discussed in section 4.4.1.1, but no specific features were identified as potentially active with the exception of two locations, the Reinach fault and in the vicinity of the alignment of seismicity near Fribourg. The orientation and style of faulting for ruptures within the source zones was specified to correspond to the various fault system orientations and reactivation styles on a zone-by-zone basis. Earthquake ruptures were specified to be located symmetrically on the epicentres (the epicentre is at the midpoint of the rupture). Ruptures were allowed to extend beyond the source boundary for those epicentres located closer than a half rupture length to source zone boundaries. Three distributions for earthquake focal depths were developed from the recorded seismicity, one for the Molasse basin region, one for the central Alps and southern Germany, and a general distribution applied to all other regions. Earthquake ruptures were modelled as rectangular, with the rupture area defined by the relationship:

$$\text{mean rupture area} = 10^{(M - 3.934)} \tag{4-16}$$

The aspect ratio was specified to be 1:1 until the maximum rupture width (based on crustal thickness and expected fault dip) for a source is reached. For larger ruptures, the width is held constant at the maximum width and the length is obtained by dividing the rupture area by this width.

The geometry of the seismic sources developed by the EG1a expert team was based on their seismotectonic regions shown on Figure 4-12. These seismotectonic regions were subdivided into a number of source zones. Alternative interpretations of the geometry of seismic sources and the subdivision of seismotectonic regions into source zones were defined. Figure 4-18 shows the overall seismic source logic tree developed by the EG1a expert team. Only a partial logic tree is shown indicating the seismic source issues addressed.

The first level of this logic tree addresses the issue of reactivation of the Permo-Carboniferous trough fault system. If this system is assumed to be reactivated (PC Active – "Yes" branch), then the configuration of source zones within the western Molasse and eastern Molasse basin seismotectonic regions and the Basel area in the southern Rhine Graben follows the trend of these features as shown on Figure 4-19. If this system is assumed not to be reactivated (PC Active – "No" branch), then the alternative source zone configuration of these seismotectonic regions is shown on Figure 4-20.

The second level of the logic tree shown on Figure 4-18 addresses whether or not the Reinach fault is an active seismic source. This assessment is conditional on the first level of the logic tree; it is only addressed if the Permo-Carboniferous trough fault system is not being reactivated. If the Reinach fault is considered active, then it is modelled as a line source labelled RF on Figure 4-20. If not, then two alternative source zones (F2d or F2f) are used to model the earthquake potential in the vicinity of the 1356 Basel earthquake. These alternatives are included on the third level of the logic tree.

The fourth level of the logic tree addresses whether or not the Fribourg Fault line source (FF on Figure 4-20) should be used to represent the observed alignment of seismicity as a fault-specific seismic source. If "Yes", then the remainder of the western Molasse basin seismotectonic region (E2) is treated as a single source zone (a combination of zones E2c, E2d, and E2e shown on Figure 4-20). If "No", then zones E2c, E2d, and E2e are treated as separate source zones. This assessment is also conditional on the Permo-Carboniferous trough fault system not being reactivated.

The fifth level of the logic tree addresses the zonation of the northern compressional seismotectonic region of the Alps (D1). Three alternatives are modelled: combining zones D1b, D1c, D1d, and D1e into a single source; two sources consisting of a combined D1b, D1c, and D1d and a separate D1e; or three sources D1b, D1c, and a combined D1d-D1e. This issue is independent of the assessment of reactivation of the Permo-Carboniferous trough fault system.

The branches associated with the assessment are shown at representative locations, but occur along all paths through the logic tree.

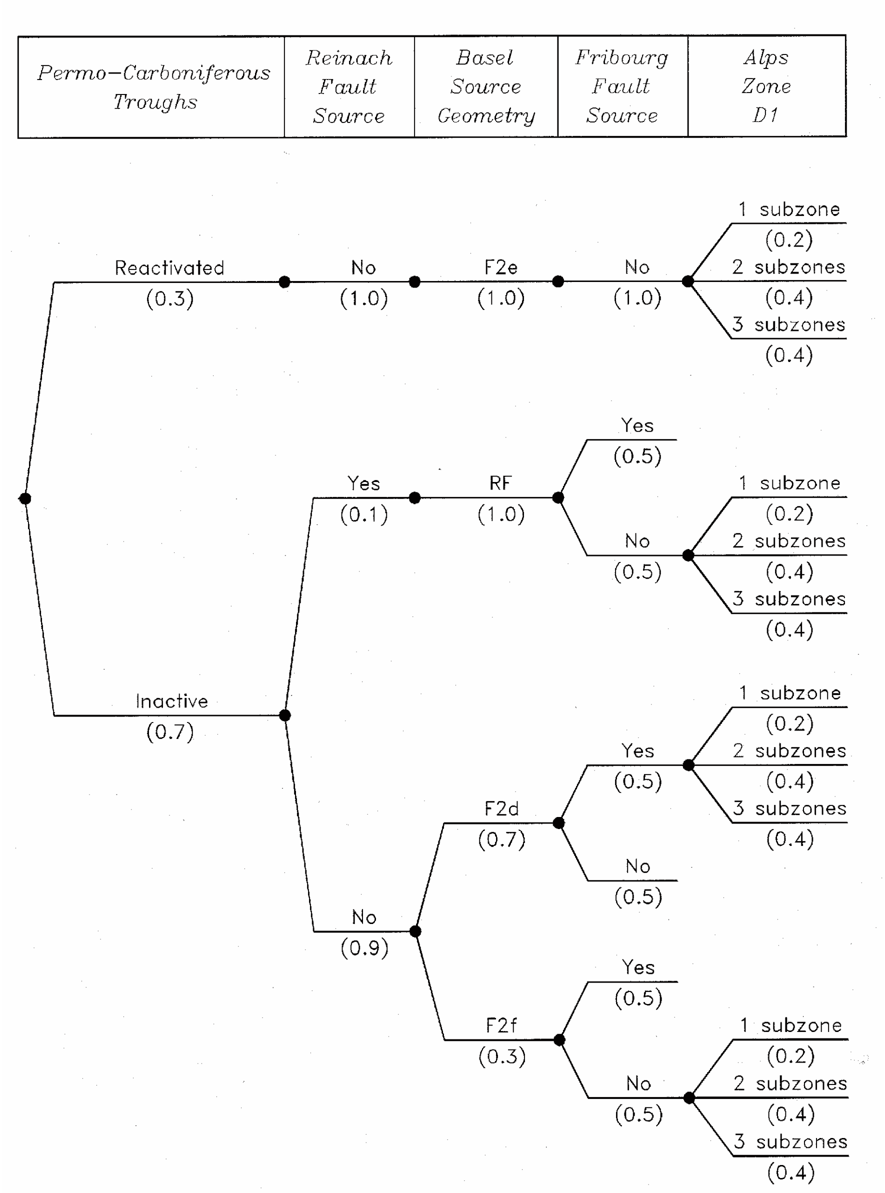


Fig.4-18: Logic tree for EG1a seismic source zonation

The combined set of source definition logic tree branches leads to 21 alternative sets of seismic source zones.

EG1b

Expert team EG1b considered the following issues in their interpretations of seismic sources. Spatial stationarity of seismicity was considered a viable conceptual model and kernel smoothing of seismicity within large regional zones was incorporated as a weighted alternative. However, geological / seismotectonic interpretations of source zones within the large regional zones was the preferred approach, with a uniform spatial distribution of seismicity within individual source zones. The orientation and style of faulting for ruptures within the source zones was specified to correspond to identifiable fault system orientations and reactivation styles on a zone-by-zone basis. No individual fault zones were considered sufficiently identified to be treated as fault-specific line sources, although a very narrow north-south oriented source zone was defined for the Fribourg area. Earthquake ruptures were modelled to be confined within the boundaries of the defined seismic source zones.

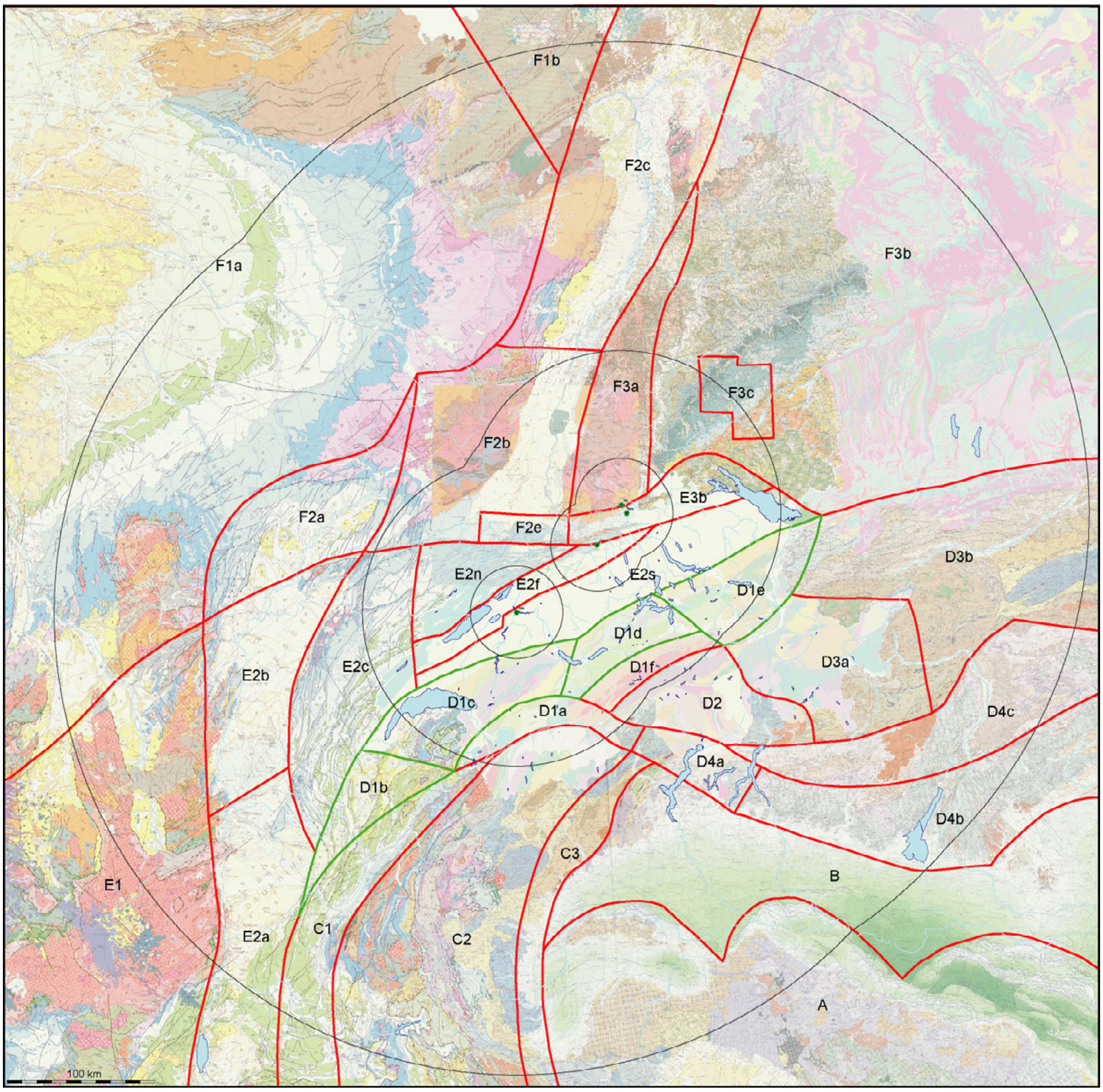


Fig.4-19: Seismic source zones defined by expert team EG1a under the assumption that the Permo-Carboniferous troughs are being reactivated

The depth distribution of earthquake hypocentres was defined for each of the regional source zones (Figure 4-13) and applied to all source zones within the large regional zones. Earthquake ruptures were modelled as rectangular, with the rupture area defined by the relationship:

$$\text{mean rupture area} = 10^{(1.02M - 4.084)} \qquad (4\text{-}17)$$

The aspect ratio was specified to be 1:1 until the maximum rupture width (based on crustal thickness and expected fault dip) for a source is reached. For larger ruptures, the width is held constant at the maximum width and the length is obtained by dividing the rupture area by this width.

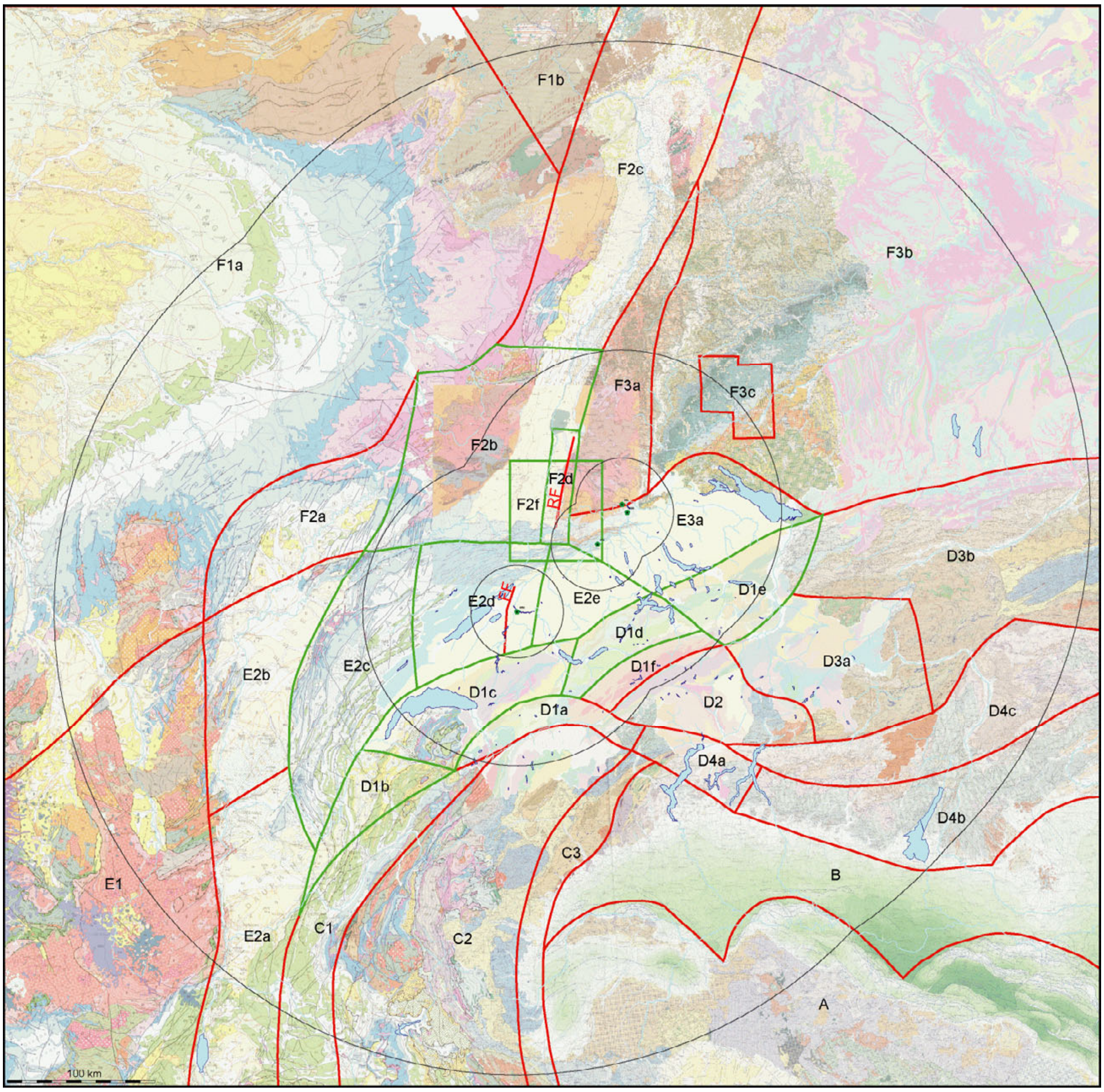


Fig.4-20: Seismic source zones defined by expert team EG1a under the assumption that the Permo-Carboniferous troughs are not being reactivated

Figure 4-21 shows the overall seismic source logic tree developed by the EG1b expert team. The first level addressed the overall zonation approach. The "large-scale" approach uses the seismotectonic regions shown on Figure 4-13 as seismic source zones. The spatial distribution of seismicity within these sources is modelled using Gaussian kernel smoothing. Three alternative values of the kernel smoothing parameter *h* are used, as indicated by the second level of the logic tree. Spatial density functions were computed separately for each large-scale source based on the earthquakes within the source boundary.

The alternative zonation approach is the "small-scale" zonation in which the large seismotectonic regions are subdivided into individual source zones. These source zones are shown on Figure 4-21. Seismicity within these source zones was modelled with a uniform spatial distribution. The remaining levels of the seismic source logic tree address alternative configurations of these source zones. These alternatives affect the maximum rupture dimensions that can occur within a single source and were used by the team to assess limiting values for maximum magnitude.

The third level of the logic tree addresses the source zone configuration in the area of Basel. One conceptual model is that the reactivated features in this area extend from the southern Rhine Graben into the northern Jura. This is modelled by combining sources RG1 and AE1 into a single source zone. The favoured conceptual model is that the reactivated features in the Basel area of the southern Rhine Graben are separate from those in the northern Jura.

The fourth level of the logic tree addresses the source zone configuration in the northern Jura. If the central northern Jura source AE1 is combined with the southern Rhine Graben source RG1, then the remaining portion of the northern Jura consists of two separate source zones. If the northern Jura is separate from the southern Rhine Graben, then four alternative zone configurations are included, as indicated on Figure 4-21.

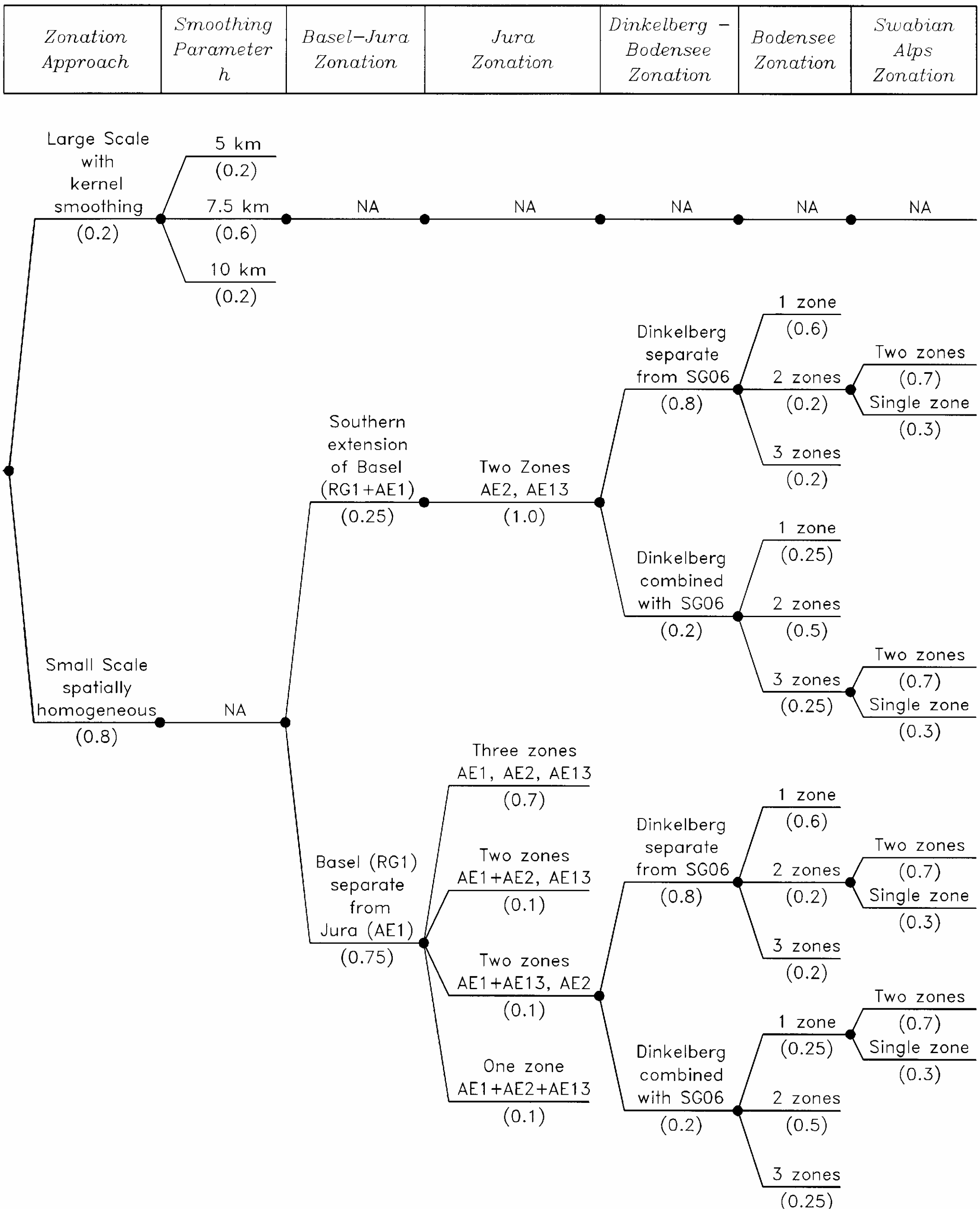


Fig.4-21: Logic tree for EG1b seismic source zonation

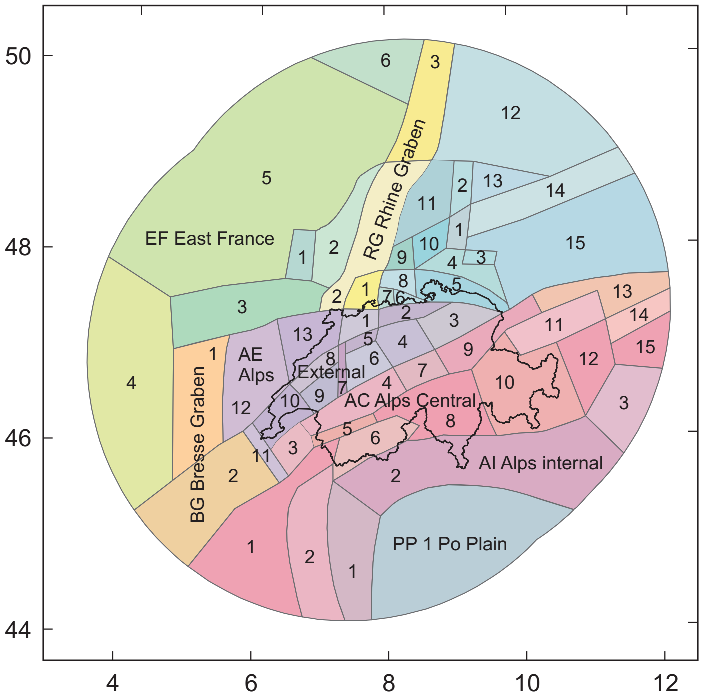


Fig.4-22: "Small-scale" seismic source zones defined by expert team EG1b

The fifth and sixth levels of the logic tree addressed zonation in the Dinkelberg and Bodensee regions of the Southern Germany seismotectonic region (source zones SG5, SG6, SG7, and SG8). This evaluation is independent of the source zone interpretations in the southern Rhine Graben/northern Jura. The fifth level addresses treating zones SG5 and SG6 as separate or combined sources. The sixth level addresses treating SG6, SG7, and SG8 as one, two, or three sources.

The seventh level of the logic tree addresses the source zone configuration in the Swabian Alb (Schwäbische Alb). Zones SG1 and SG2 are treated either as separate sources or combined into one source zone. This assessment is independent of the other small-scale source zone configuration assessments, and is shown only on representative branches on the logic tree.

The result of the logic tree assessments is one set of "large-scale" source zones and 60 sets of "small-scale" source zones.

The EG1b expert team considered that the exact boundaries of the source zones shown on Figure 4-22 are uncertain. They expressed this uncertainty by including alternative zone boundaries for two critical sources near the sites of interest for the hazard study. The northern and southern boundaries of source zone AE were given two alternative locations ± 5 km north and south of those shown on Figure 4-22. Similarly, the eastern boundary of source zone AE7 (Fribourg) was modelled as uncertain, with alternative locations 2.5 km west and 5 km east of the location shown on Figure 4-22. These alternatives were used for the hazard calculation, but not the assessment of maximum magnitude and earthquake recurrence parameters.

EG1c

Expert Team EG1c considered the following issues in their interpretations of seismic sources. Spatial stationarity of seismicity was considered to potentially play a role in evaluating seismic hazards and concentrations of seismicity were used along with geology and tectonics in the delineation of seismic sources. The spatial distribution of seismicity within individual source zones was modelled as uniform. The team made the assessment that no individual mapped fault in the region should be considered as a preferential location for earthquakes over adjacent faults of similar characteristics and thus did not include fault-specific sources. Preferred rupture orientations, styles of faulting and focal depth distributions were specified on a source-by-source basis. Ruptures were allowed to extend beyond the source boundary for those epicentres located closer than a half rupture length to source zone boundaries. Exceptions to this specification were applied to the Rhine Graben, Po Plain, Eastern France and Bavaria sources. The ruptures were modelled to be confined within these sources and not extend into the Jura and Alps regions. Earthquake ruptures were modelled as rectangular, with the rupture area defined by the relationship:

$$\text{mean rupture area} = 10^{(1.04M - 4.244)} \qquad (4\text{-}18)$$

The aspect ratio was specified to be 1:1 until the maximum rupture width (based on crustal thickness and expected fault dip) for a source is reached. For larger ruptures, the width is held constant at the maximum width and the length is obtained by dividing the rupture area by this width. The seismic source zones developed by the EG1c team were based on the zonation shown on Figure 4-5. Figure 4-23 shows the seismic source logic tree that defines the alternative source zone configurations, shown on Figures 4-24 and 4-25.

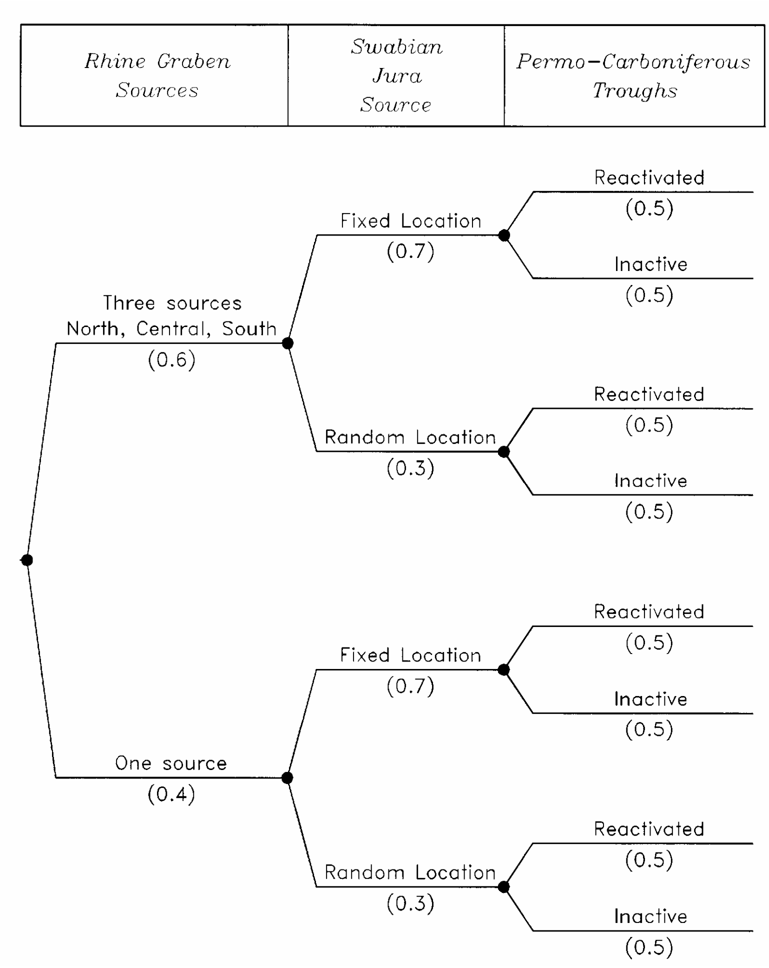


Fig.4-23: Logic tree for EG1c seismic source zonation

The first level of the logic tree addresses the zonation of the Rhine Graben, either as a single source (RHEG on Figure 4-24) or as three sources (RHGN, RHGC, RHGS on Figure 4-25).

The second level addresses seismic source zonation for the concentrated seismicity zone in the Swabian Jura. The preferred approach is to model this concentration with a local source zone (SWAB on Figure 4-24). The alternative is to consider that the seismicity is not spatially stationary and that similar concentrations could occur at random locations within southern Germany. For this conceptual model, the concentrated seismicity is included in the assessment of the overall seismicity rate for the larger source zone and no localised source is used (Figure 4-25). This assessment is independent of the Rhine Graben zonation assessment.

The third level of the logic tree addresses the issue of reactivation of the Permo-Carboniferous troughs. If they are reactivated, then the appropriate source zone configuration is shown on Figure 4-24 (zones NSPG, ZURI, and BAWU). If not, then the appropriate source zone configuration is shown on Figure 4-25 (zones BLAF, ZUR2, and BAW2). This assessment is independent of the previous two assessments.

The result of the logic tree assessments is eight sets of source zones.

The Basel source zone (BASL on Figure 4-24) was treated as a special zone. The observed earthquake frequency within the source zone was assumed to decay away from the boundary over a distance of 30 km. This decay was modelled by a Gaussian decay with a standard deviation of 10 km.

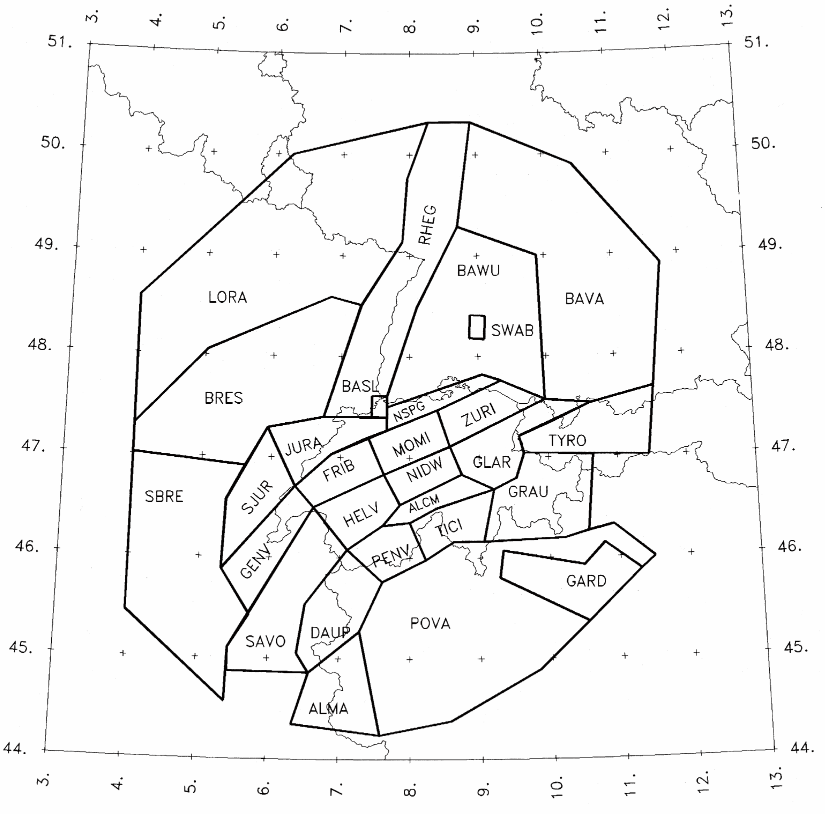


Fig.4-24: Seismic sources defined by expert team EG1c

<u>EG1d</u>

Expert team EG1d considered the following issues in their interpretations of seismic sources. Spatial stationarity of seismicity was considered to potentially play a role in evaluating seismic hazards. To address this issue, alternative spatial distributions of seismicity within individual source zones were included in the model. The team made the assessment that no individual mapped fault in the region should be considered a preferential location for earthquakes over adjacent faults of similar characteristics and thus did not include fault-specific sources. Styles of faulting were specified on a source-by-source basis. Earthquake ruptures were assumed to be random in orientation. The focal depth distribution of earthquakes was defined using empirical depth distributions for earthquakes north and south of the Helvetic front. Ruptures were allowed to extend beyond the source boundary for those epicentres located closer than a half rupture length to source zone boundaries. Earthquake ruptures were modelled as rectangular, with the rupture area defined by the relationship:

$$\text{mean rupture area} = 10^{(0.91M - 3.424)} \tag{4-19}$$

The aspect ratio (length:width) was specified to be 2.5:1 until the maximum rupture width (based on crustal thickness and expected fault dip) for a source is reached. For larger ruptures, the width is held constant at the maximum width and the length is obtained by dividing the rupture area by this width.

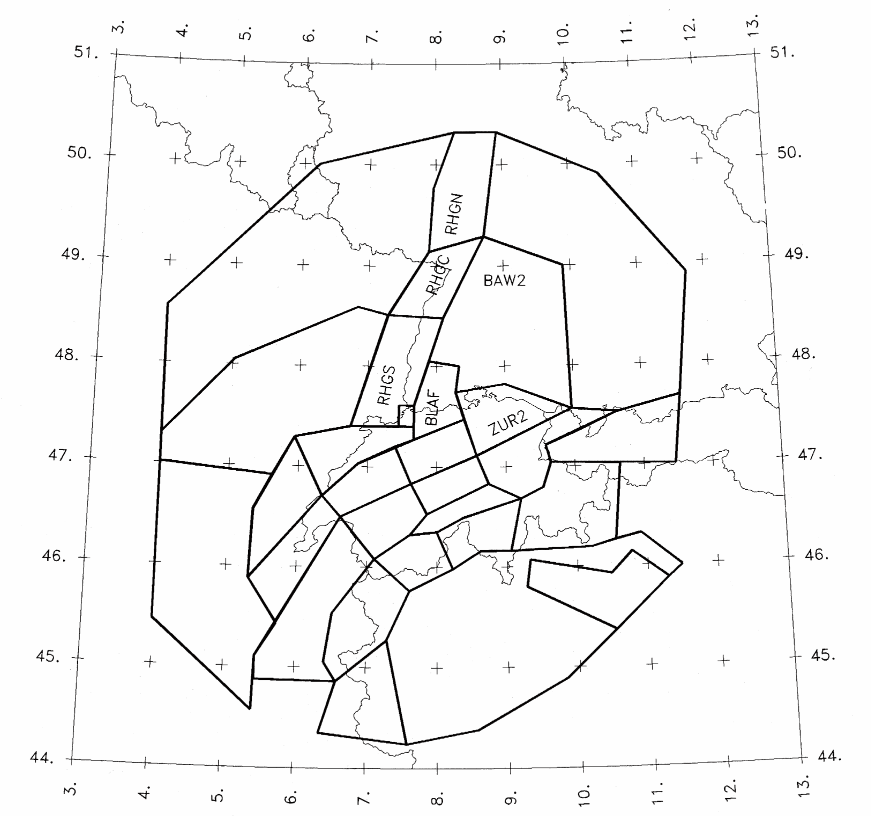


Fig.4-25: Alternative seismic sources defined by expert team EG1c

Figure 4-26 presents the seismic source logic tree developed by expert team EG1d. The individual seismic sources correspond to the regions shown on Figures 4-16 and 4-17.

The first level of the logic tree addresses the issue of spatial stationarity of seismicity. Three alternative conceptual models are incorporated in the analysis. The "low" stationarity model uses a uniform spatial distribution of seismicity within each source. The "medium" and "high" stationarity models use spatial density functions computed using Gaussian kernel smoothing with the smoothing parameter *h* set to 15 km and 5 km, respectively. The spatial density functions for the "medium" and "high" spatial stationarity models were computed for the entire region (without source zone boundaries) and then normalised to sum to unity within each source zone. Epicentral uncertainty was included in the kernel density estimation by using a modified smoothing parameter for each earthquake:

$$h' = \sqrt{h^2 + \sigma_{loc}^2} \tag{4-20}$$

where σ_{loc} is the location uncertainty for the earthquake given in the PEGASOS catalogue.

The remaining levels of the logic tree address assessments of specific subdivisions of the regional zones shown on Figure 4-16. Each assessment is considered to be independent of the other assessments, and only representative branches are shown on the logic tree.

The second level of the logic tree addresses the subdivision of the Helvetic Alps (XHHA) into a crystalline portion (XHA) and a non-crystalline portion (HA). The third level addresses subdivision of the Cyrstalline Alps (XWCA) into separate western (XWA) and central (XCA) sources. The fourth level addresses subdividing the Southern Rhine Graben / Basel (SRGB) source into separate Basel (B) and Southern Rhine Graben (SRG) source regions.

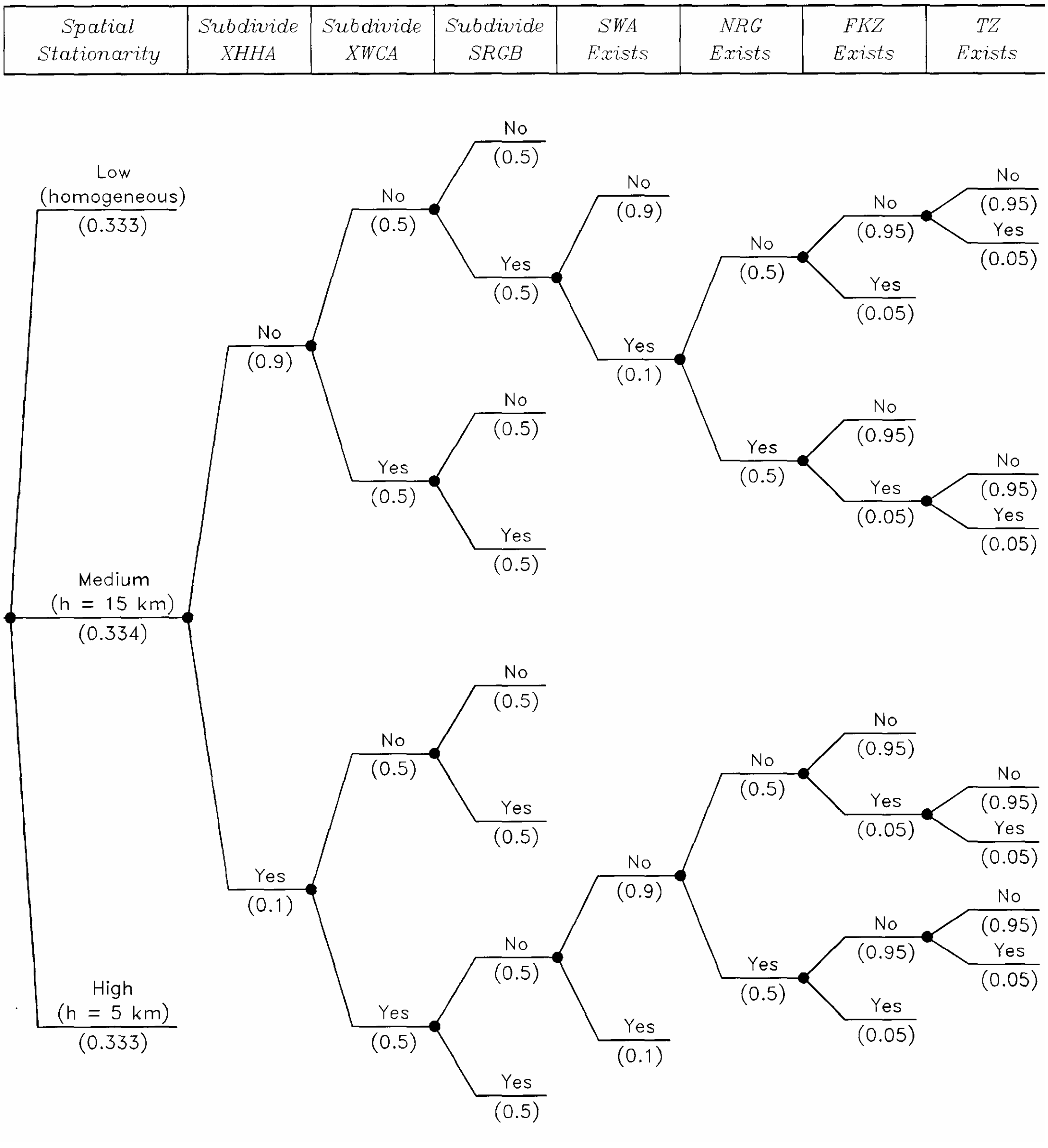


Fig.4-26: Logic tree for EG1d seismic source zonation

The fifth through eighth levels address the existence of separate seismic sources for specific elements shown on Figure 4-17. Level five addresses the existence of a distinct Swabian Alb (SWA) source, level six the existence of a distinct Northern Rhine Graben (NRG) source, level seven the existence of a distinct Freiburg-Konstanz zone (FKZ) source, and level eight the existence of a distinct South Rhine Graben Transfer Zone (TZ) source. These four levels lead to 16 different configurations of the European Background (E) source.

In total, the seismic source logic tree leads to 128 seismic source sets.

4.4.3 Maximum Earthquake Magnitudes

This section describes the methods used by the SP1 expert teams to assess maximum magnitude distributions for their seismic sources and presents the individual team results.

EG1a

It is the interpretation of expert team EG1a that the assessment of maximum magnitude should be made for large regional zones with similar geological / tectonic characteristics. Therefore, maximum magnitude distributions were developed for their seismotectonic regions (e.g. Figure 4-12), termed macrozones. These distributions were then applied to the individual source zones that make up the macrozones. Two approaches were used to develop the maximum magnitude distributions, the "EPRI" approach described in section 4.1.2.1, and a version of the Kijko & Graham (1998) approach modified by the team. In applying the "EPRI" approach, the extended crust prior ($\mu_{m^u} = 6.4, \sigma_{m^u} = 0.84$) was applied to all seismotectonic regions except E1, F1, and F3, to which the non-extended crust prior was applied ($\mu_{m^u} = 6.3, \sigma_{m^u} = 0.5$). The distributions resulting from the "EPRI" and "Kijko" approaches were given equal weight in the EG1a seismic hazard model.

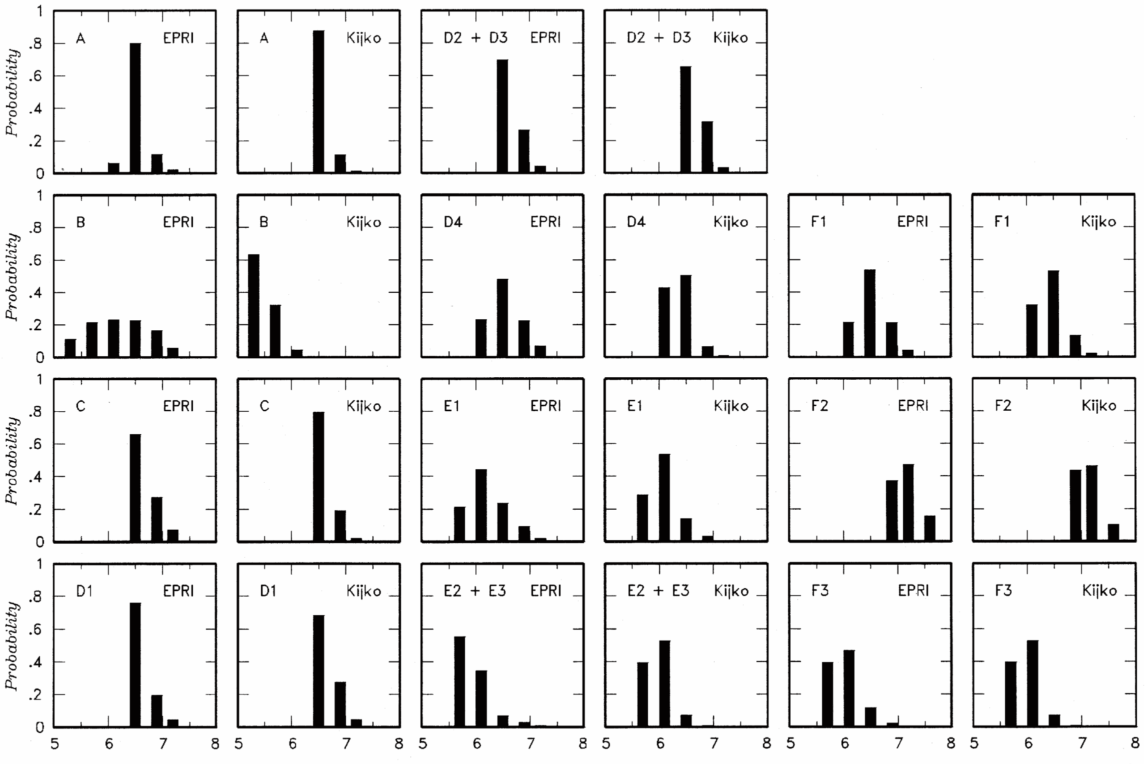


Fig.4-27: Maximum magnitude distributions developed by the EG1a expert team

As a final step in the maximum magnitude assessment, geological information was used to assess the upper limit on possible rupture lengths within each macrozone. Using the empirical relationship between surface rupture length, SRL, and magnitude developed by Wells & Coppersmith (1994) [$M = 5.08 + 1.16 \log(SRL)$], these limiting rupture lengths were used as upper truncation points in the maximum magnitude distributions.

Figure 4-27 shows the resulting maximum magnitude distributions developed by the EG1a expert team. In general, the "EPRI" and "Kijko" approaches resulted in similar maximum magnitude distributions.

EG1b

Expert Team EG1b used the "EPRI" approach to assess maximum magnitude distributions for their "large-scale" and "small-scale" source zones. The extended crust prior was applied to the assessment for all source zones except Eastern France (EF), Southern Germany (SG), and the "small-scale" sources that make up these two "large-scale" sources. The unbounded upper tail of the "EPRI" maximum magnitude distributions was considered to be unrealistic by the EG1b expert team. Three bases for truncation of the upper tail were developed:

1. A probability cutoff at a probability of 0.05. This was applied to a few of the "large-scale" source zones.
2. Maximum rupture area determined by the maximum source dimension and fault width (dependent on crustal thickness and expected fault dip). This maximum rupture area (RA) was converted into a limiting magnitude using the empirical relationship $M = 4.07 + 0.98 \log(\text{RA in km}^2)$ developed by Wells & Coppersmith (1994). This provided limits for most of the "small-scale" sources.
3. A maximum rupture length of 200 km was applied to all sources. Using the crustal thickness and expected fault dips, a maximum rupture area was used to define a limiting maximum magnitude as in the second limiting criteria.

The minimum value resulting from the above three criteria was used to define the limiting maximum magnitude for each source. The resulting maximum magnitude distributions for large-scale sources are shown on Figure 4-28 and those for small-scale sources are shown on Figure 4-29 and 4-30.

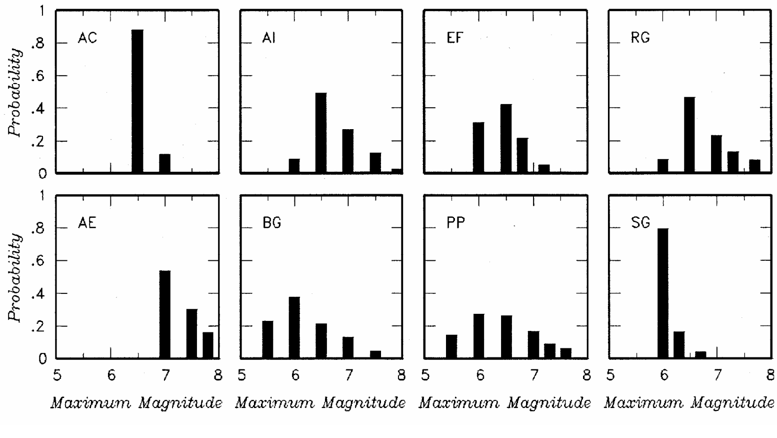


Fig.4-28: Maximum magnitude distributions for "large-scale" sources developed by the EG1b expert team

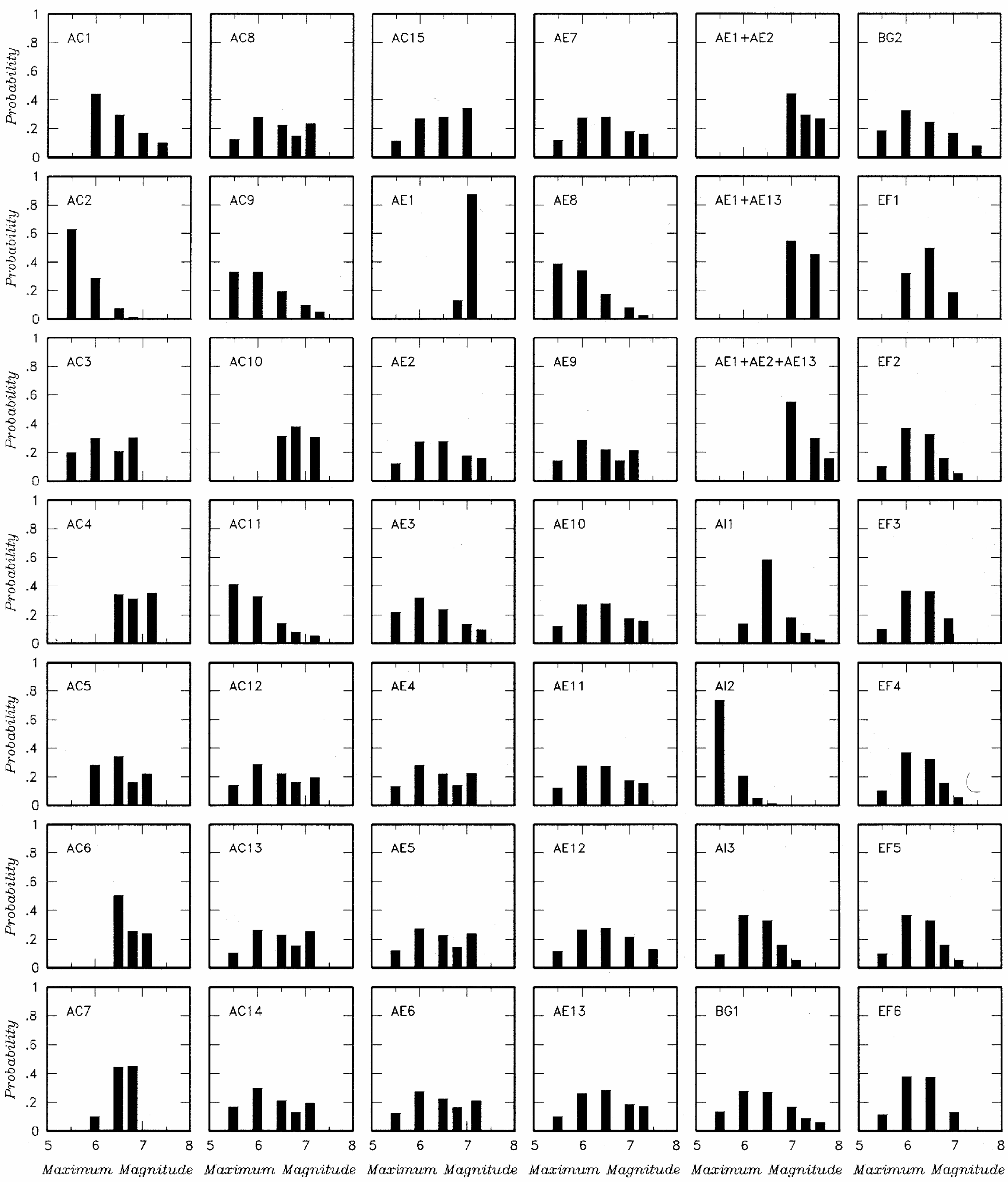


Fig.4-29: Maximum magnitude distributions for "small-scale" sources developed by the EG1b expert team

EG1c

The EG1c expert team used three approaches for assessing maximum magnitude. The first approach, labelled "Branch A", was to assess a distribution for a single value of maximum magnitude that applies to all sources in the study region. The second approach, labelled "Branch B", was to assess maximum magnitude distributions on a source-by source-basis using the Bayesian "EPRI" approach. The prior distribution for maximum magnitude was assumed to be uniform over the range of M 5.5 to 7.25 (rounded to 7.3 for the analysis). The third approach, labelled "Branch C", was to simulate jointly select sets of maximum magnitudes and earthquake recurrence parameters that produce synthetic earthquake catalogues that match the recorded earthquake catalogue within an acceptable tolerance level.

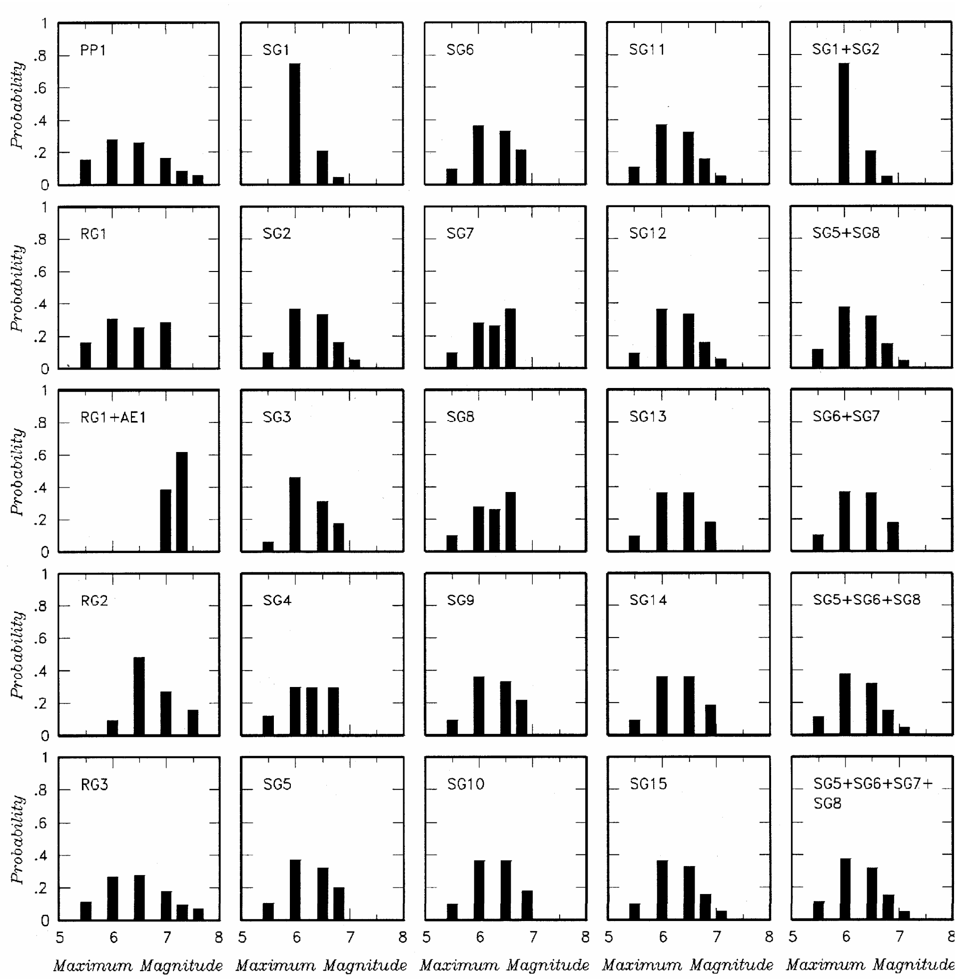


Fig.4-30: Maximum magnitude distributions for "small-scale" sources developed by the EG1b expert team (continued)

Although the distribution for maximum magnitude and recurrence parameters was estimated jointly in this approach, it was found that the resulting maximum magnitudes had a very low correlation with the rate parameters or with the *b*-values. Hence, the Branch C marginal distribution for maximum magnitude was treated as being independent of the rate and b-value joint distribution in the seismic hazard model. The resulting maximum magnitude distributions are shown on Figure 4-31 and 4-32. The results for each approach are labelled "A", "B" or "C". In general, the Branch B and Branch C approaches yield similar maximum magnitude distributions.

EG1d

The EG1d expert team used the "EPRI" approach with the extended crust prior distribution to assess maximum magnitude distributions for all seismic sources. Two equally weighted alternatives were used for truncation of the upper tail of these distributions, M 7.5 and M 8.0. The uncertainties in earthquake location and magnitude estimates were included in calculation of the updating likelihood functions for each source (Equation 4-3). Figures 4-33 and 4-28b show the resulting maximum magnitude distributions for the various source zone combinations. The EG1d expert team used eight alternative approaches for estimating earthquake recurrence parameters (see section 4.4.4.4). Because the different approaches produce different estimates of the *b*-value and number of earthquakes within a source, they affect the likelihood function for updating the maximum magnitude prior distribution. Accordingly, posterior maximum magnitude distributions were developed for each of the eight earthquake recurrence assessments.

There was only a small variation among the resulting maximum magnitude distributions. The distributions plotted on Figure 4-33 and 4-34 are an average of the eight distributions used in the seismic hazard model.

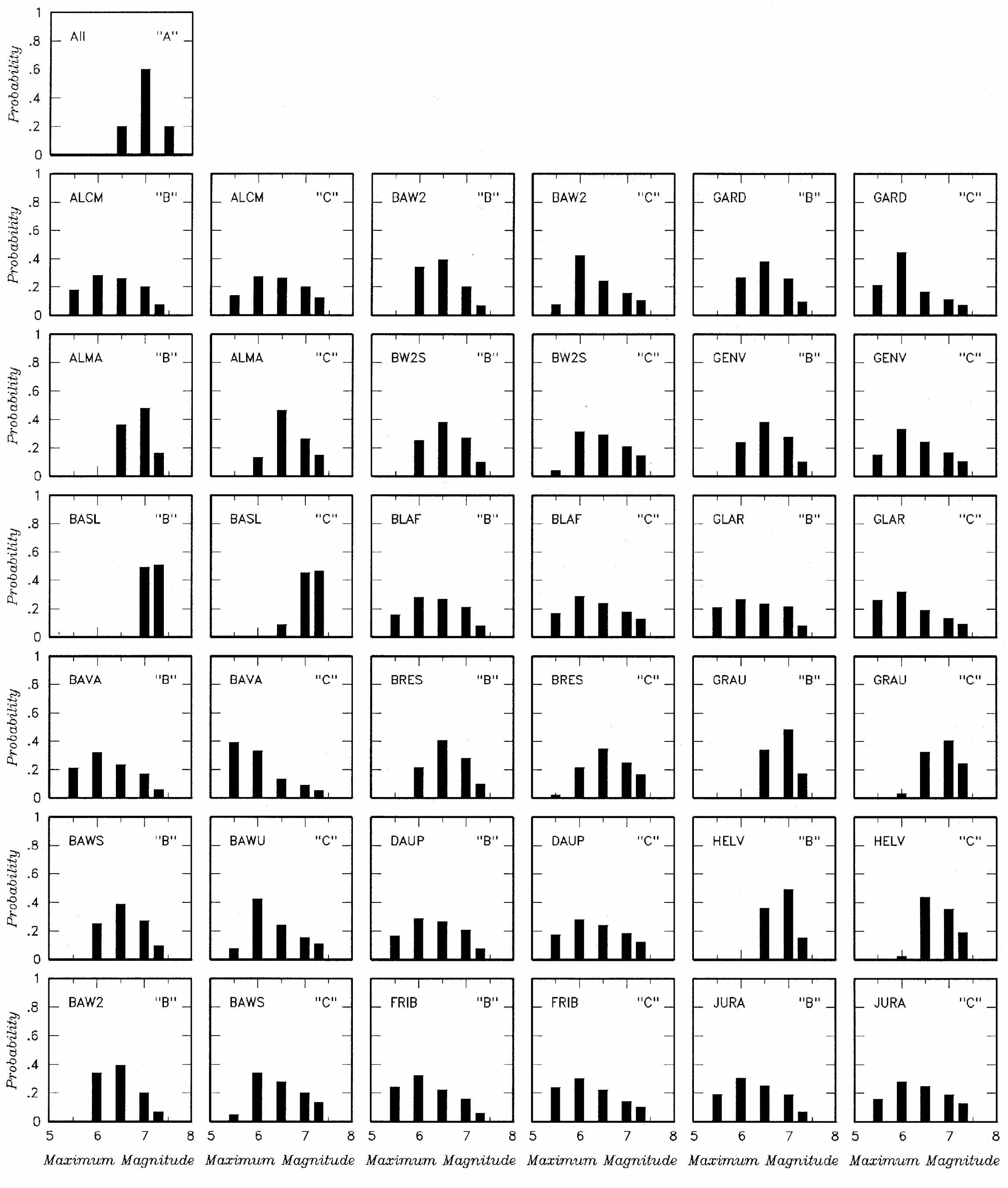


Fig.4-31: Maximum magnitude distributions developed by the EG1c expert team

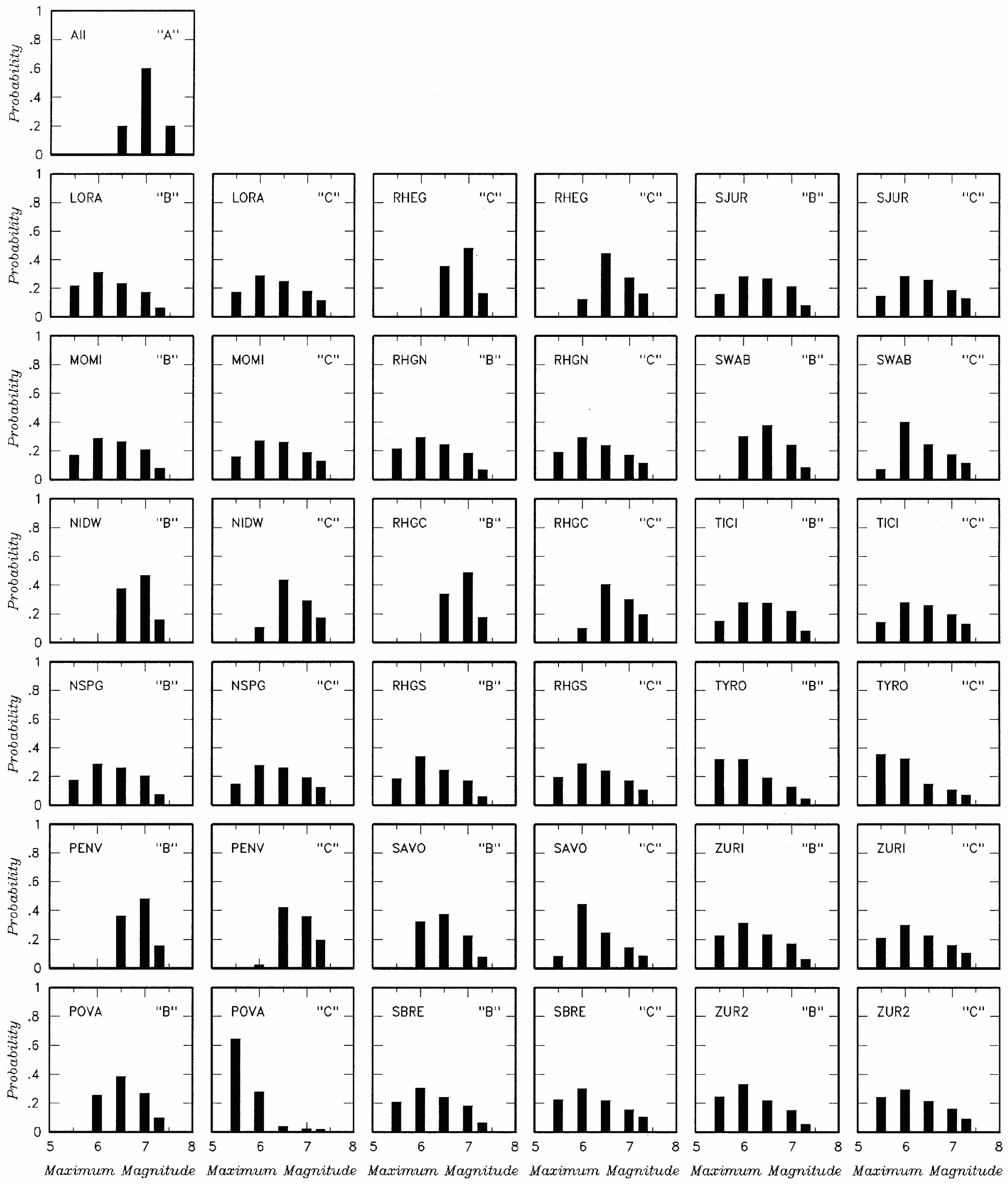


Fig.4-32: Maximum magnitude distributions developed by the EG1c expert team (continued)

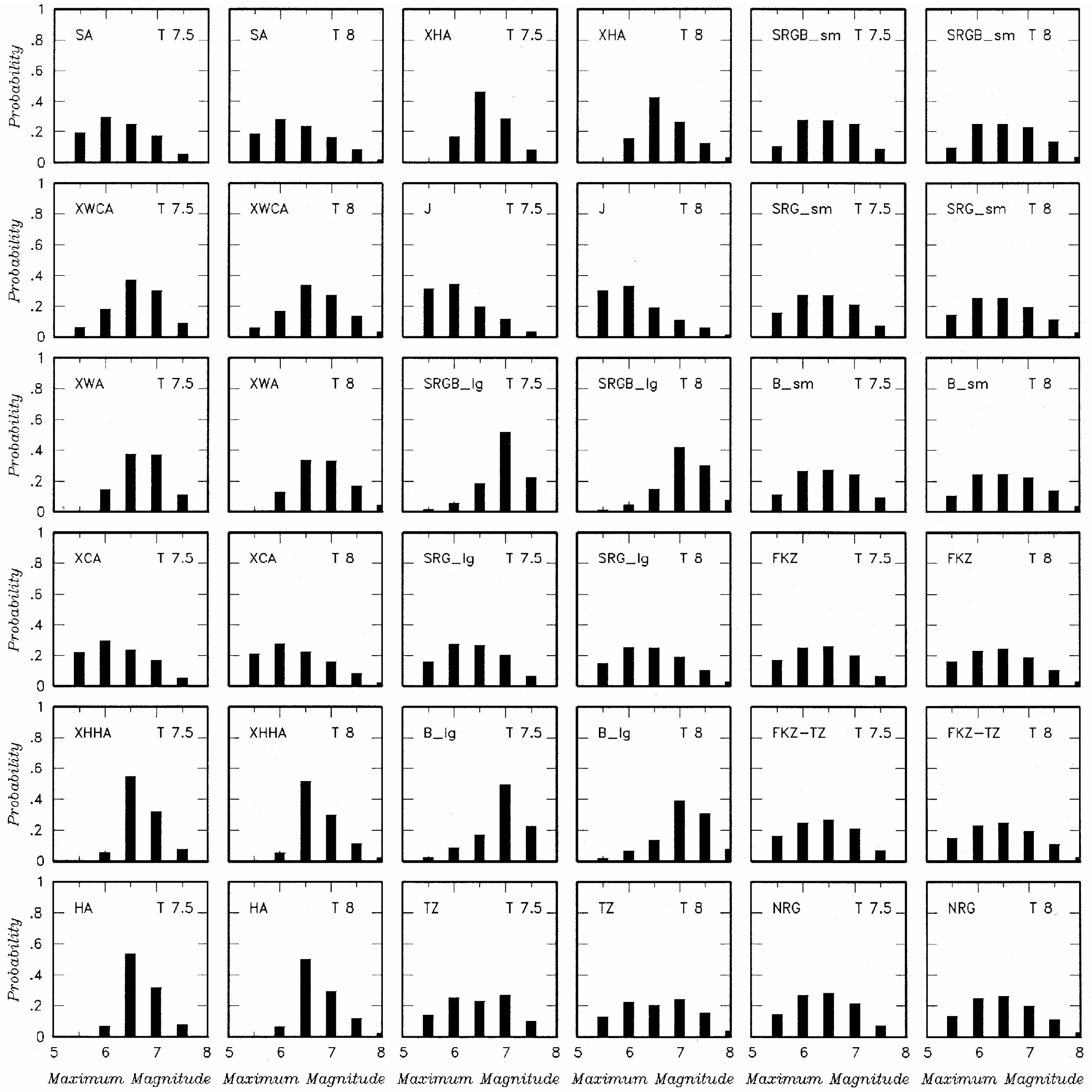


Fig.4-33: Maximum magnitude distributions developed by the EG1d expert team

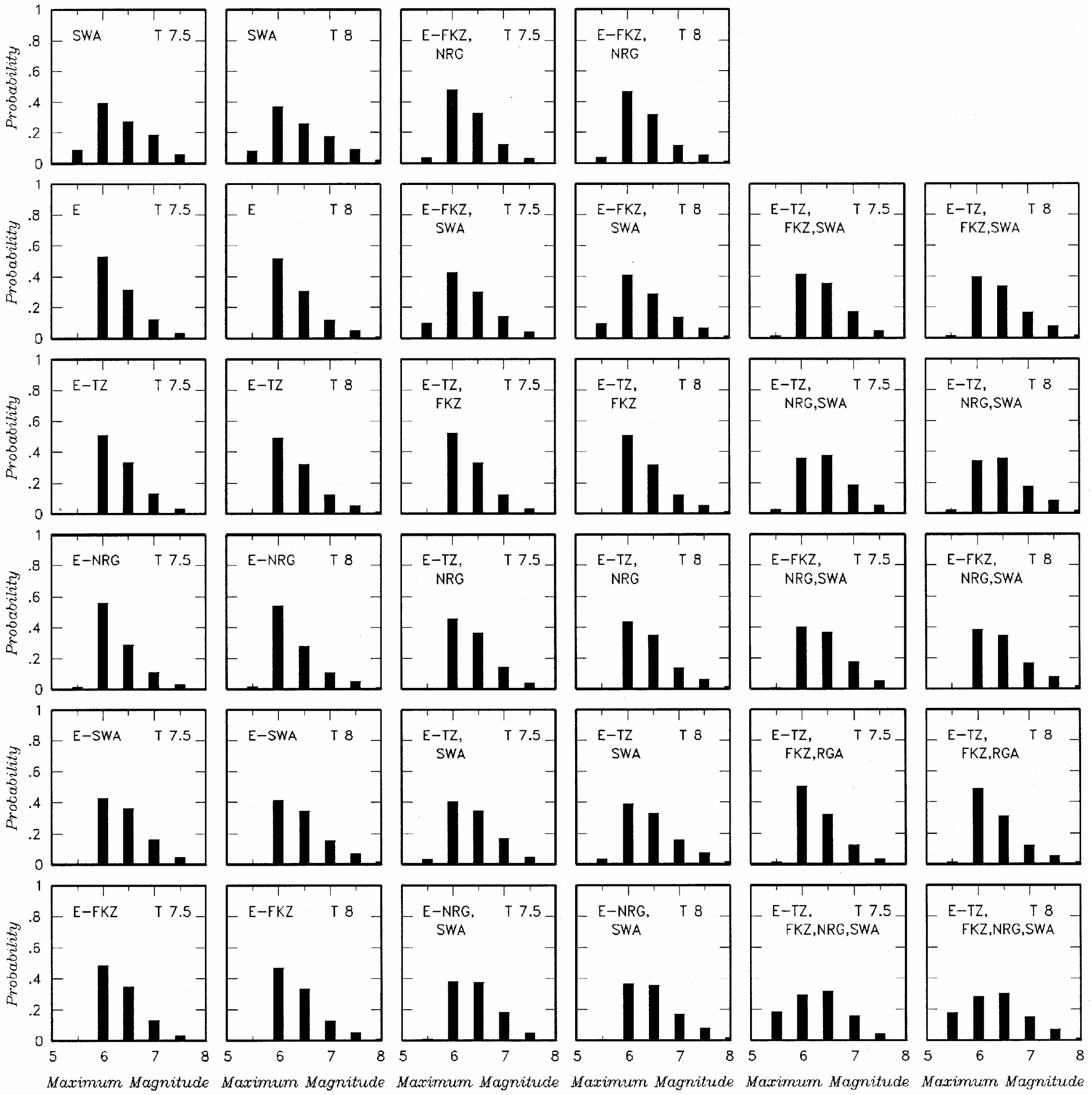


Fig.4-34: Maximum magnitude distributions developed by the EG1d expert team (continued)

4.4.4 Earthquake Recurrence Relationships

This section describes the earthquake catalogue analysis performed by the SP1 expert teams and the methods the teams used to assess earthquake recurrence parameter distributions for their seismic sources.

EG1a:

The EG1a expert team used the PEGASOS catalogue as the basis for earthquake recurrence parameter assessments. The catalogue was reviewed by the team and questionable events and explosions were removed. The team reviewed the performance of various declustering approaches on identifying known aftershocks and concluded that the algorithm of Gardener & Knopoff (1974) with the parameters suggested by Grünthal (1985, modified by personal communication 2002) performed the best in declustering the earthquake sequences chosen for analysis, and the PEGASOS catalogue declustered using this approach was selected for use in estimating earthquake recurrence parameters.

The EG1a expert team evaluated catalogue completeness in six regions corresponding to the five countries whose earthquake catalogues were used to assemble the PEGASOS catalogue; Austria, France, Germany, Italy, and Switzerland, plus a western Alps zone. The estimated completeness intervals were based on examination of "Stepp" plots (e.g. Figure 4-9) and histograms of seismicity rates within the "macrozones" used for maximum magnitude estimation. Table 4-2 lists the estimates times when complete catalogue reporting began.

Tab.4-2: Catalogue completeness developed by the EG1a expert team

Completeness Region	Year Catalogue Becomes Complete for Magnitude:							
	2.3	3.1	3.9	4.7	5.4	6.2	6.6	7.0
Switzerland	1975	1900	1879	1750	1680	1500	1200	1200
S. Germany			1825	1775	1500	1250	1250	1000
E. France		1975	1820	1820	1820	1820	1820	1000
W. Alps			1900	1820	1750	1750	1750	1000
N. Italy		1975	1900	1800	1400	1200	1200	1000
W. Austria		1900	1900	1850	1670	1550	1550	1200

Expert team EG1a used the truncated exponential recurrence model to represent earthquake recurrence in all of their seismic source zones. They estimated the recurrence parameters using a two-step process. The first step was to estimate the appropriate *b*-values for the macrozones that make up the study region (the seismotectonic regions shown on Figure 4-12). Combined estimates for multiple macrozones were made when the data within one macrozone were insufficient to yield a well constrained *b*-value. The uncertainty in the *b*-value for a macrozone or group of macrozones was specified using a standard deviation, σ_b, of 0.1. The uncertainty in the *b*-value was represented in the seismic hazard model by the three-point discrete distribution developed by Keefer & Bodily (1983): a weight of 0.63 applied to the 50th percentile value (the estimated *b*-value for the macrozone or macrozones) and a weight of 0.185 applied to the 5th and 95th percentile values ($\pm 1.645\sigma_b$). The *b*-value is assumed to be correlated across all seismic sources that make up a macrozone.

The second step was to estimate the activity rate for each seismic source using the specified *b*-values for the host macrozone. The rate of earthquake activity was estimated using the likelihood formulation of Equation 4-14 with the *b*-value held fixed. The EG1a expert team included alternative estimates using different magnitude ranges and catalogue periods for the following two cases.

Case 1: Two values of minimum magnitude, m_0, were used in estimating the rate parameter for sources in Austria, France and Italy. These alternatives addressed the uncertainty in selecting the appropriate magnitude range to which the truncated exponential recurrence model is applicable. One alternative applied the truncated exponential model to the full magnitude range of complete data and the value of m_0 was set to the lowest magnitude considered completely reported in the earthquake catalogue for the source zone. The other alternative applied the truncated exponential model to only the larger magnitude of interest in the hazard calculation and the value of m_0 was typically set to M 4.3. Figure 4-35 shows an example of the maximum likelihood recurrence relationships obtained for those sources to which Case 1 was applied.

Case 2: The EG1a expert team addressed the possibility that a change in activity rate in Switzerland and Southern Germany occurred at the time 1970 – 1975 by including alternative estimates of recurrence rates based on pre-1975 data and post-1975 data. For the pre-1975 data, two magnitude ranges were used for the rate estimation, as was done for Case 1. For post-1975 data, only a fit to all of the data was included because of the limited range in magnitude typically found in the data. Figure 4-36 shows an example of the maximum likelihood recurrence relationships obtained for those sources to which Case 2 was applied.

In addition, the recurrence rate for the 1356 Basel event was specified to be one event in a 2000-year period (rather than one event in the catalogue completeness period of post 1200 A.D.), based on consideration of the available paleoseismic data for the region.Table 4-3 lists the seismic sources that make up each macrozone or macrozones with correlated *b*-values and indicates the recurrence parameter cases applied to the source zone. Given a specified fixed *b*-value and the magnitude and time intervals for the data, Equation 4-14 was used to estimate the maximum likelihood rate parameter $N(m_0)$. (Note that the penalty term for the *b*-value was dropped because *b* was fixed.) The uncertainty in $N(m_0)$ was obtained by calculating the relative likelihoods for a range of values of $N(m_0)$ and normalising these relative likelihoods into a discrete distribution. This uncertainty distribution was represented in the seismic hazard model by the five-point discrete approximation developed by Miller & Rice (1983), in which weights of 0.10108, 0.24429, 0.30926, 0.24429, and 0.101080 are applied to values at the 0.034893, 0.211702, 0.5, 0.788298, and 0.965107 percentile, respectively, of the resulting cumulative distribution.

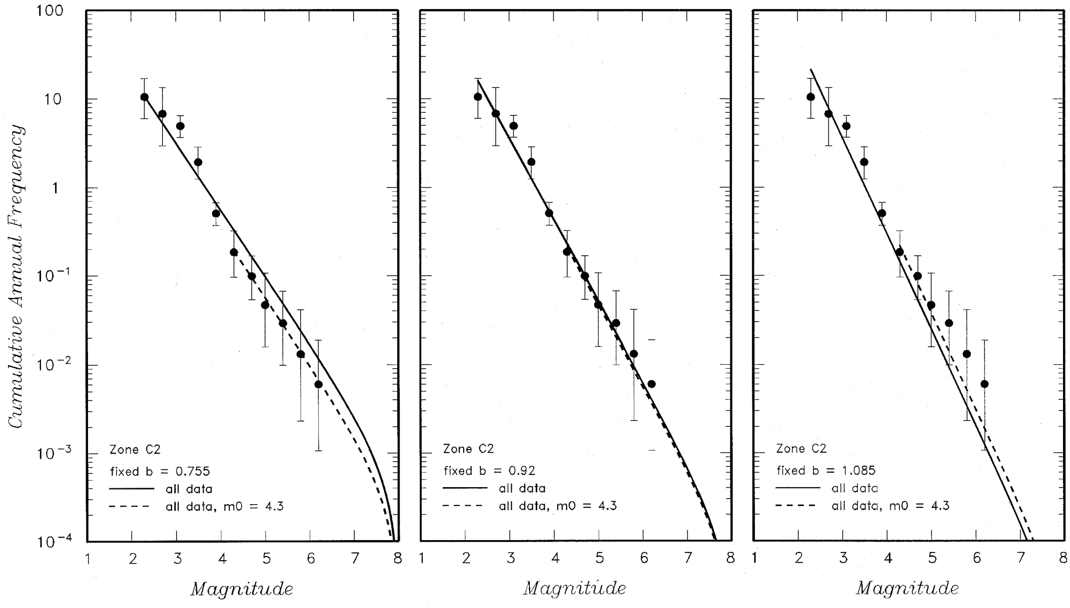


Fig.4-35: Example maximum likelihood recurrence relationships for Case 1: Fitting all complete data and fitting data for magnitudes larger than 4.3

The observed cumulative seismicity rates are shown by the solid circles. The error bars represent nominal 90 percent confidence intervals based on the number of earthquakes in each magnitude interval. The three *b*-values are the specified macrozone *b*-value and $\pm 1.645\,\sigma_b$.

Figure 4-37 shows the resulting distribution of recurrence rate for the two seismic sources shown on Figures 4-35 and 4-36. The distribution of recurrence rates includes the alternative maximum magnitude assessments.

Figures 4-38 through 4-41 show the sensitivity of earthquake recurrence estimates for four macrozones to the various modelling approaches. The two maximum magnitude approaches produce essentially the same recurrence estimates because they lead to similar maximum magnitude distributions (Figure 4-27). The use of the alternative time and magnitude intervals for estimating recurrence parameters produces a relatively large difference in the northern Alps macrozone D1, a much smaller difference in the Molasse – Jura macrozone E2 + E3, and little difference in the Rhine Graben and southern Germany macrozones F2 and F3, respectively.

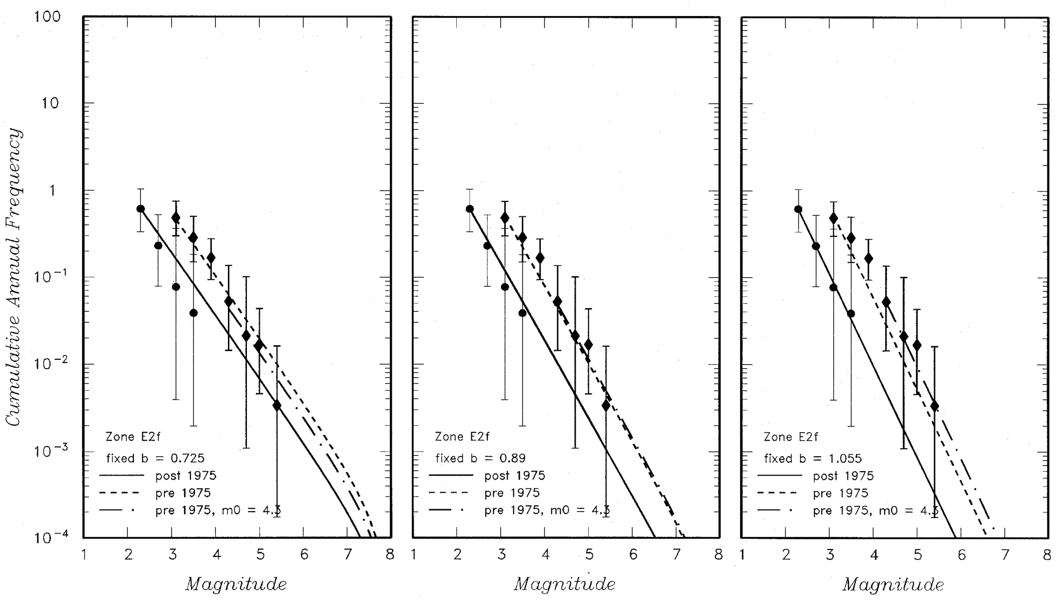


Fig.4-36: Example maximum likelihood recurrence relationships for Case 2: fitting all post-1975 data, all pre-1975 complete data and fitting pre-1975 data for magnitudes larger than 4.3

The observed cumulative post-1975 seismicity rates are shown by the solid circles and the pre-1975 seismicity rates by the solid diamonds. The error bars represent nominal 90 percent confidence intervals based on the number of earthquakes in each magnitude interval. The three *b*-values are the specified macrozone *b*-value and ± $1.645\sigma_b$.

Tab.4-3: Recurrence rate estimation parameters for the EG1a seismic sources

Sources with correlated *b*-values	*b*-value	Seismicity Rate Alternatives	
A	0.96±0.165	All data All data, m_0 ~ 4.3	(wt 0.5) (wt 0.5)
B	1.00±0.165	All data All data, m_0 ~ 4.3	(wt 0.5) (wt 0.5)
C1, C2, C3	0.92±0.165	All data All data, m_0 ~ 4.3	(wt 0.5) (wt 0.5)
D1a, D1b, D1c, D1e, D1f, D1bcd, D1bcde, D1de	0.93±0.165	Post-1975 data Pre-1975 data Pre-1975 data m_0 ~ 4.3	(wt 0.333) (wt 0.334) (wt 0.334)
Sources with correlated *b*-values	*b*-value	Seismicity Rate Alternatives	
D2, D3a, D3b	0.94±0.165	Post-1975 data Pre-1975 data Pre-1975 data m_0 ~ 4.3	(wt 0.333) (wt 0.334) (wt 0.334)
D4a, D4b, D4c	1.00±0.165	All data All data, m_0 ~ 4.3	(wt 0.5) (wt 0.5)
E1	0.95±0.165	All data All data, m_0 ~ 4.3	(wt 0.5) (wt 0.5)

E2a, E2b, E2c, E2d, E2e, E2cde, FF, E2dF2f, E2eF2f, E2cdeF2f, E2n, E2s, E2f, E3a, E3aF2f, E3b	0.89±0.165	For E2a, E2b: All data (wt 0.5) All data, $m_0 \sim 4.3$ (wt 0.5) For the rest of sources: Post-1975 data (wt 0.333) Pre-1975 data (wt 0.334) Pre-1975 data $m_0 \sim 4.3$ (wt 0.334)
F1a, F1b, F2c	0.95±0.165	All data (wt 0.5) All data, $m_0 \sim 4.3$ (wt 0.5)
F2a, F2b, F2b_RF, RF, F2bpcy, F2bF2f, F2d, F2e, F2f	0.90±0.165	Post-1975 data (wt 0.333) Pre-1975 data (wt 0.334) Pre-1975 data $m_0 \sim 4.3$ (wt 0.334)
F3a, F3aF2f, F3b, F3c	0.88±0.165	Post-1975 data (wt 0.333) Pre-1975 data (wt 0.334) Pre-1975 data $m_0 \sim 4.3$ (wt 0.334)

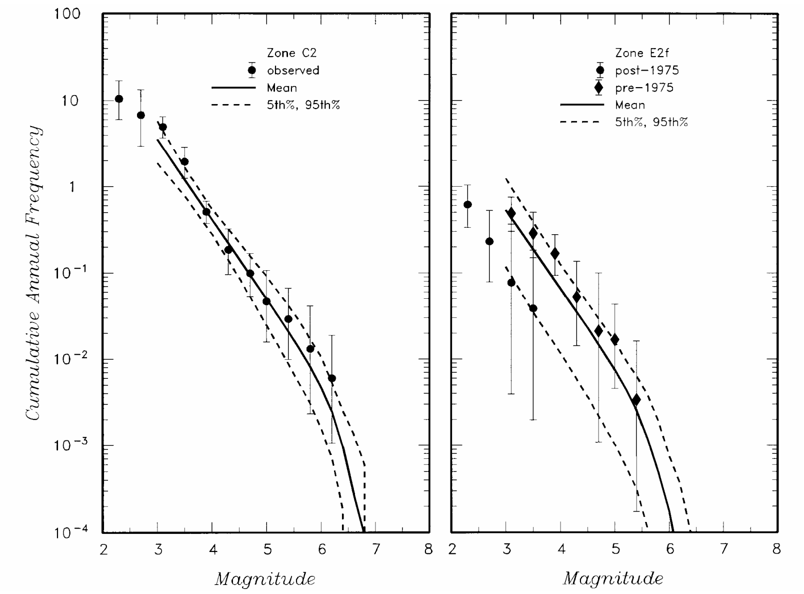


Fig.4-37: Example distributions of recurrence rates for sources shown on Fig. 4-19 and 4-20

The distribution in recurrence rate incorporates the alternative maximum magnitude assessment approaches, the resulting maximum magnitude distributions, alternative b-values, alternative magnitude ranges for assessing $N(m_0)$, and the distributions for $N(m_0)$.

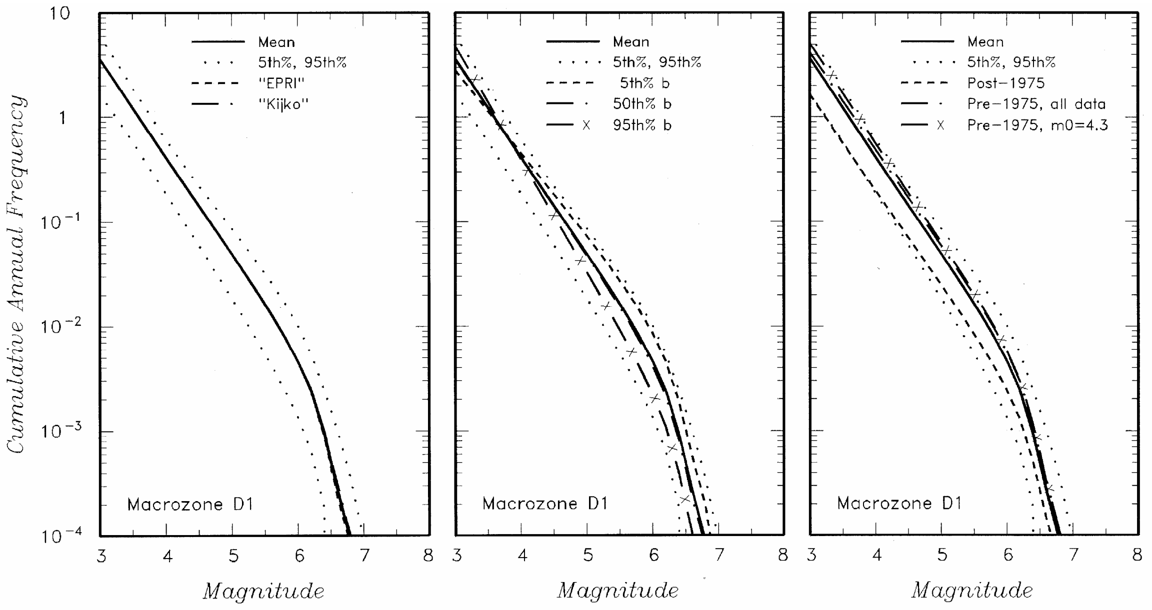


Fig.4-38: Sensitivity of earthquake recurrence estimates for macrozone D1 (northern Alps) to alternative modelling approaches

Each plot shows the mean, 5th and 95th percentile recurrence estimates over all uncertainties. The left plot shows effect of maximum magnitude approach, the centre plot shows the effect of the fixed *b*-value, and the right plot shows the effect of the alternative time and magnitude intervals used in fitting the recurrence parameters.

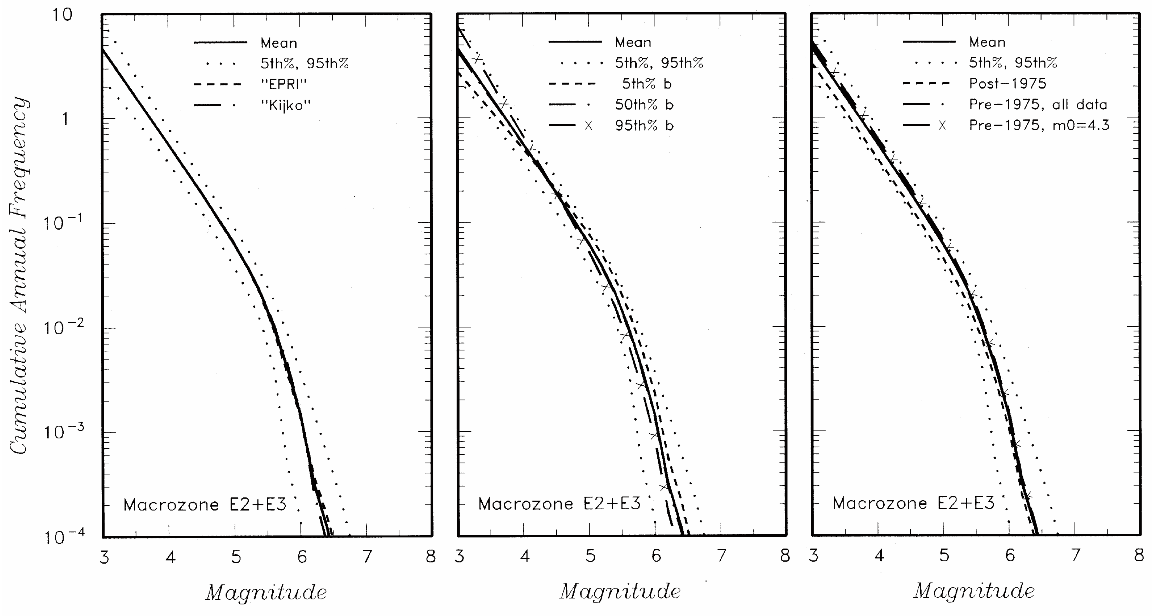


Fig.4-39: Sensitivity of earthquake recurrence estimates for macrozone E2 + E3 (the Molasse and Jura) to alternative modelling approaches

Each plot shows the mean, 5th and 95th percentile recurrence estimates over all uncertainties. The left plot shows the effect of maximum magnitude approach, the centre plot the effect of the fixed *b*-value, and the right plot the effect of the alternative time and magnitude intervals used in fitting the recurrence parameters.

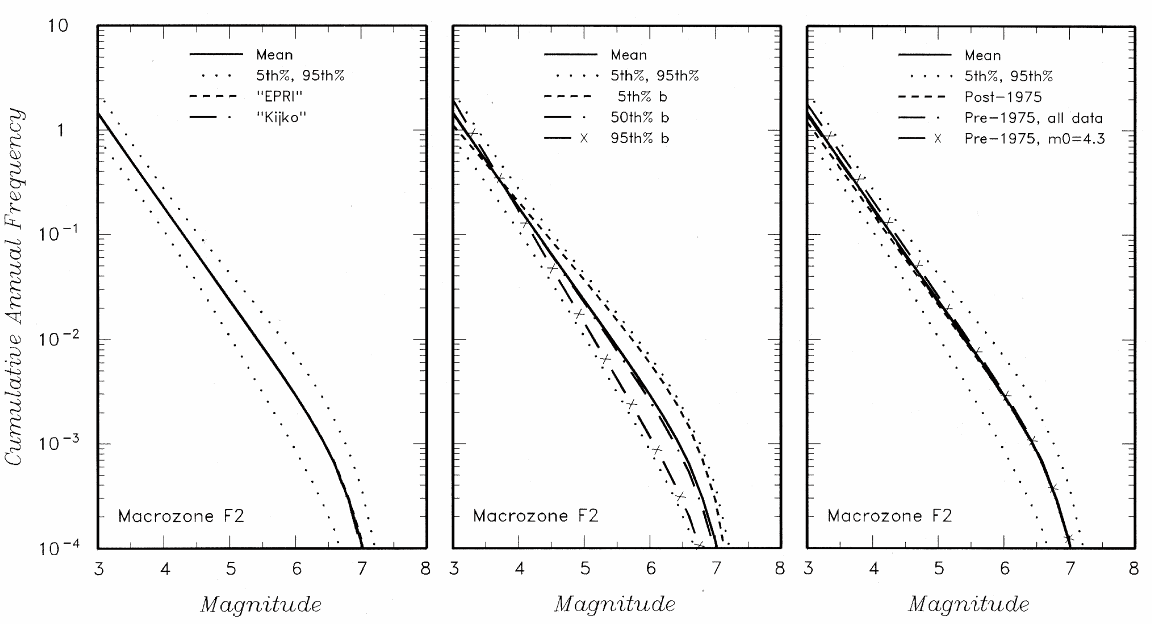


Fig.4-40: Sensitivity of earthquake recurrence estimates for macrozone F2 (the Rhine Graben) to alternative modelling approaches

Each plot shows the mean, 5^{th} and 95^{th} percentile recurrence estimates over all uncertainties. The left plot shows the effect of the maximum magnitude approach, the centre plot shows the effect of the fixed *b*-value, and the right plot shows the effect of the alternative time and magnitude intervals used in fitting the recurrence parameters.

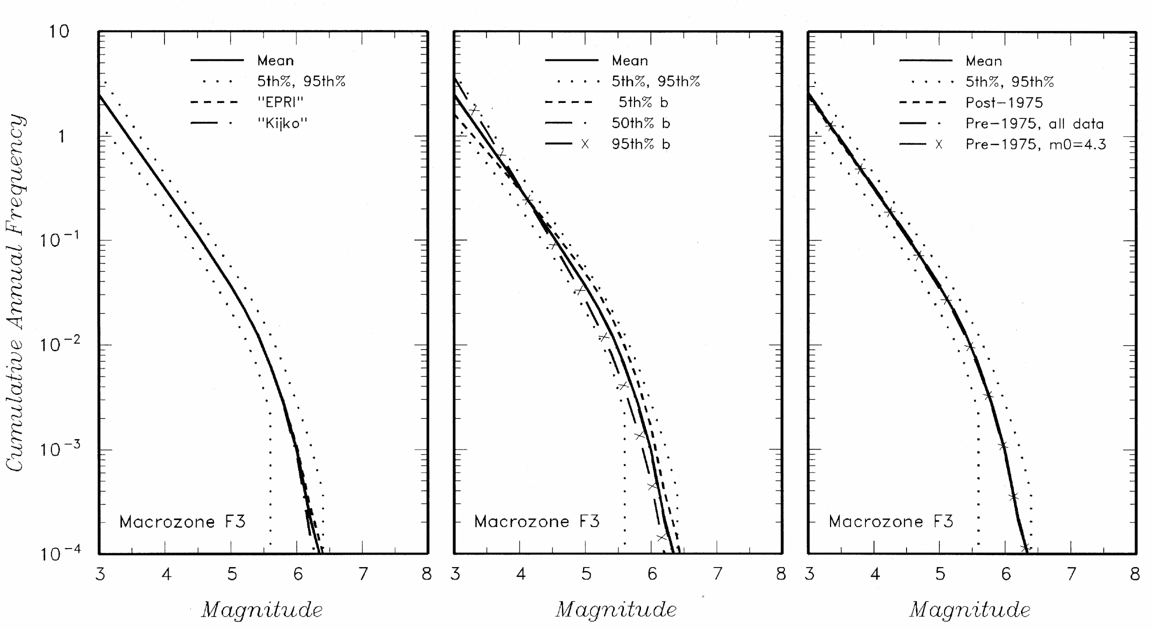


Fig.4-41: Sensitivity of earthquake recurrence estimates for macrozone F3 (southern Germany) to alternative modelling approaches

Each plot shows the mean, 5^{th} and 95^{th} percentile recurrence estimates over all uncertainties. The left plot shows the effect of the maximum magnitude approach, the centre plot shows the effect of the fixed *b*-value, and the right plot shows the effect of the alternative time and magnitude intervals used in fitting the recurrence parameters.

EG1b:

The EG1b expert team used the PEGASOS catalogue as the basis for earthquake recurrence parameter assessments. The catalogue was reviewed by the team and mining-related events were removed. The team reviewed the performance of various declustering approaches for identifying known aftershocks and concluded that the algorithm of Gardener & Knopoff (1974), with the parameters suggested by Grünthal (personal communication 2002), performed the best in declustering the earthquake sequences chosen for analysis, and the PEGASOS catalogue declustered using this approach was selected for use in estimating earthquake recurrence parameters.

The EG1b expert team evaluated catalogue completeness in five regions corresponding to the five countries whose earthquake catalogues were used to assemble the PEGASOS catalogue: Austria, France, Germany, Italy and Switzerland. The estimated completeness intervals were based on examination of a modified form of "Stepp" plots developed by one of the team members, G. Grünthal. Table 4-4 lists the estimated times when complete catalogue reporting began.

Tab.4-4: Catalogue completeness developed by the EG1b expert team

Completeness Region	Year Catalogue Becomes Complete for Magnitude:								
	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0
Switzerland	1880	1880	1860	1825	1770	1650	1575	1250	1250
S. Germany	1965	1870	1865	1865	1860	1200	1200	1200	1200
E. France	1970	1965	1810	1810	1750	1650	1650	1650	1650
N. Italy	1975	1975	1875	1850	1750	1750	1600	1600	1600
W. Austria	1975	1900	1875	1875	1550	1550	1550	1550	1550

Expert team EG1b used the truncated exponential recurrence model to represent earthquake recurrence in all of their seismic source zones. The parameters of the model were estimated using the likelihood formulation of Equation 4-14 without the use of a prior for the *b*-value. For some of the "small-scale" seismic sources, there is insufficient data to provide a reliable estimate of the *b*-value. Therefore, several sources were grouped together and a common *b*-value was estimated for the combined data. Table 4-5 lists these source groupings. Figure 4-42 shows examples of the distribution of earthquake recurrence rates estimated for a "large-scale" and a "small-scale" seismic source.

Tab.4-5: Grouping of "small-scale" seismic sources for b-value estimation by the EG1b expert team

Grouped sources for estimation of a common *b*-value	Source *b*-value is applied to:
AC11, AC13, AC14	AC13
AC12, AC15	All
AE2, AE3, AE4	AE2
AE3, AE4, AE5, AE6, AE7, AE8, AE9, AE10, AE11	All
AE12, AE13	All

Grouped sources for estimation of a common *b*-value	Source *b*-value is applied to:
AI2, AI3	AI3
BG1, BG2	BG1
EF3, EF4, EF5	EF4
SG1, SG3	SG3
SG2, SG4, SG9, SG10, SG11, SG12, SG13, SG14, SG15	All
SG5, SG6, SG7, SG8	All

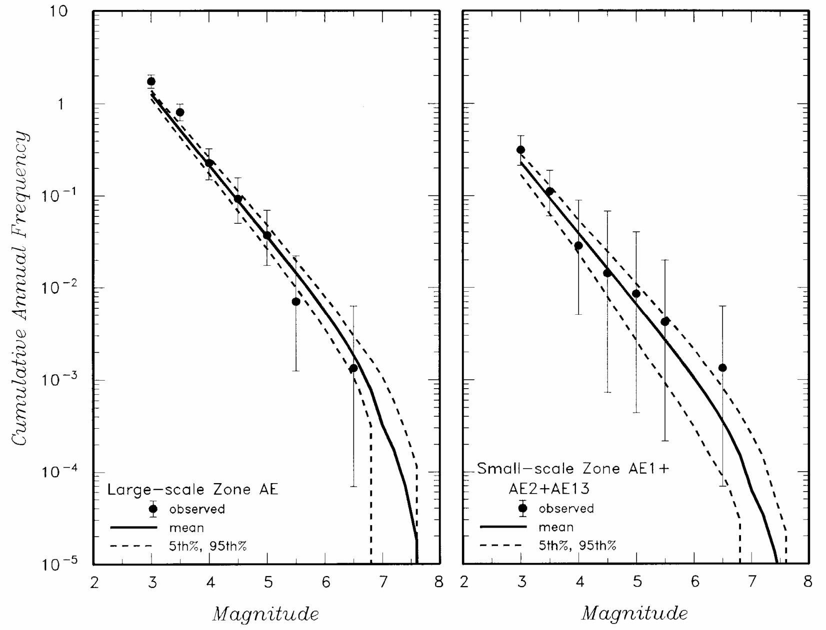


Fig.4-42: Example distributions of recurrence rates for seismic sources developed by expert team EG1b

The distribution in recurrence rate incorporates the maximum magnitude distributions and joint distributions for *b*-values and $N(m_0)$.

Figure 4-43 shows the effect of the zonation approach on the mean recurrence estimates for four large-scale zones. The differences in the recurrence estimates are small and occur primarily above magnitude M6, reflecting the differences in the maximum magnitude distributions between the large-scale and small-scale zones.

EG1c:

The EG1c expert team used the PEGASOS catalogue as the basis for earthquake recurrence parameter assessments. The team used a modified version of the Reasenberg (1985) approach developed by Musson (1999, 2000) to decluster the PEGASOS catalogue. The parameters (time and distance windows) of the approach are derived from the PEGASOS catalogue as part of the process.

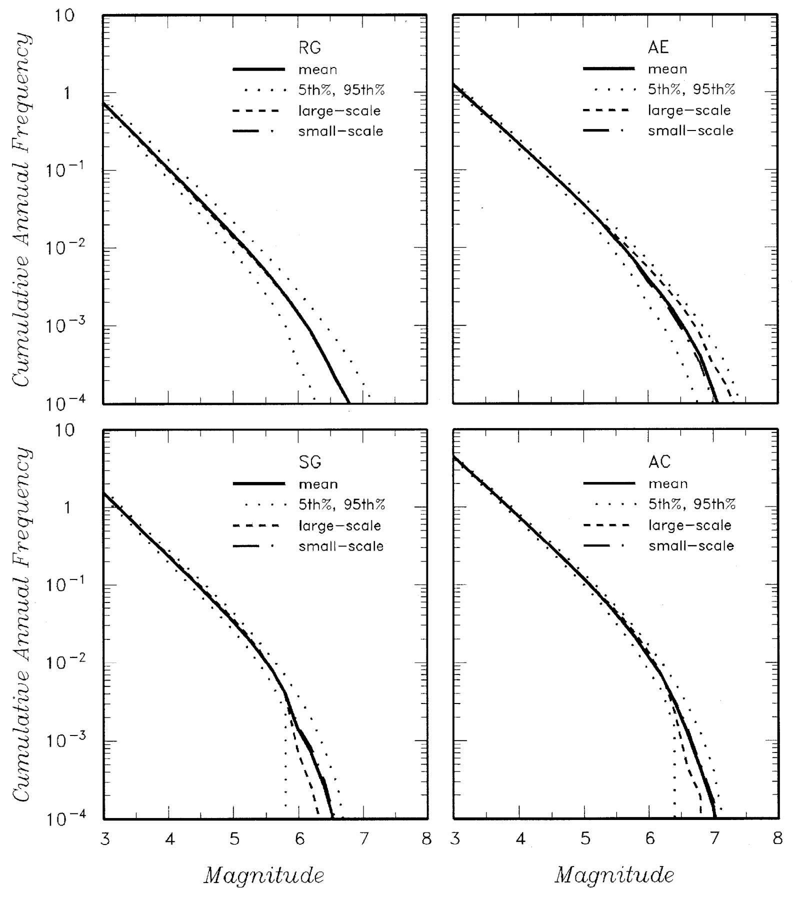


Fig.4-43: Comparison of recurrence estimates for large-scale and small-scale zonation approaches

Each plot shows the mean recurrence estimate for the indicated large-scale zone and the composite recurrence for all of the small-scale zones that make up the large-scale zone. The distribution in recurrence rate incorporates the two zonation approaches, the maximum magnitude distributions and the joint distributions for *b*-value and $N(m_0)$.

The EG1b expert team evaluated catalogue completeness using two approaches: a historical approach based on an evaluation of the history of earthquake reporting in the region, and a statistical approach based on the use of "Stepp" plots. The results of the two approaches were combined to produce estimated completeness intervals for seven areas within the study region. The seven completeness regions are shown on Figure 4-44 and the completeness intervals are listed in Table 4-6.

Expert team EG1c used the truncated exponential recurrence model to represent earthquake recurrence. The team used three approaches for assessing the earthquake recurrence parameters that were coupled with the approaches used to estimate maximum magnitude (see section 4.4.3.3).

The first approach, labelled "Branch A", used the penalised maximum likelihood method (Equation 4-14). The *b*-value prior was set to 0.9 based on an analysis of the whole catalogue. The weight on the prior was set to 50. The recurrence parameters were estimated using $m_0 = 3.5$. A joint distribution for *b*-value and $N(m_0)$ was developed using normalised relative likelihoods for a grid of $N(m_0)$ - *b*-value pairs.

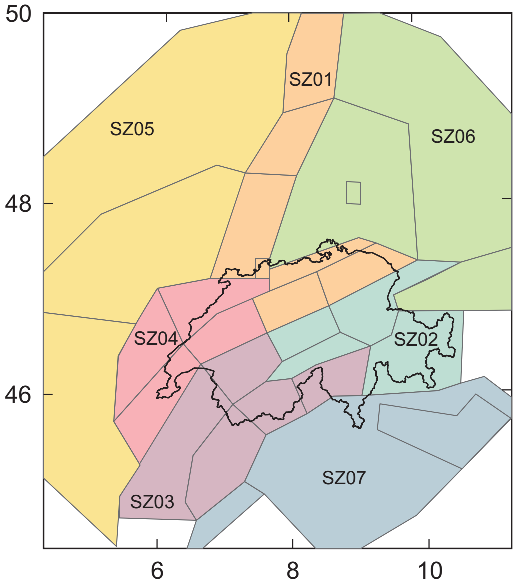


Fig.4-44: Catalogue completeness regions defined by expert team EG1c

The second approach, labelled "Branch B", used a two-stage process. First, the *b*-value for each source was estimated using the method of least-squares. This *b*-value was then used as a local prior in the penalised maximum likelihood estimation of a joint distribution for *b*-value and $N(m_0)$.

The third approach, labelled "Branch C", used simulation to jointly select sets of maximum magnitudes and earthquake recurrence parameters that produce synthetic earthquake catalogues that match the recorded earthquake catalogue within an acceptable tolerance level. Although the distribution for maximum magnitude and recurrence parameters was estimated jointly in this approach, it was found that the resulting maximum magnitudes had a very low correlation with the rate parameters or with the *b*-values. Hence, the Branch C joint distribution for *b*-value and $N(m_0)$ was treated as being independent of the marginal distribution for maximum magnitude.

Tab.4-6: Catalogue completeness developed by the EG1c expert team

Completeness Region*	Year Catalogue Becomes Complete for Magnitude:								
	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0
SZ01	1960	1920	1700	1650	1550	1350	1200	1200	1100
SZ02	1976	1920	1750	1700	1700	1600	1270	1270	1200
SZ03	1976	1940	1820	1750	1750	1670	1500	1500	1200
SZ04	1976	1920	1810	1800	1750	1550	1500	1500	1200
SZ05	1960	1920	1800	1550	1500	1500	1200	1200	1100
SZ06	1976	1960	1870	1850	1650	1650	1200	1200	1100
SZ07	1960	1960	1800	1750	1750	1750	1200	1200	1100

* See Figure 4-44

Figure 4-45 shows examples of the recurrence rate distributions developed using the three approaches for the NSPG (graben inversion) source.

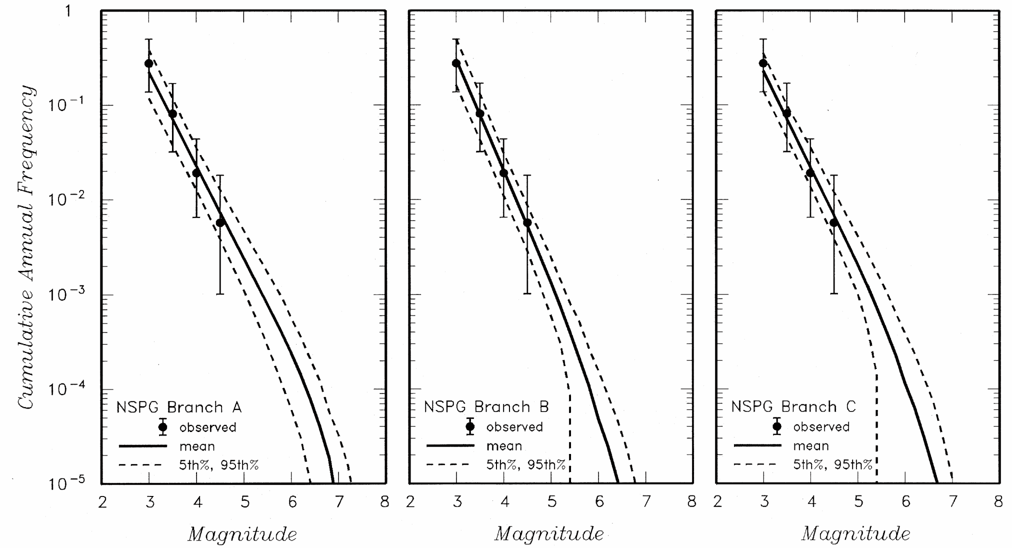


Fig.4-45: Example recurrence rate distributions developed for the NSPG (graben inversion) seismic source by expert team EG1c

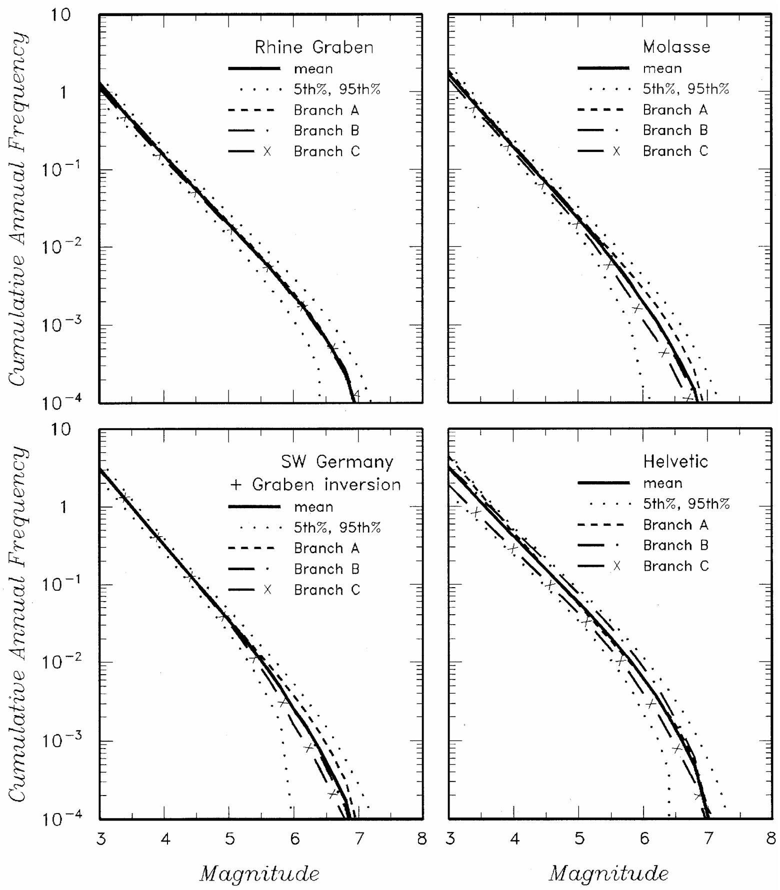


Fig.4-46: Comparison of recurrence estimates for the three combined maximum magnitude recurrence parameter approaches

Each plot shows the mean, 5th, and 95th percentile recurrence for the indicated seismotectonic region, and the mean recurrence estimate obtained using the three modelling approaches. The distribution in recurrence rate incorporates the three modelling approaches and the resulting maximum magnitude and joint b-value-N (m_0) distributions.

Figure 4-46 compares the recurrence rate distributions obtained using the three modelling approaches for four seismotectonic regions (see Figure 4-15). The computed recurrence rates are the composite for all of the sources within the seismotectonic region.

EG1d:

The EG1d expert team used the PEGASOS catalogue as the basis for earthquake recurrence parameter assessments. The team reviewed the catalogue and identified two possible sets of mining-related events (induced events and potential quarry blasts). One set was located in a specific mining region on the France / Germany border. The other set was identified by statistical analysis of the catalogue. The team evaluated the effect of removing just the first set or both sets on the resulting hazard and concluded that there was little effect. They removed both sets for the final catalogue analysis. The team also examined the effect of three declustering approaches on the resulting hazard estimates: the Reasenberg (1985) approach, the Gardener & Knopoff (1974) approach using the original Gardener & Knopoff time and distance windows, and the Gardener & Knopoff (1974) approach using the time and distance windows developed for Europe by Grünthal (1985, 2002 personal communication). The group concluded that the use of the different declustering approaches produced an insignificant difference in hazard and selected the catalogue declustered using the Grünthal time and distance windows for estimating the earthquake recurrence parameters.

The EG1d team evaluated catalogue completeness on a country-by-country basis using both "Stepp" plots and a method developed by Wiemer & Wyss (2000). They represented the uncertainty in assessing completeness by developing two sets of completeness estimates. These alternatives, listed in Table 4-7, were used to develop alternative sets of recurrence parameters. Equal weight was assigned to the two completeness models.

Tab.4-7: Catalogue completeness developed by the EG1d expert team

Country	Completeness Period	Complete Magnitude Model 1	Complete Magnitude Model 2
Switzerland	1300 – 1600	6.0	6.0
	1600 – 1750	5.5	5.7
	1750 – 1880	4.7	5.0
	1880 – 1977	3.0	4.2
	1977 – 2001	1.8	1.9
Germany	1300 – 1620	6.0	6.5
	1620 – 1870	5.4	5.6
	1870 – 1980	3.1	3.5
	1980 – 2001	3.0	3.1
Austria	1700 – 1896	5.5	6.0
	1896 – 1978	3.1	3.3
	1978 – 2001	2.5	2.5
Italy	1775 – 1880	5.5	5.7
	1880 – 1979	4.1	4.3
	1979 – 2001	3.2	3.2
France	1700 – 1880	5.3	5.3
	1880 – 1978	3.7	4.0
	1978 – 2001	2.2	2.2

Expert team EG1d used the truncated exponential recurrence model to represent earthquake recurrence. The team used a two-step approach for the development of earthquake recurrence estimates.

The first step was the estimation of a regional *b*-value. Four alternative regional *b*-values were estimated using maximum likelihood: one for the instrumental (post-1975) data only, one for all complete data, one for the historical (pre-1975) data only, and one for all complete data, allowing for a change in rate at 1975. These regional *b*-values were used as constraints in subsequent analyses and were given equal weight in the seismic hazard model.

The second step was the estimation of the earthquake recurrence parameters $N(m_0)$ and *b*-value for each source. Five alternative methods were used.

1. The *b*-value was fixed at one of the regional *b*-values and $N(m_0)$ was estimated from all of the complete data using maximum likelihood. This model has one free parameter $N(m_0)$, and is labelled BX.
2. Joint estimation of *b*-value and $N(m_0)$ from all of the complete data using maximum likelihood. This model has two free parameters and is labelled BF.
3. The *b*-value was fixed at one of the regional *b*-values and $N(m_0)$ was estimated from all of the complete data using maximum likelihood allowing for a rate change at 1975. The value of $N(m_0)$ for use in hazard assessment is then computed as the weighted (for the period length) average of the pre- and post-1975 values of $N(m_0)$. This model has two free parameters and is labelled BX2.
4. Joint estimation of *b*-value and $N(m_0)$ from all of the complete data using maximum likelihood allowing for a rate change at 1975. The value of $N(m_0)$ for use in hazard assessment is then computed as the weighted (for the period length) average of the pre- and post-1975 values of $N(m_0)$. This model has three free parameters and is labelled BF2.
5. A Bayesian error-weighted *b*-value was computed for each source, with the weight assigned to the regional and local *b*-values inversely proportional to their errors of estimation. The resulting *b*-value was used to estimate $N(m_0)$ from all of the complete data using maximum likelihood. This model has between one and two free parameters, depending on the relative weight assigned to the local *b*-value, and is labelled BB.

$$b_{Bayes} = \left(\frac{\sigma^2_{b-regional}}{\sigma^2_{b-regional} + \sigma^2_{b-local} / N_{local}} \right) b_{local} + \left(\frac{\sigma^2_{b-local} / N_{local}}{\sigma^2_{b-regional} + \sigma^2_{b-local} / N_{local}} \right) b_{regional} \qquad (4\text{-}21)$$

where $\sigma_{regional}$ is the error of estimation of the regional *b*-value, σ_{local} is the error of estimation of the zone-specific *b*-value, and N is the local data sample size.

The fit of each of the above models to the observed data was given an Akaike Information Criterion (*AIC*) score (Imoto 1991, Ogata 1999).

$$AIC = -2LL + 2K + (2K(K-1)/(N-K-1) \qquad (4\text{-}22)$$

where LL is the log(likelihood) for the fit to the data, K is the degrees of freedom, and N is the sample size. These scores were used as relative weights to assign to the resulting estimates of recurrence parameters in the seismic hazard model. Figure 4-47 shows an example for a source zone of the five recurrence estimates for each of four regional *b*-values. Expert team EG1d included the uncertainty in earthquake location in their recurrence parameter estimation by simulating 50 catalogues using the location errors in the PEGASOS catalogue for each earthquake and averaging the estimated recurrence parameters.

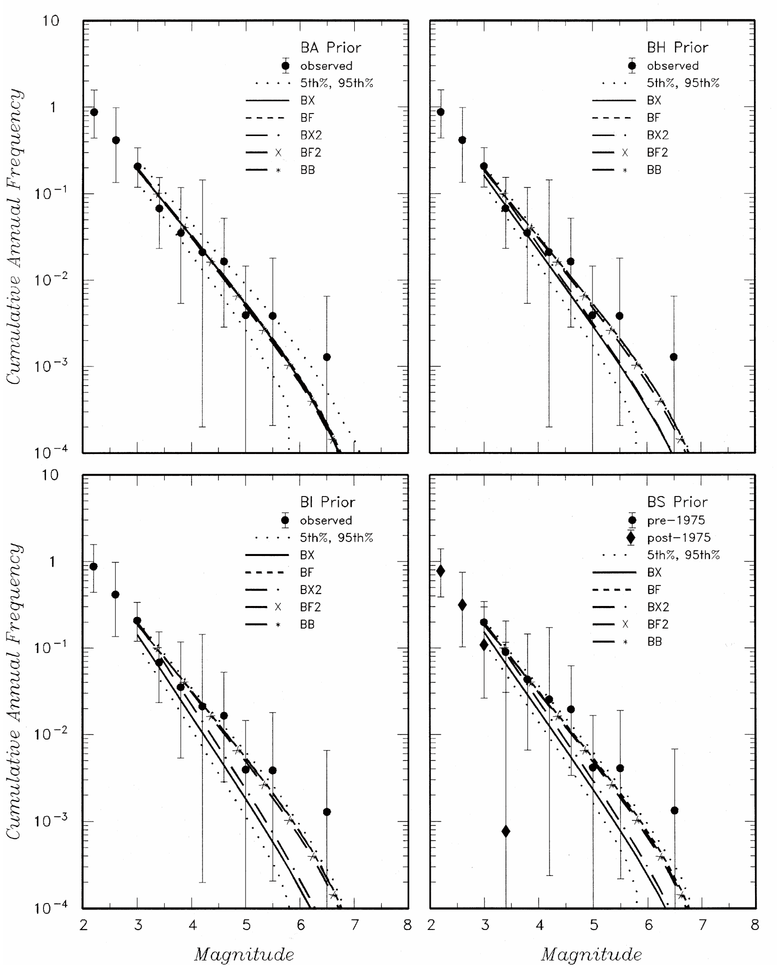


Fig.4-47: Example recurrence rates computed using the five approaches developed by expert team EG1d using the four regional b-values

Figures 4-48 through 4-51 show the effect of the alternative recurrence modelling approaches on the mean recurrence rate in four seismotectonic regions. The alternative approaches produce the largest differences in the Helvetic Alps.

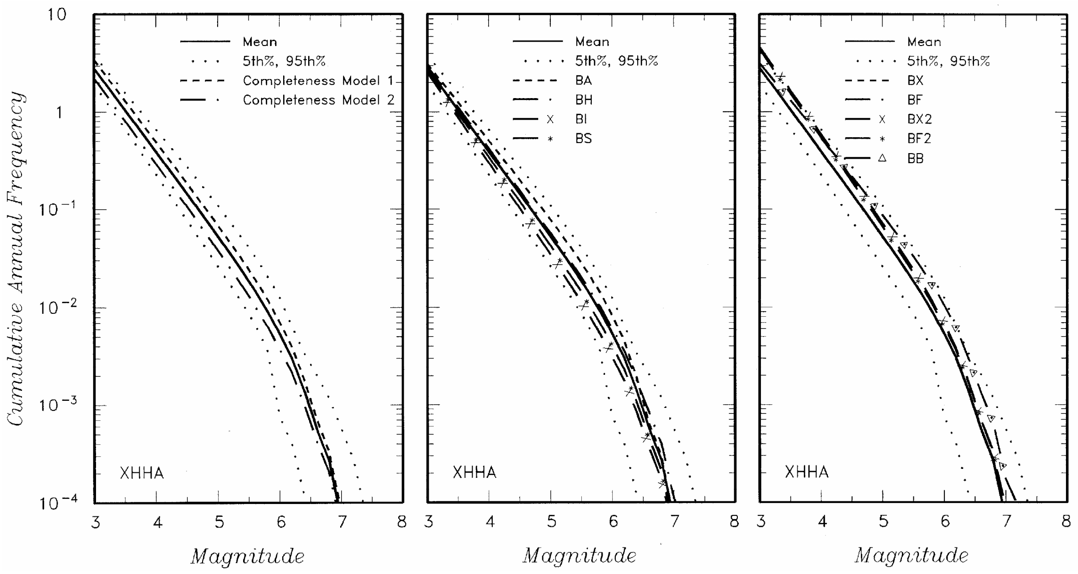


Fig.4-48: Effect of recurrence modelling approaches on mean recurrence rate for the Helvetic Alps seismotectonic region (XHHA)

Each plot shows the mean, 5th, and 95th percentile recurrence incorporating the alternative zonations, alternative maximum magnitude distributions, the weighted modelling approaches, and the resulting joint *b*-value-$N(m_0)$ distributions.

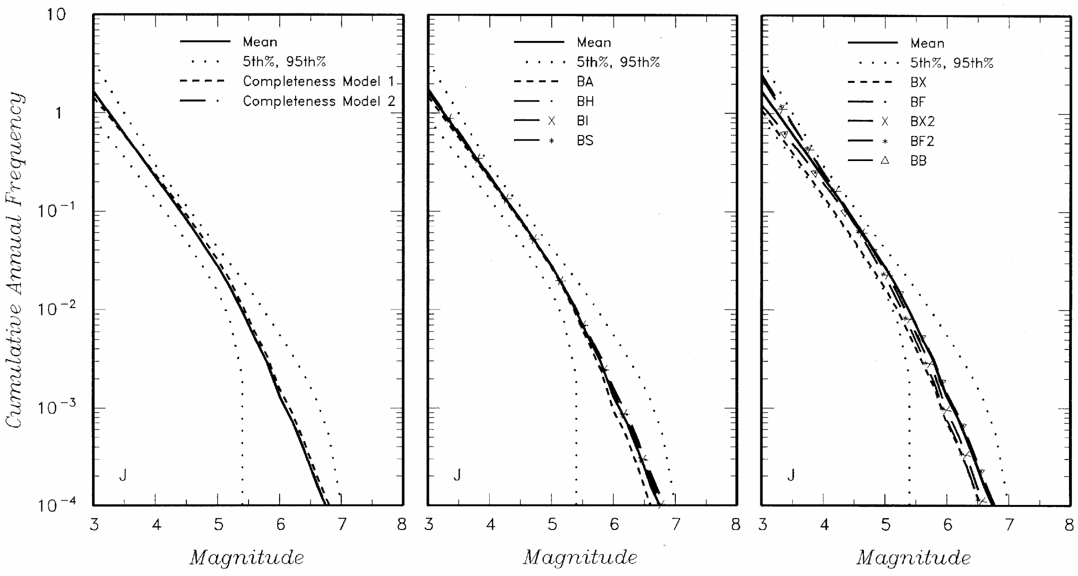


Fig.4-49: Effect of recurrence modelling approaches on mean recurrence rate for the Jura seismotectonic region (J)

Each plot shows the mean, 5th, and 95th percentile recurrence incorporating the alternative maximum magnitude distributions, the weighted modelling approaches, and the resulting joint *b*-value-$N(m_0)$ distributions.

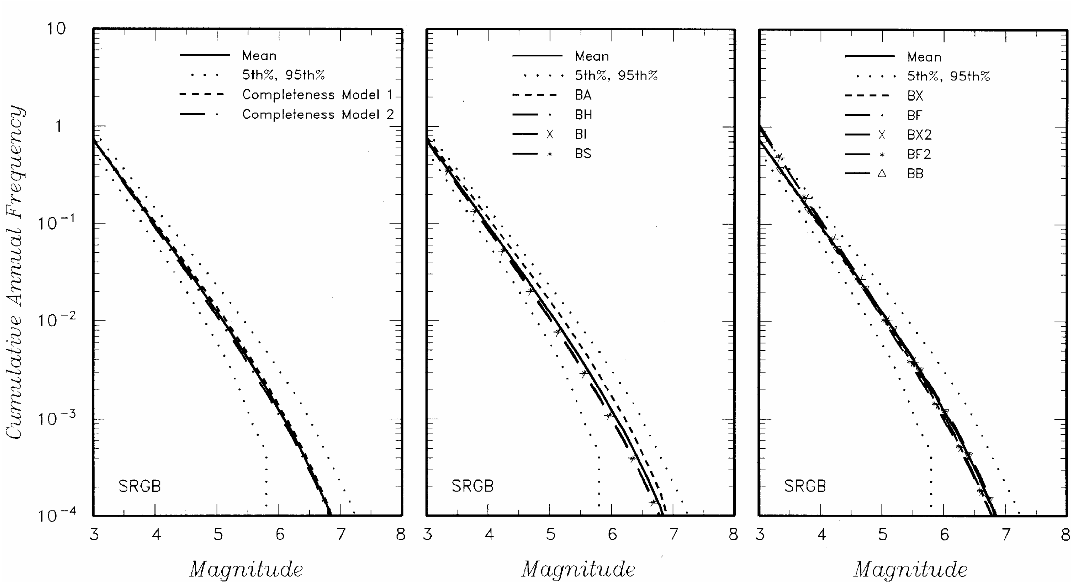


Fig.4-50: Effect of recurrence modelling approaches on mean recurrence rate for the Southern Rhine Graben/Basel Alps seismotectonic region (SRGB)

Each plot shows the mean, 5^{th}, and 95^{th} percentile recurrence incorporating the alternative zonations, alternative maximum magnitude distributions, the weighted modelling approaches, and the resulting joint b-value-$N(m_0)$ distributions.

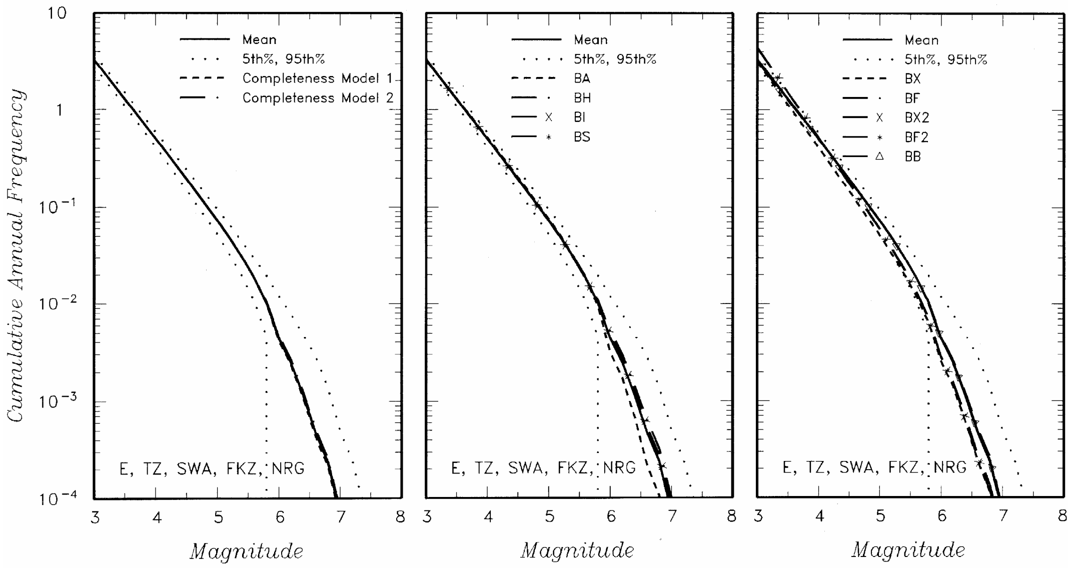


Fig.4-51: Effect of recurrence modelling approaches on mean recurrence rate for the European Background seismotectonic region (E)

Each plot shows the mean, 5^{th}, and 95^{th} percentile recurrence incorporating the alternative zonations (TZ, SWA, FKZ, NRG), alternative maximum magnitude distributions, the weighted modelling approaches, and the resulting joint b-value-$N(m_0)$ distributions.

4.5 Summary of Seismic Source Characterisation Expert Assessments

In this section we present a comparison of the seismic source characterisations developed by the four SP1 expert teams.

4.5.1 Seismotectonic Framework

The four SP1 expert teams developed their seismotectonic frameworks using similar primary elements, the reaction of the Alps and Alpine Foreland to the northwest motion and counter-clockwise rotation of the Adria microplate. Figure 4-52 compares the primary seismotectonic regions identified by the four teams. There was overall agreement among the four SP1 teams on the general seismotectonic framework for the region and the four teams identified similar main seismotectonic elements: the Rhine Graben, the Jura / Molasse regions, Helvetic and Crystalline subdivisions of the Alps, and the southern Germany region.

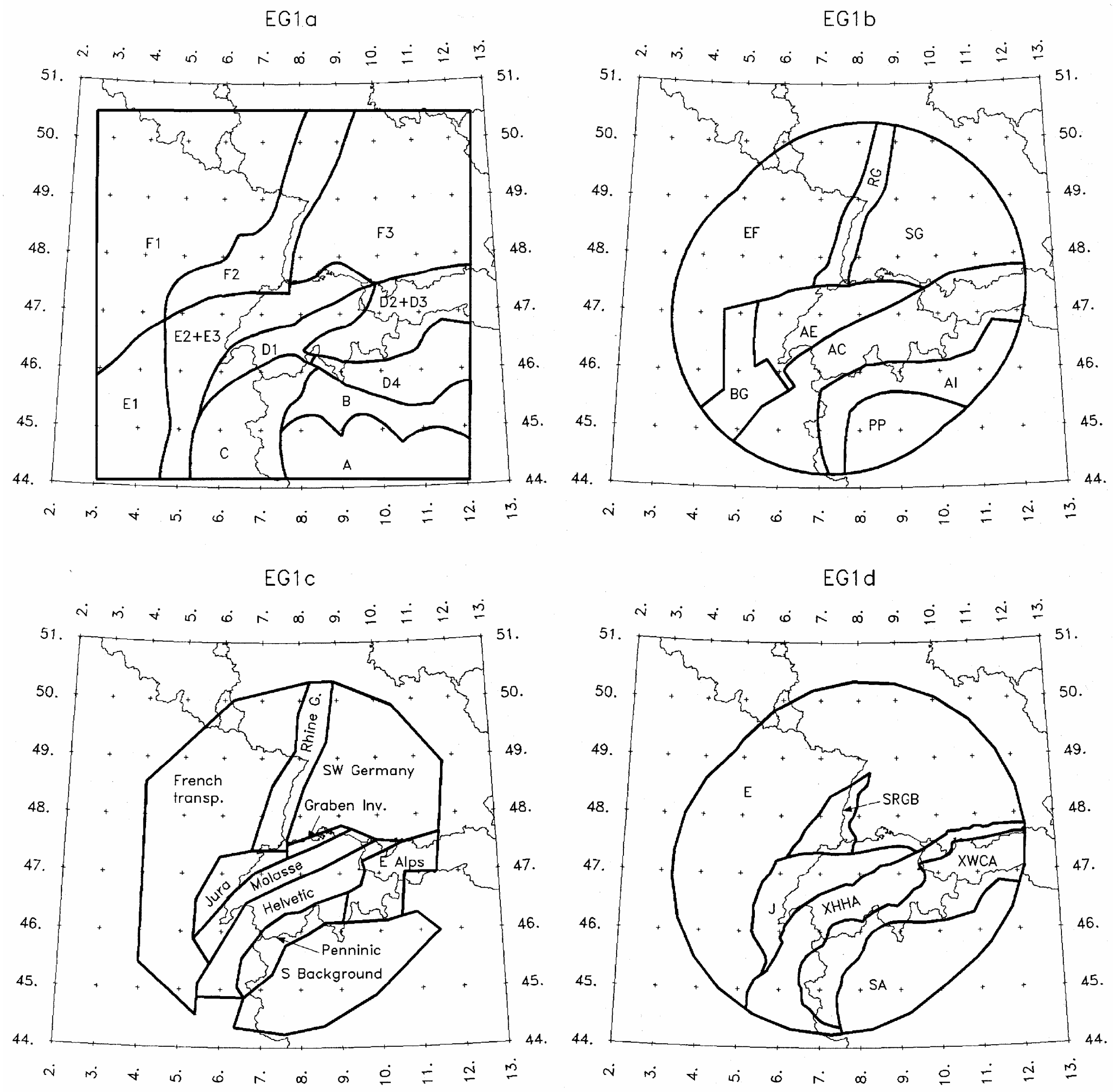


Fig.4-52: Comparison of the primary seismotectonic regions developed by the four SP1 expert teams

4.5.2 Seismic Source Definition

The four SP1 expert teams developed seismic sources using somewhat different approaches. Teams EG1a and EG1c subdivided their seismotectonic regions into sources with interpreted homogeneous characteristics. Team EG1a used two approaches, one employing large regional zones (shown on Figure 4-52) and spatial smoothing of seismicity, and one in which the large regional zones were subdivided into smaller homogeneous regions. Team EG1d used the seismotectonic elements shown on Figure 4-52, with three levels of spatial smoothing. They also introduced some additional subdivisions of the larger seismotectonic elements. Figure 4-53 shows the maximum level of individual source zone definition developed by the four SP1 expert teams.

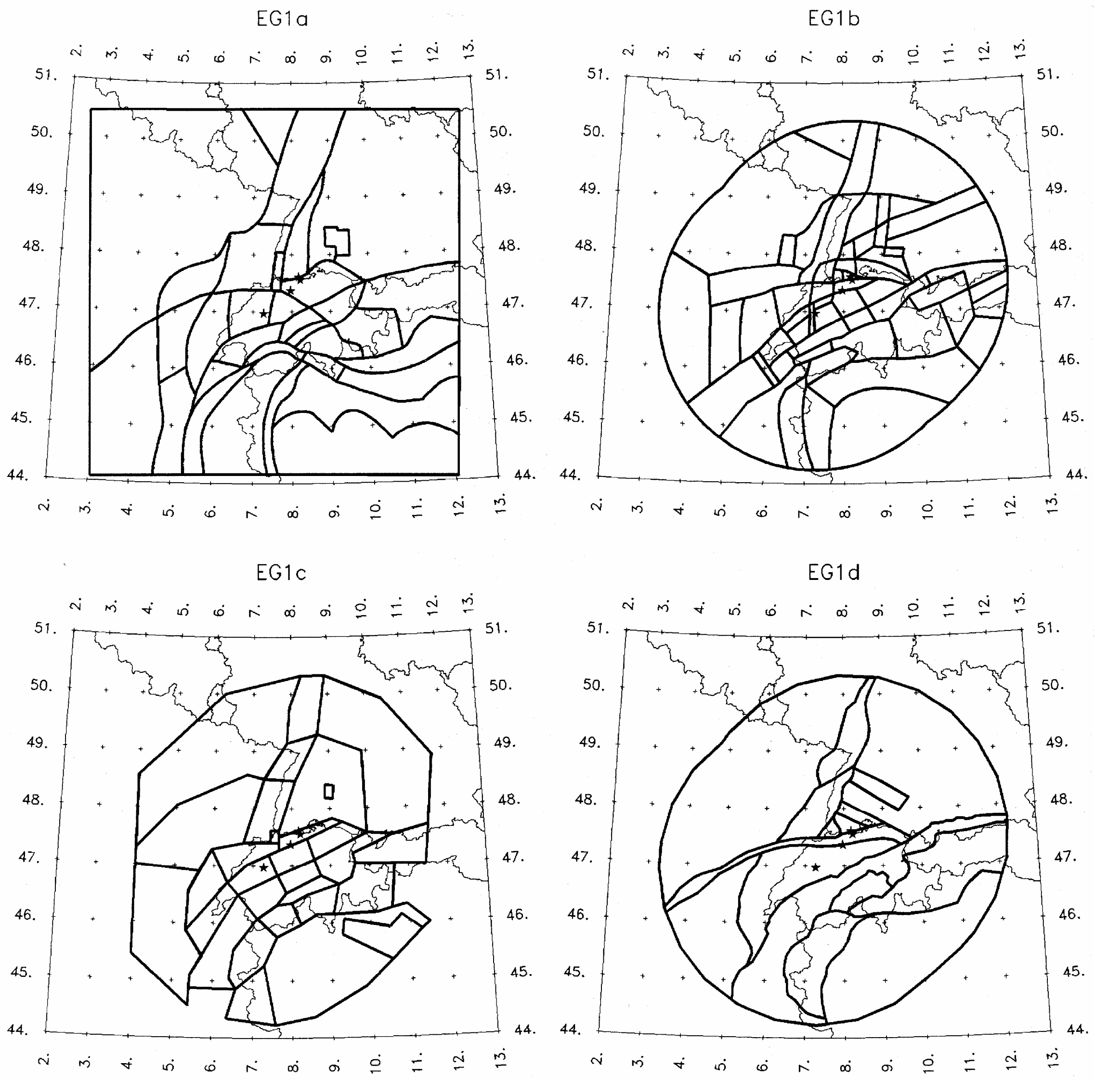


Fig.4-53: Comparison of the most detailed seismic source definition developed by the four SP1 expert teams

The stars show the locations of the four NPP sites

All of the teams discussed the issue of identification of feature-specific seismic sources (i.e. individual mapped faults). Three of the teams concluded that no identified feature was more likely to be the locus of earthquake activity than adjacent similar features. Team EG1a introduced the Reinach and Fribourg faults as potential fault-specific seismic sources with weights of 0.07 and 0.35, respectively, of being seismic sources. Team EG1b did define a seismic source zone (AE7) that essentially represents the Fribourg fault as defined by team EG1a.

The teams also addressed the issue of reactivation of the boundary faults of the Permo-Carboniferous grabens. Teams EG1a and EG1c included source zone alternatives specifically defined to represent the Permo-Carboniferous graben structures as seismic source elements. The EG1b team considered reactivation of Permo-Carboniferous structures in defining the preferred orientation of faulting. Team EG1d discussed the Permo-Carboniferous structures as one potential set of features that may be undergoing reactivation in the present stress field, but did not include specific source elements to represent them.

Other important seismic source definition elements are the specification of earthquake rupture dimensions and the earthquake depth distribution. Figure 4-54 compares the relationships between the mean rupture length and earthquake magnitude specified by the SP1 expert teams for seismic sources in Northern Switzerland. These were defined in terms of a relationship between earthquake magnitude and rupture area and length-to-width aspect ratio. The break in slope represents the point when the rupture width times the sine of fault dip equals the maximum seismogenic thickness of the crust. For larger magnitudes, the teams specified that the rupture length be computed by dividing the fault area by the maximum fault width. The differences are primarily due to the larger length:width aspect ratio specified by team EG1d (2.5:1 compared to 1:1) and the greater maximum crustal thickness (45 km compared to 30 km).

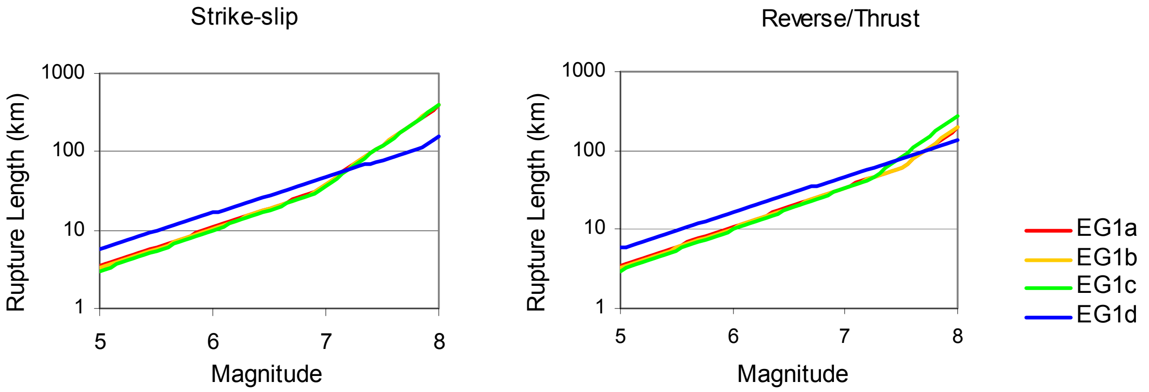


Fig.4-54: Comparison of relationships between mean rupture length and earthquake magnitude specified by the four SP1 expert teams for Northern Switzerland

Figure 4-55 compares the depth distributions for earthquakes in seismic sources in Northern Switzerland specified by the four teams. These distributions represent the distributions based on small earthquakes adjusted for the effect of rupture size using the method proposed by *Toro* (*2003b, TP1-TN-0373*). At larger magnitudes, the depth distributions for expert team EG1d extend to shallower depths than those of the other teams because of the narrower rupture widths resulting from the specified length:width aspect ratio of 2.5:1.

4.5.3 Maximum Magnitude

All of the expert teams used the "EPRI" approach for assessing maximum magnitude. Expert team EG1a included alternative estimates based on the "Kijko" approach and expert team EG1b reviewed considered estimates based on the "Kijko" approach in defining their maximum magnitude distributions. The teams used either solely the extended-crust prior distribution or a mixture of the extended- and non-extended crust priors (depending on location) developed by Johnston et al. (1994).

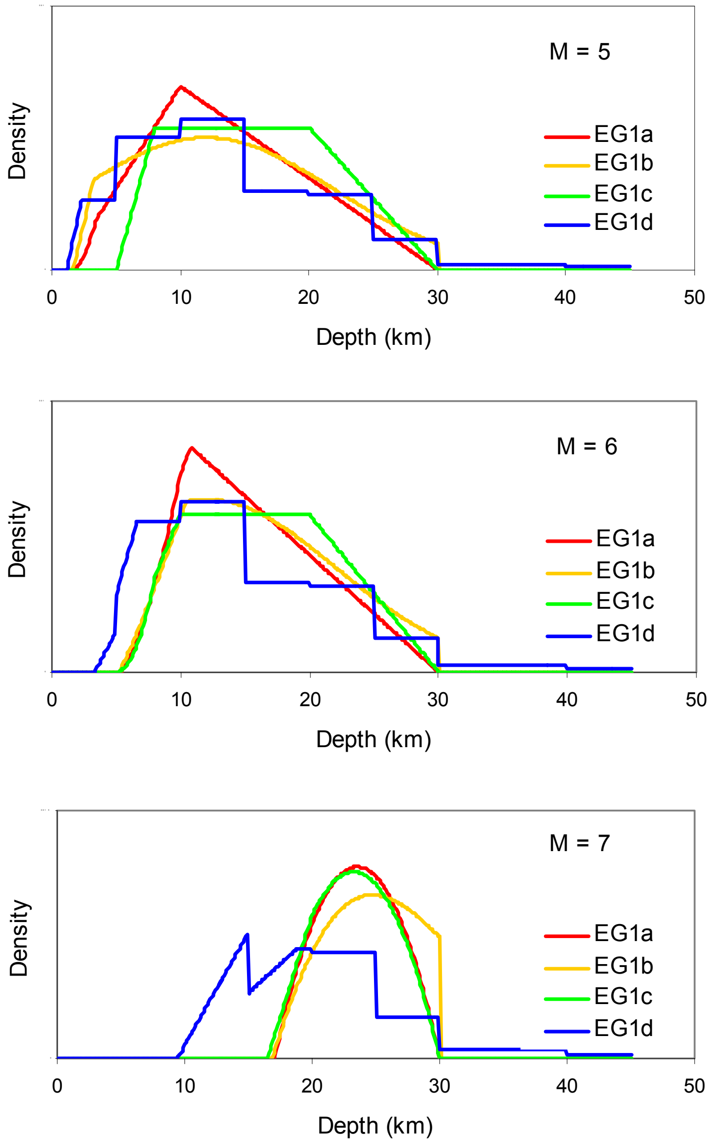


Fig.4-55: Comparison of earthquake hypocentre depth distributions specified by the four SP1 expert teams for Northern Switzerland

All of the teams introduced an upper-tail truncation of the prior distributions to reflect their interpretations of the upper limit of possible ruptures in the region. These truncation points were either source-specific (teams EG1a and EG1b) or general (teams EG1c and EG1d). Figures 4-56, 4-57 and 4-58 compare the maximum magnitude distributions developed by the SP1 expert teams for three areas: Basel, Fribourg, and Northern Switzerland near the border with Germany. The maximum magnitudes have been grouped into ½ magnitude unit bins. The distributions for Basel incorporate the possibility that the 1356 earthquake occurred in the seismic source to the south.

4.5.4 Earthquake Recurrence

Earthquake Catalogue Analysis

All four expert teams used the PEGASOS catalogue for estimating earthquake recurrence parameters. The teams evaluated alternative declustering approaches. Expert team EG1d developed initial recurrence parameter estimates using the results of three declustering approaches.

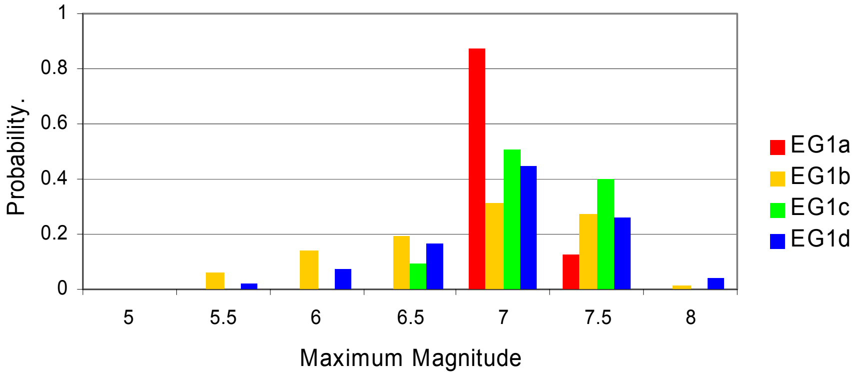


Fig.4-56: Comparison of maximum magnitude distributions developed by the four SP1 expert teams for the Basel region

The specific seismic sources are: EG1a – macrozone F2; EG1b – weighted average for RG, RG1, and RG1 + AE1; EG1c – BASL; EG1d – weighted average for SRGB_lg, SRGB_sm, B_lg, and B_sm.

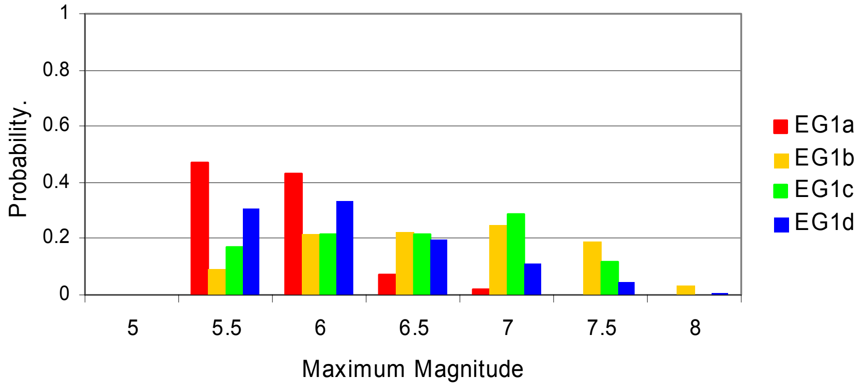


Fig.4-57: Comparison of maximum magnitude distributions developed by the four SP1 expert teams for the Fribourg region

The specific seismic sources are: EG1a – macrozone E2 + E3; EG1b – weighted average for AE and AE7; EG1c – FRIB; EG1d – J.

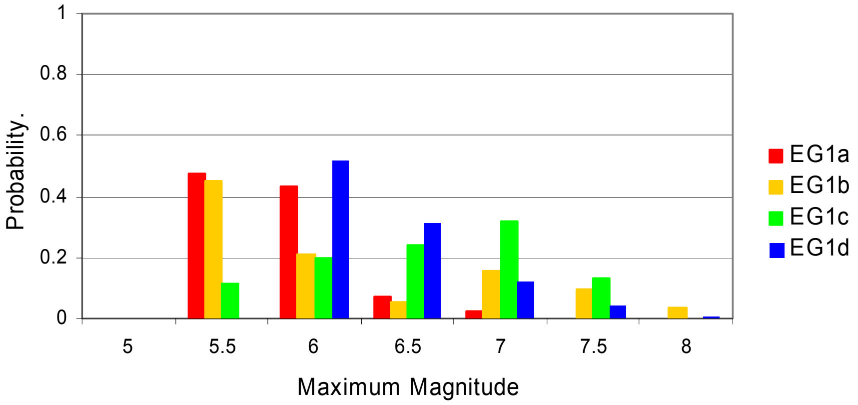


Fig.4-58: Comparison of maximum magnitude distributions developed by the four SP1 expert teams for Northern Switzerland near the border with Germany

The specific seismic sources are: EG1a – macrozone E2+E3; EG1b – weighted average for AE, AE2, AE1+AE2, and AE1+AE2+AE13; EG1c – weighted average for BLAF and NSPG; EG1d – weighted average for E and E-TZ.

After reviewing the recurrence rates and the results of sensitivity analyses performed using the recurrence parameters developed using the alternative declustering approaches, expert team EG1d concluded that the differences were small and that the Gardener & Knopoff (1974) approach using the time and distance windows developed for Europe by Grünthal (1985, 2002 personal communication) was their preferred approach. Expert teams EG1a and EG1b also used this approach for declustering the catalogue. Expert team EG1c used its own approach for declustering.

Each team developed estimates of catalogue completeness. Teams EG1a, EG1b, and EG1d relied primarily on a version of "Stepp" plots to assess catalogue completeness (e.g. Figure 4-21). Team EG1c combined this method with a historical analysis to develop estimates of catalogue completeness. Figure 4-59 compares the catalogue completeness estimates for Northern Switzerland developed by the four teams. Team EG1c developed separate estimates for northwestern and northeastern Switzerland (see Figure 4-44) and team EG1d developed two sets of completeness estimates.

The potential for a change in seismicity rate at about 1975 was explicitly incorporated as an alternative conceptual model in the recurrence parameter estimates developed by expert teams EG1a and EG1b. The effect of this alternative model was most pronounced for seismic sources in the Helvetic Alps (seismotectonic region D1 for EG1a, see Figure 4-38, and seismotectonic region XHHA for EG1d, see Figure 4-48).

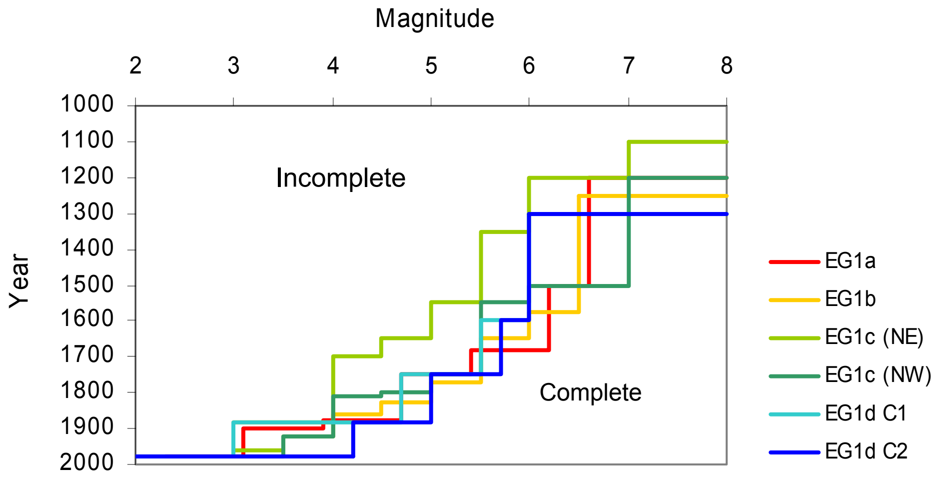


Fig.4-59: Comparison of earthquake catalogue completeness estimates for Northern Switzerland developed by the four SP1 expert teams

Earthquake Recurrence Estimates

All four expert teams used the truncated exponential mode (Equation 4-10) to represent the earthquake recurrence for individual seismic sources. Distributions for earthquake recurrence parameters were developed primarily using the relative likelihood methods described in section 4.1.3.1.

Figure 4-60 compares the overall predicted earthquake recurrence rates for the study region developed by the four expert teams. These predicted recurrence rates incorporate the full distribution of seismic source alternatives, maximum magnitude distributions, and recurrence parameter distributions that represent each team's seismic source model. The predicted mean seismic moment rates for the study region are listed in Table 4-8. Note that there are slight differences in the area covered by each model (Figure 4-52). The predicted recurrence rates and mean seismic moment rates are very similar.

Tab.4-8: Predicted seismic moment rates for study region based on SP1 expert team models

Expert Team	Mean Seismic Moment Rate (dyne-cm/year)
EG1a	2.1×10^{24}
EG1b	1.9×10^{24}
EG1c	2.1×10^{24}
EG1d	1.7×10^{24}

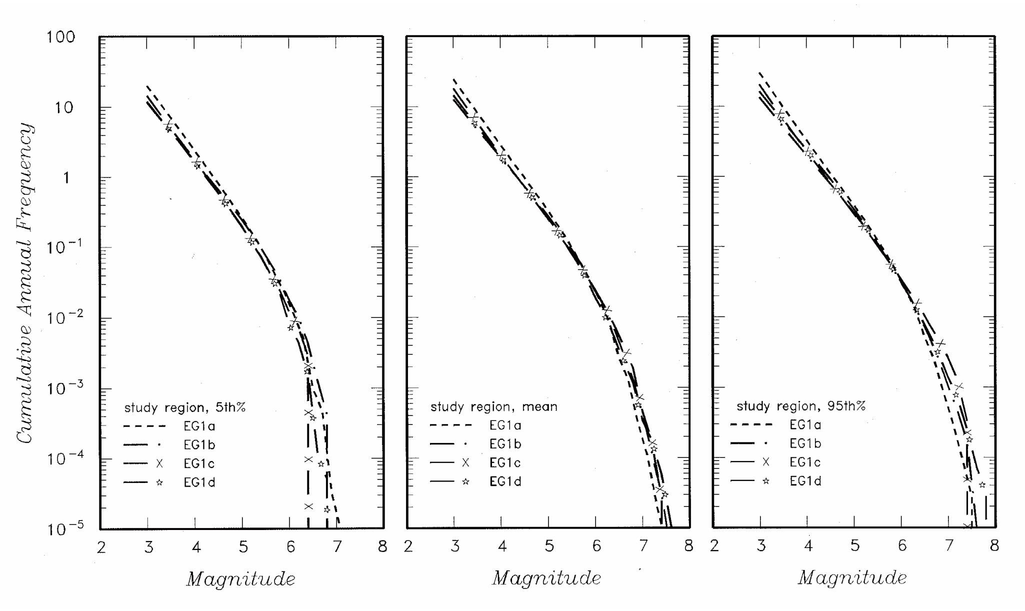


Fig.4-60: Comparison of predicted earthquake recurrence rates for the region covered by each expert team's seismic source model

Figures 4-61, 4-62 and 4-63 show the spatial distribution for the mean frequency of earthquakes exceeding M 5, 6, and 7, respectively, predicted by each expert team's seismic source model. These maps incorporate the alternative spatial distribution models developed by the expert teams. The white areas on Figure 4-63 for expert teams EG1a and EG1b indicate regions where the largest value of maximum magnitude is equal to, or slightly less than, M 7. It is interesting to note that the seismic source models for team EG1c, based on small-scale source zones with uniform spatial distributions of seismicity, and team EG1d, based primarily on large-scale zones with spatial smoothing, produce very similar spatial distributions of the mean frequency of earthquakes.

As indicated in presentations at WS-4, the seismic hazard is largely due to nearby earthquakes. Figures 4-64 and 4-65 show comparisons of the predicted earthquake recurrence rates with distances of 25, 50, and 100 km from the Beznau and Mühleberg plant sites, respectively. Comparisons are shown for the mean, 5th percentile, and 95th percentile cumulative frequency of earthquakes. The relative order of the predicted earthquake frequencies varies somewhat between the two sites and over the different distance ranges. The relative order is consistent with the relative order of the individual SP1 expert team seismic hazard results shown in chapter 8.

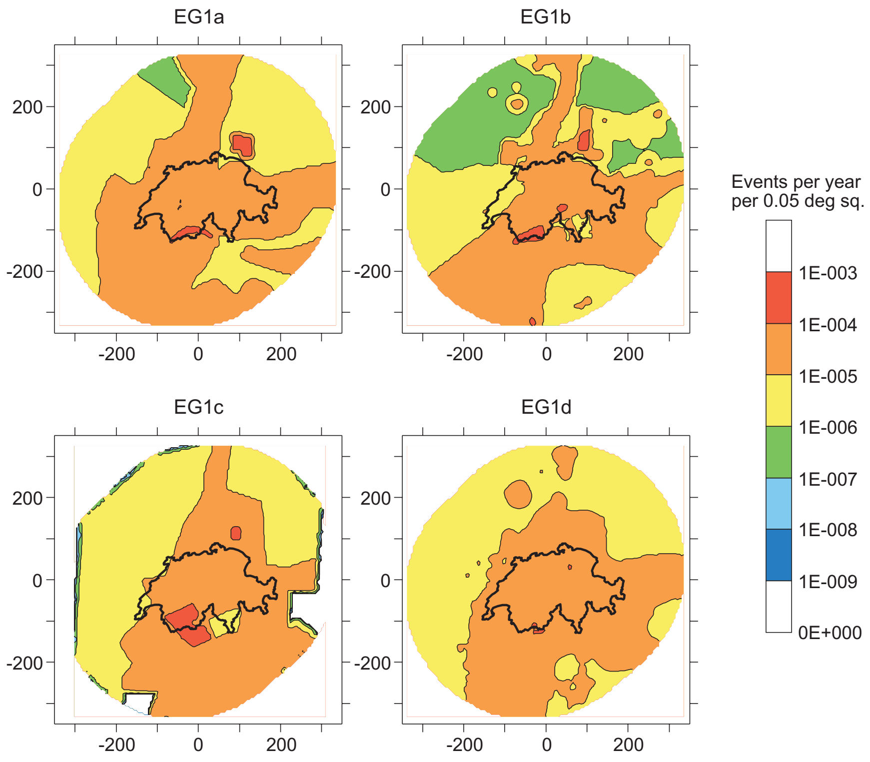


Fig.4-61: Spatial distribution of the mean frequency of earthquakes with magnitudes ≥ M 5 Units are earthquakes per year per 0.05° longitude × 0.05° latitude

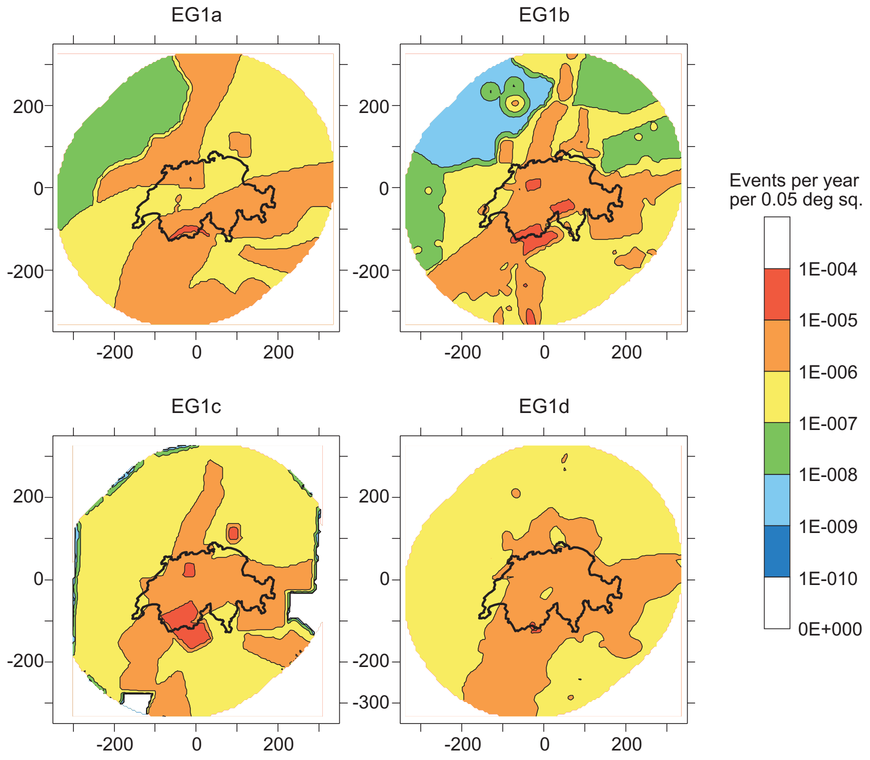


Fig.4-62: Spatial distribution of the mean frequency of earthquakes with magnitudes ≥ M 6 Units are earthquakes per year per 0.05° longitude × 0.05° latitude

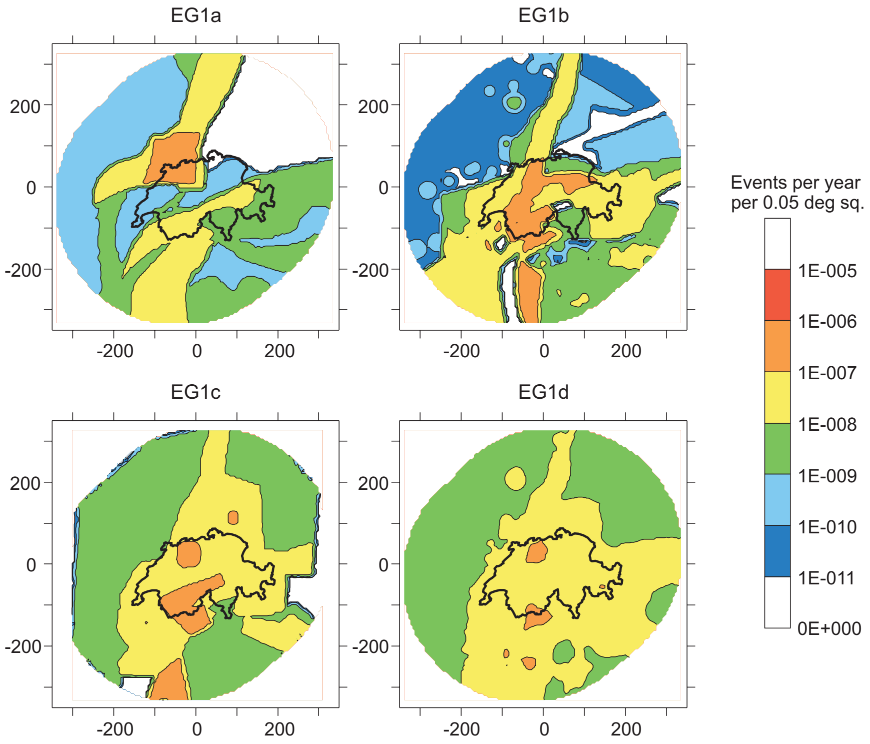


Fig.4-63: Spatial distribution of the mean frequency of earthquakes with magnitudes ≥ M 7 Units are earthquakes per year per 0.05° longitude × 0.05° latitude

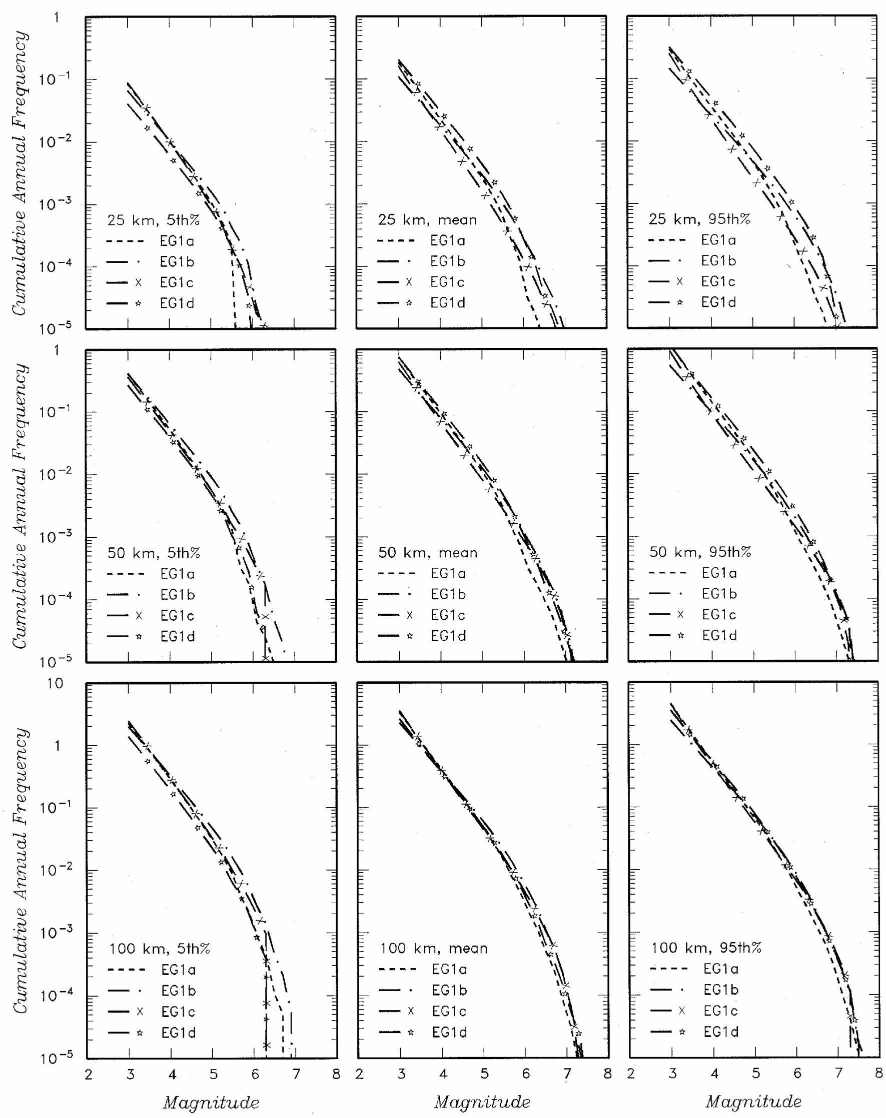


Fig.4-64: Comparison of mean, 5th and 95th percentile cumulative earthquake frequencies predicted by the four SP1 expert teams' seismic source models within 25, 50, and 100 km of the Beznau site

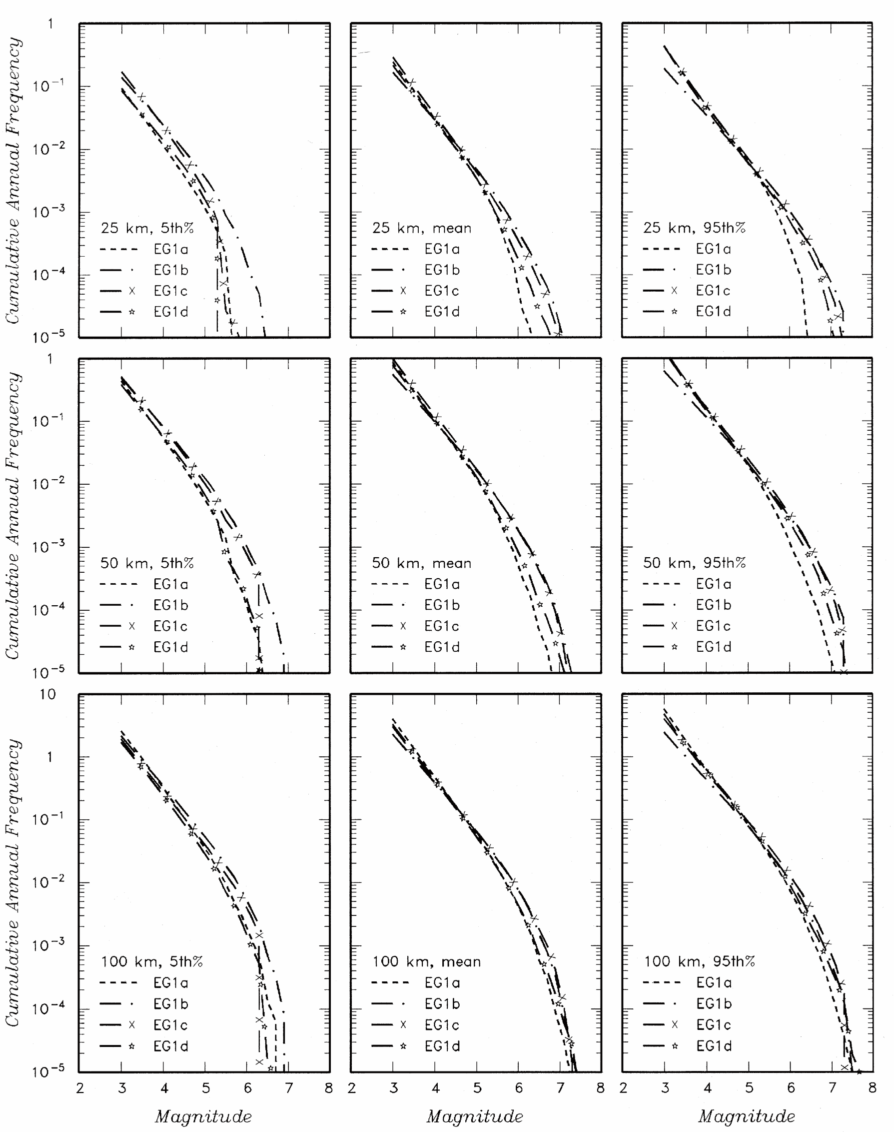


Fig.4-65: Comparison of mean, 5th and 95th percentile cumulative earthquake frequencies predicted by the four SP1 expert teams' seismic source models within 25, 50, and 100 km of the Mühleberg site

5 GROUND MOTION CHARACTERISATION

5.1 Ground Motion Characterisation Methodology

5.1.1 Ground Motion Characterisation Requirements (Median H, median V/H, Aleatory H, Maximum H, Maximum V, Upper tail)

The SP2 experts were tasked with developing ground motion models for horizontal acceleration response spectral values and vertical / horizontal response spectral ratios at 5 % damping as a function of earthquake magnitude, site-to-source distance and style of faulting. The models were required to be applicable to a reference rock site condition in Switzerland. The project specified that the expert models be based on moment magnitude to be consistent with the seismic source characterisation, but the selection of the distance measure was left to the experts. The models were required to be applicable to the magnitude range of 5.0 to 7.5, distances up to 200 km, and all styles of faulting (strike-slip, reverse and normal). Eight spectral frequencies plus the peak acceleration were specified. The spectral frequencies are 50 Hz, 33 Hz, 20 Hz, 10 Hz, 5 Hz, 2.5 Hz, 1.0 Hz, and 0.5 Hz.

For the horizontal component, the experts were required to develop models for the median spectral acceleration, the aleatory variability (standard deviation) of the $\log_{10}$ spectral acceleration, and the maximum spectral acceleration. The horizontal component is defined as the geometric mean of the two horizontal components. For the vertical component, the experts were required to develop models for the median V/H ratio and the maximum vertical spectral acceleration, but not for the aleatory variability. The aleatory variability was not required for the V/H ratio because the vertical UHS is computed by scaling the horizontal UHS rather than computing an independent vertical UHS (see section 2.4).

The median and aleatory variability describe a statistical distribution for the spectral acceleration for a given magnitude, distance, style of faulting, and spectral frequency. To avoid extrapolating these statistical distributions beyond their range of applicability, the experts were also required to set limits on the distributions. They were required to develop models for the maximum spectral acceleration on the horizontal and vertical components. The maximum spectral acceleration may be dependent on the magnitude, distance, and style of faulting. For the horizontal component, the experts were required to evaluate the upper tail of the ground motion distribution and develop models that describe any deviations from a log-normal distribution.

5.1.2 Approaches for Ground Motion Characterisation for Median GM

The experts were provided with a strong motion database containing European strong motion data (the WAF database, section 3.4.4). This database was available for the experts to derive new attenuation relations if desired. The experts were also provided with an extensive list of existing attenuation relations. Early in the project, the experts decided to use the existing ground motion prediction equations and not conduct regression analyses to derive new equations from the database. The exception to this approach was that a new stochastic point source model was developed based on the Swiss ground motion data.

The existing attenuation relations can be grouped into two main categories: empirical attenuation relations and simulation-based attenuation relations.

5.1.2.1 Empirical Attenuation Relations

Empirical attenuation models are ground motion prediction equations based on regression analyses of empirical strong motion data. The models are usually based on recordings of earthquakes in specific tectonic regions and thus represent the source, path, and site characteristics of that region. Models developed for the same region may have significant differences due to the subset of the data used in the regression or the parameterisation used for the prediction equation (e.g. how the model extrapolates to magnitudes and distances not well covered by the data).

There are a large number of empirical attenuation relations available. A recent summary is given by Douglas (2001). During discussions at the workshops, the experts developed a set of nine attenuation relations that they agreed were representative of the range of applicable models. These nine empirical attenuation relations are listed in Table 5-1.

The strength of the empirical attenuation relations is that they are based on observations. They do not depend on assumptions of model parameters. The weakness is that they apply only to the region from which the data were selected and to the magnitude and distance range in the data set. In the application of the models in the hazard analysis, in many cases they will need to be extrapolated beyond the range of the empirical data used to develop the models.

5.1.2.2 Numerical Simulation-Based Ground Motion Prediction Equations

Numerical simulations produce computer-generated ground motions based on models of the tectonic environment, including seismic source, travel path and site effects. The suite of computed motions is then used in a regression analysis to develop the ground motion prediction equation. There are two main classes of numerical simulations: point source models and finite source models. Point source models are the simplest and have the fewest number of model parameters. This is the most widely used numerical simulation model for predicting ground motions.

In the stochastic model, the numerical simulation is used to compute the Fourier amplitude spectrum and the duration of the shaking. Random vibration theory is then used to convert the Fourier amplitude and duration to response spectral values. Since random vibration theory is used, these numerical simulation models are called "stochastic" models.

Region-specific attenuation of the Fourier amplitude with distance is often determined empirically using recordings from small earthquakes. The duration is either computed using simple analytical models or using region-specific models based on empirical observations.

The scaling of the Fourier amplitude and the duration with earthquake magnitude is based on analytical models of source scaling. The most commonly used source scaling model is the omega-squared spectrum.

The major source of uncertainty is in the selection of the median stress drop and its possible magnitude dependence. Finite source simulations are far more complex and vary significantly in the seismological approaches used to estimate ground motion and in the number of parameters required. These differences can lead to considerable variation in predicted ground motions. The five numerical models selected by the experts are also listed in Table 5-1.

5.1.2.3 Magnitude Conversion

Unless the attenuation relation is project-specific from inception, conversion factors are often needed to account for differences in the parameterisation of the various attenuation relations. As shown in Table 5-1, the candidate equations use different measures of magnitude, distance, and horizontal component. The magnitude scales used in the candidate models include M_w, M_s, M_L, and M_{JMA}. The hazard calculation uses M_w. Therefore, approaches were needed to convert the models to a common M_w magnitude. Several empirically based magnitude conversion relations were available to the experts. These are summarised in Table 5-2. As an example, the alternative magnitude conversions from M_s to M_w are shown in Figure 5-1. The largest effects of the magnitude conversion are for the smaller magnitudes.

Tab.5-1: Candidate equations for prediction of horizontal median motions

Model	Method	Region	Mag	Dist [1]	Horiz Comp
Abrahamson & Silva (1997)	Empirical	WUS	M_w	R_{rup}	Geo
Ambraseys et al. (1996)	Empirical	Europe	M_s	R_{jb}	Larger-env
Ambraseys & Douglas (2000)	Empirical	WUS	M_s	R_{jb}	Larger-env
Atkinson & Boore (1997)	Numerical	EUS	M_w	R_{hyp}	Both
Berge-Thierry et al. (2000)	Empirical	Europe	M_s	R_{hyp}	Both
Boore et al. (1997)	Empirical	WUS	M_w	R_{jb}	Geo
Campbell & Bozorgnia (2003)	Empirical	WUS	M_w	R_{seis}	Geo
Lussou et al. (2001)	Empirical	Japan	M_{JMA}	R_{hyp}	Both
Sabetta & Pugliese (1996) [2]	Empirical	Italy	M_s, M_L	R_{jb}, R_{epi}	Larger-PGA
Somerville et al. (2001)	Numerical	EUS	M_w	R_{jb}	Geo
Spudich et al. (1999)	Empirical	Exten	M_w	R_{jb}	Geo
Toro et al. (1997)	Numerical	EUS	M_w	R_{jb}	Geo
Bay (2002a)	Numerical	Swiss	M_w	R_{jb}	
Rietbrock (2002)	Numerical	Swiss	M_w	R_{jb}	

[1] Distances defined as in Abrahamson & Shedlock (1997)
[2] Equations presented for both distance metrics

Tab.5-2: Summary of magnitude conversion relations considered by the experts

Type	Conversion relation	Formula
$M_S - M_w$	Free (1996)	$M_S = -3.872 + 2.071\ M_w - 0.076\ M_w^2$
	Ambraseys & Free (1997)	$M_S = -5.780 + 2.567\ M_w - 0.108\ M_w^2$
	Bungum et al. (2003)	$M_S \leq 6.5$: $M_S = -7.176 + 3.062\ M_w - 0.148\ M_w^2$ $M_S > 6.5$: $M_S = M_w$
	Ekström & Dziewonski (1988)	$M_S \leq 6.1$: $M_S = -3.391 + 1.563\ M_w$ $M_S > 6.1$: $M_S = M_w$
	PEGASOS catalogue report *SED (2002, EXT-TB-0043)*	$M_S \leq 6.1$: $M_S = -2.52 + 1.37\ M_w$ $M_S > 6.1$: $M_S = M_w$
	Equivalence	$M_S = M_w$
$M_{JMA} - M_w$	Fukushima (1996)	$M_{JMA} = 0.91\ [-17.92 - \log(M_o^{-1} + 10^{-17} M_o^{-1/3})]$ where $M_o = 10^{1.5\,(Mw + 10.7)}$ (M_o in dyne-cm)
	Heaton et al. (1986)	$M_{JMA} = M_w$
	after Free (1996)	$M_{JMA} = -3.872 + 2.071\ M_w - 0.076\ M_w^2$
$M_L - M_w$	PEGASOS catalogue report *SED (2002, EXT-TB-0043)*	$M_L(SED) = 0.58 + 0.87\ M_w$
	PEGASOS catalogue report *SED (2002, EXT-TB-0043)*	$M_L(ING) = M_w + 0.3$
	Equivalence	$M_L(ING) = M_w$

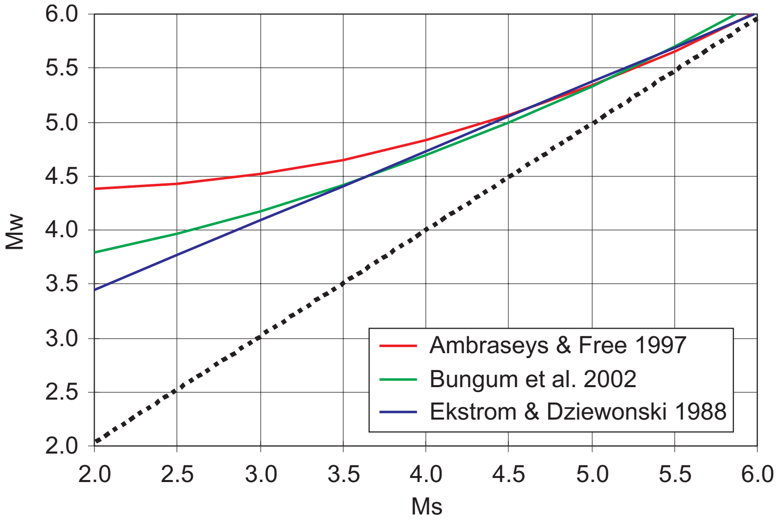


Fig.5-1: Comparison of different $M_w - M_s$ conversions

5.1.2.4 Distance Conversion

As shown in Table 5-1, the candidate models use a range of distance metrics. The Joyner-Boore (JB) distance is used by nine of the 14 candidate models. All five SP2 experts selected the JB distance measure, so the five candidate models that used other distances metrics (rupture distance, hypocentral distance, seismogenic distance) required conversion to JB distance. The distance conversions were assessed in *Bommer* (*2002, EG2-TN-0238*) and *Scherbaum & Schmedes* (*2002, EG2-TN-0256*). All five experts adopted the same distance conversion scheme as described in *Scherbaum & Schmedes* (*2002, EG2-TN-0256*). Since the conversion of the distance measures depends on the source depth distribution, the distance conversion could not be done by the SP2 experts without having the final source characterisation from the SP1 models. Therefore, the distance conversion was handled by the TFI-team using the method selected by the experts. An example of the distance conversion from hypocentral distance to JB distance is shown in Figure 5-2. The distance conversion has the largest effect for short distances.

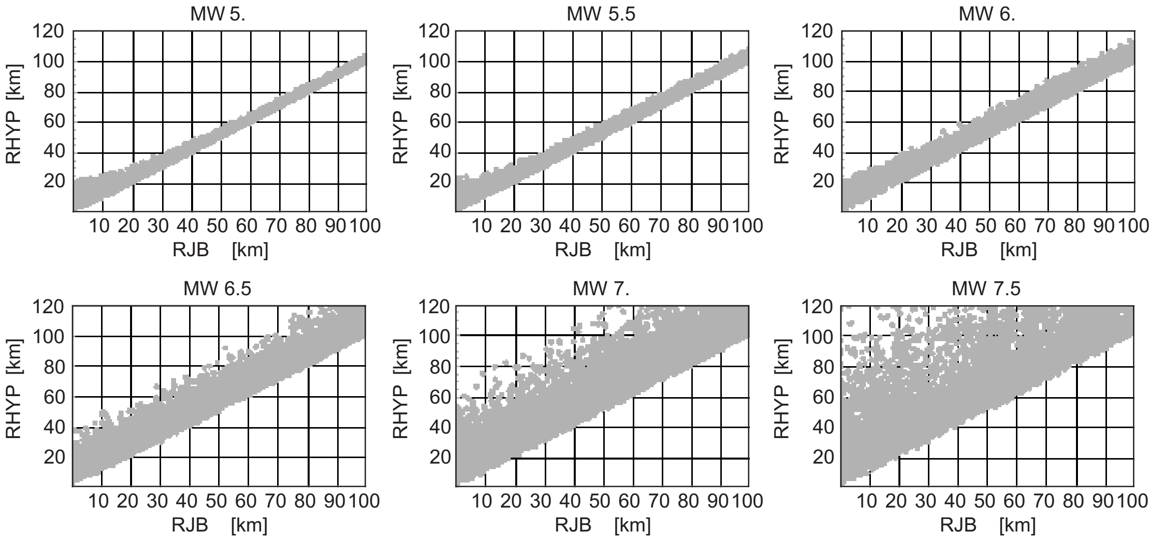


Fig.5-2: Distance conversion from hypocentral distance to JB distance. (Fig. 4 from *Scherbaum & Schmedes 2002, EG2-TN-0256*).

5.1.2.5 Component Conversion

In several instances, the ground motion component predicted by the candidate attenuation relation also required conversion. There are four different definitions of horizontal component used by the candidate equations: geometric mean of the two horizontal components, larger spectral acceleration of the two horizontal components, spectral acceleration associated with the component with the larger PGA, and both horizontal components. The project specifications required the ground motion to be estimated for the geometric mean of the two horizontal components, so candidate models using the other definitions required conversion. These conversions were addressed in *Roth* (*2002e, TP2-TN-0269*). The conversion is shown in Figure 5-3. The component conversion has only a small effect on the ground motions.

A second class of 'component conversion' is estimation of vertical motion from horizontal, where the attenuation study predicts horizontal motion only. In this case, the available tools were ratios of the two components (*Bertrand 2002, EXT-TN-0217* and *Roth & Farrington 2002, TP2-TN-0246*).

5.1.2.6 Spectral Frequencies

Many of the candidate models do not include prediction equations for all of the spectral frequencies required by the PEGASOS Project. The necessity of using more frequencies than published in several of the attenuation relations was considered by the SP2. All five experts adopted the same simple mathematical interpolation as described in *Hölker* (*2002b, TP2-TN-0270*).

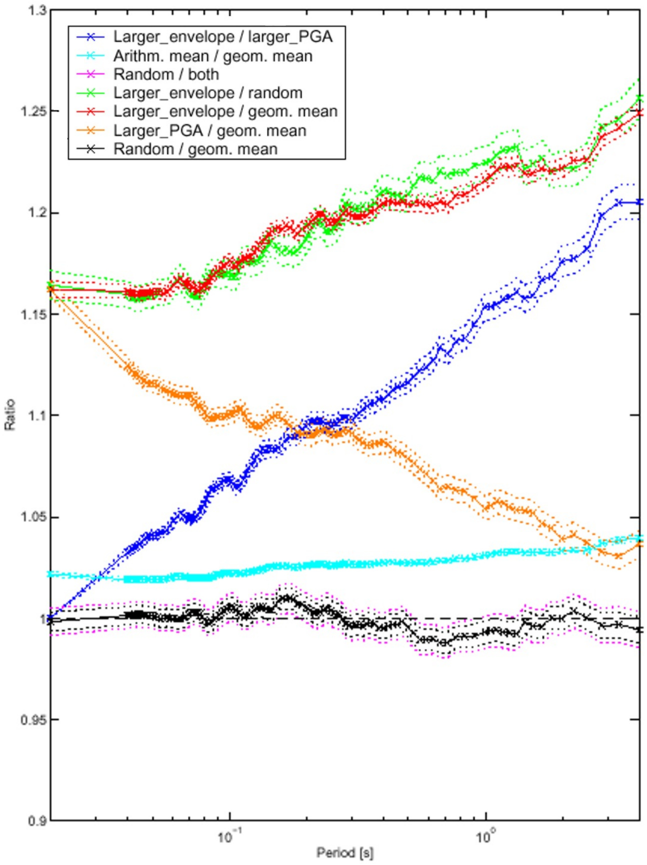


Fig.5-3: Ratios of spectral ordinates (5 % damping) from the WAF worldwide database using different definitions of the horizontal component of motion. After *Roth* (*2002e, TP2-TN-0269*).

5.1.3 Approaches for Aleatory Variability of Horizontal Ground Motion

Each of the candidate attenuation studies included estimates of aleatory variability. The aleatory variability is most often modelled as a function of spectral frequency only, but some of the recent studies also incorporate a magnitude dependence into the aleatory variability (e.g. Abrahamson & Silva 1997, Campbell 1997, Campbell & Bozorgnia 2003), with larger magnitude earthquakes leading to smaller aleatory variability .

Applying the conversion factors described above may introduce additional aleatory variability. For example, if an attenuation relation was developed using M_S for magnitude, then the conversion from M_w to M_s will have aleatory variability. If there is no correlation between the residuals based on M_s and the M_w, then there will be additional aleatory variability in the ground motion due to the aleatory variability in the magnitude conversion. On the other hand, if there is a strong correlation, then there may not be an increase in the aleatory variability of the ground motion.

The increase in the aleatory variability (assuming no correlation between the residuals and the conversion parameter) was assessed empirically for the effects of horizontal component conversions (*Hölker 2002c, TP2-TN-0307*) and assessed using numerical modelling for the effects of changes in distance metric (Scherbaum et al. 2004). Increases in the aleatory variability due to magnitude conversions were accounted for by standard propagation of error. As an example, the effect of the distance conversion from JB distance to hypocentral distance on the aleatory variability for the Berge-Thierry model is shown in Figure 5-4 (Figure 44 from Scherbaum ES).

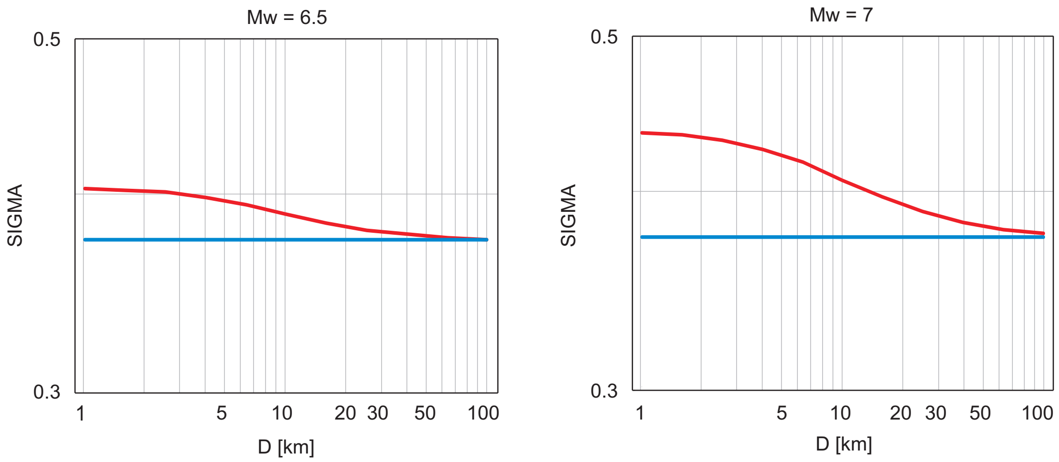


Fig.5-4: Effect of distance conversion from Joyner-Boore distance to hypocentral distance on the ground motion model variability for the Berge-Thierry ground motion model (Berge-Thierry et al. 2000)

5.1.4 Approaches for Characterisation of Maximum Ground Motion

Two approaches to characterising the maximum ground motion for a given magnitude and distance were available to the support the experts' estimates of the maximum ground motion: setting limits on the ground motion and modifying the upper tail of the ground motion variability (see section 2.5).

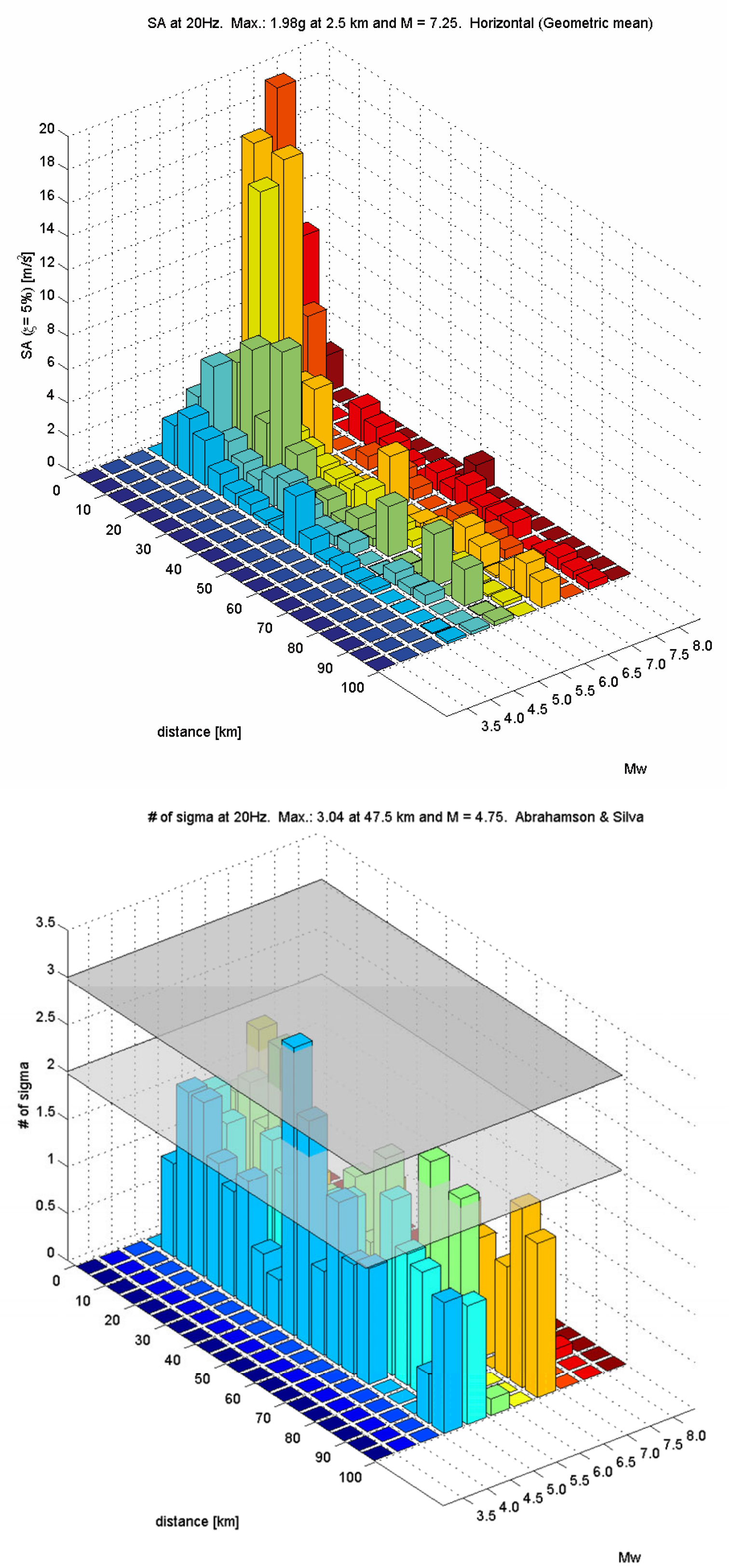


Fig.5-5: Maximum observed horizontal (geometric mean) ground motions in magnitude-distance space for a frequency of 20 Hz

The maximum value is 1.98 g at a distance of 2.5 km from a M 7.25 earthquake. The corresponding distribution of residuals is given in the lower part of the figure. After *Roth* (*2002f, TP2-TN-0309*), page 9.

Studies of empirical maxima were available to the experts. The WAF empirical database and a search tool (*Roth 2002c, TP2-TN-0245*) were provided to the experts. The dependence of the maximum recorded ground motions on the earthquake magnitude and distance were provided to the experts (*Roth 2002f, TP2-TN-0309*). Residual plots for selected attenuation relations were also available (*Hölker 2000a, RDZ-TN-0214*) and allowed direct evaluations of the applicability of the log-normal distribution using normal probability plots of the residuals. An example plot of the largest recorded spectral acceleration at 20 Hz is shown in Figure 5-5. An example of the evaluation of the applicability of the log-normal distribution at the upper tails is shown in Figure 5-6.

Since the empirical database only represents the maxima from the existing set of observations, numerical simulations were also used to consider earthquakes that have not been recorded. Initially, dynamic and kinematic models were considered for application, but the dynamic models were not advanced to the stage that they were ready for engineering applications. This is an active area of research and, in several years, dynamic models may be applicable. In this study, only kinematic models are used.

The approach of using numerical simulations to determine the maximum ground motions is intuitively appealing. It allows a physical basis for the selection of maximum ground motions. The difficulty encountered with the use of kinematic models is that the modellers themselves have been conditioned to discount extreme ground motions in the past. In the early days of numerical simulations of strong ground motions for engineering applications (in the 1980s), the simulation methods tended to overestimate the recorded ground motions. Randomness was added into the source properties to calibrate the kinematic models against recorded ground motions. These studies were focused on the median ground motions. In the PEGASOS study, the modellers were asked to consider worst-case source parameters. The modellers had difficulty with the basic concept of maximum ground motions (e.g. zero chance of being exceeded). They developed source parameter combinations (e.g. static stress drop, rupture velocity, rise-time) that they considered to be extremely unlikely, but it was difficult for them to state that a worse combination of source parameters was impossible (e.g. zero chance of occurring). The work done on the maximum ground motions in the PEGASOS Project is the most advanced study to date, but this is a topic that will be the subject of ongoing research over the next several years.

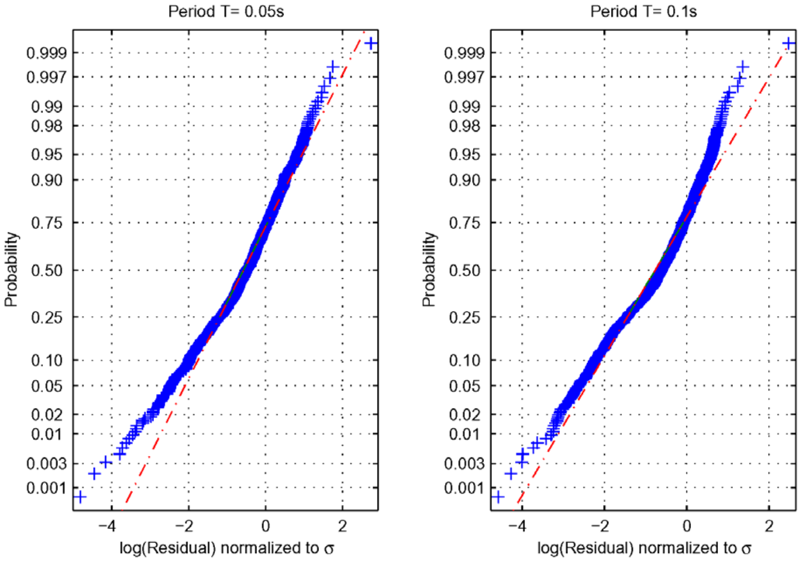


Fig.5-6: Residuals of ground motion model by Campbell & Bozorgnia (2003)

Horizontal data from Europe and the Middle East, all sources, rock (V_{S30} = 750 m/s), frequencies 20 and 10 Hz. After *Hölker & Roth (2002, TP2-TN-0231)*, page 32.

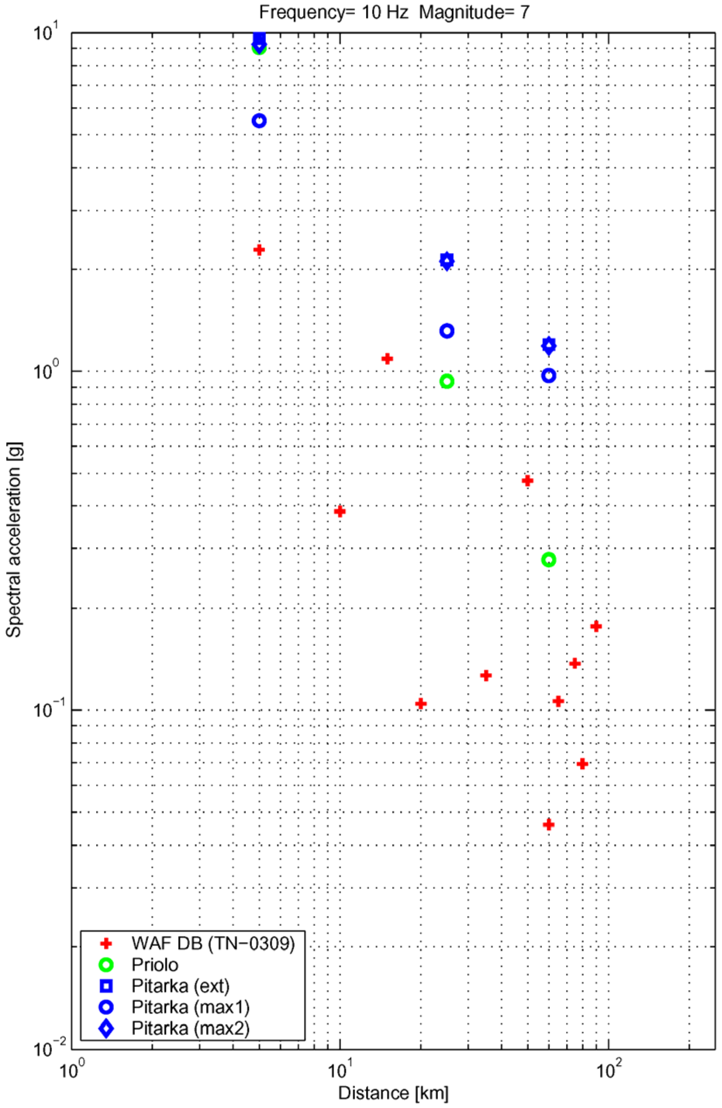


Fig.5-7: Maximum empirical and simulated ground motion data for 10 Hz and magnitude 7.0.

Modified after *Hölker & Roth* (*2003, TP2-TN-0333*).

Two numerical simulation studies were performed for the PEGASOS Project, in which upper bound motions were estimated based on limits of the earthquake source parameters (*Priolo et al. 2002a, EXT-TN-0278*, *Priolo et al. 2002b, EXT-TN-0303*, and *Pitarka et al. 2002, EXT-TN-0277*). In these studies, the modellers (Pitarka and Priolo) were asked to estimate the worst-case source properties and then compute the resulting ground motion using kinematic models. These simulations only accounted for source effects and wave propagation effects in a flat layered crustal model. Exotic focusing of waves due to 3-D velocity structure was not considered in the simulations.

An example of the maximum ground motions for a magnitude 7.0 earthquake from the kinematic simulations is shown in Figure 5-7.

5.1.5 Adjustments of Rock Spectral Accelerations to a Reference Rock Site Condition

An important issue requiring interaction between the SP2 and SP3 experts was the selection of the reference rock site condition (see section 2.3.2). The SP3 experts decided to use a reference rock site condition that had a shear wave velocity greater than the highest shear wave velocity at the depth of embedment for any of the four sites, so that SP2 rock motions could be used as the input motions into the soil profile for the site response at any of the four sites. This approach led to the selection of a shear wave velocity of 2000 m/s for the reference rock. Most of the candidate models were developed for rock velocities much less than 2000 m/s (Table 5-1), so adjustment factors were needed for all but one model (Boore et al. 1997).

The approach used to compute the adjustment factors was to conduct a suite of site response calculations for a wide range of generic site (V_s) profiles. The adjustment factor is given by the ratio of computed motion on the surface of the profile to reference rock motion. These adjustment factors correspond to the amplification factors discussed in chapter 6.

As a group, the SP2 experts established representative central, upper, and lower values for the shear-wave velocity in the upper 30 m (V_{s30}) for each candidate ground motion model (*Lacave et al. 2003, TP2-TN-0363*, table on p.2). Generic V_s profiles were developed (*Lacave et al. 2003, TP2-TN-0363*) to model the velocity profile from the surface (with a specified V_{s30} value) to a maximum of 2000 m/s at depth. The amplification factors relative to the reference rock condition were computed for each site V_s profile. An example of the site adjustment factor for a V_{s30} velocity of 750 m/s is shown in Figure 5-8.

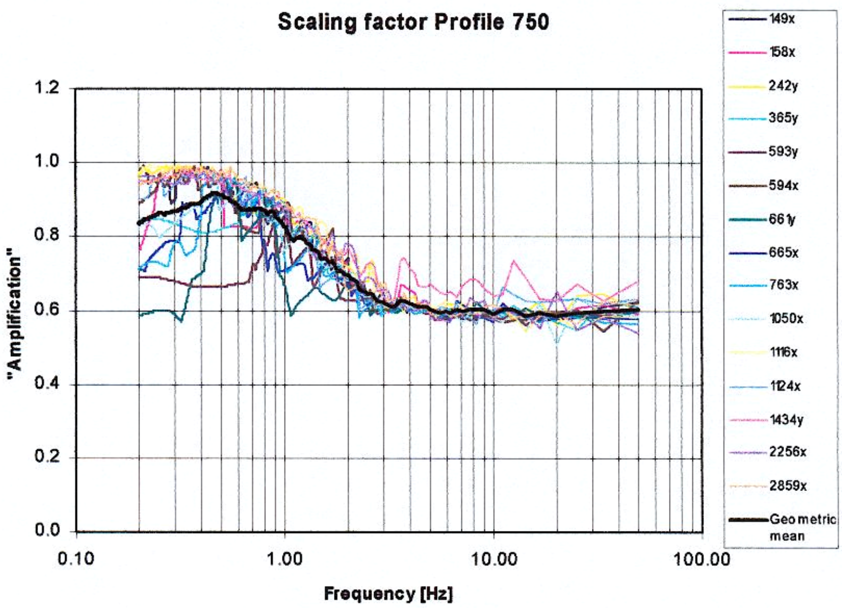


Fig.5-8: Site transfer functions calculated using time-history analysis and the generic profile for $V_{s,30}$ of 750 m/s (after *Lacave et al., 2003 TP2-TN-0363*).

While there was consensus on the range of V_{s30} values to use for each ground motion model, each SP2 expert evaluated his own weights for the central, upper, and lower V_{s30} values for each model.

5.1.6 Adjustments to Swiss Conditions

A central issue in the evaluation of the ground motion models is the question of their applicability to Switzerland, and particularly to northwest Switzerland where the NPP sites are located. As is common in regions with low seismicity rates, there are a very small number of strong ground motion recordings in Switzerland, and they are from small magnitudes ($M < 5$). Using the ground motion data available at the beginning of the project, the ground motions in Switzerland were about a factor of 3 lower than ground motions in other parts of Europe. An example is shown in Figure 5-9, in which the peak accelerations from magnitude 3.4 – 4.0 earthquakes from Switzerland are compared to peak acceleration from similar magnitude earthquakes in other parts of Europe. This comparison shows much lower peak accelerations in Switzerland.

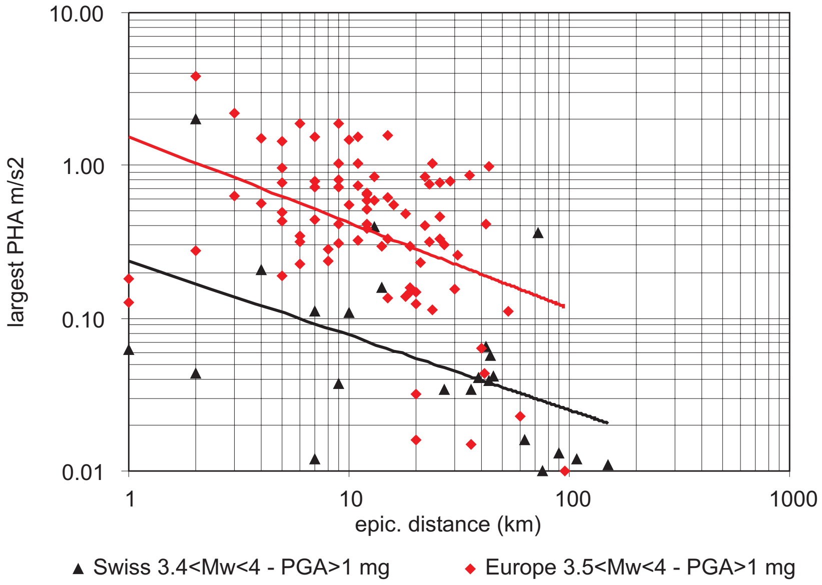


Fig.5-9: Comparison of PGA values between Switzerland and Europe in the M range 3.4 – 4.0

No site selection applied. Straight lines represent the regression performed on the data (from Sabetta's elicitation summary, see Vol.4).

The magnitude dependence of the residuals of Swiss ground motions using the candidate models were also evaluated. The residuals for 2 Hz spectral acceleration based on the Ambraseys et al. (1996) model are shown in Figure 5-10 as a function of magnitude. The residuals in this figure indicate that the bias toward smaller ground motion is reduced as the magnitude increases. Thus, an important issue is what would be the residuals for events with $M > 5$?

Bay (2002a) developed a stochastic point source model based on the recorded ground motions from strong motion and broadband network data in Switzerland. Since this model fit the Swiss ground motion data, it produced very low ground motions for small magnitude earthquakes (consistent with the data). In particular, Bay found stress drops of 5 – 10 bars for the Swiss earthquakes. Bay did not think that these low stress drops would apply to larger magnitude earthquakes, so she proposed a model with stress drop increasing as a function of magnitude and a second model with a constant 30 bars for large magnitudes.

The parameters of stochastic point source models are often highly correlated, making inversions to estimate the parameters difficult. Since the Swiss-specific model was considered an important candidate model, an independent evaluation of the point source parameters was conducted by Rietbrock using the Swiss data. The results of his inversion (*Rietbrock 2002, EXT-TN-0306*) led to higher stress drops (a mean of 49 bars), but the other parameters in the model adjusted themselves to fit the low ground motions. So while the Rietbrock model had some differences in parameters values from Bay, the predicted ground motions from the two models were similar.

The Bay model and the Rietbrock model are the only ground motion prediction equations selected for consideration by the experts that were developed specifically for Swiss conditions. The main approach used by the experts to adjust the other available ground motion models to Swiss conditions is the hybrid model (Campbell 2003). In this approach, the point source stochastic model is used to estimate scale factors between the region for which the model was developed (host region) and Switzerland (target region).

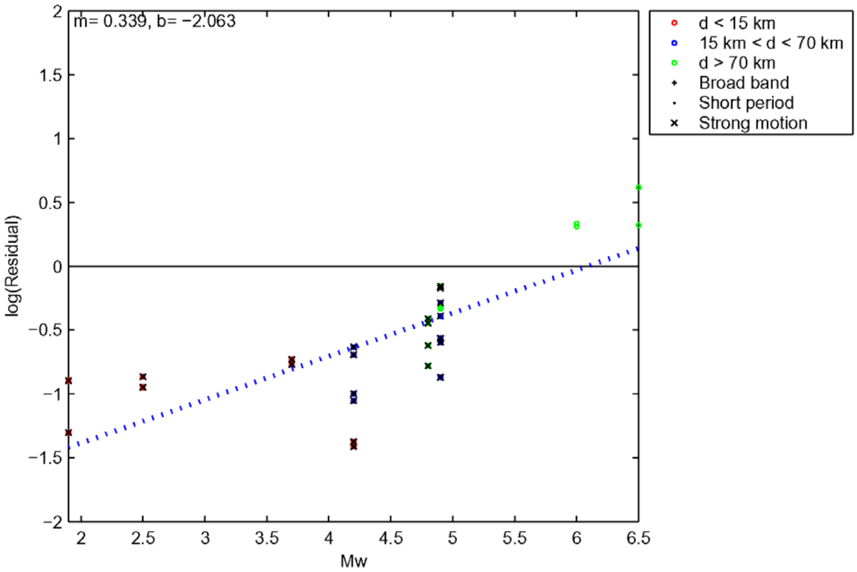


Fig.5-10: Residuals of the ground motion model of Ambraseys et al. (1996), horizontal component, with respect to magnitude, based on data from Switzerland, all sources, rock (V_{S30} = 750 m/s), period = 0.5 sec, No = 30

The point source model parameters are estimated for the host region and for the target region. Then, the ground motion is computed using the stochastic model for each set of model parameters. The ratio of the computed ground motions gives the scale factor from the host region to the target region. In this manner, the hybrid model uses the stochastic model only to compute relative differences in the ground motion models between the two regions. The region-specific and site-specific parameters of the stochastic point source model that can be adjusted using the hybrid approach are as follows: kappa, Q(f), crustal amplification factors, stress drop, and duration. The hybrid approach can be used to make adjustments for differences in one or more of these parameters.

Given the low ground motions from small magnitude earthquakes in Switzerland, the experts had to decide if this implied that the ground motions from larger magnitude earthquakes would also be low. Because of its importance, this issue was discussed several times during the project. In general, the experts did not accept that the ground motions in Switzerland should be significantly different from ground motions obtained in tectonically similar regions for magnitudes greater than 5.0 beyond corrections for the site conditions.

The M 4.8 St. Dié earthquake occurred on February 22, 2003, shortly before WS-3. This earthquake provided the experts with an important set of ground motions from a Swiss region earthquake approaching the lower limit of M5. An evaluation of the ground motions from the St. Dié earthquake showed that the recorded ground motions were consistent with the candidate attenuation relations (Figure 5-11, *Roth 2003, TP2-TN-0367*). This was important new information that the experts considered as part of their evaluation of the Swiss-specific nature of their models.

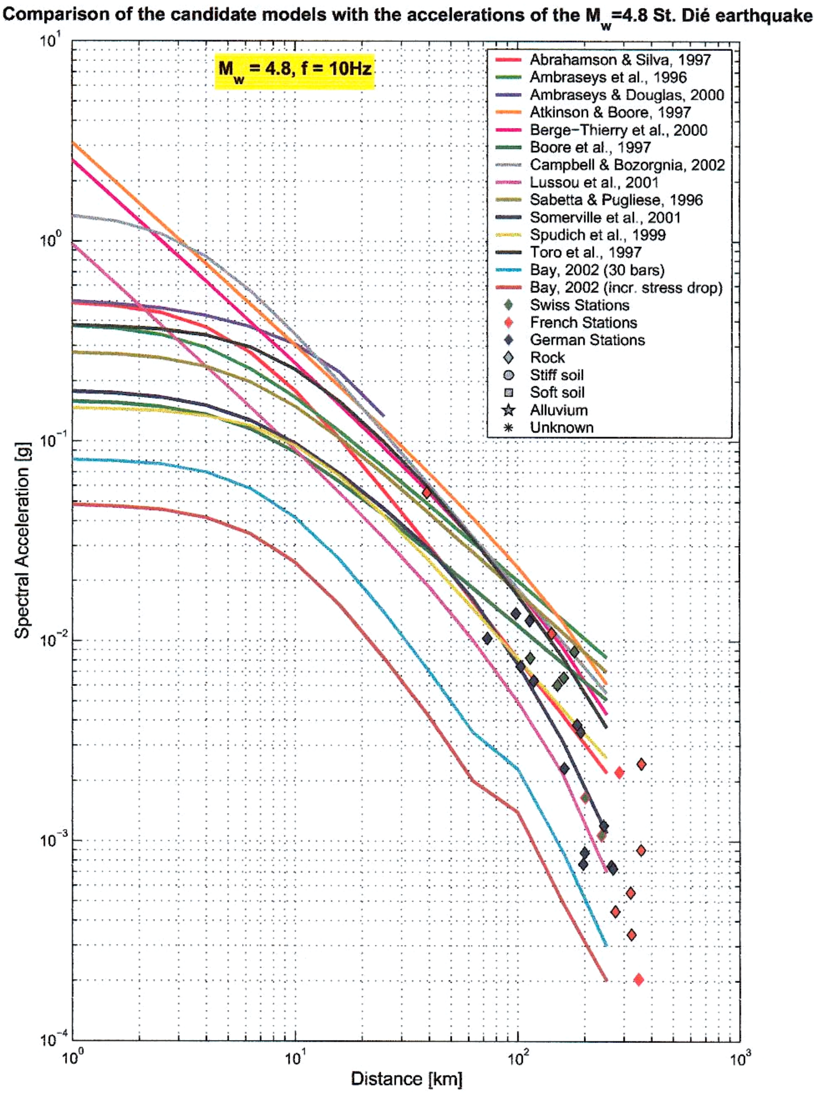


Fig.5-11: Comparison of St. Dié rock site recordings and candidate ground motion models for spectral acceleration at 0.1 second (after *Roth 2003, TP2-TN-0367*)

5.1.7 Style of Faulting

Three style of faulting types are generally considered in the SP1 source models: strike-slip, reverse and normal. Some of the candidate ground motion models include a distinction between reverse and strike-slip earthquakes, but they do not distinguish between normal and strike-slip earthquakes. Because the SP1 source models include a significant fraction of earthquakes with normal style of faulting, special studies of ground motions from normal earthquakes were considered. A special additional SP2 workshop was held following WS-4 to discuss this topic (section 5.2.6).

This topic was extensively studied as part of the Yucca Mountain ground motion characterisation because the local faults are primarily normal style of faulting. There is much less strong ground motion data from normal faulting earthquakes than from strike-slip and reverse earthquakes, which leads to large uncertainty in statistical analyses of sparse normal faulting ground motion data. As a result, different studies of the style of faulting factor for normal faulting earthquakes have come to different conclusions ranging from no difference between strike-slip and normal to 20 – 40 % lower ground motion for normal faulting earthquakes.

5.2 SP2 Workshops and Elicitation Meetings

In this volume, only key highlights of the workshops are given. The full workshop summaries are given in Volume 3 of this report.

5.2.1 WS-1 / SP2: Key Issues and Data Needs

The SP2 data needs workshop (WS-1) was held on October 16 – 18, 2001 in Zürich. All five SP2 experts attended the full workshop. This workshop was held concurrently with the SP1 and SP3 data needs workshops. Two common sessions were held: a general session with all three subprojects that introduced the project, and a session focused on the interface between SP2 and SP3 that was attended by SP2 and SP3 experts.

During WS-1, the SP2 experts reviewed the alternative approaches for ground motion characterisation:

- Use existing attenuation relations
- Develop new empirical attenuation relations
- Develop new numerical simulation-based attenuation relations
- Use the hybrid approach to modify existing attenuation relations.

Developing a new empirical attenuation relation is a major task and since there was not a significant increase in the empirical database of European strong ground motions, the experts concluded that a new model would not be significantly different from the existing models based on European data. The experts reached a consensus that new empirical attenuation models should not be developed for the PEGASOS Project. Instead, existing attenuation relations would be used. The option for considering modifications to the existing attenuation relations using the hybrid approach, described below, was left open.

The numerical simulations are grouped into point source models and finite source models. The most widely used approach is the point source omega-squared stochastic model (referred to here simply as the "stochastic model", see section 5.1.2.2). Finite source models require many additional source parameters. The experts reached a consensus that a Swiss-specific stochastic model should be considered, but that finite source models would not be considered for the prediction of the median ground motion. (Finite source models are considered in the evaluation of the maximum ground motion). The application of the stochastic model requires estimating several parameters for Switzerland: stress parameters, geometrical spreading, Q, kappa, and crustal amplification.

The experts learned that Bay was working on a study to estimate these parameters using both strong motion (from M3 – M4 earthquakes) and weak motions from broadband regional recordings from earthquakes in Switzerland. In her preliminary results, Bay found that the stress parameters for Swiss earthquakes were small (5 – 10 bars), implying that the ground motions in Switzerland were lower than average. This started the discussion of a central issue which continued to WS-4: Are ground motions in Switzerland significantly smaller than in other parts of Europe?

The experts identified existing attenuation relations that they considered as candidate models. They concluded that Switzerland is a transition between active and stable regions. The southern part of Switzerland may behave as an active region but the northern part may behave as a stable region. Therefore, the experts considered ground motion models developed for both active and stable regions. The list of candidate models was later expanded to a total of 12 existing models and two Swiss-specific stochastic models. The full set of candidate models are listed in Table 5-1.

The issue of the hands-off (interaction) between the rock ground motion model for SP2 and the site response model for SP3 was discussed in a joint session between SP2 and SP3. The main issue was that SP2 and SP3 needed to have a method for achieving a consistent definition of "rock" site conditions. In WS-1, this issue was not resolved.

At the end of WS-1, the experts compiled a list of data requests. The key data requests included the following:

- expansion of the set of candidate attenuation relations;
- prepare plots of residuals from the candidate attenuation relations;
- expansion of the WAF database to include recordings from short distances and large magnitude that were not adequately represented in the European data set;
- development of a stochastic model-based attenuation relation based on the Bay study;
- summarise largest empirical ground motions and conduct numerical simulations for evaluating the maximum ground motions;
- evaluate rock site conditions for European strong motion stations.

5.2.2 WS-2 / SP2: Evaluation of Models

The SP2 workshop on evaluation of models was held on April 16 – 18, 2002 in Zürich. All five SP2 experts were present for the entire workshop. The main focus of the workshop was to:

- review the empirical database;
- discuss the strengths and weaknesses of the candidate ground motion models;
- discuss approaches for vertical ground motion
- evaluate alternative numerical simulation methods for constraining the maximum ground motions and define additional simulations
- prepare for the elicitations that would take place between WS-2 and WS-3.

The experts were presented with the empirical database that was complete for central Europe. Additions to the database to include additional earthquakes outside of central Europe were discussed by the experts. The representative "rock" site condition of the European strong motion data was discussed again. The experts learned that SP3 would use a reference shear wave velocity of 2000 m/s to define rock for their site amplification models. The sparse velocity information available for European strong motion stations indicates that a typical shear wave velocity for European rock sites is about 1000 m/s. The procedure for accounting for this difference between the SP2 rock and SP3 rock was left unresolved at this workshop (it was finally resolved in WS-4).

The issue of low ground motions in Switzerland was again addressed in depth. Possible causes of the low ground motions, including effects of hard rock site conditions, magnitude biases, and small magnitude scaling were discussed. The experts asked for additional studies to be conducted to see if small earthquakes recorded for hard rock sites in California showed a similar trend. If so, then the effect would not be applicable to larger magnitude earthquakes.

Another topic that was discussed extensively at the workshop was the focal depth of the earthquakes and the impact of using JB distance in most of the candidate models. Since the JB distance does not include the effect of depth, its use could underestimate the aleatory variability of the ground motion at short distances from small magnitude earthquakes. The data set of focal depths being used by SP1 was presented to the SP2 experts. Given the preliminary focal depth distributions and the observation that focal depths of European earthquakes used to derive the attenuation relations are not well known, the SP2 experts concluded that JB distance was adequate.

There are two approaches that can be used for computing the vertical component uniform hazard spectra (UHS): use separate vertical attenuation relations and recompute the hazard, or use the V/H ratio and scale the UHS computed for the horizontal component (see section 2.4.1). At the time of WS-2, the PEGASOS Project had not yet selected the approach that it would use. Therefore, the experts were asked to prepare for both approaches until a decision was made by the project.

Four alternative numerical simulation methods for estimating the maximum ground motions were presented to the experts. Three methods were based on kinematic models and one method was based on dynamic models. The dynamic models have the advantage over kinematic models that they are based on more physical properties of the source; however, in his presentation on dynamic models, Bouchon, an invited resource expert, noted that dynamic models are not advanced enough to be used to reliably estimate high frequency ground motions. Based on this information, the experts dropped the dynamic models as a potential method for evaluating the maximum ground motions. The experts gave their preferences from the three kinematic models. Based on difficulties that the modellers had in focusing on maximum ground motions in WS-2, the experts prepared their own detailed scope of work for the modellers including specific consideration of both sub-shear and super-shear rupture velocities and forward directivity.

At the end of WS-2, the SP2 experts identified additional data requests. The key data requests are listed below:

- Evaluate stress drops from small magnitude earthquakes (M 3 – 4) recorded for hard rock sites in California to see if they also give low stress drops.
- Ground motion residual plots
- Evaluations of velocity profiles from strong motion rock sites in other regions of the world
- Apply the hybrid model to adjust attenuation relations from California and Italy to Swiss conditions
- Conduct numerical simulations for upper bound ground motions
- Conduct additional empirical evaluations of the applicability of the log-normal distribution at the upper tail of the distribution.

5.2.3 Elicitation Interviews

In the first formal applications of expert elicitation to seismic hazard studies in the 1980s, ground motion experts were interviewed for their opinions on ground motions from various magnitude-distance combinations. The TFI-team then used the expert opinions to develop the models. The elicitation interview is now a much different process. Rather than eliciting final ground motion values from the experts, the elicitation interviews in the PEGASOS Project served as a preliminary evaluation and gave the experts the opportunity for feedback from the TFI-team prior to the presentation of their models to the other experts.

The elicitation meetings were held in July 2002. During the elicitation meetings, the experts met individually with the TFI-team and described their preliminary models (logic trees). The purpose of these meetings is to work through the experts' models, help them work though any difficulties they had in developing parts of the models and identify inconsistencies in the models. At the elicitation meetings, the experts described the general approach that they were planning on using for developing their models and presented their initial logic trees. Based on interaction with the TFI-team, the details of the models were then developed for presentation to the other experts at WS-3.

Examples of items discussed at the elicitation meetings included: separation of aleatory variability and epistemic uncertainty; technical basis for selecting weights, structure of logic trees and how to develop a system for assigning weights to branches.

5.2.4 WS-3 / SP2: Initial Feedback on Experts' Estimates

The SP2 workshop on initial feedback for experts was held on October 1 – 3, 2002 in Zürich. All five SP2 experts were present for the entire workshop. The main focus of the workshop included:

- presentation of results of maximum ground motion simulations
- presentation of statistical evaluations of upper tails of distributions
- presentation of approaches used by experts
- comparison of results of initial models.

The statistical evaluations of the distribution of the upper tail were presented using normal probability plots which show if a set of data follow a normal distribution. If the ground motion residuals deviated from a log-normal distribution at the upper tail, it would be seen in the normal probability plots. The results of the statistical analysis did not show any systematic and repeatable trend for truncating the ground motion at a given number of standard deviations independent of the amplitude (Figure 5-12).

Two sets of numerical simulations directed at estimating the maximum ground motion were presented. The experts had requested these simulations to provide a technical basis for their maximum ground motion model. The simulations only considered the maximum ground motions due to source effects and wave propagation in the flat crustal model. The modellers selected the worst combinations of source parameters that they considered to be possible and then simulated the ground motions at a set of locations located at a fixed Joyner-Boore distance. The largest ground motion was then tabulated. The discussions between the experts and the modellers at the workshop highlighted the difficult problem of estimating maximum ground motions. A maximum value is the value that has zero chance of being exceeded, but the modellers generally presented their simulations in terms of source combinations that they considered to be very unlikely to occur. The difference between "very unlikely" and zero probability was noted by the experts. Given this difficultly in evaluating the physical plausibility of the source combinations, the experts requested an independent review of their source model parameters of the two sets of simulations.

In the second half of WS-3, the focus changed from presentations of material to the experts to presentations of models by the experts. Each expert presented his general approach for developing the logic tree and weights of the models for the median horizontal ground motion, the V / H ratio, and the aleatory variability. The experts provided a peer review of each other's models by questioning the expert about the details of the models.

During WS-3, following the presentations of the evaluations of the upper tails and the maximum ground motions from the simulations, individual elicitation meetings on the maximum ground motions were held with each expert. As with the previous elicitation meetings, the experts presented their initial approach to the TFI-team and, through discussions with the TFI-team, worked out any difficulties with their models. The approaches for the initial models of the maximum ground motions were then presented by each expert to the other experts for feedback and peer review.

At the end of WS-3, the SP2 experts identified additional data requests. Key requests were:

- additional documentation of simulations for maximum ground motion and independent review of the source parameter combinations.
- more complete set of normal probability plots using other large data sets for evaluating the upper tail
- correct misunderstandings in the horizontal component definitions for the larger component

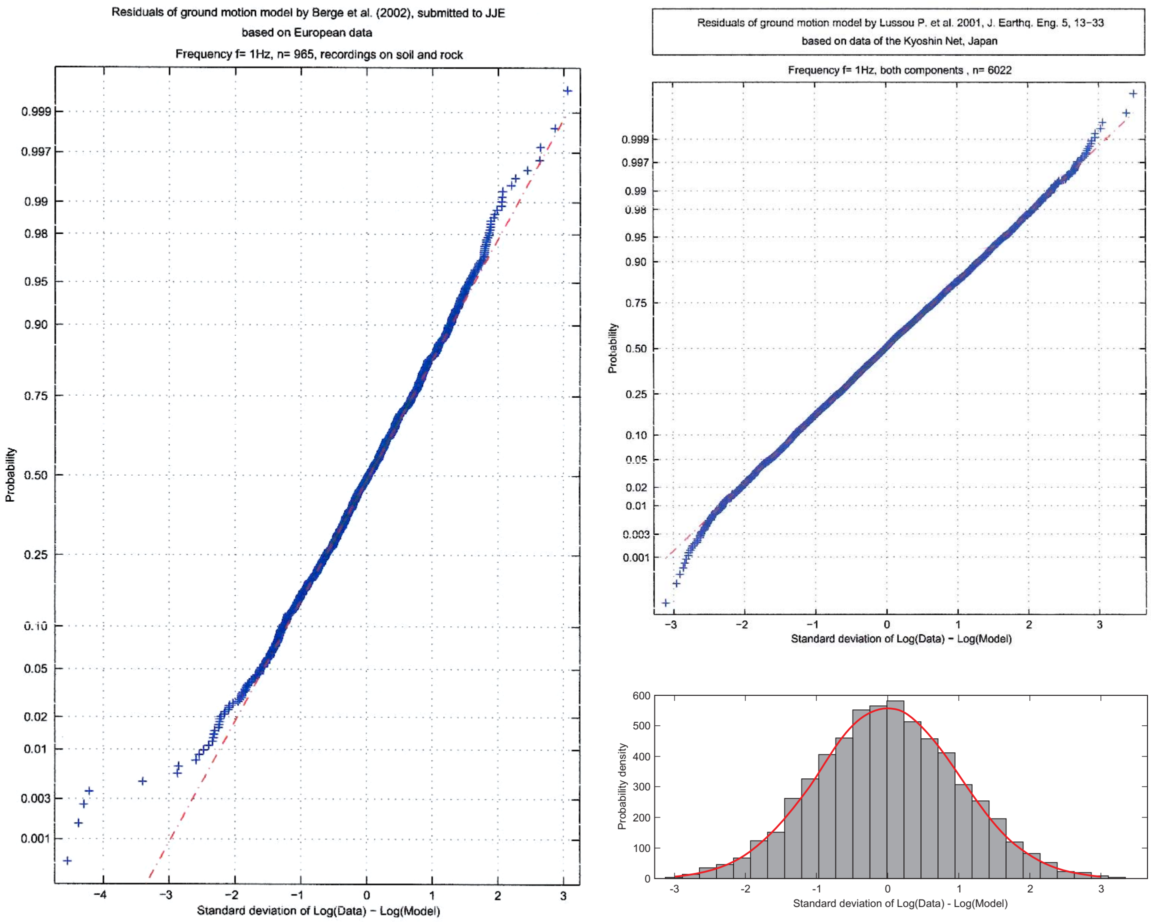


Fig.5-12: Residual plots for spectral acceleration at 1 Hz from Berge-Thierry et al. (2000) and Lussou et al. (2001)

After *Hölker* (*2002a, RDZ-TN-0214*).

5.2.5 WS-4 / SP2: Feedback on Experts' Estimates

The SP2 workshop on hazard feedback for experts was held on February 24 – 27, 2003 in Zürich. All five SP2 experts were present for the entire workshop. The main focus of the workshop included:

- interaction between the subprojects
- presentation of revised models by experts
- presentation of feedback on hazard sensitivity studies.

The SP2 experts presented any modifications they had made to their previous models to the other experts for peer review.

A key item of discussion between SP2 and SP3 was the interface between SP2 and SP3 in terms of the definition of reference rock. Up to this time, the SP2 experts had been free to use their own individual definitions of reference rock, with the understanding that SP3 would provide response spectral scale factors to account for the differences between each SP2 rock and the common SP3 one ($V_s = 2000$ m/s). At WS-4, a change was made. The SP2 experts decided that they would all use the $V_s = 2000$ m/s value. This required that they convert each of the candidate equations to $V_s = 2000$ m/s. The SP2 experts developed a consensus on the range of V_{s30} values for each candidate model. Scale factors were then developed as a function of the V_{s30} values, which corrected the models to $V_s = 2000$ m/s. The representative velocity profiles were provided to SP3 for computing the response spectral scale factors.

A second key item of discussion between SP1 and SP2 was the style of faulting for the sources in Switzerland. The SP1 models included a high percentage of normal faulting earthquakes. Most existing attenuation relations were not developed using normal faulting data. Therefore, the SP2 experts decided that they would need to modify their models to account for the style of faulting (normal, strike-slip or reverse). An additional workshop meeting day was added.

The third key item of discussion was the ground motions from the St. Dié earthquake. This magnitude 4.8 earthquake occurred shortly before the workshop. It represented the largest event recorded by strong motion stations in Switzerland. Preliminary ground motions from this earthquake were shown to the experts. The experts concluded that the ground motions from this earthquake were critical for their evaluations of the Swiss-specific aspects of strong ground motions.

The experts received feedback on the impact of aspects of their models on the hazard through the hazard sensitivity studies. These sensitivity calculations *(Toro 2003d, TP4-TN-0352)* were not based on the full expert models. They were intended to test the range of models from the five experts and did not represent mean centred models. One key result of the feedback was that Scherbaum had a very high uncertainty. Part of this large uncertainty was due to misinterpretations of Scherbaum's model which were later corrected, but it also caused Scherbaum to conclude that he needed to correct the candidate models using the hybrid approach. This led Scherbaum to develop a set of hybrid model corrections for each of the candidate models that he considered.

At the end of WS-4, the SP2 experts identified several additional data requests. The key data requests are listed below:

- Develop comparisons of the strong motion data from the St. Dié earthquake with the predictions from the candidate models
- Develop representative velocity profiles for each candidate model.

5.2.6 SP2 WS4a: Meeting on Scaling Factors for Style of Faulting

Based on the feedback on WS-4, an additional meeting was held for SP2 experts to discuss the style of faulting factors for normal faulting earthquakes. Most attenuation relations do not include a factor to distinguish between normal faulting and strike-slip faulting earthquakes.

The issue of ground motions for normal faulting earthquakes had been addressed as part of the Yucca Mountain studies. In the Yucca Mountain reviews, all available strong motion data from normal faulting earthquakes around the world had been compiled. Despite this effort, the strong motion data set from normal faulting events remains sparse. Three main models were developed in the Yucca Mountain study: an empirical attenuation relation by Spudich et al. (1999) for extensional regime earthquakes (both strike-slip and normal faulting); adjustment factors for the

Abrahamson & Silva (1997) model to scale strike-slip to normal faulting based on mean residuals and stress parameter differences between normal and strike-slip events based on the point source stochastic model.

These models were discussed by the experts. Central to the discussion is the large uncertainty in ground motions from normal faulting earthquakes due to the small number of recordings.

A key result from this additional meeting was that the experts decided to classify each of the candidate attenuation relations in terms of the percentages of difference focal mechanism that are represented by the model for candidate models that do not specify style of faulting factors. This allowed the experts to estimate of the starting point for each model and then to develop style of faulting factors for each model. In general, this information was not given by the authors of the attenuation relations, but it was derived by the experts and the TFI-team based on their knowledge of the data sets used in each model. This characterisation of the styles of faulting for each candidate model represents an important improvement in the parameterisation of ground motion models for Europe.

5.2.7 WS-5: End-of-Project Workshop

The end-of-project workshop was held in Davos on February 27, 2004. This workshop was held jointly with SP1 and SP3. During the workshop, the general approaches used by each expert or expert group in each subproject were discussed and examples of the hazard results were shown.

5.3 SP2 Expert Model Development

5.3.1 Development of Initial Logic Trees (and Elicitation Summaries)

Following SP2 WS-2, the experts developed their initial approach for evaluating the strengths and weaknesses of each candidate attenuation relation in terms of its applicability to predicting ground motions in Switzerland for the required magnitude and distance range. The evaluations considered the size of the database, magnitude and distance range sampled by the database, and conversions that were required to make the model applicable to Switzerland.

This initial approach was presented to the TFI-team during the elicitation meeting. With feedback from the TFI-team, the experts then developed their first complete model (logic trees and weights) for the median ground motion, aleatory variability of the median ground motion, and V/H ratio. This initial model was presented to the other experts for review and comments at SP2 WS-3. This initial model did not include maximum ground motions.

During SP2 WS-3, the experts developed their initial approach for maximum ground motions using information presented at the workshop. A second set of elicitation meetings was held during the middle of WS-3, in which the experts presented their approach for maximum ground motions to the TFI-team. With feedback from the TFI-team, the experts developed their first complete model (logic tree and weights) for the maximum ground motion. This model was presented to the other experts for review and comment at the end of WS-3.

5.3.2 Model Revisions

Model revisions occurred after each stage of feedback. The first revision of the expert models occurred following the feedback from the elicitation meeting. The models discussed at the elicitation meeting were incomplete. The first complete set of models was presented at WS-3. At this workshop, the experts provided peer review of each other models by discussing and questioning the approaches, logic tree branches, and weights used by each expert. Based on the feedback at WS-3, the experts revised their models of the median ground motion and their initial models of the maximum ground motions.

The revised models were presented to the other experts for discussion and peer review at WS-4. There were two forms of feedback at WS-4: feedback from comparisons of the ground motion models, and feedback from comparisons of the hazard computed using representative alternative models. The final revisions to the models were made following WS-4 (and the extension of WS-4 to cover style of faulting effects).

5.3.3 Model Implementation

5.3.3.1 Composite Model Approach

The ground motion is parameterised for the final rock hazard computations at the following spectral frequencies: 0.5 Hz, 1 Hz, 2.5 Hz, 5 Hz, 10 Hz, 20 Hz, 33 Hz, 50 Hz and at peak acceleration. The implementation of the logic trees results in: (a) a set of alternative estimates of the median horizontal ground motion, aleatory variability of the horizontal ground motion and V/H ratios at each spectral frequency, earthquake magnitude, fault style, and distance, and (b) the weight associated to each individual branch of the logic tree.

Ground motions have been modelled for seven magnitudes [5.0, 5.5, 6.0, 6.5, 7.0, 7.5, 8.0] and 14 distances (1.0, 1.6, 2.5, 4.0, 6.3, 10, 16, 25, 40, 63, 85, 100, 160, 250 kilometres).

The ground motion arising from the implementation of the SP2 logic trees has been parameterised using a composite model approach. At each distance, magnitude and spectral frequency, and, for each fault style, the alternative estimates of the median ground motion are sorted in order of ascending spectral acceleration. The weights associated with the sorted median amplification factors are summed, resulting in a cumulative distribution of the amplification factors. The stair-steps cumulative distribution function was somewhat smoothed by interpolating the values between the step centres. The values of the ground motion are selected for cumulative distributions corresponding to the following fractiles: 0.13 %, 2.28 %, 16 %, 50 %, 84 %, 97.72 %, and 99.87 %. The seven fractiles correspond to median, ± 1σ, ± 2σ, and ± 3σ levels. By using the discrete fractiles, no assumption regarding symmetry of the epistemic uncertainty is made.

For the aleatory variability, the same process is repeated, but with the sorting performed on the amplitude of the aleatory variability.

A conversion to account for different distance measures was conducted using the Scherbaum conversion factors. (These conversions may be updated in the final model to incorporate the SP1 depth distributions). Two sets of conversions were done. The first converted the distances to JB distances and the second converted the distances to rupture distance. The main differences between the JB distance and the rupture distance occur for small magnitudes at short distances. However, to avoid potential jumps in the models at bin boundaries, the conversions were applied to all the bins (unlike what had been done for the sensitivity computations, where the conversion was not applied to the smallest magnitude and shortest distance bin ($M < 5.5$, $D < 10$)).

The values of ground motion resulting from this procedure are input directly into the rock hazard software without further parameterisation or fitting.

The maximum ground motion estimates are also parameterised in a similar manner. Tables of the maximum ground motion are developed for the same magnitude and distance bins, for each style of faulting and for the seven fractiles.

5.3.3.2 Distance Measures

In developing the composite model described above, a distance conversion is needed because the attenuation relations selected by the experts use different distance measures. A conversion for different distance measures was conducted using the Scherbaum conversion factors (*Scherbaum & Schmedes 2002, EG2-TN-0256*).

Since the Scherbaum distance conversion factors depend on the depth distribution and the style of faulting, these factors were different for each SP1 source model. Therefore, different distance conversions were done for each SP1 source model using th depth distribution and fault style for the controlling source zone (TP4-SUP-0068).

5.3.3.3 Maximum Ground Motion

The experts specify the maximum ground motions in one of two ways. It is given either by the value of maximum ground motion at each magnitude-distance pair in the composite model or by the maximum number of standard deviations from a reference model. For example, Cotton used the Abrahamson & Silva (1997) model as a reference and then set the maximum ground motion as a fixed number of standard deviations above the median as given by this model. In this approach, the attenuation relation is simply used as a method for defining the magnitude and distance dependence of the maximum ground motion.

5.3.4 Development and Review of Preliminary HIDs

Following WS-3, the preliminary HIDs were developed for each expert. The preliminary HIDs, to be used as a base for the sensitivity hazard computations, were based on single paths through the logic tree for each expert. That is, only one branch tip was considered for each expert. This allowed the preliminary models to be simple, yet allowed the testing of the implementation of each SP2 expert's model. The single branch tips selected were not central values for each expert. Rather, they were selected to sample the range of ground motion models from all of the five SP2 experts. So, in aggregate, the five selected branch tips indicate the range of the hazard.The HIDs were sent to the expert prior to WS-4 for review. In this review process, the experts checked that their models were correctly interpreted. Three of the five experts found errors or misinterpretations in the HID that required revision. The HIDs were corrected and reviewed again by the experts. All of the preliminary HIDs were approved by the 13th of April 2003

5.3.5 Sensitivity Hazard Computations

Following WS-3, the TFI-team used the initial models presented at WS-3 to develop representative models (called TFI models) that were then used in the sensitivity hazard comparisons. These sensitivity calculations focused the attention of the experts on aspects of their models that were most important for the hazard. With this feedback, the experts re-evaluated the key aspects of their models.

5.3.6 Development and Review of Final HIDs

Following WS-4a, the HIDs were developed for each expert based on the draft elicitation summaries. In some instances, there was not enough information in the elicitation summaries to fully define the model. In these cases, the experts were contacted and the additional information was requested.

The draft HIDs were provided to each expert for review. In some cases, errors were found by the experts and revised HIDs were produced and again provided to the experts for review. All of the HIDs were approved by the 9th of November 2003.

5.3.7 Documentation of Final Expert Models (Elicitation Summaries)

The expert models are fully documented in the elicitation summaries. These summaries give the quantitative model parameters (logic tree and weights) and also describe the technical basis for the selected logic tree and weights. The elicitation summaries are documents entirely written by the experts. The project only provided an outline to ensure a certain uniformity in the structure of the different summaries.

5.4 Features of SP2 Expert Models

Detailed descriptions of the features of the experts' models are given in the elicitation summaries. Only the highlights of key aspects of the models are summarised in this chapter.

5.4.1 Median Horizontal Motion

The logic trees for the median horizontal ground motion were similar for all of the experts. A representative logic tree is shown in Figure 5-13.

The main branches are:

- Candidate equations
- Magnitude conversion
- Horizontal component conversion
- V_{s30} scaling
- Kappa scaling
- Style of faulting scaling.

Some of the experts changed the order of the branches, but since each branch acts linearly (in terms of the log ground motion) the order of the branches does not matter.

5.4.1.1 Candidate Equations

Each of the experts developed weights for the branches of the candidate equations that varied as a function of the magnitude and distance. In most cases, there were three magnitude ranges and three distance ranges considered.

The approaches that the five SP2 experts used to evaluate the set of candidate models were very different. The general philosophy of each expert is described below. The candidate models considered by each expert (e.g. given non-zero weight for some M−R range) are listed in Table 5-3.

Bommer

Bommer developed a grading system based on aspects of the data set and explanatory variables used to derive the candidate model: coverage of the data set in M−R, selected distance metric, tectonic environment of the data set, site condition of the data set, and inclusion of additional explanatory variables considered important. This grading system was then used to assign weights to each candidate model for each magnitude and distance range. Bommer included all of the models except for the Swiss-specific point source model. Bommer concluded that since this model was based on small magnitude earthquakes, it could not be reliably extrapolated to magnitudes greater than 5, which is the range of interest in the study.

Bungum

Bungum followed an approach of selecting a subset of eight candidate models that he considered to be reliable and representative of the alternative tectonic regimes. Bungum used judgement to assign the model weights, with an emphasis based on the tectonic regimes. About 40 % of the weight was given to European models, 30 % to global models, 20 % to Eastern US models, and 10 % to the Swiss-specific point source model.

Cotton

Cotton focused on the seismological applicability of each candidate model to Switzerland using the macroseismic and weak motion studies as guides. He considered four classes of models: European models, global models, Swiss-specific point source models, and Eastern US models. For each model, he considered the parameters that required conversion, magnitude and frequency range, the range of focal depths, and similarities to Swiss source and wave propagation conditions including stress drops, faulting style, and distance attenuation rates. Cotton considered the European models to be close to the Swiss case for mid-range distances, the global models to be better constrained for large magnitudes and short distances and the stochastic point source models to better represent the Swiss attenuation. The EUS models could not be excluded because Switzerland is partly an intraplate environment, but they were given low weight because of the non-crystalline nature of the foreland.

Sabetta

Sabetta considered the magnitude range, frequency range, site condition, data set size, style of faulting, and tectonic region of each candidate model. He assigned the weights using judgement. Sabetta gave a relatively high weight to the Swiss-specific point source model (20 – 25 %). He concluded that this model should receive the higher weight because it was the only model representing the Swiss conditions. He used the increasing stress drop (A_{inc}) and the constant stress drop of 30 bars (A_{30}) models, with the highest weight given to the A_{inc} model.

Tab.5-3: Candidate models included in the experts' models for the median ground motion

Model	Bommer	Bungum	Cotton	Sabetta	Scherbaum
Empirical					
Abrahamson & Silva (1997)	√		√	√	√
Ambraseys et al. (1996)	√	√	√	√	√
Ambraseys & Douglas (2000)	√		√		
Berge-Thierry et al. (2000)	√	√	√	√	√
Boore et al. (1997)	√		√		
Campbell & Bozorgnia (2003)	√	√	√		
Lussou et al. (2001)	√		√	√	√
Sabetta & Pugliese (1996)	√	√	√	√	
Spudich et al. (1999)	√	√	√	√	√
Numerical Simulations					
Atkinson & Boore (1997)	√		√		
Somerville et al. (2001)	√	√	√	√	√
Toro et al. (1997)	√	√	√		
Swiss-Specific Stochastic Model					
Bay (2002a)			√	√*	
Rietbrock (2002)		√	√		

* Modified geometrical spreading

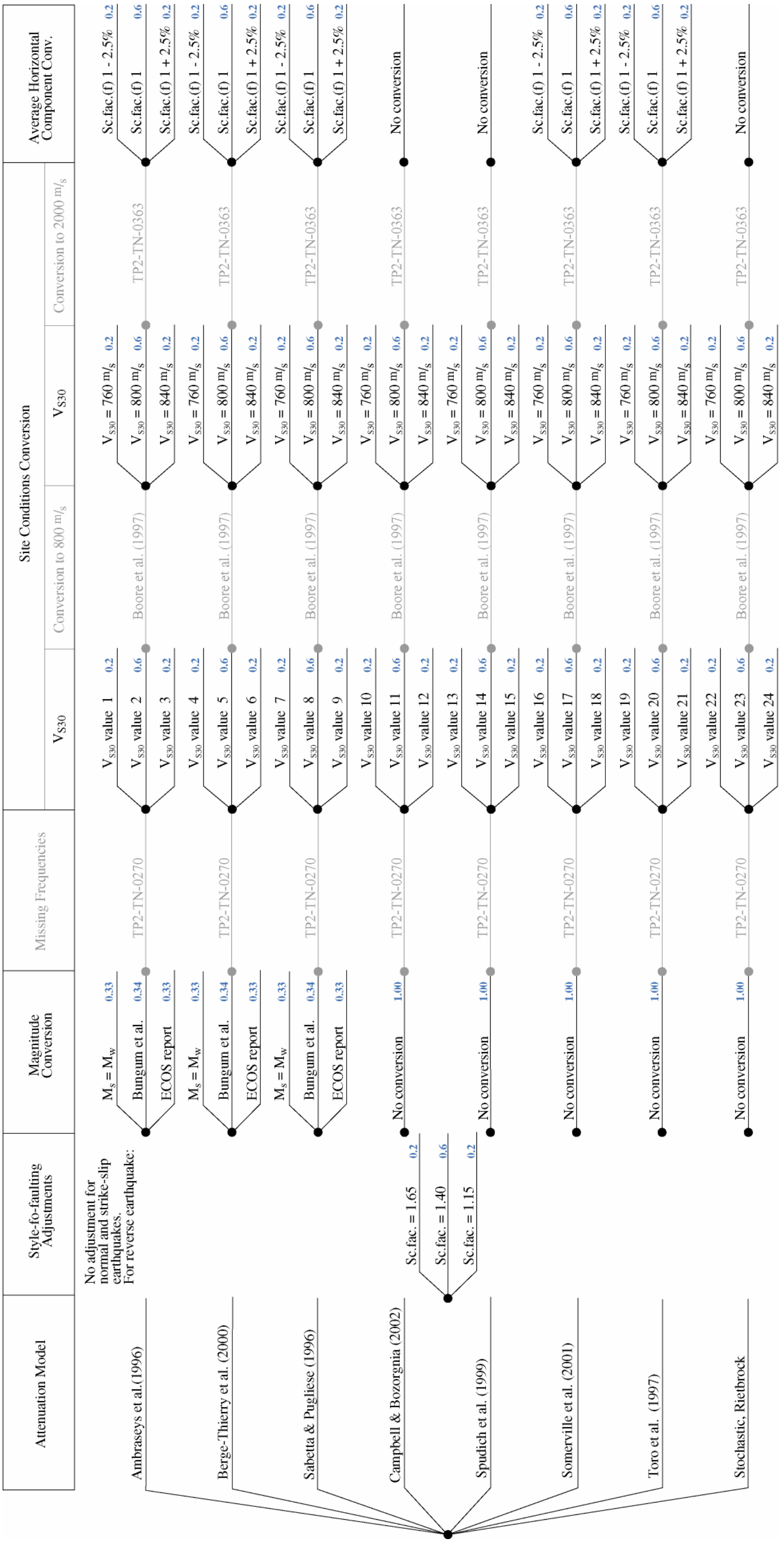


Fig.5-13: Representative logic tree for the median horizontal component (H. Bungum's tree)

Scherbaum

Scherbaum did not want to select his weights using subjective judgements. Therefore, he developed a comprehensive and objective method for assigning the weights to the branches. In this approach, he first evaluated each attenuation relation based on four main features: general remarks, magnitude coverage, distance coverage and frequency coverage. Numerical values were assigned to each qualitative evaluation to arrive at the initial weights. This approach assured that the development of the initial weights was well documented and repeatable.

The key aspect of Scherbaum's model is that he then updated his initial weights by evaluating each model in terms of its ability to match various strong motion data sets, and the St. Dié recordings, in terms of a likelihood. This allowed the strong motion data to drive the weights rather than just the qualitative evaluations.

5.4.1.2 Magnitude Conversion

All five experts applied magnitude conversions to convert from moment magnitude to the magnitude measure required for each candidate model. The models considered are listed in Table 5-4.

5.4.1.3 Horizontal Component Conversion

All five experts converted the horizontal components using the models from *Roth* (*2002e, TP2-TN-0269*). The size of the component conversion is small is most cases (see Fig 5-3).

Tab.5-4: Magnitude conversion

Model	Bommer	Bungum	Cotton	Sabetta	Scherbaum
$M_w \rightarrow M_s$					
Free (1996)	√			√	
Bungum et al. (2003)	√	√		√	
PEGASOS catalogue report (*SED 2002, EXT-TB-0043*)	√	√			
Ambraseys & Free (1997)			√		√
Ekström & Dziewonski (1988)				√	
$M_w = M_s$		√	√		
$M_w \rightarrow M_L / M_s$					
PEGASOS catalogue report (2002)	√		√		
$M_w = M_L / M_s$	√		√	√	√
$M_w \rightarrow M_{jma}$					
Fukushima (1996)	√		√	√	
$M_w = M_{jma}$	√		√	√	√
$M_{jma} = M_s$	√				

5.4.1.4 Missing Frequencies

Missing frequencies were estimated by interpolating the coefficients of each candidate model. The experts all used the coefficients derived in *Hölker* (*2002b, TP2-TN-0270*).

5.4.1.5 V_{s30} Correction

The experts all used the same method for correcting for differences in the V_{s30} of the attenuation relations and the reference rock velocity of 2000 m/s (Scherbaum model). The experts all used the same set of reference V_{s30} values for the candidate models, with only small changes in the weights assigned to each V_{s30} model.

5.4.1.6 Kappa Correction

Cotton and Scherbaum applied corrections for kappa differences between the candidate models and Switzerland. These two experts considered the kappa correction to be part of the V_{s30} scaling. Bungum also applied kappa corrections for two candidate models, independent of the V_{s30} scaling. The main effect of kappa correction is at the high frequencies (Figure 5-14).

The other two experts did not include this correction. Bommer noted that kappa is sometimes considered a source effect and sometimes a site effect. Given this uncertainty, they concluded that including kappa corrections could not be used. This leads to significant differences at very high frequencies.

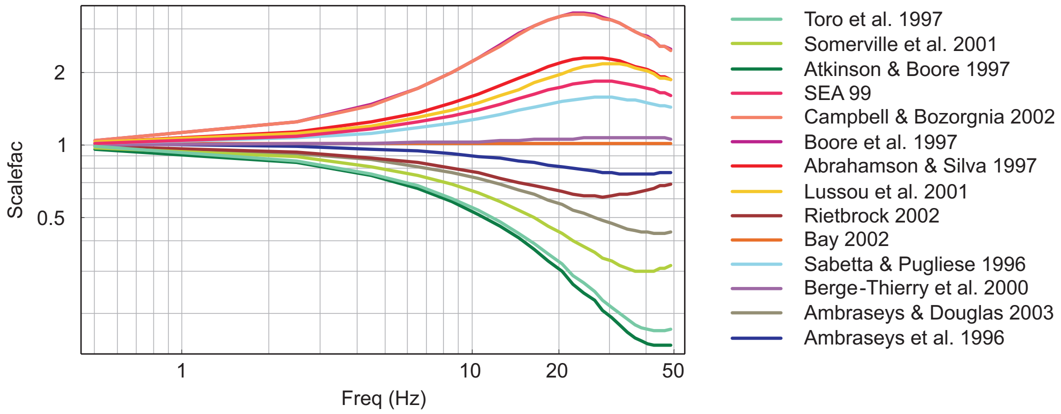


Fig.5-14: Conversion for the effect of kappa differences for a reference kappa of 0.02155 s

5.4.1.7 Style of Faulting Scaling

Many of the candidate models include a difference between ground motions from strike-slip and reverse-slip earthquakes, with reverse-slip earthquakes yielding 10 – 40 % larger ground motions than strike-slip earthquakes, but they do not include a difference between normal and strike-slip earthquakes.

All five experts accounted for the differences between strike-slip and reverse-slip earthquakes, but not all incorporated a difference between strike-slip and normal slip earthquakes. Given the importance of normal faulting events for the sources from SP1, the approaches to the style of faulting factor are discussed here.

There is much less strong motion data from normal faulting earthquakes than from strike-slip or reverse earthquakes. Given the relatively small data sets, the style of faulting factors for normal faults are not well resolved. Bommer and Sabetta use the limited empirical evaluations to justify smaller ground motions (0 – 25 % smaller) from normal faulting earthquakes. In contrast, Bungum, Cotton, and Scherbaum conclude that there is not enough data to support a reduction in ground motion for normal faulting earthquakes. They assume that the ground motion from normal faulting earthquakes is equal to the strike-slip motion.

5.4.2 Evaluation of Proponent Models for Applicability to Switzerland

Bommer, Bungum and Sabetta had difficulty understanding why Swiss ground motion should be significantly different from ground motions obtained elsewhere under tectonically similar conditions, even accounting for possible differences in site conditions. They considered the low ground motions for small magnitude earthquakes to represent a weak motion to strong motion scaling issue. Finally, the ground motions from the St. Dié earthquake were consistent with the candidate ground motion models without Swiss-specific adjustments at distances greater than 80 km. All three experts concluded that no Swiss-specific adjustments were needed.

Cotton and Scherbaum took a different approach. They both used the hybrid approach to modify the candidate models for Swiss conditions. They concluded that the candidate models should be corrected for geometrical spreading, Q, and kappa in addition to the V_{s30} correction.

5.4.3 Median V/H Ratio

The experts generally used the same approach for the V/H ratio as for the median horizontal ground motion. The differences are highlighted below.

Bommer and Bungum use the same approach for the V/H ratio and the median horizontal, but the set of candidate equations is reduced to those that give both horizontal and vertical models. The weights of the logic tree branches are renormalised to sum to unity.

Cotton considered that the V/H ratio was strongly dependent on the site condition. Since the reference site has a shear wave velocity of 2000 m/s, Cotton only considered V/H ratios for the three candidate models that were applicable to hard rock conditions: Lussou et al. (2001), Campbell & Bozorgnia (2003) and Somerville et al. (2001).

Sabetta used the same approach for the V/H ratio and the median horizontal. Since all of the models he used for the horizontal also include a vertical, there was no need to change the weights.

Scherbaum used the same approach for the V/H ratio and the median horizontal. The difference in the application is that he used the vertical data to evaluate the models for updating the initial weights.

5.4.4 Aleatory Variability for Horizontal Ground Motion

An important issue for the aleatory variability is the possible magnitude dependence of the variability. Some experts adopted a magnitude-dependent model and applied it to all of the candidate models, regardless of whether the candidate model included a magnitude-dependent standard deviation.

A second important issue is the effect of parameter conversion (magnitude, distance) on the aleatory variability. Some of the experts increased the published aleatory variability to account for the additional variability caused by the conversion of the parameters. This increase is based on an assumption that there is no correlation between the residuals of the ground motion and the residuals of the magnitude conversion.

Bommer used the Abrahamson & Silva model for the aleatory variability as a base level to capture the magnitude dependence. This value was then scaled up or down to estimate the range of variability for each candidate model. He included his estimate of the increase in variability due to parameter conversion.

Bungum evaluated the range of aleatory variability from the alternative candidate models and developed a representative range of the magnitude-independent values as a function of period. He then considered both constant and magnitude-dependent models. No increase in variability was included for parameter conversion.

Cotton used the same models for the aleatory variability as for the median horizontal, but the weights are revised to give more weight to models that include a magnitude-dependent variability. The increase in the variability due to the magnitude conversion is considered using propagation of errors.

Sabetta used the Abrahamson & Silva standard deviation as the base model because it included magnitude dependence and was representative of other models in an average sense. To capture the epistemic uncertainty, he increased and decreased the variability from the Abrahamson & Silva model by 15 %.

Scherbaum evaluated both the median and the variability in his update to his initial weights. Therefore, the same weights are given to the aleatory variability as was given to the median horizontal.

5.4.5 Maximum Ground Motions for the Horizontal Component

There were several different approaches used to develop the models for the maximum ground motion.

Bommer, Cotton, and Sabetta evaluated the largest empirical observations and the maximum values from the numerical simulations. They then selected a representative attenuation relation and set a maximum number of standard deviations that was consistent with the evaluated models. The reference models selected are shown in Table 5-5 for each expert. The selected attenuation relation is not critical as it is simply a reference model.

Bungum also evaluated the largest empirical observations and the maximum values from the numerical simulations. Based on judgement, he then anchored a reference model at M7.5 and 1 km distance and added uncertainty. Scherbaum used a third approach. He used the Swiss-specific point source model with a maximum stress drop. He considered maximum stress drops of 150, 200 and 250 bars.

Tab.5-5: Models used for maximum horizontal ground motion

Model	Bommer	Bungum	Cotton	Sabetta	Scherbaum
Ambraseys et al. (1996) with 1.7, 2.8, and 3.6 sigma				√	
Anchored Somerville et al. (2001) with -50 %, 0 %, and +100 % values		√			
Abrahamson & Silva (1997) with 4, 5, and 6 sigma			√		
Ambraseys et al. (1996) with 2.5 to 4.5 sigma	√				
Swiss point source, with 150, 200, and 250 bars					√

5.4.6 Maximum Ground Motions for the Vertical Component

Vertical ground motions are not as well studied as horizontal ground motions. Four of the five experts concluded that the best approach was to estimate the maximum vertical by scaling the maximum horizontal. The approaches used are summarised in Table 5-6.

Cotton considered that extreme vertical ground motions are due to non-vertical incidence so that the maximum is from S waves. Therefore he used the maximum horizontal for the maximum vertical.

Bungum concluded that he did not have a sufficient basis for independently assessing the vertical maximum ground motions. Noting V/H ratios from large earthquakes are generally between 0.5 and 1.0, he selected a ratio of 2/3 for scaling the maximum horizontal.

Scherbaum and Sabetta considered that there was no evidence for the V/H ratio for the maximum ground motions to be different from the V/H ratio for the median. Therefore, they used the median V/H ratio described previously to scale the maximum horizontal.

Bommer was the only expert to develop a maximum vertical not based on simply scaling the maximum horizontal. He used the same approach for the vertical and horizontal and his resulting model has the same number of standard deviations above the Ambraseys vertical model.

Tab.5-6: Models used for maximum vertical ground motion

Model	Bommer	Bungum	Cotton	Sabetta	Scherbaum
Ambraseys et al. (1996) with 2.5 to 4.5 sigma	√				
Median V/H * Max H				√	√
2/3 * Max H		√			
Max H			√		

5.4.7 Upper Tail of the Ground Motion Distribution for the Horizontal Component

Bommer, Bungum, Cotton, and Sabetta concluded that there was no clear evidence from the normal probability plots to support a deviation from a log-normal distribution at the upper tail. Bommer and Cotton did not introduce any truncation, whereas Bungum and Sabetta specified three alternative values at which to sharply truncate the log-normal distribution (see Table 5-8).

Scherbaum considered that the data do not rule out a modification to the log-normal distribution at the upper tail. He considered two models: one in which there was no modification and one in which the distribution at 3 sigma is extrapolated linearly to the maximum values defined in section 5.4.5. This modification makes the distribution fatter in the 4 sigma range, adding slightly to the hazard for very low probability levels.

Tab. 5-8: Models used for the upper tail of the ground motion distribution

Model	Bommer	Bungum	Cotton	Sabetta	Scherbaum
Log-normal, no truncation	√		√		√
Log-normal, truncation at 3.0, 3.5 and 4.0 σ		√			
Log-normal, truncation at 2.5, 3.0 and 3.5 σ				√	
Log-normal distribution up to 3 σ and taper down to max. GM					√

5.5 Summary of Ground Motion Experts' Assessments

This section compares the results of the experts' models.

5.5.1 Median Horizontal Motion

The distance dependence of the median ground motion for peak acceleration and T = 1 second spectral acceleration for a magnitude 6 earthquake are compared in Figures 5-15 and 5-16.

The magnitude dependence of the median ground motion for peak acceleration and T = 1 second spectral acceleration for a distance of 10 km are compared in Figures 5-17 and 5-18.

The median spectra for a magnitude 6 earthquake at a distance of 10 km are compared in Figure 5-19. This figure also compares the Boore et al. (1997) model for a site with an average shear wave velocity of 2000 m/s over the top 30 m. The average of the five experts is similar to the Boore model, indicating that the median model is similar to California for hard rock. This similarity with the Boore model results because the expert models do not have significant Swiss-specific effects for the source. Swiss-specific effects due to wave propagation are stronger, but they are only apparent at large distances that do not contribute significantly to the hazard.

The epistemic uncertainty in the median horizontal ground motion is large. As an example, the epistemic uncertainty for the peak acceleration is shown in Figure 5-20. The large uncertainty results from the wide range of candidate attenuation models considered to be applicable to Switzerland and the required conversions (magnitude, V_s, kappa, geometrical spreading). This large epistemic uncertainty is an important feature of the ground motion models. As will be shown in chapter 8, at low probabilities the mean hazard curves are sensitive to the upper fractiles (e.g. > 90^{th} fractile) of the ground motion models.

It may be possible to reduce epistemic uncertainty with additional analyses. First, new attenuation relations could be developed using the desired parameters (e.g. moment magnitude) and thereby reduce the epistemic uncertainty. Second, the ground motions from the 2003 St. Dié and the 2004 M 4.8 Rigney earthquakes could be studied in detail to help constrain the Swiss-specific ground motions for moderate magnitudes.

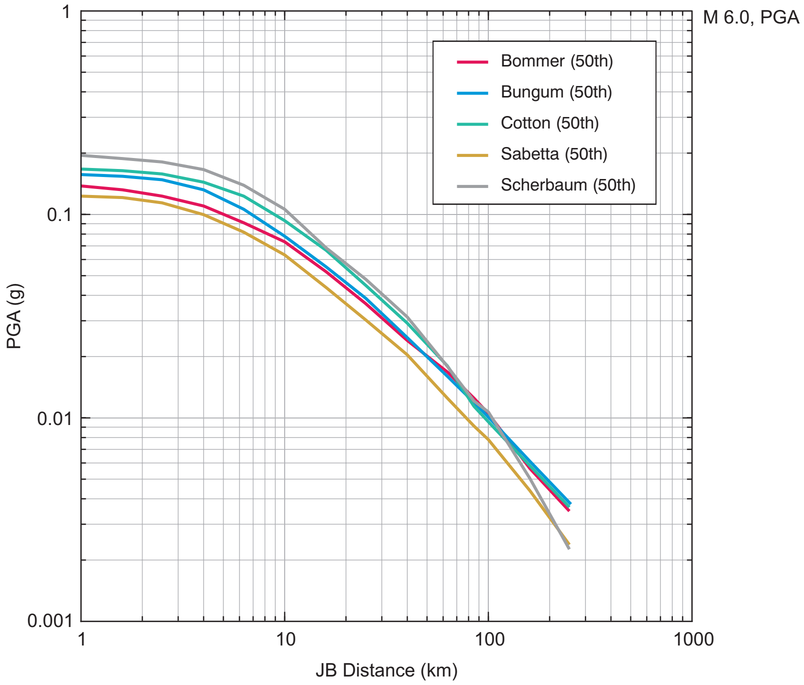


Fig.5-15: Comparison of the 50th fractile of the median peak acceleration for a magnitude 6.0 earthquake with a normal mechanism

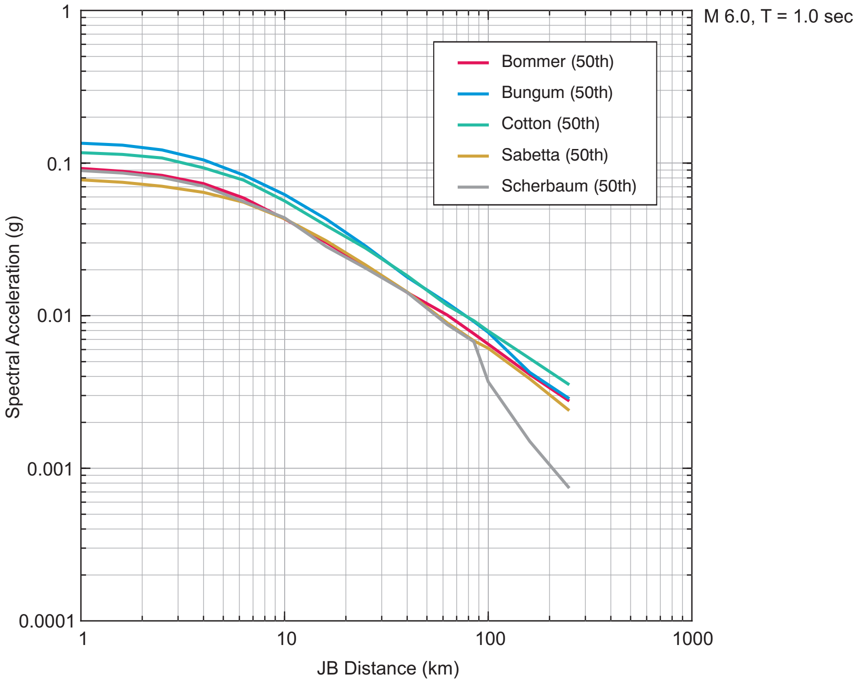


Fig 5-16: Comparison of the 50th fractile of the median T = 1 second spectral acceleration for a magnitude 6.0 earthquake with a normal mechanism

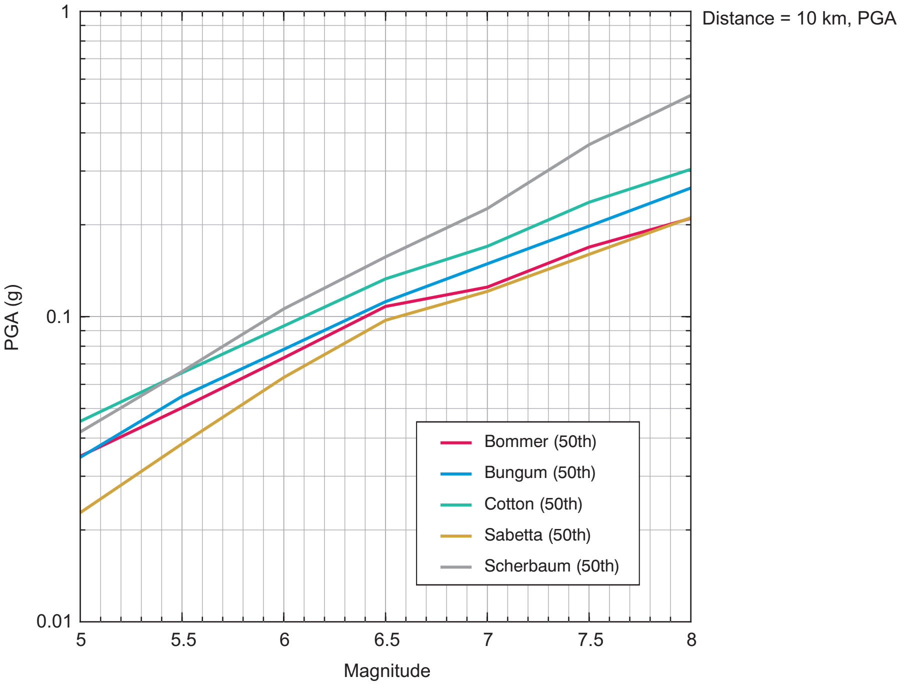


Fig.5-17: Comparison of the 50th fractile of the median peak acceleration for a JB distance of 10 km and a normal mechanism

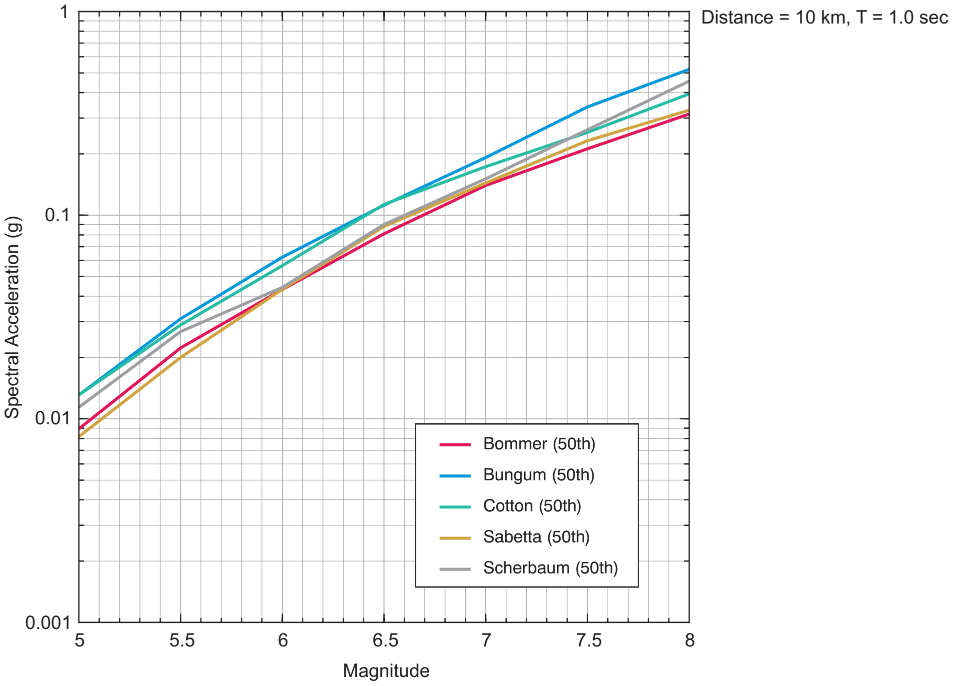


Fig.5-18: Comparison of the 50th fractile of the median T = 1 second acceleration for a JB distance of 10 km and a normal mechanism

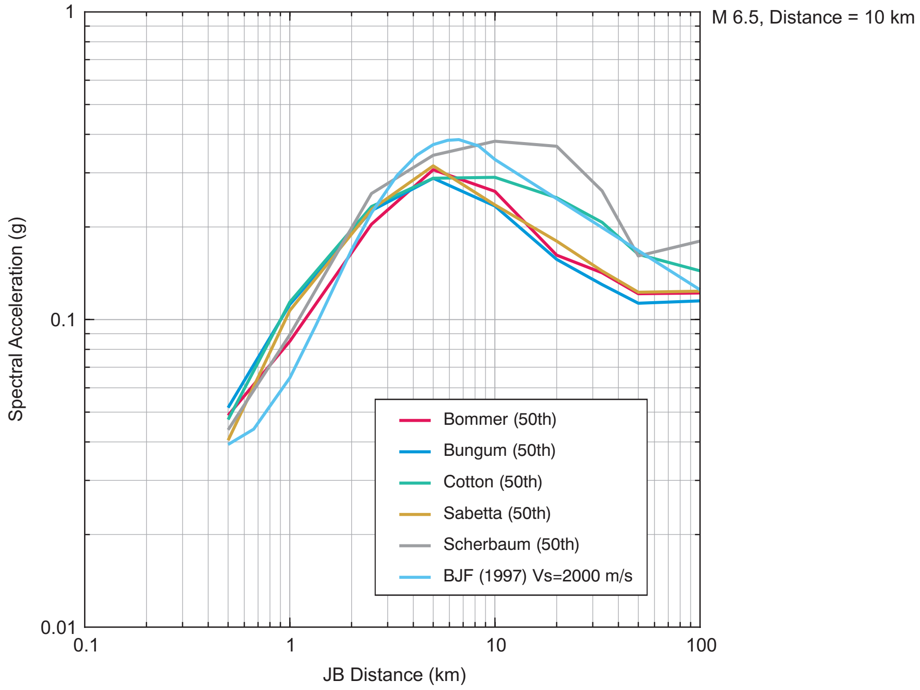


Fig.5-19: Comparison of the 50th fractile of the median spectral acceleration for a magnitude 6.5 earthquake at JB distance of 10 km and a strike-slip mechanism, the Boore Joyner Funal median is also shown for comparison.

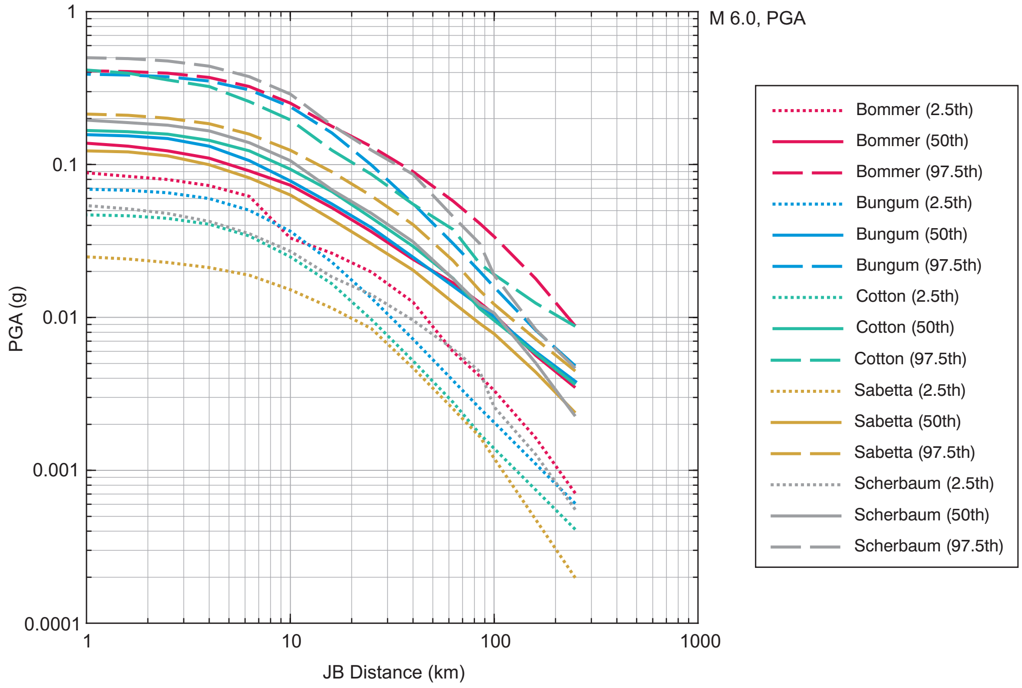


Fig.5-20: Comparison of the epistemic uncertainty of the median peak acceleration for magnitude 6.0 earthquake and a normal mechanism

5.5.2 Median V/H Ratio

The V/H ratio is only used to scale the horizontal component UHS. Therefore, the key part of the V/H ratio model is for the earthquakes that dominate the hazard. For annual probabilities less than 1E-4, the hazard is dominated by moderate magnitude earthquakes at short distances. Therefore, our concern is with the V/H ratio from moderate magnitudes at short distances.

The median V/H ratios from the five expert models for a magnitude 6 earthquake at a distance of 10 km are compared in Figure 5-21. The median V / H ratio has greater range in values between the experts than the median horizontal spectrum shown previously (Figure 5-19).

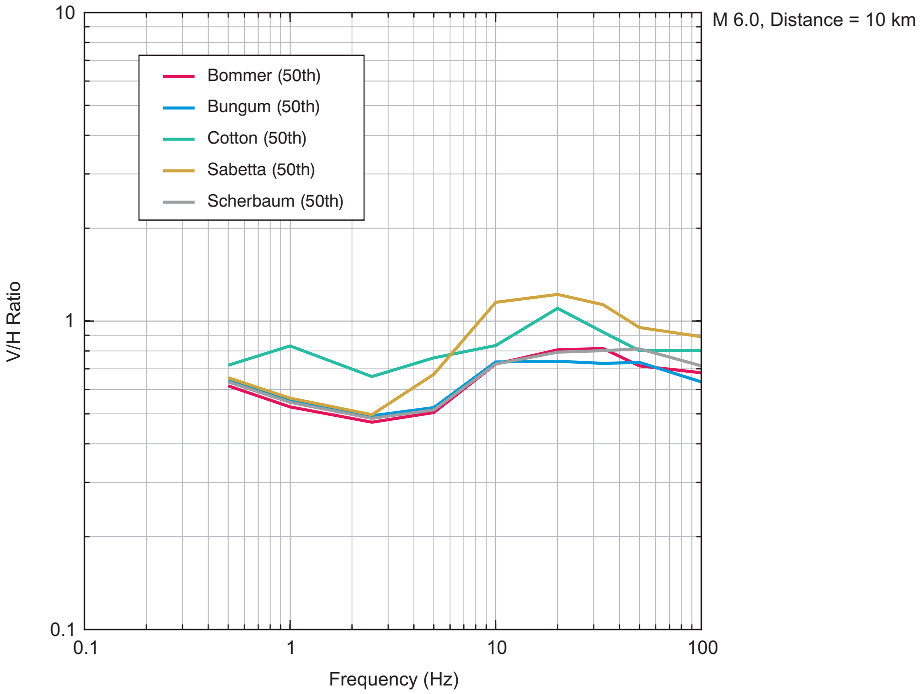


Fig.5-21: Comparison of the 50th fractile of the median V / H ratio for magnitude 6.0 earthquake at a distance of 10 km and a normal mechanism

5.5.3 Aleatory Variability for Horizontal Ground Motion

The aleatory variability has a large effect on hazard for the low probability levels. The median value of the aleatory variability for the horizontal peak acceleration and T = 1 second spectral acceleration from the five expert models for a distance of 10 km is shown as a function of magnitude in Figures 5-22 and 5-23.

The median value of the aleatory variability for the horizontal peak acceleration and T = 1 second spectral acceleration from the five expert models for a magnitude 6 earthquake is shown as a function of distance in Figures 5-24 and 5-25.

5.5.4 Maximum Ground Motions for the Horizontal Component

The median value of the maximum horizontal peak acceleration and T = 1 second spectral acceleration from the five expert models for a distance of 10 km is shown as a function of magnitude in Figures 5-26 and 5-27.

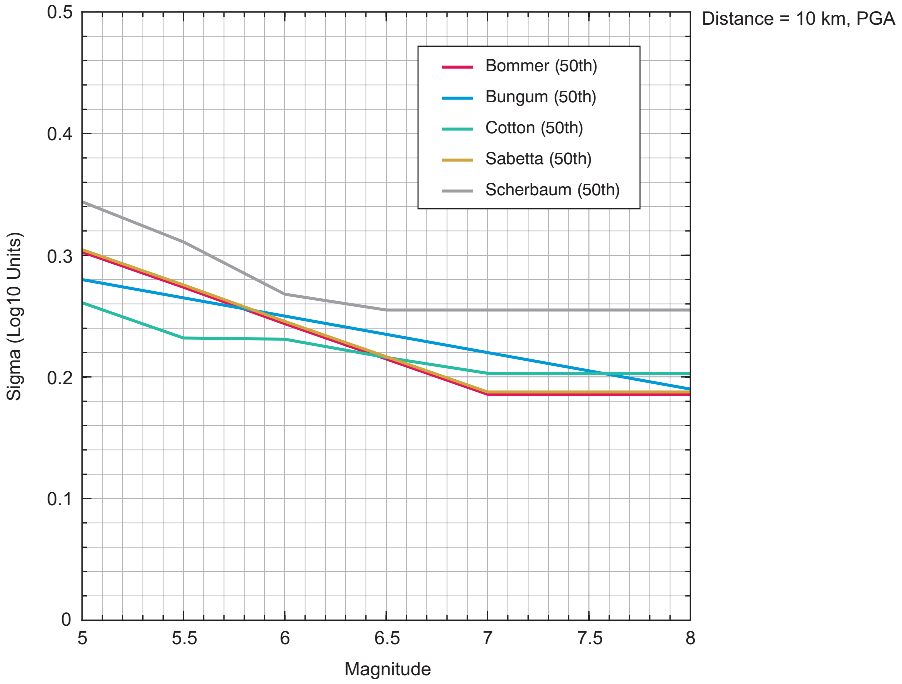


Fig.5-22: Comparison of the 50th fractile of the aleatory variability of the peak acceleration for a distance of 10 km

(Bommer is equal to Sabetta)

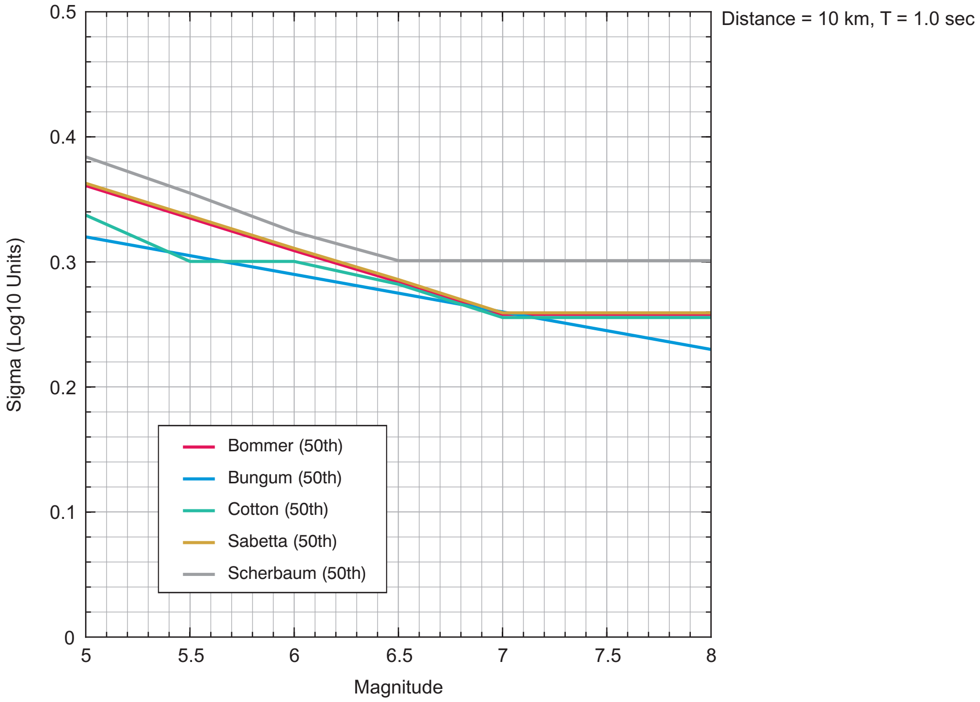


Fig.5-23: Comparison of the 50th fractile of the aleatory variability of the T = 1 second spectral acceleration for a distance of 10 km

(Bommer is equal to Sabetta)

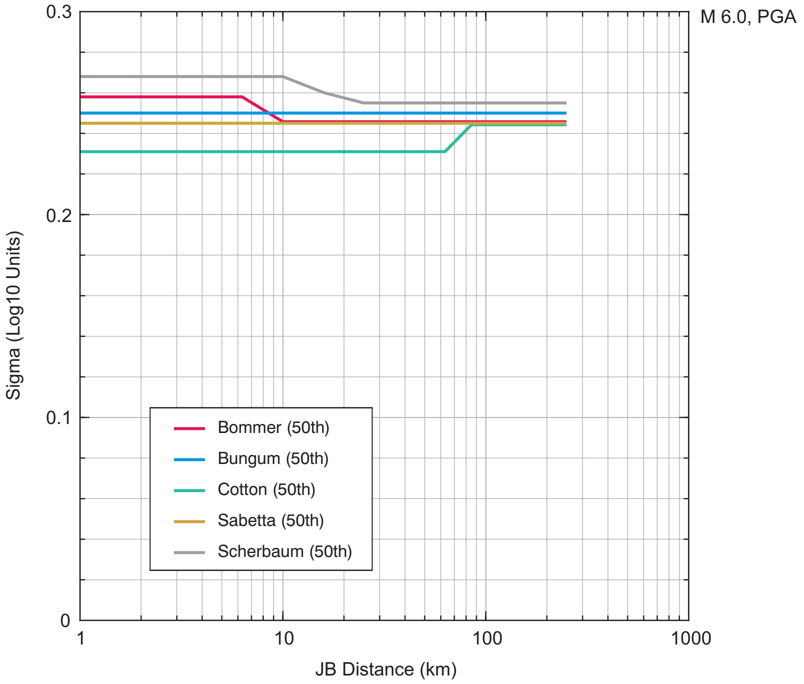


Fig.5-24: Comparison of the 50th fractile of the aleatory variability of the peak acceleration for a magnitude 6.0 earthquake

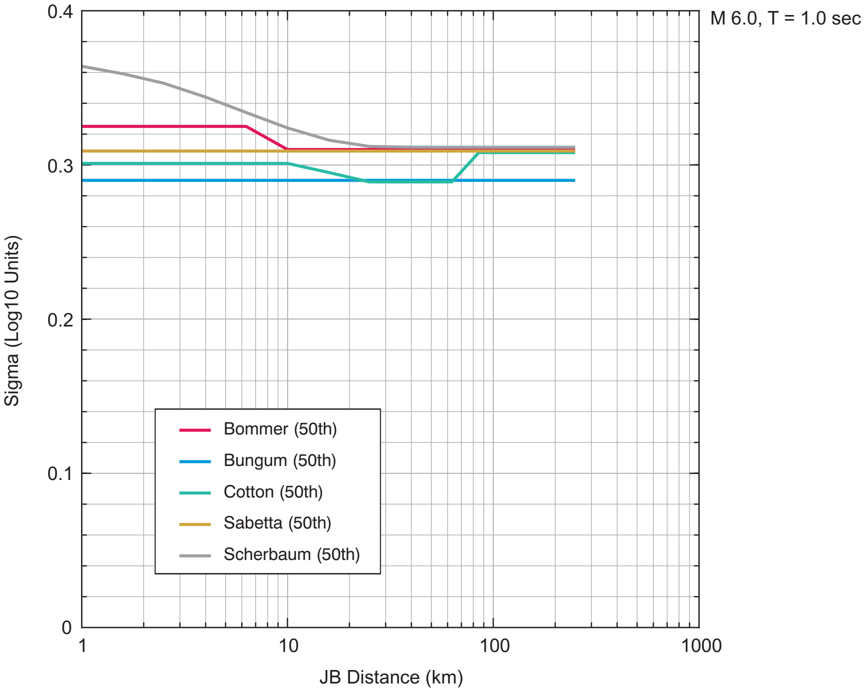


Fig.5-25: Comparison of the 50th fractile of the aleatory variability of the T = 1 second spectral acceleration for a magnitude 6.0 earthquake

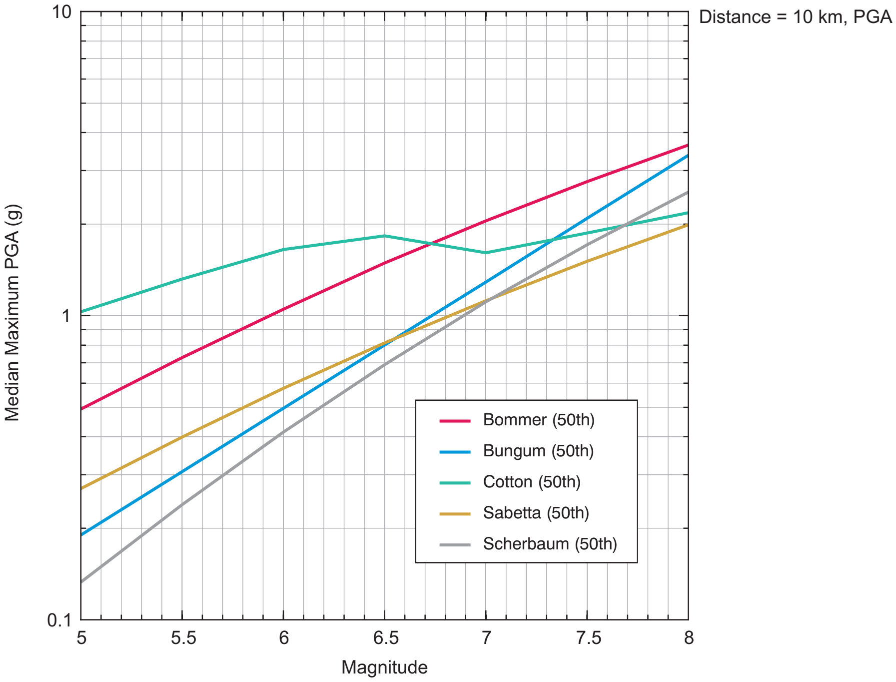


Fig.5-26: Comparison of the 50th fractile of the maximum peak acceleration for a distance of 10 km

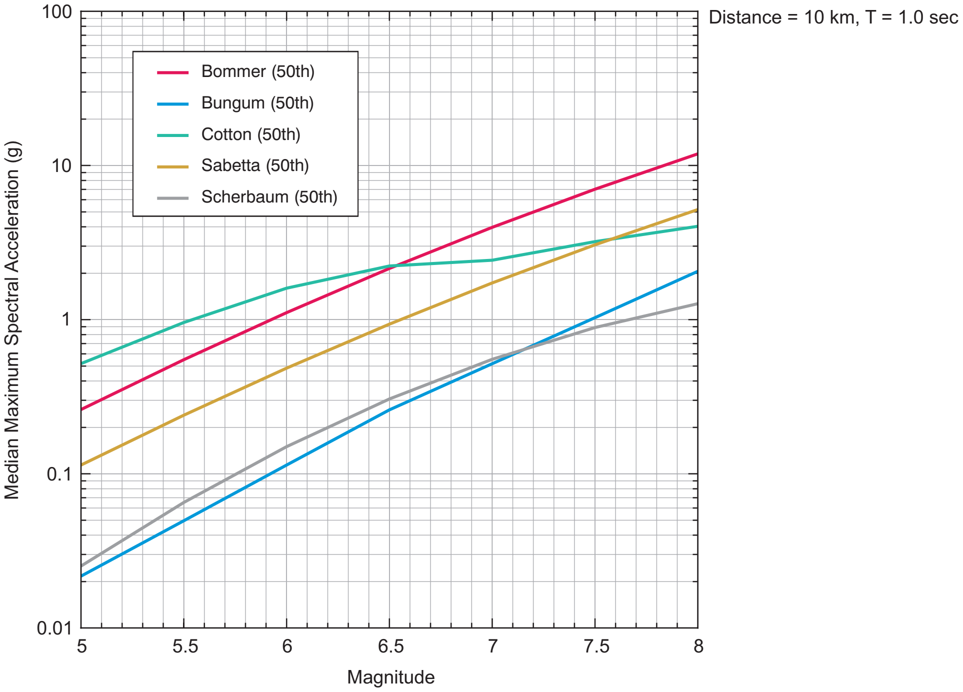


Fig.5-27: Comparison of the 50th fractile of the maximum T = 1 second spectral acceleration for a distance of 10 km

The median value of the maximum horizontal peak acceleration and T = 1 second spectral acceleration from the five expert models for a magnitude 6 earthquake is shown as a function of distance in Figures 5-28 and 5-29.

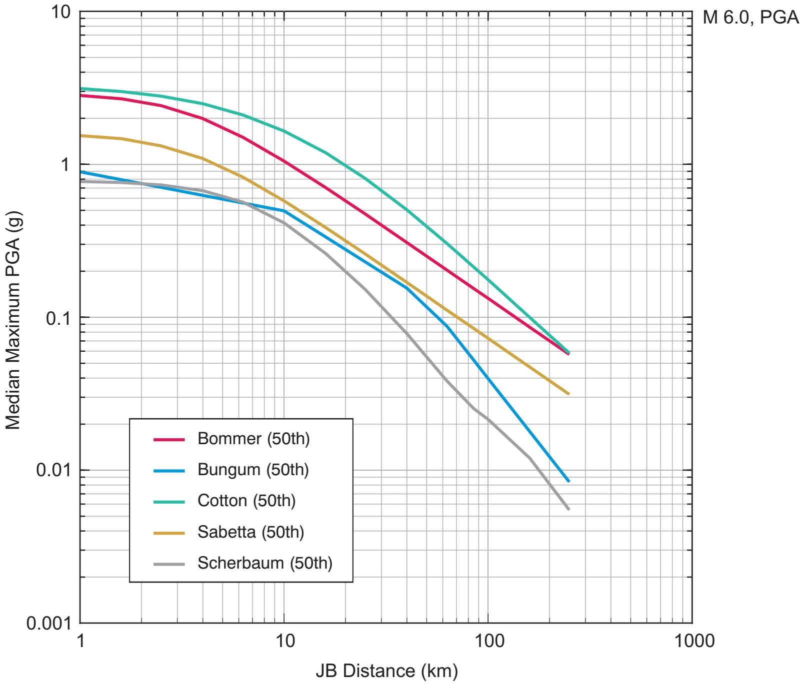


Fig.5-28: Comparison of the 50th fractile of the maximum peak acceleration for a magnitude 6.0 earthquake

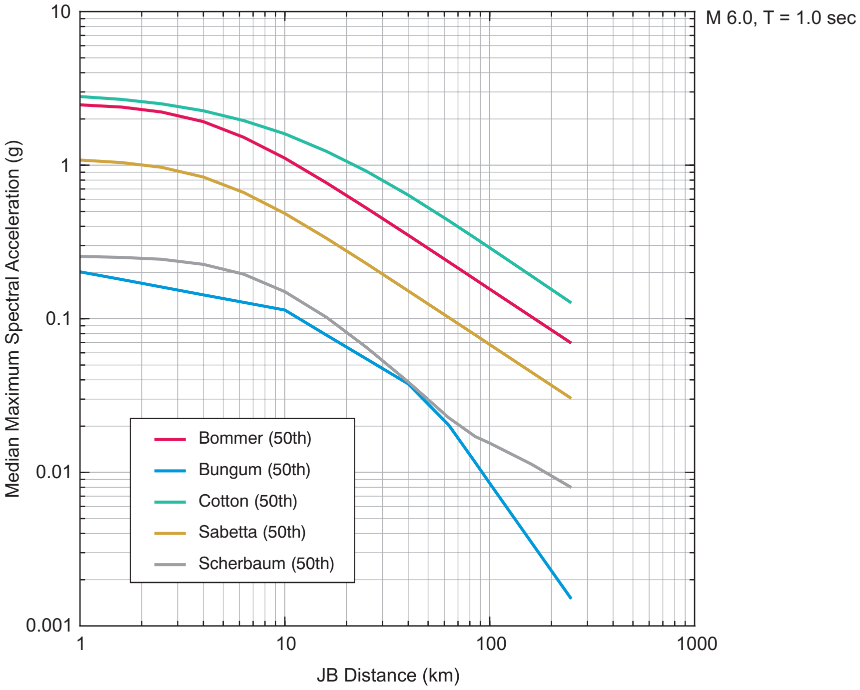


Fig.5-29: Comparison of the 50th fractile of the maximum T = 1 second spectral acceleration for a magnitude 6.0 earthquake

5.5.5 Maximum Ground Motions for the Vertical Component

The median value of the maximum horizontal peak acceleration and T = 1 second spectral acceleration from the five expert models for a distance of 10 km is shown as a function of magnitude in Figures 5-30 and 5-31.

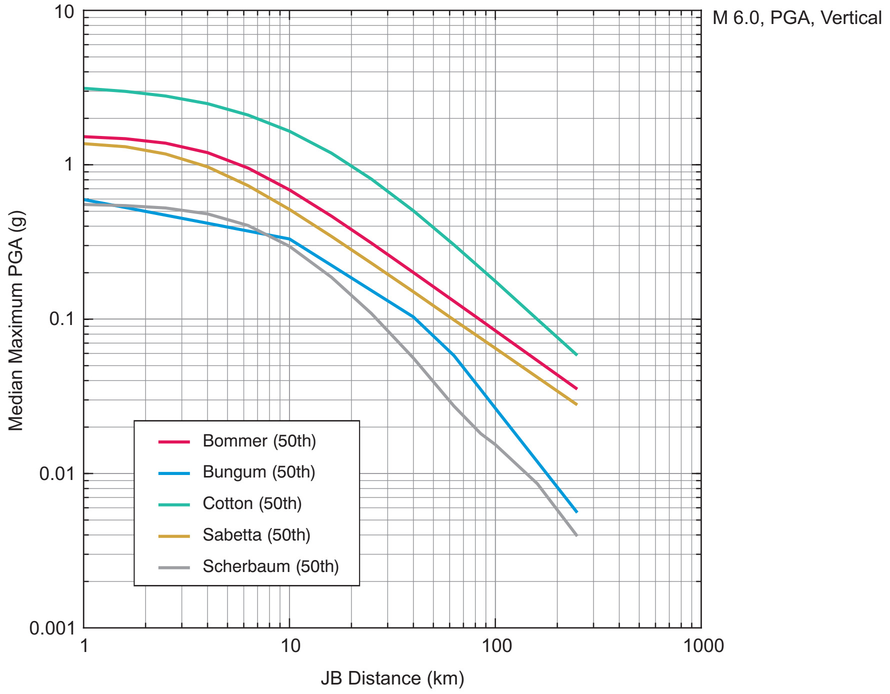


Fig.5-30: Comparison of the 50th fractile of the maximum vertical peak acceleration for a magnitude 6.0 earthquake

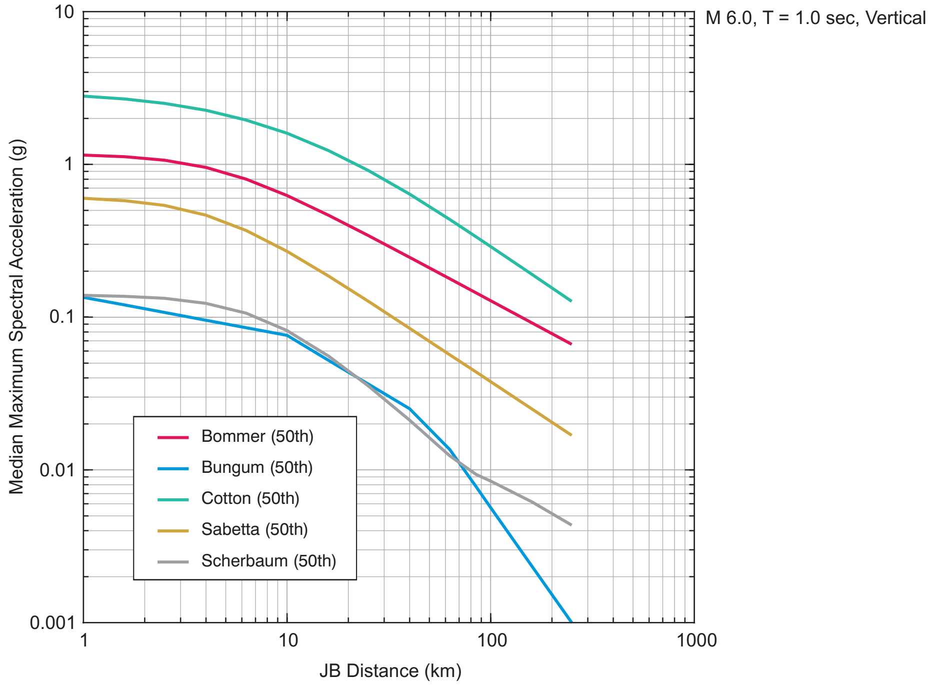


Fig.5-31: Comparison of the 50th fractile of the maximum vertical T = 1 second spectral acceleration for a magnitude 6.0 earthquake

6 SITE RESPONSE CHARACTERISATION

6.1 Site Response Characterisation Methodology

6.1.1 Methodologies for PSHA with Site Response

In the PEGASOS Project, the site response effects are addressed in terms of response spectral amplification functions. The amplification function is defined as the ratio of the response spectra for 5 % of critical damping of the ground motion of interest (at the surface or at certain depths) and of the input ground motion, which corresponds to a free-surface rock ground motion. The computational methods applied for site response characterisation are 1-D equivalent-linear site computations, 1-D true non-linear site effect computations, 1-D site effect computations including effects due to oblique wave incidence, and 2-D site effect computations.

6.1.2 1-D Equivalent-Linear Site Response Computations

The 1-D equivalent-linear computational scheme is the simplest possible and most widely used computational scheme used to evaluate site-specific seismic response. This scheme assumes vertically propagating plane S waves for the horizontal components of ground motion and vertically propagating plane P waves for the vertical component. Non-linear behaviour of the soil response is treated in an approximate manner through the use of the equivalent-linear approach.

The commonly used equivalent-linear approach was first introduced by Seed & Idriss (1970), based on a general equivalent-linear theory developed by Iwan (1967). The basic approach is to approximate a second order non-linear equation, over a limited range of its variables, by a linear equation and by minimising the average of the difference between the two systems. This was done in an ad-hoc manner for ground response modelling by defining an effective strain which is assumed to exist for the duration of excitation. This value is usually taken as 65 % of the peak strain calculated for each layer, using a linear analysis. Modulus reduction and hysteretic damping curves are then used to define new parameters for each layer based on the effective strain computations. The linear response calculation is repeated, new effective strains evaluated, and iterations performed until the changes in parameters are below some tolerance level. This iterative procedure was formalised into a computer code called SHAKE (Schnabel et al. 1972). This code has become the most widely used analysis package for 1-D site response computations.

The advantages of the equivalent-linear approach are that complex parameterisation of non-linear soil models is avoided and the mathematical simplicity of a linear analysis is preserved.

The 1-D equivalent-linear computational scheme has been used to successfully model observed site effects and represents a stable, mature and reliable method of estimating the effects of site conditions on strong ground motions as long as the input rock ground motion is not very strong (see, for instance, EPRI 1993).

6.1.2.1 Time History Method (TH)

Different acceleration time histories with nearly identical response spectra as input motion can result in different amplification functions even within the context of equivalent-linear computations. This variability due to the different acceleration time histories corresponds to an aleatory variability. In order to obtain an estimate of both a reliable median value and the aleatory variability of the amplification functions, the amplification functions were calculated for a series of different time histories.

Site response computations were carried out using the computer program SHAKE91, which is essentially identical with the original program (Schnabel et al. 1972). 15 time histories, recorded on so-called rock sites, were used for each case of otherwise constant input parameters.

To allow an evaluation of the dependence of the amplification functions on earthquake magnitude, sets of 15 time histories were selected for three moment magnitude levels: M 5, M 6 and M 7 (*Lacave 2002, TP3-TN-0151*). These time histories were scaled to PGA values of 0.1 g, 0.4 g and 0.75 g to allow an evaluation of the influence of the ground motion level on the amplification factors. The magnitude 6 time histories were applied to all possible site models (all combinations of soil profiles and material models) (*Augello 2002a, TP3-TB-0047*), whereas the magnitude 5 and 7 time histories were only used with one or two site models per site (*Augello 2002b, TP3-TB-0049*).

6.1.2.2 Random Vibration Theory Method (RVT)

An important aspect of epistemic uncertainty in the site response computations was the limited number of soil profiles (shear wave velocity profiles) and limited modern testing of the material behaviour at the four sites. This uncertainty called for some kind of randomisation of the site models (see section 6.1.6). Such a randomisation, however, could not have been handled with reasonable effort if time history calculations had to be carried out. In combination with the variation of the other parameters, the number of required computations would have become unfeasible within project schedule and budget. For this reason, computations based on random vibration theory (RVT) were performed.

In the RVT-based computational scheme, the control motion power spectrum was propagated through the 1-D soil profile using the plane wave propagators of Silva (1976). The equivalent-linear formulation was employed for the treatment of non-linear material behaviour. Random process theory was used to predict peak time domain values of shear strain based upon the shear strain power spectrum. The purely frequency domain approach obviated a time domain input motion and there was therefore no need for a suite of analyses with different input time histories.

The RVT computations were carried out for each site model for PGA levels of 0.05 g, 0.10 g, 0.20 g, 0.30 g, 0.40 g. 0.50 g, 0.75 g, 1.00 g, 1.25 g and 1.50 g (*Silva 2002a, TP3-TB-0046* and *Silva 2002b, TP3-TN-0204*). To provide statistical stability in median estimates, 50 realisations were computed for each magnitude, rock PGA value and site model. The RVT and SHAKE results were compared in detail (*Travasarou 2002, TP3-TN-0212*). The resulting amplification functions turned out to be fairly similar around the site's fundamental frequencies. However, a systematic deviation could be observed in the low frequency range, where the SHAKE results gave significantly higher amplifications than the RVT results. This tendency could also be observed in many, but not all, cases in the high frequency range towards PGA.

6.1.3 1-D True Non-linear Site Effect Computations

When the input rock motion becomes very large (e.g. PGA > 0.4 g), non-linear soil behaviour can no longer be adequately approximated by an equivalent-linear model. The commonly accepted domain of validity of the equivalent-linear approximation is for strains smaller than 0.1 % to 0.5 %.

Since very high ground motion levels were expected for low probabilities of occurrence, the SP3 experts requested a set of true non-linear computations of site response.

In a first phase, 1-D true non-linear computations were carried out for Beznau, Gösgen and Leibstadt with the computer program SUMDES (Li et al. 1992), modified by Geodeco, assuming vertically propagating S waves (*Pelli 2002, TP3-TB-0048*). At this stage, possible pore pressure build-up was not taken into account, i.e. a dry soil was implicitly assumed, due to the lack of knowledge of the corresponding soil parameters. These calculations were carried out for five time histories scaled to three PGA levels (0.41 g, 0.75 g and 1.5 g).

In parallel, non-linear computations were done for the same five time histories, scaled to 1.5 g, for Gösgen with the program DYNAFLOW (*Pecker 2002a, TP3-TN-0205*). These computations were performed using effective stresses, i.e. pore pressure build-up was taken into account based on parameters taken from sites with similar conditions. Significant differences between both results were observed, and the experts concluded that it was necessary to take into account pore pressure build-up for the sites with a high water table, i.e. for the Beznau and Gösgen sites.

As a consequence, the SUMDES computations for Beznau and Gösgen were repeated accounting for the pore pressure build-up (*Pelli 2003a, TP3-TB-0051*). The results showed that the average frequency with the highest amplification, f_p, is always lower than the elastic fundamental frequency. It was also shown that the higher the scaling factor of the input time histories, the lower the value of f_p and of the mean amplification function at f_p. The amplification of the PGA also decreased with increasing input motion. The results also suggested that there is a considerable record-to-record variability of the amplification function, especially for the highest input accelerations.

In view of the estimation of maximum ground motion that is transmittable through the soil columns, further SUMDES computations for Beznau and Gösgen were requested by the experts. These computations were conducted with input rock motion for a magnitude 7 earthquake scaled to a PGA level of 2.5 g. The results (*Pecker 2004, TP3-TN-0403*) confirmed the tendency of decreasing amplification and increasing record-to-record variability for increasing input motion levels.

6.1.4 1-D Site Effect Computations for Oblique Wave Incidence

Some 1-D site effect computations were carried out for oblique wave incidence, for S_H as well as for PS_V waves in order to assess the effects of oblique wave incidence, which were not considered in the previous 1-D computations.

Bard modelled incoming plane body waves with incidence angles varying from 0° to 80° using a Thomson-Haskell algorithm (*Bard 2002b, TP3-RF-0310*). His main conclusion was that, while the median amplification did not change much with respect to vertical incidence, the aleatory variability grew significantly.

Fäh modelled oblique wave incidence using double-couple point sources (*Fäh 2002a, TP3-TN-0167*). Multiple sources within different depth and distance ranges were modelled in order to cover the variability of possible incidence angles and corresponding ground motions. Fäh's results included incoming surface waves, and it remained an open question to what extent incoming surface waves were important for strong ground motion. His main conclusion was that the resulting amplification functions in the range of the fundamental frequencies were broader, but had lower amplitudes with respect to the case of vertical incidence.

6.1.5 2-D Site Effect Computations

The experts estimated that 2-D effects would be strongest at the Leibstadt site due to the combined effect of surface topography (terrace edge) and subsurface layering. It was therefore decided to perform 2-D simulations for Leibstadt using two different numerical techniques.

Bard carried out 2-D computations with the aid of the Aki-Larner technique for incident plane S_H waves (15 time histories) with incident angles of -30°, 0° and +30° (*Bard 2002a, TP3-TN-0186*). He separately considered a low and a high strain case. For the latter, he used the S wave velocities and damping values corresponding to what had resulted from the SHAKE computations for a PGA level of 0.4 g.

The main 2-D effects occurred at intermediate frequencies (from 2 to 6 Hz), with the strongest effects appearing close to the terrace edge where surface waves are created due to diffraction. This diffraction turned out to give rise to stronger 2-D effects when the incoming waves come from the north and weaker 2-D effects when they come from the south. This effect increases the variability if the source location is not known.

The results showed that the surface waves died out rapidly in the high strain case so that 2-D effects nearly disappeared in this situation. However, the experts stressed that the damping stemming from SHAKE computations was often considered to be overestimated. Hence, 2-D effects might be underestimated in Bard's high strain simulations.

Fäh performed 2-D SH computations for low strains using a hybrid approach of mode summation and 2-D wavefield modelling (*Fäh 2002b, TP3-TN-0240*). Mode summation was used to propagate the wavefield from the seismic source through a one-dimensional model of the crust. Two-dimensional modelling of the local structure with finite differences was then used to compute the ground motion at the Leibstadt site using the results of mode summation as input at the edges of the local 2-D model. Different source distances and depths were considered. The amplification function was calculated with respect to a bedrock model at the same distance from the corresponding source.

Fäh's results show strong 2-D amplification around the site's fundamental frequency. It turns out that the amplification as a function of frequency strongly depends on the source location. In particular, it is confirmed that 2-D effects are stronger for sources to the north than for sources to the south of the site.

6.1.6 Soil Profiles and Soil Profile Randomisation

6.1.6.1 Basic Geotechnical Data

The PEGASOS site studies primarily relied on the original geotechnical data of the period of reactor construction. Only a few additional geophysical measurements were foreseen within the framework of the project.

All the wave velocity and density data that could be found in original documents were compiled (*Zingg 2002b, TP3-TN-0132*). *Studer* (*2002, TP3-TN-0127*) evaluated the quality of the original data and came to the following conclusions: The static tests could be considered as reliable for all sites. The dynamic tests, however, were of varying quality. They were judged "acceptable" for Beznau and Mühleberg, whereas their quality could not be evaluated for Leibstadt. For Gösgen, the quality of the dynamic tests was judged "questionable", because of the lack of sufficient information. For the G-modulus and damping as a function of shear strain, it was recommended to rely on published data, except for Beznau where reliable specific laboratory data were available.

The Swiss Seismological Service performed ambient vibration measurements at Beznau, Gösgen and Leibstadt (Fäh et al. 2001, *Fäh & Wössner 2002, TP3-TN-0123*); possible velocity profiles were elaborated based on Fäh's inversion technique. Additional ambient vibration measurements were carried out at Leibstadt and Mühleberg, with classical H / V data processing to determine the fundamental frequencies (*Koller 2002a, TP3-TN-0121*). For Gösgen, a spectral analysis of surface waves (SASW technique) was performed in order to check the older cross-hole data for the unconsolidated soil deposits (*Koller 2002b, TP3-TN-0126*).

6.1.6.2 Soil Profiles Used for the Site Effect Computations

The experts developed S wave velocity profiles, median values and uncertainties on the basis of the above-mentioned data (see section 6.2.2). Furthermore, they decided which G-modulus and damping curves as a function of shear strain had to be used. Different site models could result from either differences in the velocity profile or in the material behaviour.

Koller (2002d, TP3-TN-0166) is a compilation of all soil profiles and material properties that were finally used for the site effect computations. For Beznau, three velocity profiles were defined by the experts, but only one set of material behaviour was defined since this site had more reliable site-specific data. For Gösgen, only one velocity profile, but two sets of G-modulus and damping curves, according to Hardin & Drnevich (1972) and to Ishibashi & Zhang (1993), were used. The same was decided for Mühleberg: one velocity profile and the same G-modulus and damping curves as for Gösgen.

For Leibstadt, two velocity profiles, differing only with respect to the base rock velocities, and two material models were defined. Between 30 and 50 m depth, the gravels are cemented to an unknown extent. Within the cemented gravels, the experts expected that the decay of the G-modulus with shear strain is first slower than for normal gravels, but is accelerated beyond a certain threshold. Pecker made available curves for carbonated sands in Monaco that show such behaviour. The experts believed that this was a reasonable model also for the cemented layers at Leibstadt. Since the extent of the cemented gravels is uncertain, the experts decided to use also, as an alternative material model, the standard G-modulus and damping curves.

Except for the Opalinus Clay in Beznau, where specific laboratory data were available, a shear strain-independent wave velocity and a constant damping value of 1 % was used for all rocks.

6.1.6.3 Soil Profile Randomisation

To accommodate uncertainties in the knowledge of the dynamic material properties (errors in the measurements, variations occurring over a site), S wave velocities as well as G-modulus and damping curves were randomised for the RVT computations (see section 6.1.2.2).

The profile randomisation scheme, which varies both layer velocity and thickness, was based on a correlation model developed from an analysis of variance on about 500 measured S wave velocity profiles (Silva et al. 1997). However, for each profile, the experts put limits for the variation of the velocities and layer thickness, which were thought to represent 2 σ of the parameter variations. No variation larger than 2 σ was taken into account in order to guarantee that only physically realistic configurations were used for the site response computations.

To accommodate variability in the G-modulus and damping curves, the curves were randomised about the base case values constrained by a fully negative correlation. For each random sample of the soil curves, a lower G-modulus curve was associated with a higher hysteretic damping curve. A log-normal distribution was assumed with a $\sigma_{\ln}$ of 0.35 at a cyclic shear strain of 3×10^{-2} %, with upper and lower bounds of 2 σ. The random curves were generated by sampling the transformed normal distribution with a $\sigma_{\ln}$ of 0.35, computing the change in normalised modulus reduction or percent damping at 3×10^{-2} % shear strain, and applying this factor at all strains. The random perturbation factor was tapered near the ends of the strain range to preserve the general shape of the median curves (Silva 1992).

6.1.7 Epistemic Uncertainty of Site Response

Principally, there are two sources of epistemic uncertainty of site response:

- imperfect knowledge of material properties (uncertainties in the S wave velocities, G-modulus and damping curves, unknown variation of the material properties over the site, etc.)
- inappropriate or too simple modelling: (1-D or 2-D instead of 3-D modelling, simplified material modelling, for instance equivalent-linear instead of true non-linear modelling, etc.).

6.1.8 Maximum Ground Motions for Soil

There is no well established method to estimate the maximum ground motion that a soil profile can transmit to the ground surface. However, it is recognised and admitted that the soil cannot transmit any motion due to its limited shear resistance capacity.

The maximum ground motion was estimated in the following three ways:

- using numerical analyses, such as those carried out by Pelli & Pecker with increasing input motion (*Pelli 2003a, TP3-TB-0051*, *Pecker 2002a, TP3-TN-0205*, *Pelli 2003b, TP3-TN-0353*, see section 6.1.3),
- using two alternative theoretical models based on an assumed soil constitutive behaviour (*Pecker 2003, TP3-TN-0354*),
- using observed ground motions from past earthquakes on soil sites (*Ripperberger & Fäh 2003, TP3-TN-0359*).

All these approaches were considered by the experts.

The first theoretical model was developed by Betbeder-Matibet (1993). This is a simple geotechnical model that assumes a constant shear modulus with depth and a hyperbolic constitutive law. The average soil column acceleration is limited by the available shear strength at the base of the soil profile divided by the mass of the soil column. The maximum surface acceleration is related to the average soil column acceleration based on the shape of the first fundamental mode only. It turned out that this model underpredicted the maximum accelerations obtained by the true non-linear computations. The experts concluded that the Betbeder-Matibet model had the tendency to underestimate maximum ground motion, particularly for stiff sites where higher modes are expected to be of some importance.

The second theoretical model considered was developed by *Pecker* (*2003, TP3-TN-0354*) and is based on classical soil mechanics assumptions. The advantage of this approach is that extensive experience exists with the behaviour of soils in the failure range. Pecker's model assumes an increase of S wave velocity with a power function of depth and an elastic perfectly plastic constitutive material behaviour. Three modes of vibration of the soil column are taken into account. The induced shear strain is compared at any depth with the yield strain γ_f, and it is assumed that the ground surface acceleration cannot exceed the value reached when $\gamma(z) = \gamma_f$ is attained at any depth.

The maximum ever recorded ground motion on soil has the disadvantage of being necessarily a lower bound estimate of maximum possible ground motion. Furthermore, very strong ground motion, potentially at the level of maximum ground motion, could only be found for a Californian site that might be comparable to the Gösgen site. Therefore, no site-specific maximum ground motion could be deduced from actual recordings on soil.

6.1.9 Adjustment of SP2 Rock Spectral Accelerations to a Reference Rock Site Velocity

The role of the SP2 experts was to develop empirical ground motion attenuation relations for reference rock conditions, and the role of the SP3 experts was to elaborate site-specific amplification functions with respect to reference rock conditions. However, the reference rock conditions of SP2 and SP3 were a priori not identical.

Empirical attenuation relations for rock condition are based on recordings stemming from surface rock sites that usually correspond to weathered rock. The experts of SP2 concluded from a special inquiry that the mean rock velocity of rock recording stations would be around 600 m/s.

The SP3 experts used a reference rock velocity common to all NPP sites, i.e. principally the highest base rock velocity. A value of 2000 m/s was taken as the reference velocity, corresponding to some rock layer at depth at Gösgen. All velocity profiles of the other sites were extrapolated downwards until this reference value was attained.

If ground motion computed with the rock attenuation equations of SP2 were amplified by the amplification functions of SP3 without any correction, the decrease in velocity from 2000 m/s to 600 m/s would be double counted. The experts of SP2 and SP3 discussed this problem at the first workshop and the procedure to overcome this inconsistency was finalised at WS-4 (see sections 6.2.1 and 6.2.4). The issue of the interface between SP2 and SP3 is discussed in section 2.6.3.1.

6.2 SP3 Workshops

In SP3, five workshops and three elicitation meetings were held during the project. These eight meetings are summarised in this section. For the workshops, this section gives an overview of the important technical issues, the decisions taken and the experts' requests. For a detailed account of the workshops, the reader is referred to the workshop summaries.

6.2.1 WS-1 / SP3: Key Issues and Data Needs

The SP3 data needs workshop (WS-1) was held on October 16 – 18, 2001 in Zürich. All four SP3 experts were in attendance for the full workshop. This workshop was held concurrently with the SP1 and SP2 data needs workshops.

In a joint session with SP2, Abrahamson gave a presentation on a proposed PSHA methodology that separates the rock hazard and the site effects evaluation. In this approach, the SP3 experts are required to develop models for the amplification factors (AFs), defined as the ratio (Sa_{soil}(f,)/ Sa_{rock}(f,)) at each site, where Sa is the response spectral acceleration. The experts decided that the AFs should consider a dependence on the amplitude of the rock ground motion and the earthquake magnitude.

The SP3 experts reached a consensus that the bulk of the site response calculations would be done using 1-D equivalent-linear simulations. These base simulations would be supplemented by sensitivity studies for 2-D effects and 1-D truly non-linear site response calculations. Moreover, the Leibstadt site, which has the strongest surface topography and a layer that could act as a wave trap, was selected for the 2-D sensitivity studies. The Gösgen site was chosen for the 1-D full non-linear sensitivity study, since the strongest non-linear effects were expected at this site due to the strong impedance contrast above the bedrock.

Site response calculations for the vertical component of motion are not common in engineering practice. After a discussion of alternative available techniques, the experts reached a consensus that they would use equivalent-linear 1-D simulations with vertically incident P waves for the vertical component site response.

An important issue is the interface between SP2 and SP3. This was discussed in the joint SP2-SP3 session. The key issue is that the definition of "rock" typically used in ground motion attenuation relations (e.g. SP2) is not the same as the definition of "rock" used for site response calculations (e.g. SP3). It was decided that each SP2 expert would specify the V_{S30} value applicable to his rock ground motion models. An adjustment factor to scale the ground motions to SP3 rock conditions would then be applied to each SP2 ground motion. Details of the process of developing these adjustment factors were finalised in WS-4 and are summarised in *Lacave et al.* (*2003, TP2-TN-0363*).

The geological structure and geotechnical properties at the four NPP sites were presented to the SP3 experts. The experts questioned the quality of the V_s measurements in the vicinity of the

NPP sites since these data were obtained many years ago with acquisition techniques that would no longer be used today. The experts suggested that new site data should be collected to increase the knowledge of the V_s profiles in Gösgen and Leibstadt. In Beznau, additional data should be collected to better constrain the unusually low velocity layer of Opalinus Clay. For Mühleberg, geotechnical and V_s data were considered to be of very poor quality. The presence of strong impedance contrasts in the subsurface would have to be evaluated. The TFI-team was asked to investigate whether S wave reflection measurements would be an appropriate technique to reduce the uncertainty in the knowledge of the S wave profiles at the NPP sites.

The experts requested that the complete geotechnical database report be provided and additional geological cross-sections developed.

Toro presented a methodology for the randomisation of soil profiles. This methodology was used to construct suites of V_s profiles for a given median profile s. The experts agreed that the model could provide a useful tool for modelling the uncertainty in the knowledge of the soil parameters. It was noted that, in addition to this, the technique could be used to smooth and average peaks in the 1-D-amplification modelling.

[redacted], a workshop observer of the HSK-RT, asked what the site response would be at the foundation level (embedded). At the time of WS-1, only surface motions were included in the project scope of work. This discussion led to eventual changes in the project scope to include the ground motions at the embedded foundation levels.

A final recapitulation of data needs led to a list of 21 expert requests or recommendations. The most important ones have been mentioned so far; for further details, the reader is referred to the workshop summary.

Finally, it was decided that there was a need to hold an intermediate meeting before the 2nd workshop for the presentation of results of additional site-specific investigations and to establish median soil profiles that would have to be used for the site response computations so that soil response calculations could be available for discussion at WS-2. This additional meeting became an expert group elicitation (see section 6.2.2).

6.2.2 Elicitation Meeting on Properties of Soil Profiles

The elicitation meeting on properties of soil profiles was held on February 4, 2002 in Baden. All of the SP3 experts attended the elicitation meeting. This meeting was a group elicitation in which the experts interpreted the geological and geotechnical information and developed consensus median soil profiles for each site. To provide the experts with a basis for these assessments, all previously available data as well as the results of the new analytical studies, compilations and field investigations were made available to them before the meeting.

The additional investigations were:

- Nakamura measurements at the Leibstadt and Mühleberg NPP sites (*Koller 2002a, TP3-TN-0121*)
- SASW measurements at the Gösgen NPP site (*Koller 2002b, TP3-TN-0126*)
- Construction of V_s profiles with associated uncertainty ranges based on available data (*Zingg 2002a, TP3-TN-0128*)
- A quality assessment study of the available geotechnical data sets (*Studer 2002, TP3-TN-0127*)
- Non-linear simulations of seismic soil response at Gösgen (*Modaressi 2002, TP3-TN-0133*)

In response to the experts' request for new V_s measurements at each site, Graf explained that he had contacted several specialists in the field and that it would not be possible to obtain S wave reflection measurements within the time and budget constraints of the project. The project management decided that the experts would have to rely on existing geotechnical data. A consequence of this decision was that the experts' models would have to include epistemic uncertainties that could be reduced if new geotechnical site characterisations were conducted in the future.

Using the available site information, the experts developed alternative median soil profiles for each site including the V_s profile and non-linear properties (strain-dependent normalised shear modulus and damping). The experts noted that the soil profiles should be checked for consistency with the fundamental frequencies obtained from H / V ambient vibration measurements and that small adjustments to the V_s profile should be made if needed. The soil profiles formed the basis for the site response calculations and were documented in *Koller* (*2002c, TP3-TN-0131*).

6.2.3 WS-2 / SP3: Evaluation of models

The SP3 workshop on evaluation of models (WS-2) was held on May 14 – 16, 2002 in Zürich. All four SP3 experts were in attendance for the full workshop. The goals of WS-2 were:

- To evaluate the differences between equivalent-linear and truly non-linear approaches and determine how to best use the results from the sensitivity studies using the non-linear approach.
- To discuss the strengths and weaknesses of the alternative methods for computing the site amplification factors using the equivalent-linear approach in a probabilistic hazard analysis (RVT vs. time history).
- To review the approaches for estimating the vertical component GM.
- To define additional plots and/or analyses that the experts need for the evaluation of the amplification functions.
- To prepare for the first round of elicitations, which occurred between WS-2 and WS-3

Abrahamson explained that the experts had to develop spectral amplification functions (AFs) for each site, location and frequency and that they had to address median values as well as aleatory and epistemic uncertainties. The AFs are defined as the ratios between the response spectrum of interest (at foundation level or at the free surface) divided by the response spectrum of the input motion (bedrock at hypothetical free surface). Each expert would have to determine weights for the alternative methods (e.g. 1-D equivalent-linear, true non-linear, 2-D) and model parameters (e.g. V_s profile, modulus and damping curves). Each expert was to provide the reasoning for his selection of weights to the other experts in the following workshops and all significant revisions to weights had to be subject to discussion with the other experts.

Modaressi presented the results of preliminary truly non-linear calculations for five time histories (THs) for Gösgen. The main finding was that the equivalent-linear approach is no longer valid for high level GMs. However, Modaressi warned that even the elasto-plastic non-linear approach would, strictly speaking, be out of its range of validity for input motions with PGA as strong as 1.5 g. The experts responded that the elasto-plastic modelling was nevertheless the best method available. They noted that there is no practical experience in site response for these high levels of shaking. As a result, the epistemic uncertainty would be large for this range of input rock motions. They decided that truly non-linear calculations had to be performed for the sites of Beznau, Gösgen and Leibstadt for PGA levels of 0.40, 0.75 and 1.5 g.

Discussing vertical GM, the experts confirmed that SHAKE computations of vertically incident P waves would be the main computations. They further defined three different types of P wave velocity reduction. Furthermore, it was decided to limit 2-D computations to the site of

Leibstadt and to S_H waves. Two different programs would be used, one written by Bard, based on Aki-Larner's technique, and the other developed by Fäh, based on modal summation and the finite difference technique.

It was realised between WS-1 and WS-2 that the PEGASOS Project needed thousands of 1-D site simulations. This fact incited the project management team to look for a more efficient method of site effect simulations than ordinary SHAKE-type TH calculations. Abrahamson suggested applying the Random Vibration Theory (RVT) method. Since the experts had asked for TH computations at WS-1, sufficient time was allocated at WS-2 to the explanation and discussion of the RVT method. This method was finally accepted by the experts under the condition that a sufficient number of TH computations were carried out to check the results of the RVT method.

The experts agreed with the principle of soil randomisation included in the RVT computations. However, they fixed limits for the variation of the randomised parameters in order to guarantee that only physically realistic configurations would be created by the randomisation process. In particular, the profiles had to respect the measured fundamental natural frequency and the depth to bedrock within tolerance limits defined by the experts (*Koller 2002d, TP3-TN-0166*).

Fäh emphasised the need for PS_V simulations for different angles of incidence. After discussion, the experts agreed that a sensitivity study should be carried out in order to investigate potential differences in the AFs of horizontal motion from PS_V and S_H wave propagation. Furthermore, this study would also allow alternative AFs for vertical motion to be obtained.

For the TH computations, the experts accepted the principle of scaling the natural THs to the PGA levels that would be needed.

Before the end of WS-2, the experts defined in detail all the computations that they considered necessary in order to fix AFs for the four sites (for an overview of all supporting computations, see section 3.5). Then, Abrahamson explained the elicitation work expected from the experts between WS-2 and WS-3. Finally, the experts discussed the problem of the additional workload that they had to deal with if the hazard had to be given for three elevations in the profile (free surface, reactor building foundation and intermediate depth). An additional workshop analogous to WS-3, denoted as WS-3a, would be necessary. A second WS-4 workshop would not be needed.

6.2.4 Elicitation Interviews for Surface Levels

Individual elicitation interviews took place in Wettingen with Alain Pecker (27.08.02), Jost Studer (28.08.02), Donat Fäh (29.08.02) and Pierre-Yves Bard (30.08.02).

During the elicitation meetings, the experts described their approaches for characterising the site amplification for the surface motions. At this stage, the models were not complete, but the framework of each expert's model was presented to the TFI-team. The TFI-team provided initial feedback to each expert on their models through questioning the technical basis for the model and identifying any inconsistencies. The TFI-team also helped the experts to develop the structure of their logic trees.

Examples of items discussed at the elicitation meetings included: definition of site amplification, structure of logic trees, separation of aleatory variability and epistemic uncertainty and technical basis for selecting weights.

6.2.5 WS-3 / SP3: Initial Feedback on Experts' Estimates for Surface Levels

The SP3 workshop on initial feedback on experts' estimates for surface levels (WS-3) was held on November 19 – 21, 2002 in Zürich. All four SP3 experts were in attendance for the full workshop. The goals of this workshop were:

- To present each expert's chosen approach and reasons for the preliminary weighting of the models.
- To compare the experts' preliminary estimates.
- To discuss the details of the site response calculations for truly non-linear models, 2-D effects, and the inclined PS_V case.
- To discuss methods for estimating the maximum GM on soil.
- To prepare for the first revision of the experts' estimates, which occurred following the workshop.

On the first day, each expert explained his initial model and weights and the reasoning behind it to the other experts. The discussion was focused on understanding the differences between the experts' models. The goal was to make sure that the differences were intentional and not the result of misunderstandings by the experts.

Abrahamson stressed that each expert would be responsible that his logic trees would not have any dead-end branches with undefined AFs. Furthermore, he reminded the experts that aleatory variability would be modelled by means of its own logic tree and should not be implemented as branches in the median amplification logic trees. The branches in the logic tree should only represent epistemic uncertainty.

A comparison of the AFs resulting from the experts' models was shown. For the presented examples (Leibstadt, M = 6 and PGA = 0.40 and 0.75 g), the median AFs of the different experts were very similar, with a tendency of highest amplifications for Bard and lowest values for Pecker. The epistemic uncertainties, however, were very high: Factors of 5 to 7 for the 0.4 g level, and even up to 15 for the 0.75 g level, could be observed around the site's fundamental frequency between the most extreme AFs.

On the second day, the experts discussed the different site response calculations in detail: non-linear 1-D, 2-D, 1-D PS_V computations with oblique incidence and 1-D computations with vertically incident P waves. They decided that the non-linear calculations for Beznau and Gösgen had to be done for effective stresses, taking into account pore pressure build-up, although this was only possible in a very approximate way owing to the lack of knowledge of the relevant soil parameters.

The last day started with a discussion of maximum GM on soil. The experts agreed that possible maximum horizontal accelerations were limited by the strength of the soil. However, they also agreed that the upper limit of vertical ground motion would principally not be different from the maximum values on rock.

Sprecher presented the Quality Assurance procedures with regard to 'how to proceed with the experts' models'. The hazard software (SW) specialist would help the experts to put their models into a form that is compatible with the SW input requirements. Nevertheless, the expert remained responsible for his own model and had to check that his model was correctly implemented. Both the expert and the hazard SW specialist had to sign the hazard input document (HID). This document would have to be complete so that no hazard input-relevant decisions or judgements had to be made by the SP4 computation team.

Abrahamson then presented the ideas of TFI models and sensitivity models. The TFI model is, for each subproject, a very simplified model containing one single branch for each expert. It was elaborated by the TFI. A sensitivity model is the first version of a complete model developed by the experts. Sensitivity calculations would then be made by combining the TFI models of the other subprojects (SP1 and SP2) and the full sensitivity model (SP3). This procedure allowed to evaluate the importance of the branches in terms of the impacts on the soil hazard.

Abrahamson informed the SP3 experts that each SP2 expert planned to develop his own reference rock profile from 2000 m/s (the reference base rock velocity of SP3) to the surface of his reference rock condition that is applicable to his model of the rock ground motion. For each SP2 expert's profile, a SHAKE calculation would be carried out with rock properties consistent with those used in SP3. The rock motion from SP2 would then be scaled by this SP3 / SP2 rock correction factor before being input into the soil hazard analysis computer program (SOILHAZP). (This was later changed so that the SP2 experts all used the same reference rock condition in their ground motion models).

Finally, the TFI explained work package 5 (first revision of experts’ estimates, release of the SP3 experts’ sensitivity models, sensitivity hazard computations) to the experts. The new and extended project output specifications which had been agreed between the licensees and the regulatory authority (HSK) implied that the future work of SP3 (after WS-4) had to be rescheduled. The TFI and the experts therefore discussed the technical implications, the extra effort required, and planned the additional workshop (WS-3a) and elicitation meetings.

6.2.6 WS-4 / SP3: Feedback on Experts' Estimates

The SP3 workshop on feedback on experts’ estimates was held on February 26 – 28, 2003 in Zürich. All four SP3 experts were in attendance for the full workshop. This workshop was partly held in common with the corresponding SP1 and SP2 workshops.

The goals of this workshop were:

- To present revisions to each expert's approach and reasons for the revisions.
- To compare the experts’ revised estimates and identify key branches leading to different amplification factors and differences in hazard.
- To determine likely further revisions to the experts’ models.
- To prepare for the final revision of the experts’ models, which would occur following the workshop.

In the morning of the first day, the SP2 and SP3 experts focused on details of the elaboration of the SP3/SP2 rock correction factors. Furthermore, they discussed the parameterisation of their models for the sensitivity computations. It was realised that the SP3 models did not yet include maximum GM provisions.

In the afternoon, Coppersmith and Abrahamson presented a summary of the SP1, SP2 and SP3 models in a joint session with SP1, SP2 and SP3. A lively discussion about maximum magnitudes arose since one SP1 expert team envisaged a maximum magnitude of 9. The SP2 experts stated that their models were only valid up to magnitude 7.5 or 8 at most and questioned whether larger magnitudes were physically realistic. However, Toro remarked that the very high magnitudes, even if kept in the SP1 models, would not have a big impact on the final hazard results. The question of maximum GM was then addressed. For M= 7, the SP2 experts had derived maximum PGA values on rock generally ranging from 3 g to 6 g. The experts agreed that the maximum GM at the plant sites would likely be based on maximum transmission through the soil layers. The SP3 experts concluded that the extrapolation of the soil amplification models above 1.5 g – the maximum value for PGA on rock considered so far – and therefore the issue of maximum GM became very important.

The second day was devoted to the presentation of experts' revisions following WS-3 and to comparisons between AFs resulting from the experts' models. It turned out that although the models were very different, they led to similar results for the medians. However, significant differences could be observed for the uncertainties. The importance of differentiating between aleatory and epistemic uncertainty was again discussed. McGuire explained that the aleatory variability influenced the slope of the hazard curve (probability of exceedence versus Sa_{soil}), whereas the epistemic uncertainty defined the fractiles; however, the mean hazard is not affected by the distinction between aleatory variability and epistemic uncertainty. Whether or not a certain total amount of uncertainty is taken as aleatory or as epistemic results in the same mean hazard. From examples shown, the experts concluded that the SP3 aleatory variability was nearly negligible with respect to the one stemming from SP2.

Pecker presented three different ways to elaborate maximum GM and proposed to develop an approach based on failure strain which is better known than failure stress. Given the importance of maximum GM, Fäh and Bard requested that two other people be asked to elaborate independent estimates.

The third day was for feedback on preliminary hazard calculations, discussion of expected revisions by the experts following the workshop and preparation for the next work packages (experts' estimates revision 2). McGuire showed a selection of results from the sensitivity computations *(McGuire 2003, TP4-TN-0366)*. It could be observed that the epistemic uncertainty on rock hazard seemed to be more important than the epistemic uncertainty of the AFs. The resulting total epistemic uncertainties were even smaller on soil than on rock for high frequencies, which was explained as a direct consequence of the non-linear soil behaviour.

With respect to maximum GM, it was decided that Pecker would apply the three approaches that he had suggested to each site. His work would then be reviewed by Studer. To validate the strain approach, it was proposed to apply it also to strong motion recording sites with known site characterisation (to be taken from the data base ROSRINE). All experts agreed that, first of all, a maximum PGA was looked for, but if possible, Sa_{max} should also be estimated. It was finally decided to schedule an additional one-day meeting in Nice, devoted to maximum GM.

6.2.7 SP3 WS Meeting on Maximum Ground Motion

Since the maximum GM models had not been implemented by the time of WS-4, there had not been adequate interaction between the experts on this topic. Therefore, an additional meeting was held on April 12, 2003 in Nice; all four SP3 experts were in attendance. The main topic was the presentation of alternative maximum GM evaluations and the discussion of strengths and weaknesses of each of the methods.

Pecker presented his maximum GM evaluation to the other experts. He gave an overview of the PGA levels found by three different methods, namely his own strain approach, Betbeder's method and the truly non-linear computations for high input levels. As he pointed out, spectral shapes might be taken from true non-linear runs or, empirically, from high shaking level strong motion recordings.

Abrahamson showed soil hazard curves from the sensitivity computations. His conclusion was that the maximum GM assessment and the resulting truncation would indeed have a considerable effect on soil hazard if the assessment was in the order of 2 – 3 g, as recommended by Pecker's study. Bard's model, for example, would otherwise predict up to 6 g mean accelerations for a 10^{-7} probability of non-exceedence. This value was now expected to be capped at 1.5 – 2.0 g if GM truncation was applied.

The experts finally discussed if additional analyses or studies for the evaluation of maximum GM were necessary. This was a request of Fäh and Bard at WS-4. In the end, given the schedule constraints, the experts decided not to request any additional, alternative evaluations of maximum GM. However, Geodeco was asked to run truly non-linear site effect calculations for Beznau and Gösgen using rock input accelerations of 2.5 g.

6.2.8 Elicitation Interviews for Embedded Levels

A second set of elicitation interviews were held for the embedded levels in October 2003. Individual meetings were held with each expert. At the elicitation meeting, the experts presented their initial models for the amplification for the embedded levels. The experts all used their model for the surface level as a starting model and then modified the model as needed for the embedded levels. The TFI-team provided feedback on the changes to the surface-level models. In particular, several of the candidate models were only developed for the surface, which required the experts to adjust thier logic trees to account for the missing models at the embedded levels.

Examples of items discussed include: definition of the outcropping motion, maximum motions at depth, 2-D and 3-D effects at depth, vertical ground motion at depth.

6.2.9 WS-3a / SP3: Initial Feedback on Experts' Estimates for Embedded Levels

The SP3 workshop on initial feedback on experts’ estimates for embedded levels (WS-3a) was held on October 20 – 21, 2003 in Zürich. All four SP3 experts were in attendance for the full workshop. The goals of this workshop were:

- To present each expert's chosen approach and reasons for the preliminary weighting of the models for the maximum GM on soil.
- To present each expert's chosen approach and reasons for the preliminary weighting of the models for the embedded level motions.
- To prepare for the final revision of the experts’ estimates following the workshop.

The experts presented and discussed their models for maximum GM at surface (see section 6.4.5). Worth mentioning is that Bard and Fäh introduced a bias towards higher values with respect to Pecker's estimates of maximum PGA when they defined their sub-branches to cover epistemic uncertainty. Pecker and Studer remarked that there was no reason to assume a bias for Pecker's model. Bard countered, referring to a recent publication of Bonilla et al. (2003), that the latest comparisons of non-linear model calculations with Japanese data showed that non-linear models almost always underestimated maximum GM.

Then, the workshop focused on embedded levels. According to the project specifications, 'motion at depth' was defined as the so-called 'outcropping' motion. This is twice the motion resulting from the upgoing wavefields only, where the soil above is not removed. This avoids holes in the frequency domain due to cancelling interference.

Pecker presented his approach for evaluating maximum GM at depth. The approach is the same as for the surface motions, but the effect of embedment was considered by using the strength of the soil below the depth of embedment. Pecker's results were true embedded motions and had to be multiplied by the ratio of outcropping to total motion at depth ("within" motion) from the SHAKE runs.

Studer remarked that soil strength depended on the state of stress, and that the stress underneath the NPP buildings was much higher than what was assumed for free-field conditions. This may lead to an underestimation of maximum GM. Abrahamson encouraged Studer to mention this limitation in his elicitation summary, but stressed that the experts were asked to develop their models for the free-field case only. Pecker added that he had similar concerns with respect to soil structure interaction that would significantly change the situation. Fäh further criticised that 'outcropping' motion, as specified, was not physical.

The experts presented their models for embedded levels that were all similar to the models for surface motion. As Bard mentioned, the main problem was that there were no results available for embedded motion in the PS_V and the 2-D simulations. Furthermore, there were no V / H ratios known at depth.

A comparison of the AFs for vertical GM were shown to the experts, since this had never been done before. As for horizontal GM, the differences between the experts' median estimates were small. Finally, Abrahamson presented the remaining work packages and defined their schedule.

6.2.10 WS-5: End-of-Project Workshop

This workshop was held in Davos on February 27, 2004, concurrently with SP1 and SP2. The results of the hazard computations, together with the results of some sensitivity studies, were presented to the experts.

6.3 SP3 Expert Model Development

6.3.1 Development of Initial Logic Trees (and Elicitation Summaries)

Following SP3 Workshop 2, the experts developed their initial approach for their site response models for the ground surface. Each expert presented his initial approach to the TFI-team during the first elicitation meeting. With feedback from the TFI-team, the experts then developed their first complete model (logic trees and weights) for the median amplification factor and the aleatory variability of the amplification factor for both the horizontal and vertical components. The initial models were presented to the other experts for review and comments at SP3 WS-3. The initial models did not include maximum ground motions.

During SP3 WS-3, the alternative approaches for maximum ground motions were discussed by the experts. The initial models for the maximum surface motion were developed by the experts following WS-3 and were presented to the other experts for comment and review at WS-4.

6.3.2 Model Revisions

Model revisions occurred after each stage of feedback. Following the elicitation interview, the experts modified their approaches and developed their first complete models. At WS-3, the experts provided peer review of each other models by discussing and questioning the approaches, logic tree branches, and weights used by each expert. Based on the feedback at WS-3, the experts revised their models of the median and aleatory variability of the surface amplification.

The revised models were presented to the other experts for discussion and peer review at WS-4. There were two forms of feedback at WS-4: feedback from comparisons of the surface amplification models and feedback from comparisons of the soil hazard computed using representative alternative models. At this workshop, the experts determined that their available set of candidate models for the maximum ground motion needed to be expanded. An additional workshop (WS-4a) to address maximum ground motions was added. Following WS-4a, the experts revised their models of the surface amplification factors. These were considered to be the final surface level models.

The models for the embedded levels were developed following WS-4a. The initial models were presented to the TFI-team during the second elicitation meeting. Based on feedback from the TFI-team, the experts revised their initial models and presented their revised models for the amplification at the embedded levels to the other experts for review and comment at WS-3a. Following this workshop, the experts revised their models for the embedded levels.

Some experts found that the revisions they made to their models for the embedded levels suggested some minor changes to the surface level model for consistency.

6.3.3 Model Implementation

The amplification factors and aleatory variability values as resulting from the expert models are not applicable to the soil hazard computations. They need to be associated with spectral accelerations on rock (Sa_{rock}, which depend on the underlying site effect models, e.g. SHAKE) and they need to be summarised to discrete fractiles. The details of the so-called parameterisation are described in *Hölker* (*2004a, TP3-TN-0401*). The parameterised models are data tables (AF and aleatory variability depending on Sa_{rock} and earthquake magnitude) for the various frequencies, fractiles, the 4 experts and the 4 sites. An interpolation of AF and aleatory variability values for intermediate Sa_{rock} or magnitudes is performed within the hazard software if required.

The epistemic uncertainty is parameterised by summarising the amplification factors at 17 fractiles: 0.13 %, 0.62 %, 2.28 %, 5 %, 10 %, 20 %, 30 %, 40 %, 50 %, 60 %, 70 %, 80 %, 90 %, 95 %, 97.72 % (2 sigma), 99.38 % (2.5 sigma) and 99.87 % (3 sigma).

For the maximum ground motion assessments, a parameterisation is not required, since maximum ground motions are defined directly as Sa_{soil} as a function of frequency. However, a smoothing of the weight distribution of the alternative maximum ground motion spectra was requested by the PMT. Such smoothing was achieved by spline approximation of the cumulative weight distributions at each frequency of the alternative maximum ground motion spectra. The smoothing was desired to avoid kinks in the soil hazard curves (resulting from the rough discretisation used by the experts).

6.3.4 Development and Review of Preliminary HIDs

Following WS-3, the preliminary HIDs were developed for the surface level for each expert. The preliminary HIDs, to be used as the basis for the sensitivity computations, were based on single paths through the logic tree for each expert. That is, only one branch tip was considered for each expert. This allowed the preliminary models to be simple, yet allowed the testing of the implementation of each SP3 expert's model. The single branch tips selected were not central values for each expert. Rather, they sampled the range of models given by the four experts. These HIDs covered horizontal ground motion at the surface level only and maximum ground motion assessments are not considered at this time.

The HIDs were sent to the experts prior to WS-4 for review. In this review process, the experts ensured the correct interpretation and implementation of their models. In one case, a misinterpretation was found, which led to a revision of the model and the corresponding HID. The HID was corrected and reviewed again by the expert. All of the preliminary HIDs were approved by the 13th of April.

6.3.5 Sensitivity Hazard Computations

Following WS-3, the TFI-team used the initial models presented at WS-3 to develop representative models (called TFI models) that were then used in the sensitivity hazard comparisons. These sensitivity calculations focused the attention of the experts on aspects of their models that were most important for the hazard. With this feedback, the experts re-evaluated the key aspects of their models.

It is important to note that the sensitivity hazard calculations were not intended to give preliminary estimates of the mean soil hazard for each expert. The single model branch tips were selected to sample the range of site response models from all four SP3 experts. So, in aggregate, the four selected branch tips indicate the range of the soil hazard, but the mean value of the sensitivity should not be considered represenative of the true mean hazard.

6.3.6 Development and Review of Final HIDs

Following SP3 WS-4a, the final HIDs were developed for each expert based on the draft elicitation summaries, now including vertical ground motion and a treatment of the embedded layers. In most cases, there was not enough information in the elicitation summaries to fully define the model. In these cases, the experts were contacted and the additional information was requested so that the experts' models could be accurately implemented. This additional explanatory information was then added to the elicitation summaries by the experts.

The draft HIDs were provided to each expert for review. In addition to reviewing the HID for accuracy, the experts also reviewed the interface between SP2 and SP3. For example, an issue was identified during the HID review process related to the rock vertical / horizontal ratios used for the computation of the vertical soil amplification. The SP3 experts wanted to use the V / H ratio as given by the SP2 experts. Modifications to the logic tree were made to implement this transfer of model information from SP2 to SP3 in an efficient manner.

All of the final HIDs for surface and the embedded layers were approved by the 10th of March 2004.

6.3.7 Documentation of Final Expert Models (Elicitation Summaries)

The expert models are fully documented in the elicitation summaries (see Vol. 6 of this report). These summaries give the quantitative model parameters (logic tree and weights) and also describe the technical basis for the selected logic tree and weights.

6.4 Features of SP3 Expert Models

This section describes and compares the decisions made by the experts in developing their models for the site amplification at the four sites. The complete detailed descriptions of the models for all four sites and the technical bases for decisions are given in the SP3 elicitation summaries (see Vol. 6 of this report). Here, only representative decisions are presented to highlight the differences in the experts' evaluations. The model features discussed here are generic and may not apply to all four NPP sites.

6.4.1 Median Site Amplification for Horizontal Ground Motion

The logic trees for the median horizontal ground motion had some significant differences between the experts. Fäh's logic tree was the most complicated and Pecker's logic tree was the simplest. As an example, the logic tree for Studer is shown in Figure 6-1. This tree represents an average level of complexity.

6.4.1.1 General Approach

The four SP3 experts used approaches that can be put into two groups: a "seismological approach" used by Bard and Fäh and a "geotechnical engineering approach" used by Pecker and Studer.

Bard and Fäh used approaches that are based mainly on a "physical" interpretation of site effects, which are viewed as wave propagation effects influenced by the soil geometry (not only 1-D, but also 2-D and 3-D), the wave type (S_H, S_V or P waves – while incident wavefield in the very near field of strong events might be also very different from plane waves), and the soil mechanical characteristics which, under strong shaking, are modified by non-linearities. They also take into account a significant amount of epistemic uncertainty, especially at large strain. Pecker and Studer used approaches that are strongly influenced by geotechnical engineering considerations. They put more emphasis on standard engineering methods such as the non-linear site response effects and less on complex wave propagation effects.

This difference between the seismological approach and the geotechnical approach leads to the main differences between the four SP3 models discussed in section 6.5.

6.4.1.2 Velocity Profile

For the Gösgen and Mühleberg sites, the measured profiles cover the depth to rock (V_s = 2000 m/s). For these two sites, the experts reached a consensus on a single velocity profile.

For the Beznau site, the velocity profile down to rock is not well constrained by the measurements so three alternative profiles are considered by the experts. Profile B1 is based on cross-hole measurements and profiles B2 and B3 are based on microtremor measurements. Profile B2 is based on the inversion from a single station and profile B3 is based on inversion from an array of stations. The weights assigned by the experts to these three profiles are given in Table 6-1. All of the experts gave the largest weight to the cross-hole measurements (B1). For profiles B1 and B2, Bard and Fäh gave more weight to profile B3 than to profile B2, based on a preference for the array method and a better fit of the H/V ratios. In contrast, Pecker and Studer gave more weight to profile B2 than to profile B3 because B2 is a smoother profile that is consistent with B1 in the shallow depth range.

For the Leibstadt site, two velocity profiles are considered. The main difference between the two profiles is that profile L2 includes cemented gravels below 30 m depth and profile L1 does not include cemented gravels. The four experts give similar weights to the two profiles, with the largest weight given to profile L1, because they do not consider the cemeneted layer to be continuous and the L2 profile does not match the H/V ratios measured at the site.

Tab.6-1: Weights used for the alternative velocity profiles

Profile	Bard	Fäh	Pecker	Studer
Beznau B1	0.5	0.4	0.45	0.5
Beznau B2	0.2	0.2	0.35	0.3
Beznau B3	0.3	0.4	0.20	0.2
Leibstadt L1	0.8	0.7	0.7	0.7
Leibstadt L2	0.2	0.3	0.3	0.3

6.4.1.3 Non-linear Material Properites

Two sets of non-linear material properties were selected for consideration at Leibstadt, Gösgen and Mühleberg by the experts during the February 4, 2002 elicitation meeting (see section 6.2.2): Ishibashi & Zhang and Hardin & Drnevich. For Leibstadt, an additional set of non-linear material properties for a cemented layer was considered. For Beznau, the experts reached a consensus on a single set of material properties, based on site-specific laboratory measurements.

The weights given to alternative non-linear material properities are summarised in Table 6-2. Bard considered that the Ishibashi & Zhang curves are more applicable to gravel sites than Hardin & Drnevich. In contrast, Studer and Pecker considered that the Hardin & Drnevich model has a broader range of applicability than the Ishibashi & Zhang model and it is also similar to the laboratory results for Beznau. Fäh gave equal weight to the two material property models because he considered that no reliable site-specific measurements of the soil properties were available.

Since the Hardin and Drnevich material properites have stronger non-linearity than the Ishibashi & Zhang curves, the Pecker and Studer models, which give the highest weights to Hardin and Drnevich, will show the strongest non-linearity. This difference will affect the amplification factors at high rock ground motions.

Tab.6-2: Typical weights for non-linear material properites

Model	Bard	Fäh	Pecker	Studer
Ishibashi & Zhang	0.65	0.50	0.30	0.30
Hardin & Drnevich	0.35	0.50	0.70	0.70

6.4.1.4 Site Amplification Calculation Approaches

The experts had agreed to use the 1-D equivalent-linear approach as the primary computation method for site amplification, with 1-D non-linear calculations for high levels of rock ground motion. There are three sets of 1-D equivalent-linear calculations: SHAKE, RVT without soil randomisation, and RVT with soil randomisation. All four experts used the 1-D equivalent-linear model for low to moderate ground motions and then changed to the 1-D non-linear models for high ground motions.

At the low to moderate ground motion levels, Pecker and Bard put larger weights on the SHAKE model than the RVT model. They note that the RVT model without randomisation gives similar results to the SHAKE model at the resonance frequency, but there is poor agreement away from the resonance. They consider the SHAKE model to be more physical. In contrast, Fäh and Studer give the largest weight to the RVT model because they include a wider range of input motion through the random phase assumption. Fäh uses the RVT model without randomisation because he considers that the randomisation is too great and leads to site resonances that are inconsistent with the observations at the sites. Studer uses the RVT model with randomisation because he considers the randomisation of the soil properties to be realistic, but he applied limits on the range of reasonance frequencies to select a subset of the randomised profiles.

The definition of the ground motion level that leads to the transition from the equivalent-linear model to the non-linear model was based on PGA (Fäh, Pecker and Studer) or strain (Bard). These transition levels are compared in Table 6-3. Fäh and Pecker transition to the non-linear model at ground motions about 0.4 – 0.5 g and Bard and Studer give significant weight to the 1-D equivalent-linear calculations for higher rock ground motions.

Bard is the only expert to include a linear site response branch for low to medium ground motion levels. This will result in larger high frequency content in his model at moderate shaking levels as compared to the other experts.

Bard and Fäh both include additional epistemic uncertainty to the candidate models. Bard includes it only for the non-linear runs to capture the large uncertainty associated with these calculations at large ground motion levels. Fäh includes additional epistemic uncertainty for all levels of shaking. This additional epistemic uncertainty is applied to the RVT and non-linear runs to capture the range of the models (e.g. SHAKE vs. RVT) rather than including weights for all of the alternative models. The inclusion of this additional epistemic uncertainty results in larger overall epistemic uncertainty for the Bard and Fäh models as compared to the Pecker and Studer models.

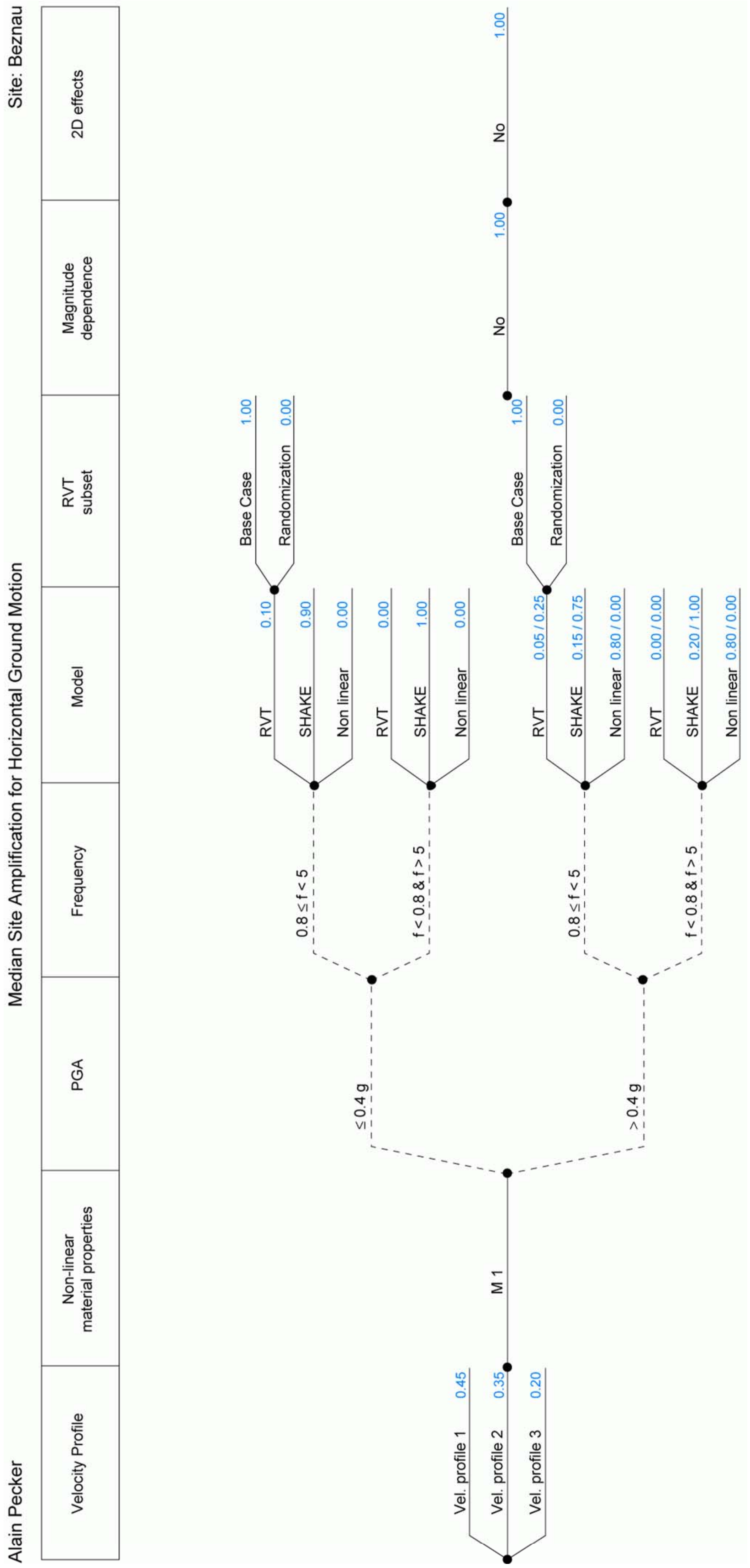


Fig.6-1: Representative logic tree for the median horizontal component (Alain Pecker's tree for the Beznau site)

6.4.1.5 Magnitude Dependence of Amplification Factor

Bard, Fäh and Studer all included the magnitude dependence of the amplification as given by the site response calculations. Bard and Studer interpolate amplification factors for intermediate magnitudes, whereas Fäh defined ground motion level bins, which are associated with certain models. In contrast, Pecker evaluated the magnitude dependence and concluded that it was not a large effect and is not seen in empirical attenuation relations for rock and soil sites. As a result, Pecker used a magnitude-independent model. The magnitude dependence in the candidate models is strongest at magnitude 5 level, so the effect of excluding magnitude dependence by Pecker is expected to be seen for cases with significant contribution from M5.

Tab.6-3: Example of typical weights for calculation approaches (horizontal component)

	Bard			Fäh				Pecker		Studer		
	Low	med	high	low	med		high	low	high	low	high	very high
				Level 1	Level 2a	Level 2b	Level 3					
PGA (g)	–	–	–	<0.2	0.2-0.4	0.4-0.8	>0.8	<0.4	>0.4		1.5-2.5 g	
Strain Level	$<\gamma r$	γr-$32\gamma r$	$>32\gamma r$	–	–	–	–	–	–	–	–	–
SHAKE	0.56	0.475	0.175					0.7	0.1	0.35		
RVT w/o randomisation	0.12	0.10	0.0375	1.0	0.8	0.4		0.3	0.1			
RVT with randomisation	0.12	0.10	0.0375							0.65		
Non-linear		0.225	0.75		0.2	0.6	1.0		0.8			1.0
Linear	0.20	0.10										
Other											Interp	
Additional Epistemic		Yes NL	Yes NL	Yes	Yes	Yes	Yes					Yes NL

6.4.1.6 Effect of Inclined Waves

Only Fäh includes a modification of the median amplification for the effect of inclined PS_V waves.

Fäh considers the wave inclination to be an important feature of wave propagation. He used inclined PS_V factors ranging from 0.8 to 1.2.

The other three experts consider that the effect of inclined PS_V waves will be seen only in the aleatory variability and not in the median amplification. Therefore, they do not include this effect in their models.

6.4.1.7 2-D / 3-D Effects

Weights given to 2-D and 3-D effects are represented in Table 6-4. The two experts using the seismological approach (Bard and Fäh) include 2-D effects for all of the sites, but with less weight for Mühleberg. In contrast, the two experts using the geotechnical engineering approach (Pecker and Studer) include 2-D effects only at Leibstadt and with low weight. This difference in weights reflects the emphasis of the seismological approach on complex wave propagation effects.

In the Fäh model, an additional 3-D effect with factors ranging from 1.0 to 1.4 is also included for the branch with 2-D effects included. With this inclusion of 3-D effects, Fäh has the strongest emphasis on effects of wave propagation through a 3-D velocity structure.

6.4.2 Median Site Amplification for Vertical Ground Motion

The experts considered a wider range of alternative methods for the vertical amplification than for the horizontal amplification. This reflects the emphasis on the horizontal component in current earthquake engineering practice and research. There is much less experience with vertical component site response studies than with horizontal component site response studies.

Tab.6-4: Example of weights used for 2-D / 3-D effects

	Bard		Fäh		Pecker		Studer	
	Yes	No	Yes	No	Yes	No	Yes	No
Beznau	0.9	0.1	0.8*	0.2		1.0		1.0
Leibstadt	0.9	0.1	0.9*	0.1	0.2	0.8	0.3	0.7
Gösgen	0.3	0.7	0.5	0.5		1.0		1.0
Mühleberg	0.2	0.8	0.1	0.9		1.0		1.0

* Additional 3-D effects considered for the branch with 2-D effects

6.4.2.1 Site Amplification Calculation Approaches

The alternative methods used by the experts are listed in Table 6-5. There are three classes of methods considered: no amplification, 1-D equivalent-linear response due to P waves (SHAKE studies), and scaling of the horizontal component by a V/H ratio. There are four alternative non-linear material models for the SHAKE runs: linear and three models of the V_p degradation. M1 is based on no change in the bulk modulus with degradation of the shear modulus, M2 is based on degrading the P wave velocity by the same factor as the shear wave velocity; and M3 is based on degrading the P wave velocity by the square root of the reduction factor in the shear wave velocity.

Four alternative models of the V/H ratio have been considered: an empirical model by Campbell & Bozorgnia (2003), a simplified model based on McGuire et al. (2002, NUREG/CR-6728), V/H ratios derived from the SP2 results for $V_s = 2000$ m/s rock, and V/H ratios from SP2 results for generic ($V_s = 500 – 1000$ m/s) rock. For the V/H ratio approach, these ratios are applied at the end of the logic tree for the horizontal amplification factor described in section 6.4.1. Hence, the expert models for horizontal motion become a branch in the assessment of vertical GM site effects. Moreover, the entire epistemic uncertainty in the horizontal motion is included in the vertical component logic tree.

Bard and Pecker included a no amplification branch. They consider that the rock models from SP2 may already incorporate some shallow soil effects that have not been removed by the V/H ratio used by the SP2 experts.

When considering SHAKE models, all experts assign the largest weight to the non-linear material model M1 (no change in bulk modulus). The experts considered this material properties model to be the physically most reliable model.

The V/H ratio approach is used by three of the four experts only (Bard, Fäh, and Studer). Since these models are empirical, they do not depend on the assumption that the vertical component is completely composed of P waves. Fäh and Studer consider the V/H ratio approach most reliable and weight it with 60 % to 100 %.

The wide range of approaches being considered and the full incorporation of epistemic uncertainty from the horizontal site effect models lead to larger epistemic uncertainty for the veritical component than for the horizontal component.

6.4.1.2 Magnitude Dependence of Amplification Factor

Pecker excludes the magnitude dependence as he did for the horizontal component. Studer has removed the magnitude dependence from his model for the vertical amplification because it is weaker than for the horizontal component. Bard and Fäh both include the magintude dependence as given in the models (either SHAKE runs or in the V/H ratios).

Tab.6-5: Example of typical weights for calculation approaches (vertical component)

	Bard		Fäh		Pecker	Studer
	PGA < 0.75 g	PGA < 0.75 g	Close	Distant		
No amp	0.2	0.2			0.30	
SHAKE Linear	0.1	0.08				
SHAKE (M1)	0.3	0.24	0.1	0.0	0.56	0.20
SHAKE (M2)						0.08
SHAKE (M3)	0.1	0.08			0.14	0.12
V/H (Campbell & Bozorgnia)	0.3	0.4	0.6	0.7		
Scale factor for V/H			Yes			
V/H from SP2 (generic rock)			0.3	0.3		
V/H from SP2 (hard rock) for R < 15 km						0.2
V/H (McGuire et al. 2002)						0.4

6.4.2.3 2-D / 3-D Effects

Only Bard explicitly considers the 2-D effects for the median vertical amplification. His weights for the four sites are listed in Table 6-6. This does not imply that Fäh does not consider that 2-D and 3-D effects occur on the vertical component, rather they are incorporated in the horizontal amplification that is scaled by the V/H ratio (which has 90 % of the weight). Pecker does not consider 2-D effects for the vertical component at Leibstadt. For Studer, some of the 2-D effects for Leibstadt are included by scaling the horizontal amplification by the V/H ratio (which has 60 % of the weight).

Tab.6-6: Example of weights used for 2-D / 3-D effects

	Bard		Fäh		Pecker		Studer	
	Yes	No	Yes	No	Yes	No	Yes	No
Beznau	0.9	0.1		1.0		1.0		1.0
Leibstadt	0.9	0.1		1.0		1.0		1.0
Gösgen		1.0		1.0		1.0		1.0
Mühleberg	0.8	0.2		1.0		1.0		1.0

6.4.3 Aleatory Variability of Horizontal Ground Motion

Each of the site effect assessments must result in a quantification of the aleatory variability as well as the amplification. In general, the experts used the same logic trees and weights for the horizontal aleatory variability as for the horizontal GM amplification for the logic tree levels on which velocity profiles, non-linear material properties and calculations are considered. On higher logic tree levels, the models for amplification and aleatory variability differ as described below.

Bard, Fäh, and Studer computed the total aleatory variability by adding the variances (square of the standard deviations) for the base models and other effects that they considered. They considered the inclined waves and 2-D effects to be independent of the variability from the base calculations. For these models, the aleatory variability is correlated to the median amplification. That is, the same branch is followed for the median and the aleatory variability.

Bard and Fäh both included the effects of inclined waves and 2-D effects, but Bard used two factors, whereas Fäh used a single combined factor. In addition, the ampltiude of the factors from the Bard model is larger, resulting in larger aleatory variabilities. For the inclined waves, he included an additional variability as large as 50 % (e.g. about 0.4 natural log units.)

Studer accounted for 2-D effects by increasing the aleatory variability by factors of 0.8 to 1.4 for the equivalent-linear models. He also added an additional source of variability for the non-linear correction. Scaling the variability by a factor of 1.4 is equivalent to adding a standard deviation equal to the base model variability. For that case, the variability from the inclined wave effects and 2-D effects is equal to the variability of the base model.

Pecker used a completely different approach. Pecker was the only expert to develop a logic tree for the aleatory variability that is independent of the median amplification. In contrast to the other three experts, he also did not combine the variability from the inclined waves and 2-D effects with the variability of the base model. Instead, he used the variability from the inclined waves and the variability from the 2-D effects as alternative estimates of the total variability. He considered that combining the variability from the inclined wave calculations and the variability from the 2-D calculations with the base model variability would overestimate the total variability. As a result, the aleatory variability in Pecker's model is much smaller than in the other experts' models.

6.4.4 Aleatory Variability of Vertical Ground Motion

As with the horizontal component, the models of the aleatory variability of the vertical ground motion are generally based on the same logic trees as the median vertical amplification.

The treatment of the aleatory variability on the vertical component is similar to that used for the horizontal component. The main difference between the vertical and horziontal component logic trees is that the vertical component model also includes a V/H ratio branch for three of the experts. Bard combines the V/H standard deviation with the horizontal amplification variability; Fäh assumes that vertical variability for the V/H ratio branch is equal to the horizontal variability (e.g. does not include the additional variability of the V/H ratio). On the "no amplification" branch, Fäh did not include any aleatory variability. Since Pecker did not include a V/H ratio branch, his model is the same as for the horizontal component.

Studer considered that the available candidate models for the vertical aleatory variability had critical deficiencies. Therefore, he assumes that the aleatory variability of the vertical component is equal to the variability of the horizontal component.

6.4.5 Maximum Ground Motions

Maxium ground motions were given by the experts in terms of alternative soil response spectra of Sa_{soil}, each of which is associated a certain weight. Separate spectra were defined for the horizontal and vertical components.

6.4.5.1 Maximum Horizontal Component

All experts used a two-step approach to obtain maximum ground motion spectra. As a first step, they define a value for PGA and then they scale a previously defined spectral shape by PGA. Scale factors greater than 1.0 are applied to the empirical observations since they are, by definition, lower bounds for the maximum possible ground motions for future earthquakes.

The weights for the PGA models are given in Table 6-7 and the weights for the spectral shapes are given in Table 6-8. For the PGA, Bard and Fäh have used just the Pecker model with a large scale factors (up to a factor of 2) to define the epistemic uncertainty. Pecker and Studer have used both the Pecker model and the Pelli simulation results with moderate scale factors (0.8 to 1.25) to define additional epistemic uncertainty. They justify the range of the scale factors by the range of friction angles considered applicable. Only Pecker included the Betbeder model. The other experts considered the maximum PGA values from this model to be too small.

Tab.6-7: Example of typical weights used for the maximum PGA for the horizontal component

	Bard	Fäh	Pecker	Studer
Pecker × 0.7	0.075			
Pecker × (0.8 – 0.85)			0.045	0.21
Pecker × 1.0	0.25	0.7	0.360	0.49
Pecker × (1.2 – 1.25)			0.045	0.21
Pecker × 1.4	0.075			
Pecker × 2.0	0.025	0.3		
Pelli × (0.80 – 0.85)			0.045	0.09
Pelli × 1.0			0.360	0.21
Pelli × (1.20 – 1.25)			0.045	0.09
Betbeder × 0.85			0.01	
Betbeder × 1.0			0.08	
Betbeder × 1.25			0.01	
Fäh empirical × 1.0	0.10			
Fäh empirical × 1.2	0.25			
Fäh empirical × 1.5	0.125			
Fäh empirical × 2.0	0.025			

Tab.6-8: Example of typical weights used for the spectral shape for the horizontal component

	Bard	Fäh		Pecker	Studer
		PGA × 1.0	PGA × 2.0		
Linear computations (16th percentile)					0.2
Linear computations (Median)	0.5				0.6
Linear computations (84th percentile)					0.2
Empirical F1		0.7	0.2		
Empirical F2	0.5	0.3	0.8	1.0	

Two types of spectral shapes are considered: site-specific calcuations based on linear models and empirical spectral shapes. For each type of spectral shape, multiple alternatives are taken into account: for the linear calculation, the 16th percentile, median, and 84th percentile values; for the empirical spectral shapes, an average shape (F1) and an envelope shape (F2).

Fäh and Pecker use only the empirical spectral shapes. This approach has the advantage that it has an empirical basis, but has the disadvantage that it is not site-specific. Studer uses only the site-specific calculations. Bard gives equal weight to the empirical approach and the site-specific calculations. Use of the linear calculations will tend to lower spectral shapes compared to the empirical model, but they will be peaked at the site-specific site resonance. This difference will affect the spectral shape of the equal hazard spectra at low probability levels.

For the empirical PGA branch, Bard only uses the empirical spectral shape. That is, for this branch, he uses the empirical maximum spectral values directly.

Tab.6-9: Example of typical weights used for the max. PGA for the vertical component

	Bard	Fäh	Pecker	Studer
No-limit			1.0	1.0 (0.5 for Leibstadt)
Pecker × 1.0		0.7	0	
Pecker × 2.0		0.3		
Fäh empirical × 1.0	0.20			(0.25 for Leibstadt)
Fäh empirical × 1.2	0.5			
Fäh empirical × 1.4				(0.25 for Leibstadt)
Fäh empirical × 1.5	0.24			
Fäh empirical × 2.0	0.05			

Tab.6-10: Example of typical weights used for the spectral shape for the vertical component

	Bard	Fäh		Pecker	Studer
		PGA × 1.0	PGA × 2.0		
Empirical F1		0.7	0.2		
Empirical F2	1.0	0.3	0.8	1.0	1.0

6.4.5.2 Maximum Vertical Component

Maximum PGA values for the vertical component based on soil strength were not available. Therefore, the experts had fewer candidate models for consideration.

The weights for the vertical PGA are given in Table 6-9 and the weights for the spectral shapes in Table 6-10.

Pecker does not include a maximum vertical ground motion for any of the sites since there is no basis for limiting the vertical motion based on the available soil models. Studer also does not limit the vertical ground motions for sites with a high water table (Beznau, Gösgen, and Mühleberg), but he does include a maximum vertical for Leibstadt.

Bard uses only the empirical approach for limiting the vertical component since the models since there is no straightforward physical mechanism that would limit the vertical ground motion. His weights on the scale factors for the empirical models are the same as for the horizontal component.

Fäh assumes that the maximum PGA values for the horizontal component computed using Pecker's method are applicable to the vertical component. The basis for this assumption is that he considers that, at these levels, S wave energy is seen on the vertical component.

6.5 Summary of Experts' Assessments of Site Response

6.5.1 Median Amplification Functions

The mean values of the median amplification functions for the free surface at the site of Leibstadt are presented in Figure 6-2 for the four experts. The figure is valid for a magnitude 6 earthquake, for low and high levels of excitation (PGA = 0.1 and 0.5 g on rock, respectively). Leibstadt is the site with the largest differences between the experts. However, even there, the differences remain astonishingly small in view of the very different expert models. In the cases of Leibstadt and Gösgen, the differences are more pronounced for the high level of excitation than for the low one. In Leibstadt, above the fundamental natural frequency, Fäh's model leads to the largest amplifications, whereas Pecker's model leads to the smallest amplifications. The probable reason is that Fäh considers strong 2-D effects even in the range of very strong motion, whereas Pecker assumes that the surface waves giving rise to the 2-D effects are strongly damped for high excitation levels.

The hierarchy of amplification values between experts varies from site to site. For Mühleberg, Pecker's, Bard's and Studer's models lead to nearly identical amplification functions, whereas Fäh's amplification is significantly weaker in the medium and high frequency range. This can probably be explained by the fact that Fäh has a branch in his model for Mühleberg where no site amplification is assumed to take place.

Figure 6-3 compares the magnitude dependence of the expert models. Again, the example of Leibstadt is shown. A pronounced magnitude dependence can be seen for Bard, whereas Pecker assumes that magnitude dependence can be neglected. Fäh's model gives higher amplifications for magnitude 5, with the amplifications for magnitude 6 and 7 being very similar. Studer's model shows an insignificant magnitude dependence. The differences between the experts are comparable for Beznau and Gösgen, whereas all models show very little magnitude dependence for Mühleberg.

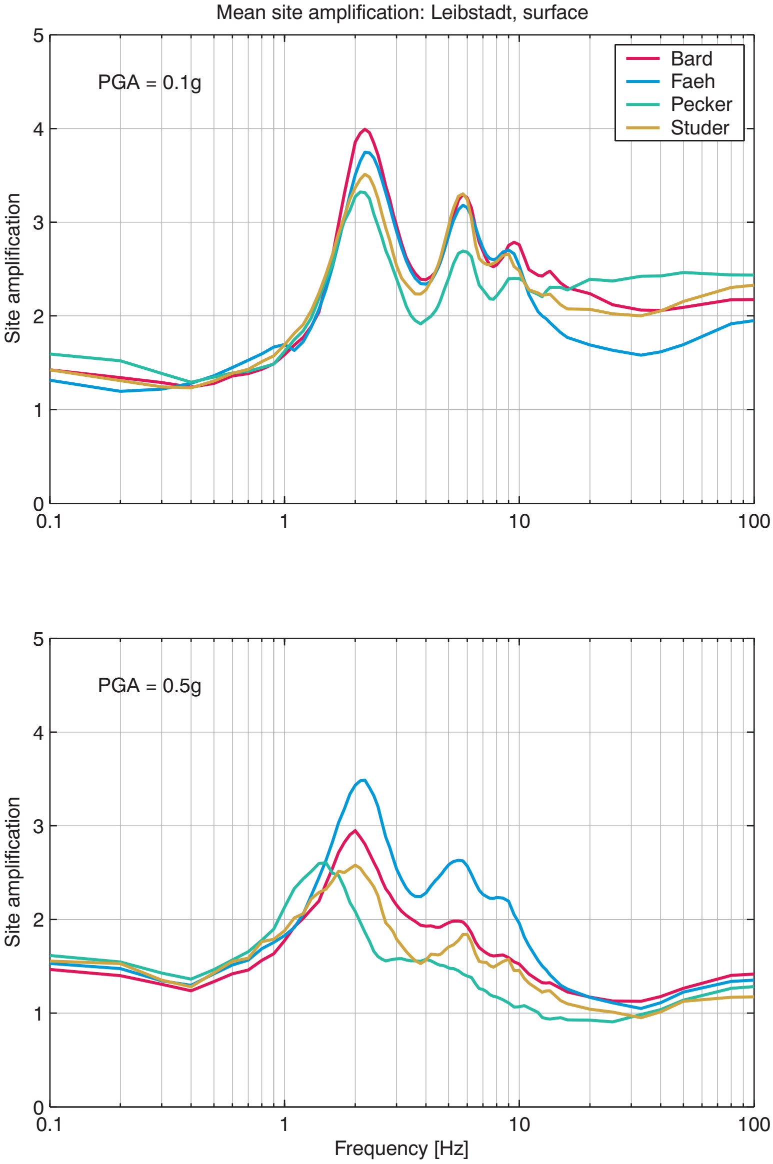


Fig.6-2: Mean values of the median amplification function for the surface at the site of Leibstadt for the four experts: low and high levels of excitation (PGA of 0.1 and 0.5 g on rock, respectively), magnitude 6

6.5.2 Aleatory Variability

The mean aleatory variabilities of the amplification functions for the free surface at the site of Leibstadt are presented in Figure 6-4 for the four experts. The figure is valid for a magnitude 6 earthquake, for low and high levels of excitation. For Beznau and Gösgen, the level of aleatory variability is very similar, whereas somewhat lower values are estimated for Mühleberg.

For the low excitation level (PGA = 0.1 g on rock), Bard assumes a significantly larger aleatory variability than the other experts, who estimate very similar variabilities, with a slight tendency for Studer's model to give the largest values. For the high excitation level (PGA = 0.5 g on rock), Bard's aleatory variability remains nearly unchanged, whereas Studer's and, to some extent, Fäh's aleatory variabilities are significantly increased, Studer's variability approaching the one given by Bard.

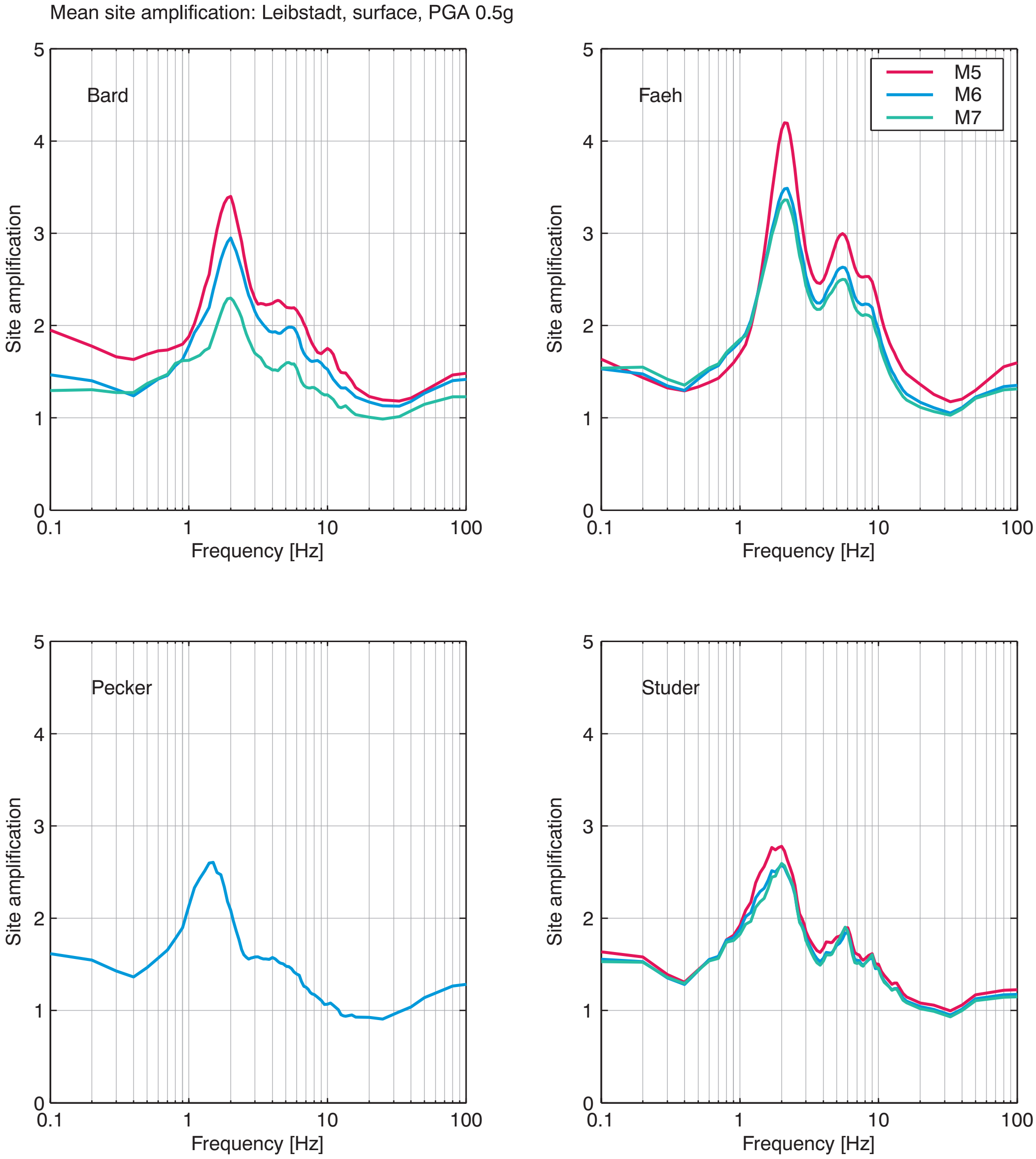


Fig.6-3: Comparison of the magnitude dependence of the mean values of the median amplification functions for the four experts: Leibstadt, PGA of 0.5 g

For the other sites, similar trends exist. Figure 6-5 compares the magnitude dependence of the expert models for aleatory variability. Again, the example of Leibstadt is shown. Only Fäh's model shows a significant magnitude dependence, between magnitude 5 on the one hand and magnitude 6 and 7 on the other hand. Again, the situation looks similar for the other sites.

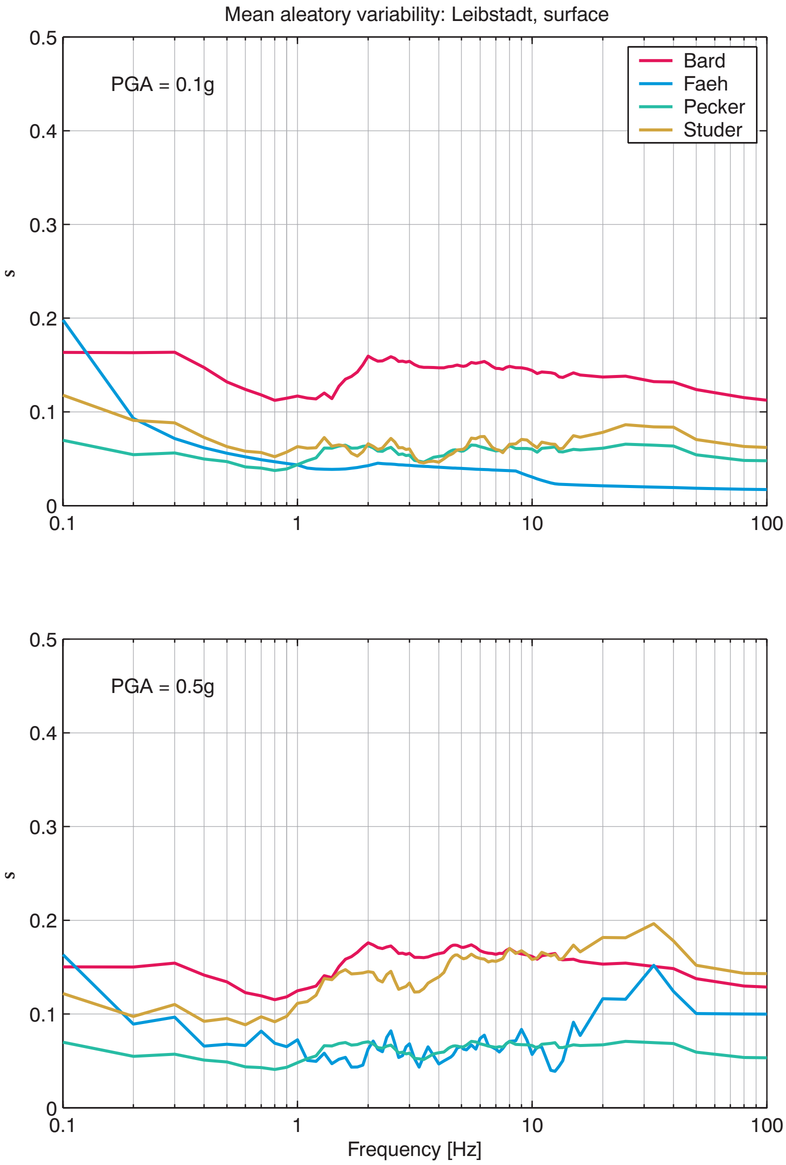


Fig.6-4: Mean aleatory variabilities of the amplification functions for the surface at the site of Leibstadt for the four experts: low and high levels of excitation (PGA of 0.1 g and 0.5 g on rock, respectively), magnitude 6

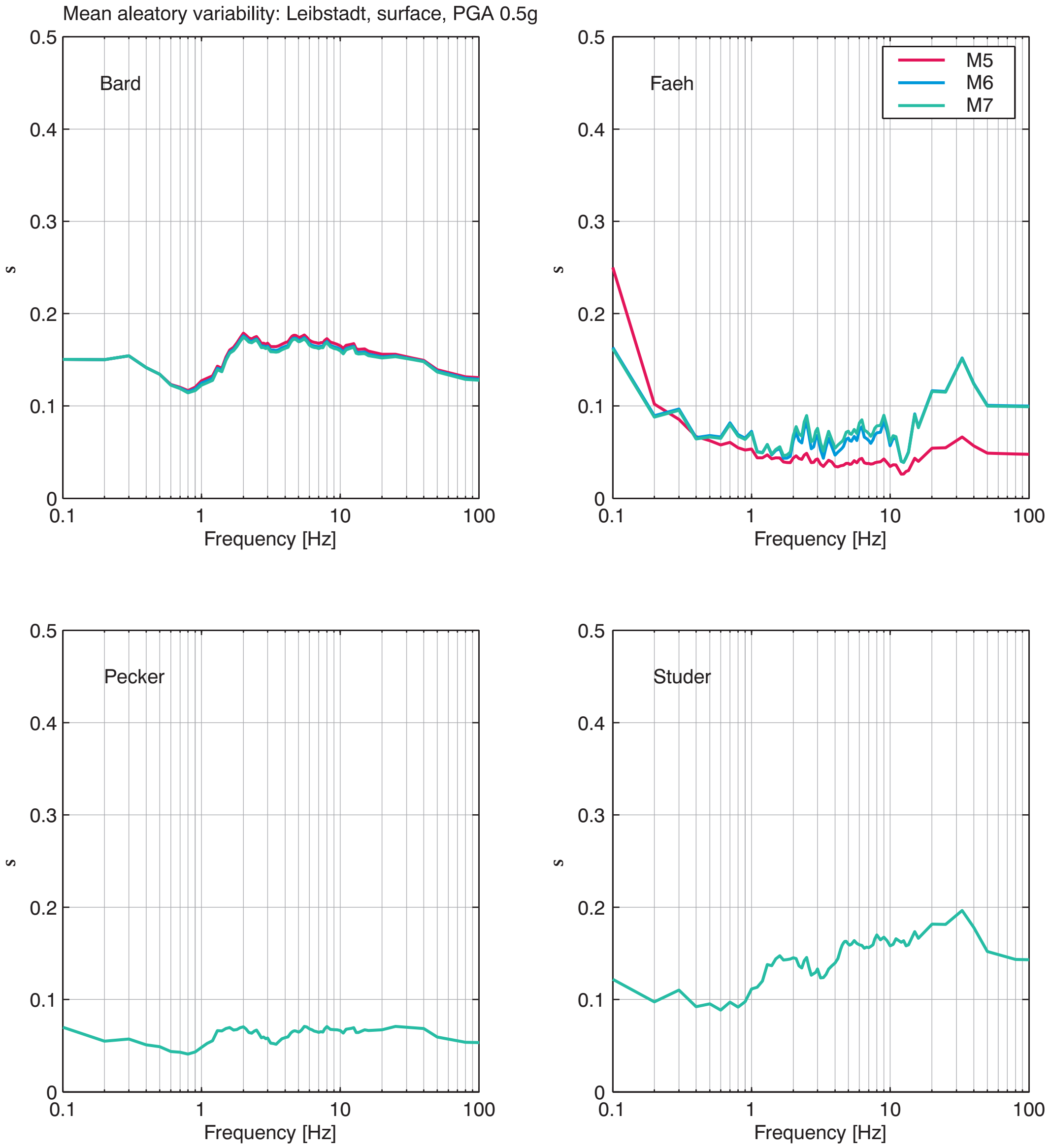


Fig.6-5: Comparison of the magnitude dependence of the mean aleatory variability of the amplification functions for the four expert models: Leibstadt, PGA of 0.5 g on rock

6.5.3 Epistemic Uncertainty of the Median Amplification Functions

The epistemic uncertainties of the median amplification functions for the free surface at the site of Leibstadt are presented in Figure 6-6 for the four experts. The figure is valid for a magnitude 6 earthquake, for an excitation level of PGA = 0.1 g on rock. Leibstadt is the site with the largest epistemic uncertainty, followed by Beznau. Bard's and Fäh's models give the highest values, whereas Pecker's epistemic uncertainty is the smallest, Studer's being in-between. The same trend exists for the other sites.

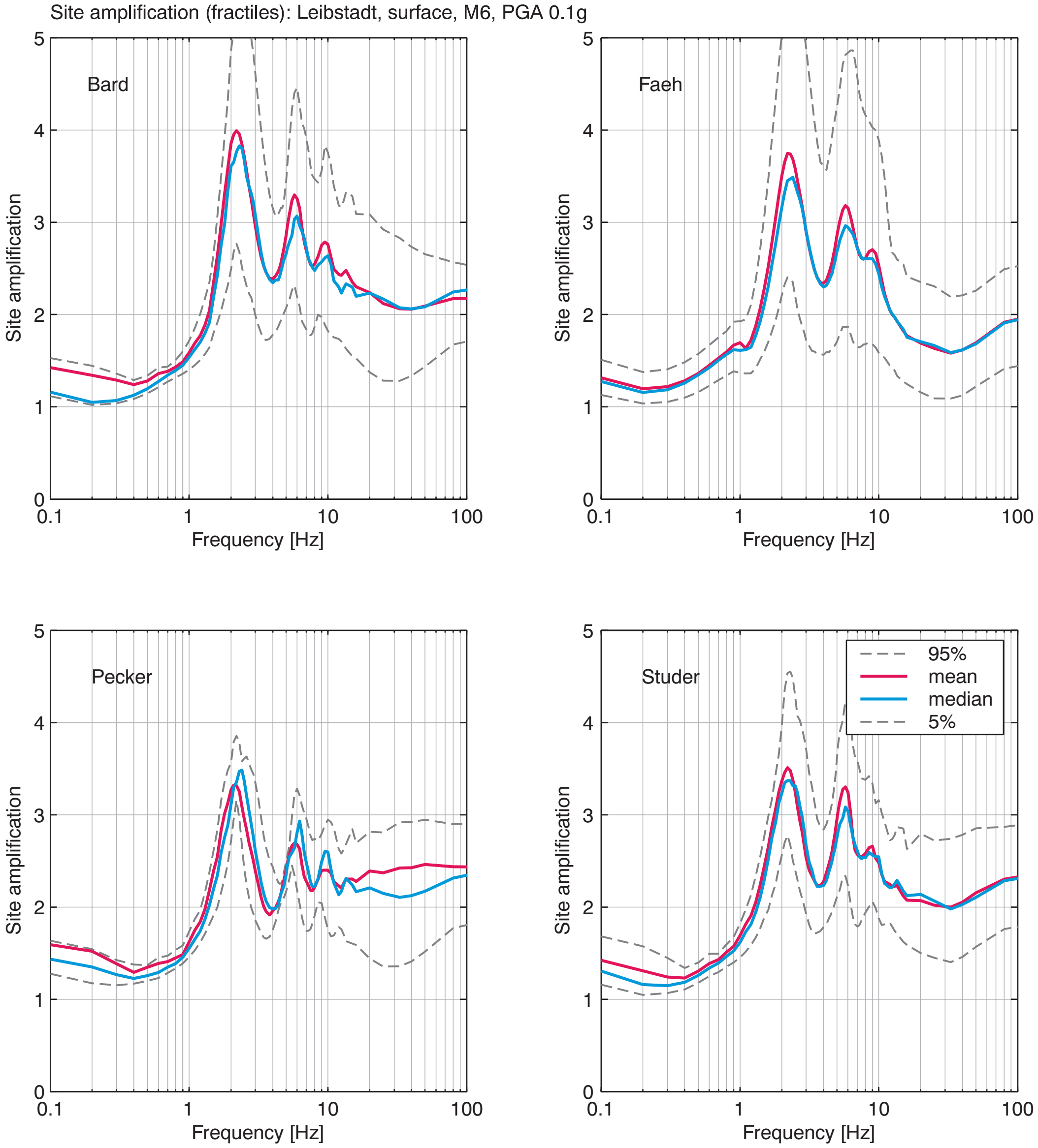


Fig.6-6: Epistemic uncertainties of the median amplification function for the surface at the site of Leibstadt for the four experts (excitation level of PGA = 0.1 g on rock, magntidue 6)

Figure 6-7 is analogous to Figure 6-6 for an excitation level of PGA = 0.5 g on rock. A comparison of these figures shows that the epistemic uncertainty increases slightly for higher excitation levels, except in the case of Bard where this increase is very pronounced. Again, Bard's and Fäh's models give the highest epistemic uncertainties, and Pecker's model the lowest.

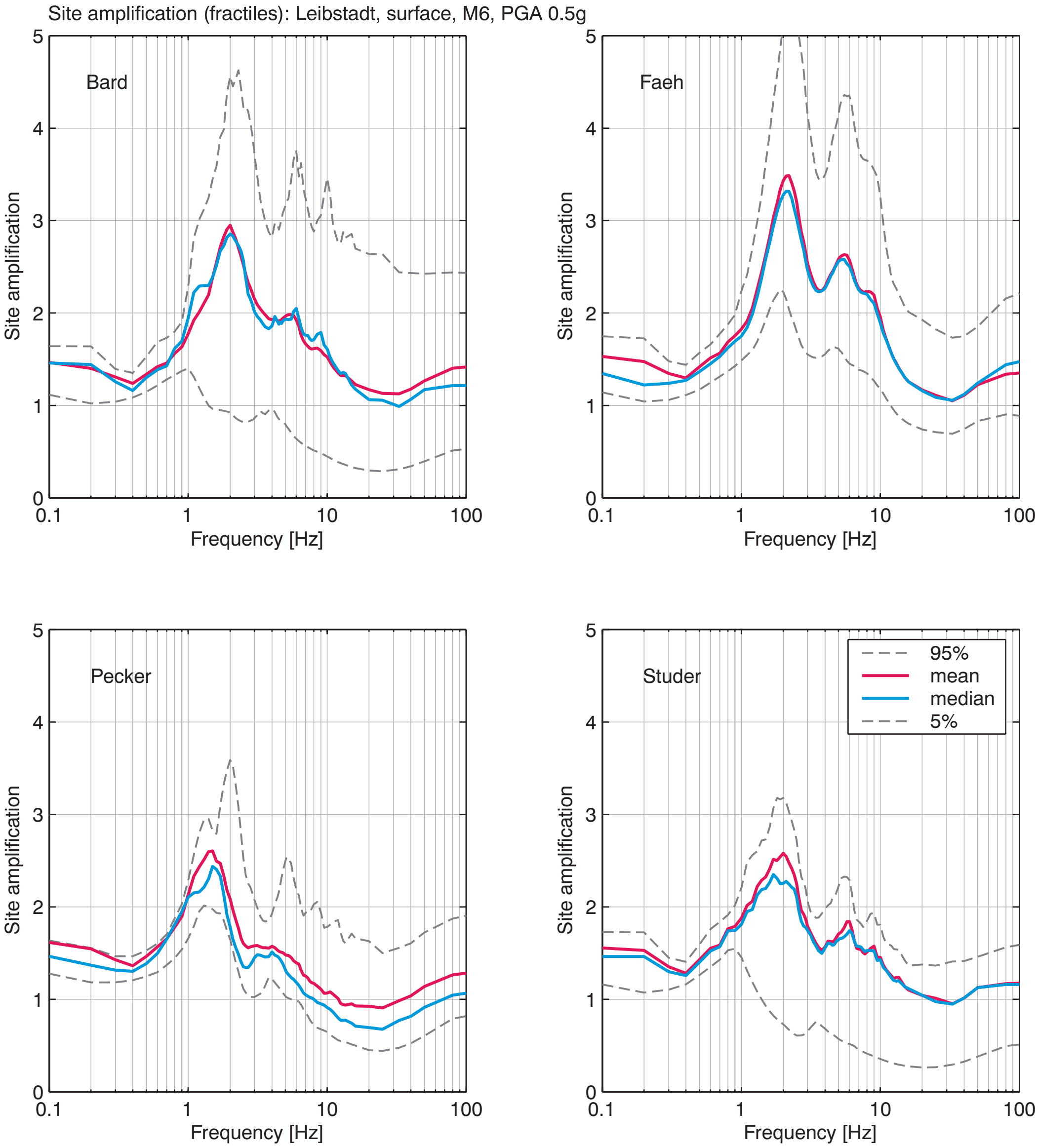


Fig.6-7: Epistemic uncertainties of the median amplification function for the surface at the site of Leibstadt for the four experts (excitation level of PGA = 0.5 g on rock, magnitude 6)

6.5.4 Epistemic Uncertainty of the Aleatory Variability

The epistemic uncertainties of the aleatory variability of the median amplification functions for the free surface at the site of Leibstadt are presented in Figure 6-8 for the four experts. The figure is valid for a magnitude 6 earthquake, for an excitation level of PGA = 0.1 g on rock.

Bard's model shows the largest epistemic uncertainty, whereas Fäh's model has nearly no epistemic uncertainty. The same trend exists for the other sites. In fact, the experts estimate very similar epistemic uncertainties of the aleatory variability for all sites.

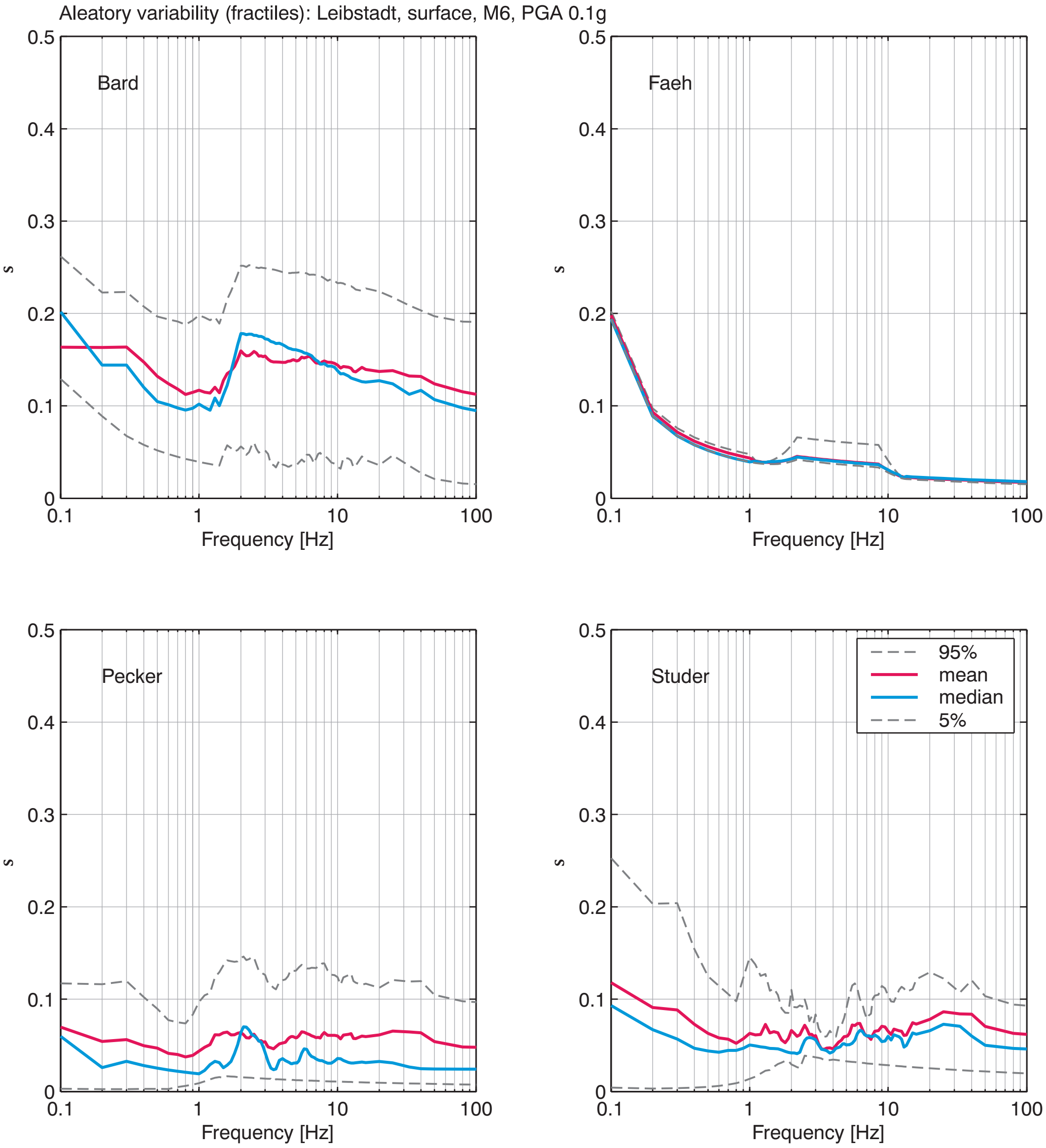


Fig.6-8: Epistemic uncertainties of the aleatory variability of the median amplification function for the surface at the site of Leibstadt for the four experts (excitation level of PGA = 0.1 g on rock, magnitude 6)

Figure 6-9 is analogous to Figure 6-8 for an excitation level of PGA = 0.5 g on rock. A comparison of these figures shows that the epistemic uncertainty increases for higher excitation levels in Fäh's and Studer's models, whereas little change can be seen for Bard and Pecker. Nevertheless, Bard's model still gives the largest epistemic uncertainty. This trend exists also for the sites of Beznau and Gösgen, whereas virtually nothing changes in the epistemic uncertainty with increasing excitation level for the site of Mühleberg.

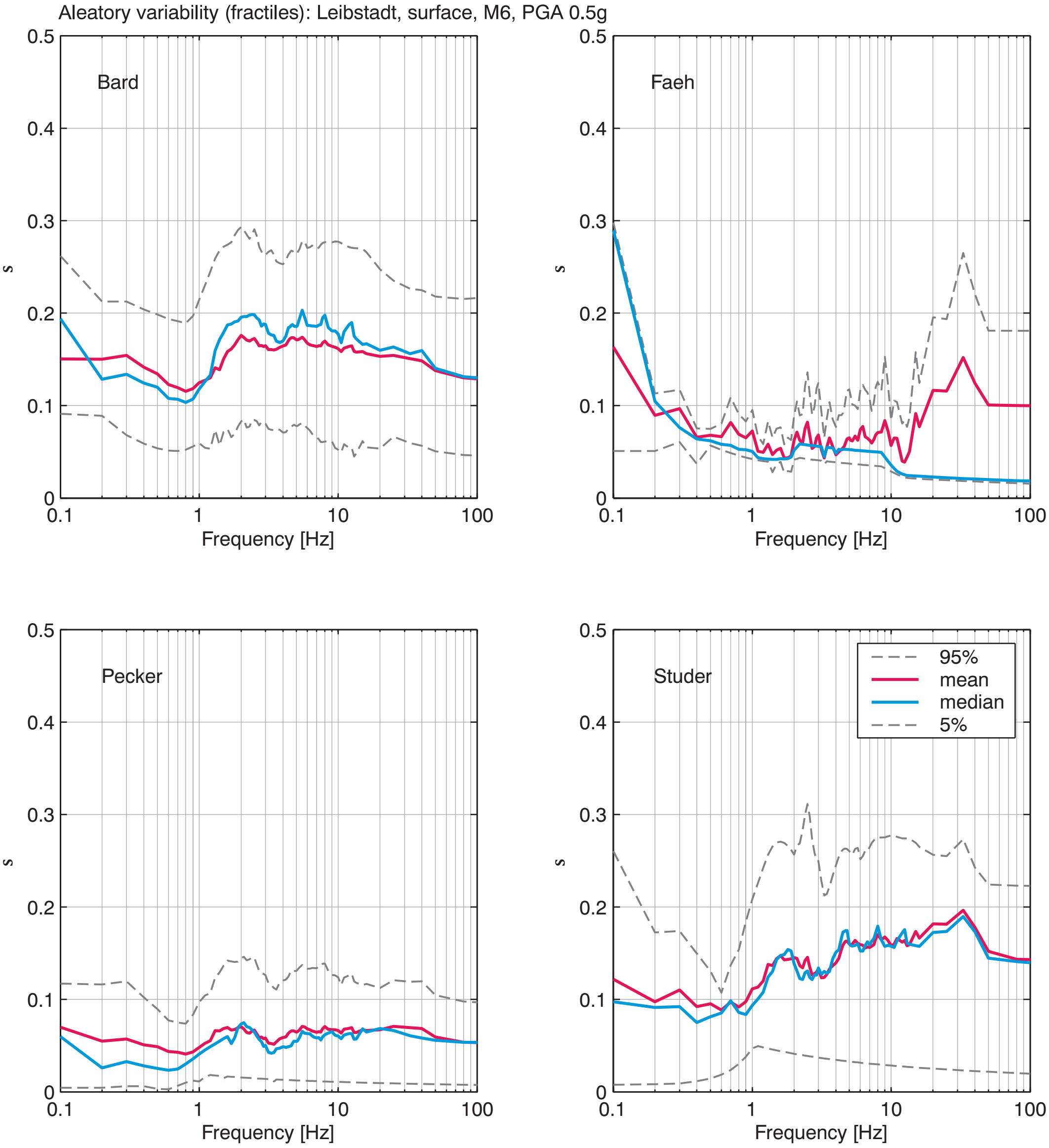


Fig.6-9: Epistemic uncertainties of the aleatory variability of the median amplification function for the surface at the site of Leibstadt for the four experts (excitation level of PGA = 0.5 g on rock)

7 SEISMIC HAZARD COMPUTATIONS

7.1 The Role of SP4

The purpose of a Probabilistic Seismic Hazard Analysis (PSHA) study is to evaluate the probability that various levels of earthquake-induced ground motions will occur or will be exceeded at a given location in a given future time period, and the uncertainty associated with this probability estimate. Subproject 4 (SP4) is in charge of performing this quantitative assessment, based on the experts' models.

Unlike the other subprojects, SP4 does not *Experts* (in the SSHAC terminology) and a TFI-team, but rather hazard analysts[11]. In terms of QA, this is appropriate because the PEGASOS SP4 analysts do not have to make any interpretation or material modification to the experts' models. The starting point – and at the same time the key element – of the work of SP4 was the *Hazard Input Document* (HID), which was developed, under the responsibility of the TFIs, at the interface between the expert elicitation block and SP4 (see Figure 3-1). Because the *Hazard Software Specialist*, who is also member of SP4, had made sure that the HID was self-contained and complete in terms of inputs required for the hazard computations, usually no further interaction with the TFIs was necessary. If any piece of information was missing, or any element in the HID was incompatible with the input requirements of the hazard software, the SP4 team would ask the TFI for clarification, additional information, or modification. The TFI would then deliver a new revision of the HID, usually after having consulted with the expert or expert group. Under no circumstances was SP4 allowed to interpret an incomplete HID and take a decision on how to fill in the gap. Because the hazard software must not limit the freedom of the experts, the software had to be modified several times to accommodate an otherwise unforeseen *Expert Model* parameterisation (see section 7.3.3). SP4 prepared the rock hazard input files (RIFs) for the rock hazard software (FRISK88MP) and soil hazard input files (SIFs) for the soil hazard software (SOILHAZP).

Computational considerations sometimes made it necessary for SP4 to introduce pinch points when computing the total seismic hazard. This reduction of the total number of branches, called algorithmic pinching, is considered to be an algorithmic decision, which is within the technical expertise of the SP4 analyst. In fact, the SP4 analyst is in a better position than the expert or the TFI to quantify the effect of algorithmic decisions on accuracy and on computational effort. Pinching by SP4 was only performed if it could be shown that it had no significant effect on the calculated total seismic hazard. Section 7.6 below provides additional details on pinching.

7.2 Hazard Result Specifications

The original specifications of the PEGASOS results, as they are described in the project plan (*Pegasos PMT 2000, PMT-TB-0001*) underwent several revisions on the initiative of HSK and the project sponsors. UAK issued the last of these revisions on 23 January 2004. It was ordered that the project results should be submitted as follows (quotation from *UAK 2004, UAK-AN-0238*):

1. *<u>Elevations:</u> The ground motion at each plant will be presented for the site-specific soil condition for the three elevation levels listed below. The ground motions at depth will be given as outcropping motion (upgoing waves only; see SHAKE 91 manual; Idriss et al. 1993)*

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[11] This organisation of the project is typical of large PSHA studies. See, for example, Stepp et al. (2001).

Plant	*Terrain Elevation [asl]*	*Elevation 1 (ground surface)*	*Elevation 2 (rel. to ground surface)*	*Elevation 3 (rel. to ground surface)*
KKB	*327 m*	*0 m*	*-6 m (emergency building)*	*-15 m (reactor building)*
KKM	*466 m*	*0 m*	*-7 m (turbine and radwaste building)*	*-14 m (reactor building)*
KKG	*382 m*	*0 m*	*-5 m (emergency-diesel building)*	*-9 m (reactor building, electrical building)*
KKL	*332 m*	*0 m*	*-6 m (emergency-diesel building)*	*-10 m (reactor building)*

2. *Components of Motion: The hazard will be computed for the geometric mean of the two horizontal components and for the vertical component.*

3. *Vibration Frequencies for Hazard Analysis: The rock hazard results will be computed for the following nine spectral frequencies: 0.5 Hz, 1 Hz, 2.5 Hz, 5 Hz, 10 Hz, 20 Hz, 33 Hz, 50 Hz and peak acceleration. The soil hazard will be computed at the nine spectral frequencies given above for the rock hazard plus one or more additional frequencies so that the site-specific soil resonance is adequately represented.*

4. *Seismic Hazard Curves for Reference Rock Site Condition: The reference rock site seismic hazard for the horizontal components for each frequency at each plant will be supplied at the following ground motion levels: 0.025 g, 0.05 g, 0.1 g, 0.15 g, 0.2 g, 0.25 g, 0.3 g, 0.35 g, 0.4 g, 0.5 g, 0.65 g, 0.8 g, 1 g, 1.25 g, 1.5 g, 2 g, 2.5 g, 3 g, 4 g, 5 g, 6 g, 8 g, 10 g etc. until the annual hazard level falls below 10^{-7}/y. The epistemic uncertainty in the reference rock site hazard curves shall be presented for the horizontal and vertical components for each frequency and each plant as follows: Plots of the 5 %, 16 %, 50 %, 84 %, and 95 % fractile levels and the mean hazard.*

5. *Seismic Hazard Curves for the Soil Site Condition: The soil site hazard for the horizontal and vertical components for each frequency at each plant will be supplied at the following ground motion levels: 0.025 g, 0.05 g, 0.10 g, 0.15 g, 0.20 g, 0.25 g, 0.30 g, 0.35 g, 0.40 g, etc. until the annual hazard level falls below 10^{-7}/y.*

6. *Epistemic Uncertainty in the Soil Hazard Curves: The epistemic uncertainty in the soil site hazard curves shall be presented for the horizontal and vertical components for each frequency and each plant as follows: Plots of the 5 %, 16 %, 50 %, 84 %, and 95 % fractile levels and the mean hazard; tables of the fractiles at 100 equally weighted levels.*

7. *Upper Limit of the Ground Motion: The upper limit of the ground motion will be provided. The hazard curves will be truncated at the upper limit ground motion.*

8. *Uniform Hazard Spectra: Uniform hazard spectra (UHS) for the horizontal and vertical components for the soil site condition will be presented for each plant for the following annual frequencies of occurrence: 1.0E-2/y, 2.1E-3/y, 1.0E-3/y, 1.0E-4/y, 1.0E-5/y, 1.0E-6/y, 1.0E-7/y. The epistemic uncertainty in the UHS will be shown in terms of the mean and the 5 %, 16 %, 50 %, 84 %, and 95 % fractiles.*

9. *Peak Velocity: In addition to the spectral acceleration at the vibration frequencies given in item 3, simplified scaling relations will be developed to facilitate the estimation of peak velocity. Two sets of scaling relations will be derived. The first set will be relative to PGA. The second set will be relative to one of the frequencies listed in item 3. For the second set, the best frequency for predicting PGV will be used. The*

simplified scaling relations will not be applied to estimate the hazard curves for peak velocity as part of the PEGASOS Project.

10. *Average Spectral Acceleration: A simplified procedure for computing attenuation relations for spectral acceleration averaged over a specified frequency band will be developed. This procedure will be based on scaling of the attenuation relation for one of the spectral frequencies given in item 3. The scaling relation will include scaling of both the median ground motion and the aleatory variability of ground motion. The simplified procedure will not be applied to estimate hazard curves for average spectral acceleration as part of the PEGASOS Project.*
11. *Hazard Sensitivities to Upper Limit GM Estimates: The sensitivity of the computed mean hazard curves for the reference rock and soil site condition to the estimates of the upper limit of the ground motion will be shown for the frequencies 1Hz, 5Hz and PGA at each plant.*
12. *Spectra at Damping other than 5 %: A technical note describing simplified scale factors for computing the response spectra for damping values other than 5 % will be prepared. The technical note will include scale factors for damping values of 0.5 %, 1 %, 2 %, 7 %, 10 %, 15 % and 25 %. The simplified scale factors will apply only to the median spectral acceleration. Changes to the aleatory variability for different damping values will not be considered. Since scale factors for different damping values do not have large uncertainties, the technical note will be developed by a contractor and will not be based on multiple expert opinion.*
13. *Time Histories: Guidelines for the future development of time histories will be provided. These guidelines will not be implemented as part of the PEGASOS project.*
14. *Deaggregation: The horizontal component rock hazard will be deaggregated in terms of magnitude, distance, and epsilon (number of standard deviations) at the following combinations of ground motion levels and frequencies[12]: 0.05 g/0.5 Hz, 0.05 g/PGA, 0.15 g/5 Hz, 0.15 g/PGA, 0.3 g/0.5 Hz, 0.3 g/PGA, 0.5 g/5 Hz, 0.7 g/PGA, 1 g/5 Hz. Plots of the deaggregation will be prepared. The controlling earthquakes will be determined.*

All of these required results are contained in Volume 2 of this report, with the exception of items 9, 10, 12, and 13, which are provided in the technical report *TP2-TB-0053 (Bommer et al. 2003)*.

7.3 Hazard Software Tools

7.3.1 FRISK88MP

The FRISK88MP[13] package consists of four programs for the calculation of seismic hazard on rock, namely PREP88, FRISK88M, POST88, and MRE88. Program PREP88 is a pre-processor that prepares input to FRISK88M, using information about the logic tree, the attenuation equations, and the seismic source parameters and geometry. Program FRISK88M calculates the seismic hazard curves for each combination of source parameters, using Equation 2-1 (see sections 2.1, 2.2, 2.5, 2.6.1, and 2.6.2). FRISK88M also produces deaggregated seismic hazard results. Typically, PREP88 and FRISK88M are run separately for each seismic source. Program POST88 computes the total seismic hazard at the site (i.e. the seismic hazard from all seismic

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[12] These frequency / ground motion pairs for the deaggregations are the result of a last revision of the final result specifications by UAK (communicated by M. Richner, sanctioned by UAK at their meeting on 23 January 2004).

[13] FRISK88MP is the name used for the PEGASOS-specific version of the FRISK88M software. See section 7.3.3.

sources) and sensitivity results, using the logic tree and the seismic hazard results from the various seismic sources. Another post-processor, MRE88, calculates marginal and joint probability distributions and summary statistics of magnitude, distance, and ground motion ε for one or more seismic sources, using the deaggregated results produced by multiple FRISK88M runs. Figure 7-1 summarises the flow of information among these programs.

In addition, the combination of results from multiple expert groups is performed by the small CMB-FRAC post-post-processing utility.

The integrated mean and fractile hazard curves computed with CMB-FRAC (which embody all SP1 and SP2 information and associated uncertainties) are passed to SOILHAZP (see below) for the calculation of soil hazard curves and uniform soil hazard spectra.

The FRISK88MP package (including its predecessors) is the most widely used PSHA software for critical facilities. It has been reviewed and qualified for use in a number of seismic hazard studies subject to the US-NRC and US-DOE QA requirements (US Code of Federal Regulations, Section 10, Part 50, Appendix B, and Section 10, Part 830). These studies include the Rocky Flats nuclear site, the Yucca Mountain Nuclear Waste Repository, the Paducah Gaseous Diffusion Plant, the North Anna and Grand Gulf early site permit applications. In addition, the FRISK88MP package has been used in a number of studies for other critical facilities such as bridges, dams and offshore oil and gas facilities.

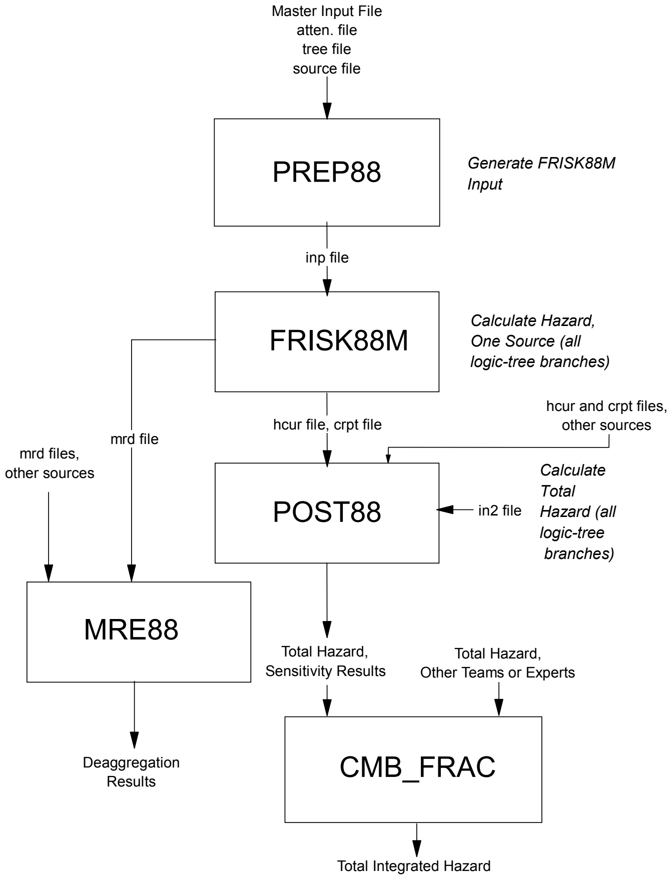

Fig.7-1: Organisation of programs and flow of information in the FRISK88M software package

7.3.2 SOILHAZP

The program SOILHAZP calculates means and fractiles of soil hazard curves and computes soil amplitudes for target hazard levels, corresponding to motion at the soil surface or at an embedded layer. SOILHAZP implements the methodology in McGuire et al. (2002, NUREG/CR-6728) for the calculation of hazard-consistent hazard results on soil (Equation 2-2; see sections 2.3, 2.5 and 2.6.3). This calculation is not standard and SOILHAZP establishes the state-of-the-art for the hazard-consistent combination of rock hazard results and amplification factors. Inputs to the program consist of rock hazard curves, median (logarithmic) soil amplification factors (SAFs), standard deviations of soil amplification factors (on logarithmic scale), and maximum values (truncations) for soil motion. Epistemic uncertainties are incorporated by considering multiple rock hazard curves (expressed as fractiles of rock hazard), multiple soil amplification models (medians and standard deviations) with weights, and multiple maximum soil amplitudes with weights.

Outputs from the program consist of fractile hazard curves and uniform hazard spectra for soil. The program is run separately for motions at the soil surface and at each embeded layer. In addition, SOILHAZP produces "raw" deaggregation output that may be used as input to an Excel spreadsheet to generate deaggregation of the soil hazard as a function of rock amplitude and magnitude.

7.3.3 Project-Specific Software Modifications

In order to accommodate all the features of the PEGASOS expert models, a number of modifications were introduced in the FRISK88MP and SOILHAZP software. Modifications to FRISK88MP include the following: enlarging arrays in order to accommodate larger logic trees, implementation of the PEGASOS ground motion models (tabular input, simultaneous consideration of maximum ground motion and upper-tail truncation), more realistic representation of ruptures within area sources (including the strict and loose boundaries), and pinching diagnostics for the efficient verification of compliance with the Operational Guidelines for moment-based pinching (see *Sprecher 2003, QA-TN-0402*).

Modifications to SOILHAZP include a more flexible and robust tabular parameterisation of amplification factors and their uncertainty and the calculation of deaggregation information. All these modifications were tested and verified as required by the PEGASOS QA Guidelines.

7.4 Rock Hazard Computations

7.4.1 Transformation of SP1/ SP2 HIDs into Rock Hazard Input Files (RIFs)

The development of the rock hazard input files (RIFs) begins with the hazard input document (HID). The HID, together with its electronic attachments, contains a complete parameterisation of the SP1 and SP2 expert models in a form that is consistent with the hazard computation methodology described in section 2.

The PEGASOS process for the development, approval, and usage of the HID formalises the flow of information from experts to TIF to SP4; this flow has been more ad-hoc in past studies. Benefits from this process include a more clear delineation of responsibilities, better documentation of the inputs, and lower chances for misinterpretation of the expert models. The introduction and implementation of the HID process constitutes a significant contribution of the PEGASOS study to PSHA practice.

The RIFs consist of three groups of files, as follows:

- Files containing the characterisation of seismic sources. This group consists of source files (extension 'src') and logic tree files (extension 'tree'). There is one source file for each seismic source in an SP1 expert model, but more than one source may use the same logic tree file. In addition, the source file may incorporate source coordinate files and variable seismicity files by reference. There is also another (global) logic tree file, which serves as input to POST88. This file contains information about the alternative ground motion models and about the global variables in the logic trees for all sources in the SP1 expert models.

– Files containing attenuation information. This group of files includes the rock ground motion attenuation files (extension 'atten') and the files containing the attenuation tables. The attenuation files contain the description and indices pointing to the appropriate attenuation tables for the alternative ground motion models, and their associated weights. The attenuation files also contain other information not related to attenuation or to source characterisation (i.e. codes controlling the type of calculations, step sizes, amplitudes to consider, site coordinates, etc.). Separate attenuation table files contain the median amplitudes, values of the standard deviation σ, upper-tail truncation values, and maximum amplitudes for each frequency, style of faulting and SP1 group. The latter is required because the distance conversions depend on the depth distributions specified by each SP1 expert group (see section 5.3.1.3).

– Intermediate input files. The control input files to POST88 (extension 'in2') contain the list of source hazard files to read, calculations options, etc. They also include the moment-based pinching parameters (see section 7.6). The control input files to MRE88 (extension 'mri') provide similar information for MRE88.

Fig. 7-2 illustrates how the four SP1 models are individually combined with the five SP2 models to produce a SP1 expert group-specific rock hazard and how these four sets of hazard results are then combined into the final rock hazard.

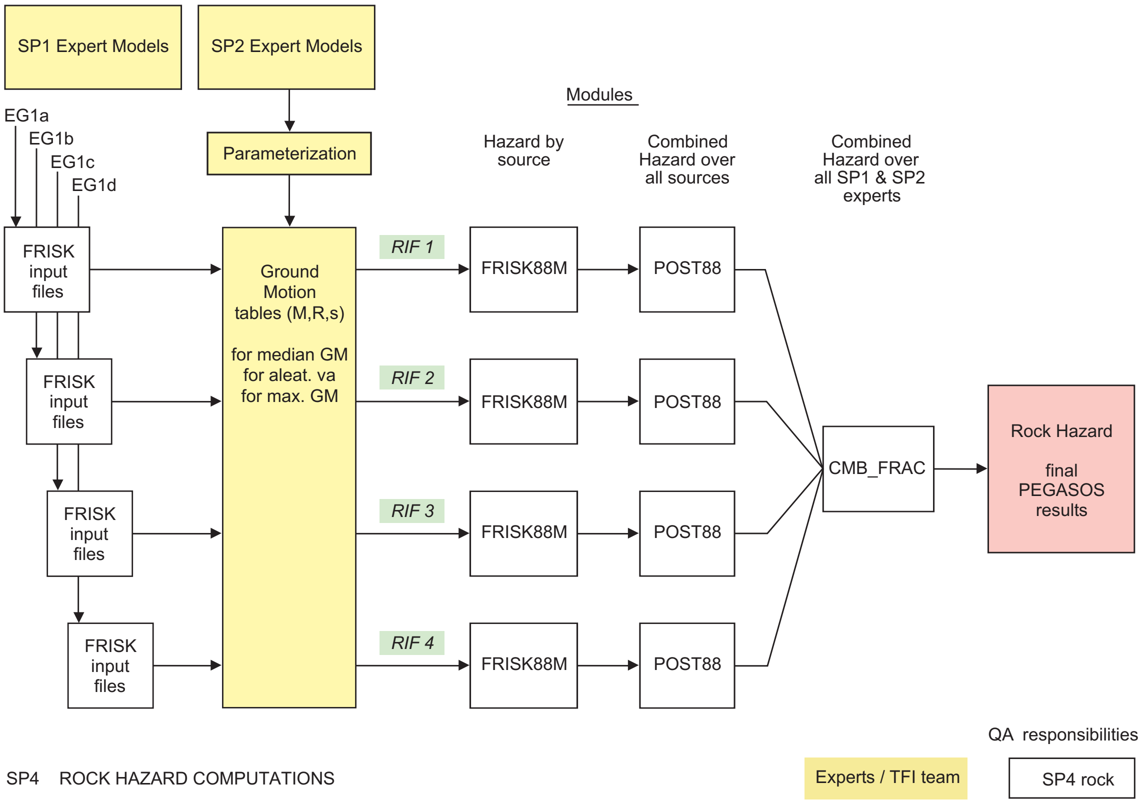

Fig.7-2: Rock hazard computation scheme

7.4.2 Rock Hazard Computation Products

The rock hazard calculations generate the following results for each site:

- Mean and fractile horizontal and vertical rock hazard curves for each frequency (namely, peak ground acceleration and spectral accelerations for 5 % damping and frequencies of 0.5, 1.0, 2.5, 5, 10, 20, 33, and 50 Hz).
- Uniform rock hazard spectra for 5 % damping.
- Deaggregation results of the hazard (in terms of magnitude, distance, and epsilon) for nine combinations of frequencies and ground motion amplitudes.
- Source sensitivity results showing (1) hazard by SP1 expert group, (2) mean hazard curves by source for each group and for selected frequencies, and (3) hazard sensitivity histograms showing the effect of epistemic uncertainty in each global variable and in the source variables of the dominant sources.
- Ground motion sensitivity results showing (1) hazard by SP2 expert; (2) mean hazard curves with and without the effect of upper limit ground motion estimates (both maximum ground motion and upper tail truncation); (3) hazard sensitivity histograms showing the effect of epistemic uncertainty in the median ground motion, in the aleatory variability, and in the truncation; (4) ground motion sensitivity histograms showing the effect of epistemic uncertainty in each variable (logic tree node).

7.5 Soil Hazard Computations

7.5.1 Transformation of Rock Hazard Input and SP3 HIDs into Soil Hazard Input Files (SIF)

The soil hazard computations require four sets of input files (SIFs).

- Set 1: The rock hazard curves (aggregated results from all source and ground motion expert models; available for eight frequencies and PGA).
- Set 2: The mean earthquake magnitudes associated with the above rock hazards.
- Set 3: The soil amplification factors and their standard deviations (aleatory variability).
- Set 4: Maximum ground motion assessments for soil (truncation amplitudes).

Data sets 1 and 2 are available from the rock hazard computations and data sets 3 and 4 are available from the SP3 expert models. Each of these data sets requires processing before being applicable as an SIF for the soil hazard computations. Figure 7-2 illustrates the input data sets and the required processing, resulting in four sets of SIFs

The following processing steps are required for the creation of SIFs:

- Set 1 (rock hazard curves): The aggregated rock hazard curves are available for eight spectral frequencies and for PGA. Each rock hazard curve must be interpolated with a dense sampling in order to obtain an accurate representation of the non-linear site response effects. The interpolation procedure is based on an Akima algorithm, a piecewise cubic polynomial interpolation (Akima 1970) that proved to be more robust than the classical spline approach. Furthermore, additional frequencies were considered in the soil hazard computations in order to capture the maximum site effects at the site resonance frequencies. The available rock hazard curves were interpolated for these resonance frequencies in two dimensions (frequency and ground motion amplitude). Additional site resonance frequencies were considered for Gösgen, Leibstadt and Mühleberg, but not for Beznau (see Tab. 7-1).

- Set 2 (mean earthquake magnitudes): The mean earthquake magnitudes associated with a particular rock hazard are required to compute appropriate soil amplification factors, because amplification factors are magnitude-dependent. Mean magnitudes for given frequencies are computed by combining the mean magnitudes obtained for the four combinations of EG1 expert group models and SP2 ground motion models (see Fig. 7-2), in the same way as is done with the CMB-FRAC code for the hazard curves. Finally, these mean magnitudes are interpolated to the same vector of spectral acceleration values as is done for the hazard curves (see set 1).
- Set 3 (soil amplification factors and aleatory variability): Median soil amplification factors and standard deviations (aleatory variability) for the individual expert models were available from the SP3 HIDs (EG3-HID-0050 to EG3-HID-0053,). Details are given in *Hölker* (*2004a, TP3-TN-0401*) and in *Hölker* (*2004b, TP3-TN-0406*).
- Set 4 (maximum ground motion on soil): Maximum soil ground motion models are used to truncate the soil hazard curves. As the original maximum ground motion assessments by the SP3 experts result in an unphysical stepwise truncation of the soil hazard curves, it was decided by the TFI-team to smooth the distribution of alternative maximum ground motion amplitudes. Details of this procedure are given in *Hölker* (*2004c, TP3-TN-0388*).

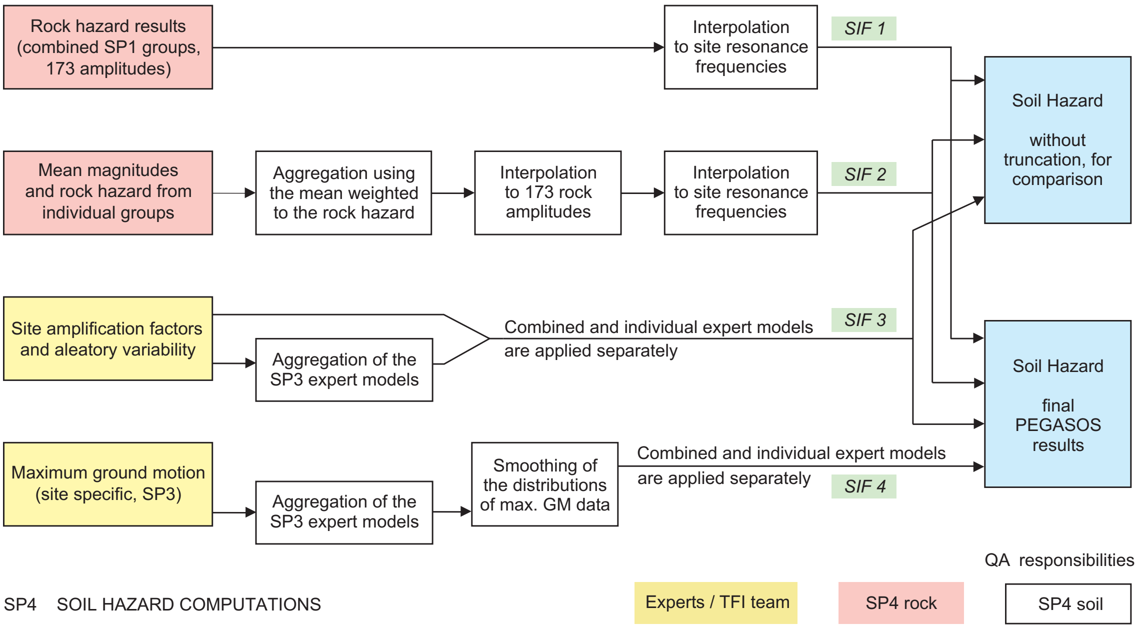

Fig.7-2: Soil hazard computation scheme

Generation of input files (SIFs) from rock hazard results (red) and SP3 soil amplification factors (yellow). The input to soil hazard computations consists of four sets of SIFs (orange labels). The preparation of these SIFs involves data processing outlined in the text and detailed in *Hölker* (*2004a, TP3-TN-0401*). Soil hazard computations (green) are performed with and without truncation of large amplitudes (SIF set 4).

7.5.2 Soil Hazard Computation Products

The soil hazard is computed for the four Swiss NPP sites, three depth levels at each site, and the frequencies specified in Table 7-1. The depth levels considered are the surface, the mean depth of facility buildings and the reactor building depth (see section 7.2).

Tab.7-1: Frequencies for which soil hazard computations were performed

'x' indicates frequencies for which the hazard is computed routinely and 'r' indicates site resonance frequencies

Site / Frequencies	0.5	1	2	2.5	4	5	5.75	10	12	13	20	33	50	PGA
Beznau	x	x		x		x(r)		x			x	x	x	x
Gösgen	x	x		x	r	X		x	r		x	x	x	x
Leibstadt	x	x	r	x		X	r	x			x	x	x	x
Mühleberg	x	x		x		X		x		r	x	x	x	x

The soil hazard calculations generate the following results for each site and depth level:

- Mean and fractile (0.05, 0.16, 0.5, 0.84, 0.95) horizontal and vertical soil hazard curves for PGA and frequencies given in Table 7-1. Hazard curves for 100 fractiles, from 0.01 to 0.99 are provided as data tables (see CD-ROM attached to the inside of the back cover of Vol.2).
- Uniform soil hazard spectra for 5 % damping.
- Site response sensitivity results showing (1) soil hazard by SP3 expert; (2) mean hazard curves with and without the effect of upper limit soil ground motion estimates; (3) hazard sensitivity histograms showing the effect of epistemic uncertainty in the median amplification factor, in the aleatory variability, and in the truncation; (4) soil ground motion sensitivity histograms showing the effect of epistemic uncertainty in each variable (logic tree node).
- Comparison of mean hazard curves for the three depth levels and the corresponding rock hazard.

7.6 Volume of the Hazard Computations and Pinching

The level of detail of the SP1 and SP2 expert models, as summarised in sections 2.6.1 and 2.6.2 and documented in chapters 4 and 5, leads to a very large number of end branches in the resulting overall logic trees.

A typical combination of a single SP1 model with the five ground motion models of SP2, as illustrated in Fig. 7-2, involves the computational treatment of 10^{26} logic tree branches. This huge amount of calculation must be performed for the four SP1 expert groups, for the eight spectral frequencies and for PGA, as well as for the four NPP sites. Under these premises, a process that transforms the complete logic trees into smaller logic trees that are essentially equivalent in terms of hazard, but are computationally feasible, is an absolute necessity. This process, to which we refer as 'algorithmic pinching', was performed by the SP4 analysts under strict guidelines and was thoroughly documented, as described below.

7.6.1 Rationale for Pinching

Calculation of PSHA always involves numerical approximations for two reasons. First, evaluation of the seismic hazard integral (over earthquake magnitude and distance) is always done numerically, not analytically. Second, the quantification of epistemic uncertainty in the models is almost always done using discrete approximations to continuous probability distributions. Thus, the PSHA analyst always makes a number of algorithmic decisions, which affect how the hazard is calculated. These decisions include the step size to use in numerical integration over magnitude and distance, the procedure to evaluate epistemic uncertainty in hazard, and the values of ground motion amplitude to consider. The pinching of logic trees is another algorithmic decision.

It is generally more practical for the SP4 analyst to make the algorithmic decisions discussed here, rather than the experts or the TFI, because the SP4 analyst is in a better position to judge the effect of these decisions on calculated hazard and the practical effect of these decisions on computer resources.

7.6.2 Accuracy Criteria and Guidelines for Source Tree and Global Tree Pinching

Two key requirements for the algorithmic decisions described above are as follows:

- They should not introduce any significant error in the results (relative to the ideal results that one would obtain if one could implement the model in the Hazard Input Document without introducing any further numerical approximations).
- They should permit calculation of seismic hazard in a reasonable time, given the capabilities and limitations of software and hardware.

The definition of what constitutes a significant error depends on the accuracy of the experts' interpretations and on the downstream effects of those errors. Considering only the latter, this study set the following primary criteria for the acceptable errors in the results:

- Acceptable error in the mean and standard deviation of total seismic hazard: 3 %, which translates into approximately 1 % error in ground motion amplitude.
- Acceptable error in the 0.50, 0.85 and 0.95 fractiles of seismic hazard: 10 % if the fractile is underestimated and 20 % if the fractile is overestimated.

One could make the argument that these acceptable errors are unnecessarily small, given the epistemic uncertainty inherent in seismic hazard, as represented by the experts' alternative interpretations and the differences between experts or expert teams[14]. Nonetheless, this study conservatively[15] ignored this argument and adopted the values defined above. Except for insignificant deviations documented in *Roth & Toro* (*2004a, TP4-TN-0399*), this study succeeded in satisfying these strict criteria.

The first type of algorithmic pinching – moment-based pinching of the source logic tree – is performed by the POST88 software under the analyst's control. This option reduces the total number of branches in the full logic tree by reducing the number of source branches associated with those sources that contribute little to the hazard, without significantly affecting the results. The analyst specifies these options after examining the mean results by source. The most radical pinching option (1-point pinching) preserves the mean hazard for the source in question. Other

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[14] This high epistemic uncertainty is easily seen in the range between the median and 0.85 fractile of the hazard results. This difference is always broad for the ground motion amplitudes of interest in this study.

[15] In this discussion, conservatism refers to achieving more precision than may actually be required, not to calculating higher hazard.

options (2- and 3-point pinching) also preserve the variance and variance plus skewness of the hazard, respectively.

To expedite the process of moment-based pinching, two steps were implemented, as follows:

- Develop operational criteria for moment-based pinching. These criteria are expressed in terms of quantities that are easy to calculate, namely the means and coefficients of variation of the hazard by source. If the pinching option for a source satisfies these operational criteria, it is assured to satisfy the primary criteria for fractiles.
- Modify the POST88 software so that it checks the operational criteria, as well as the criteria for the standard deviation, and generates a pinching report.

Toro (*2004a, TP4-TN-0394*) documents the development of the operational criteria and provides additional guidance on pinching.

Other forms of pinching affect the variables in the global logic trees and are performed by the analyst (typically by modifying the logic tree files used by POST88). The most common of these is "tree trimming", which consists of removing branches from the global logic tree if the analyst can show compliance with the primary criteria on mean and standard deviation. The following are typical cases where these modifications may be appropriate:

- One or more branches of the logic tree have very low weights. Unless this branch or branches produce very different hazards from those branches that have significant weights, it may be appropriate to eliminate this branch and assign the weight to another branch.
- Some global branches produce nearly identical hazard results. If the difference between these hazard curves is very small (relative to the total mean hazard or to the mean hazard from a dominant source), it may be appropriate to combine these branches into one representative branch. The representative branch may be selected as the one with the highest hazard, the one with hazard closest to the mean hazard or the one with the highest weight.

Errors in the mean and standard deviation (more precisely, in the variance) of hazard are cumulative. Therefore, it was necessary to calculate the cumulative errors over all SP1 expert groups and compare the resulting total errors to the maximum values specified by the primary criteria. This process is documented in *Roth & Toro* (*2004b, TP4-TN-0400*).

7.6.3 Compliance with Operational Criteria in the Case of Moment-Based Pinching

The SP4 analysts typically introduced tree trimming after a careful review of the contributions to the total hazard of the different global branches and of a variance analysis. They also knew the error in variance introduced by global tree pinching (see section 2.6.1.4) and how much error margin was still available for moment-based pinching. They verified compliance with the operational criteria for moment-based pinching by generating the POST88 pinching report (as per the guidelines in *Toro 2004a, TP4-TN-0394*), examining this report and modifying the pinching options until the criteria were met.

As a consequence of their simplicity, the operational criteria are sub-optimal in the sense that a pinching option may meet the primary criteria but fail the operational criteria. In a few cases it was necessary to introduce additional moment-based pinching beyond that allowed by the operational criteria. Additional tests were then performed to verify that these pinching options satisfied the primary accuracy criteria. These tests, which compare exact and pinched fractiles for a source or group of sources, are documented in *Roth & Toro* (*2004a, TP4-TN-0399*).

7.6.4 Compliance with Accuracy Criteria in the Case of Global Tree Pinching

When the SP4 analysts introduced pinching of the global logic trees, they verified compliance with the primary criteria by means of additional tests. These tests compared the mean and standard deviation before[16] and after pinching. *Toro* (*2004b, TP4-TN-0395*), *Toro* (*2004c, TP4-TN-0397*) and *Roth* (*2004, TP4-TN-0398*) document these tests.

Verification of compliance with the criteria on fractiles is not necessary in the case of global tree pinching because the branches being eliminated have very low probabilities and/or their corresponding hazards are similar to those of other branches. In this regard, it is useful to recall that the highest fractile subject to the primary criteria is 0.95 and that the criteria on fractiles have tolerances of 10 or 20 % (depending on the sign of the error), whereas the criteria on mean and standard deviation have tolerances of only 3 %.

Most of the tests discussed in this section and in section 7.6.3 were performed on the results for one SP1 team. *Roth & Toro* (*2004b, TP4-TN-0400*) document compliance with the primary criteria in terms of the integrated rock results, which are obtained using standard error propagation techniques. These calculations consider only the errors in the mean and standard deviation because the errors in fractiles actually diminish as the results are aggregated.

7.6.5 Summary

In summary, the PEGASOS Project set a series of simple accuracy rules for the hazard computations. SP4 strictly adhered to these rules and managed to stay below the imposed error levels throughout the chain of computations. This process allowed SP4 to obtain accurate results within reasonable time and resource constraints.

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[16] Various approaches were used to allow the efficient computation of the exact result. A commonly used approach was to use full pinching of the source logic tree for both sets of runs. This step does not affect the mean hazard and causes a moderate decrease in the standard deviation of the total hazard, thus allowing verification of the relative errors in the mean and standard deviation.

8 HAZARD RESULTS

8.1 Final Hazard Results

The integrated hazard results provide a representation of seismic rock hazard and its uncertainty at the four sites, based on the four SP1 expert teams' and five SP2 experts' models. Separate rock hazard results are obtained for PGA and for spectral accelerations at 0.5, 1, 2.5, 5, 10, 20, 33, and 50 Hz. These rock hazard results, combined with the site-specific SP3 expert models in the soil hazard software (see section 7.2.4), provide a representation of seismic soil hazard and its uncertainty at the four sites. For each site, soil hazard results are obtained for the aforementioned ground motion measures and, in addition, for spectral accelerations at one or two site-specific resonance frequencies. Volume 2 of this report encompasses the full catalogue of hazard results, without any comment or interpretation. Here, we present and discuss a subset of results, the same for all four NPP sites.

Figures 8-1 and 8-2 show the mean rock and soil hazard at surface for PGA, while Figures 8-3 and 8-4 show the uniform hazard spectra (UHS) for an annual probability of exceedence of 10^{-4}, for rock and soil conditions, respectively. In all the figures, the mean and median hazard curves convey the central tendency of the computed exceedence probability, while the separation between the remaining fractiles conveys the effect of epistemic uncertainty on the computed exceedence probability.

The epistemic uncertainty is high, even at low ground motion amplitudes. This may be surprising but reflects the uncertainty about the parameters (recurrence rate, stress drop, kappa, etc.) associated with the moderate to weak magnitude earthquakes in this part of Europe that dominate the seismic hazard (see below). The epistemic uncertainty is larger at low frequencies, since the hazard is more sensitive to M_{max} of stronger distant earthquakes.

Figures 8-5 and 8-6 show the deaggregation of the mean hazard for two opposite combinations of ground motion amplitude and horizontal spectral acceleration: 0.05 g and 0.5 Hz in Figure 8-5 and 0.7 g and PGA in Figure 8-6. The figures show the deaggregation into magnitude-distance-ε bins in the upper part of the figure and into the three components separately in the lower part. ε is the difference between the logarithm of the annual exceedence probability and the mean logarithm of exceedence probability (APE), for that magnitude and distance, measured in units of the standard deviation σ of log (APE). Figure 8-5 shows that the 0.05 Hz spectral accelerations are mainly caused by moderate earthquakes ($M < 7.0$) located at Joyner-Boore distances less than 20 km from the site. This is valid for all the sites. With increasing ground motion amplitude and frequency, the contribution from larger, more distant events decreases rapidly (Figure 8-6).

Figures 8-7 through 8-24 show the same type of results for the other three sites.

8.1.1 Beznau

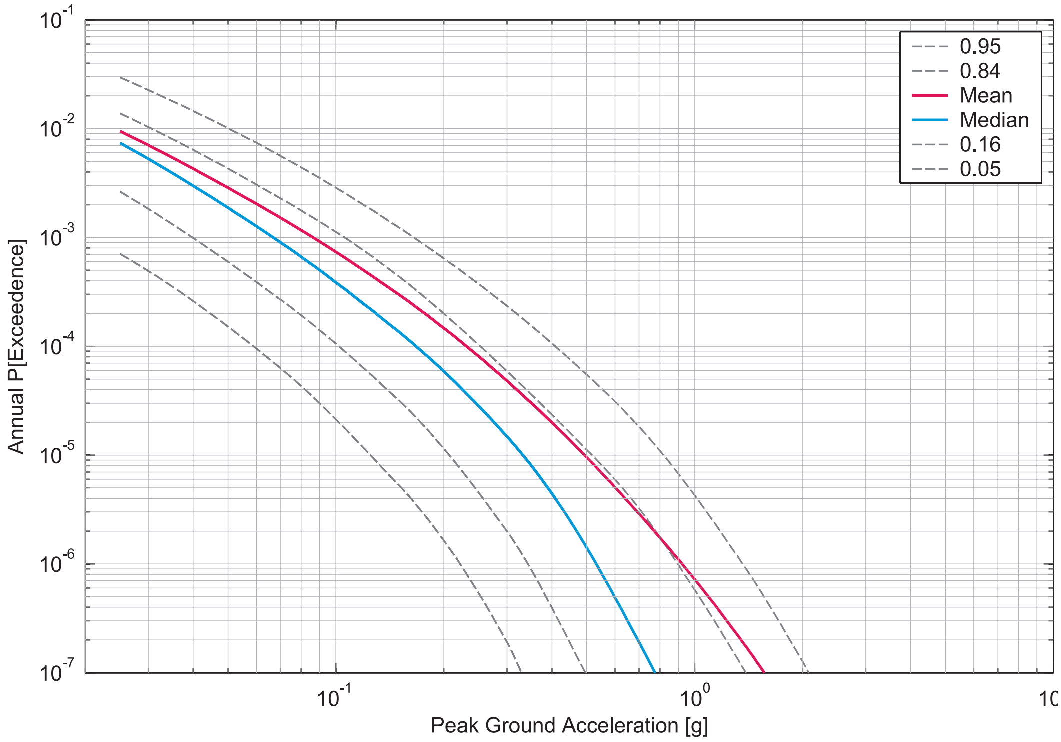

Fig. 8-1: Beznau, horizontal component, rock, surface, mean hazard and fractiles, PGA

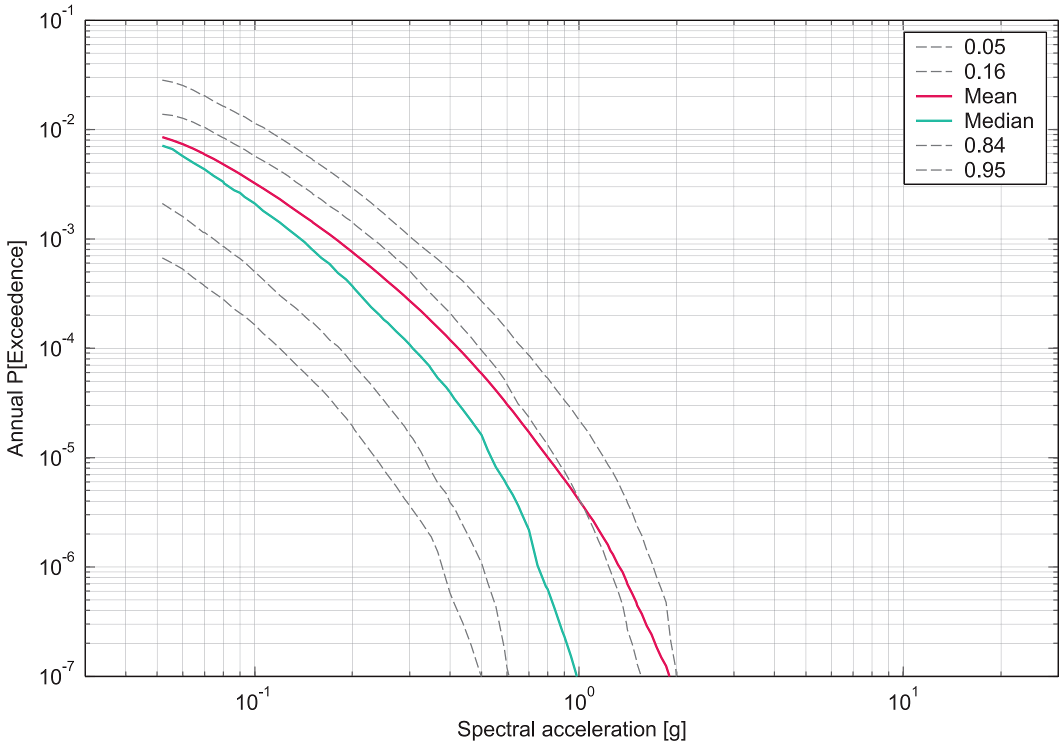

Fig. 8-2: Beznau, horizontal component, soil, surface, mean hazard and fractiles, PGA

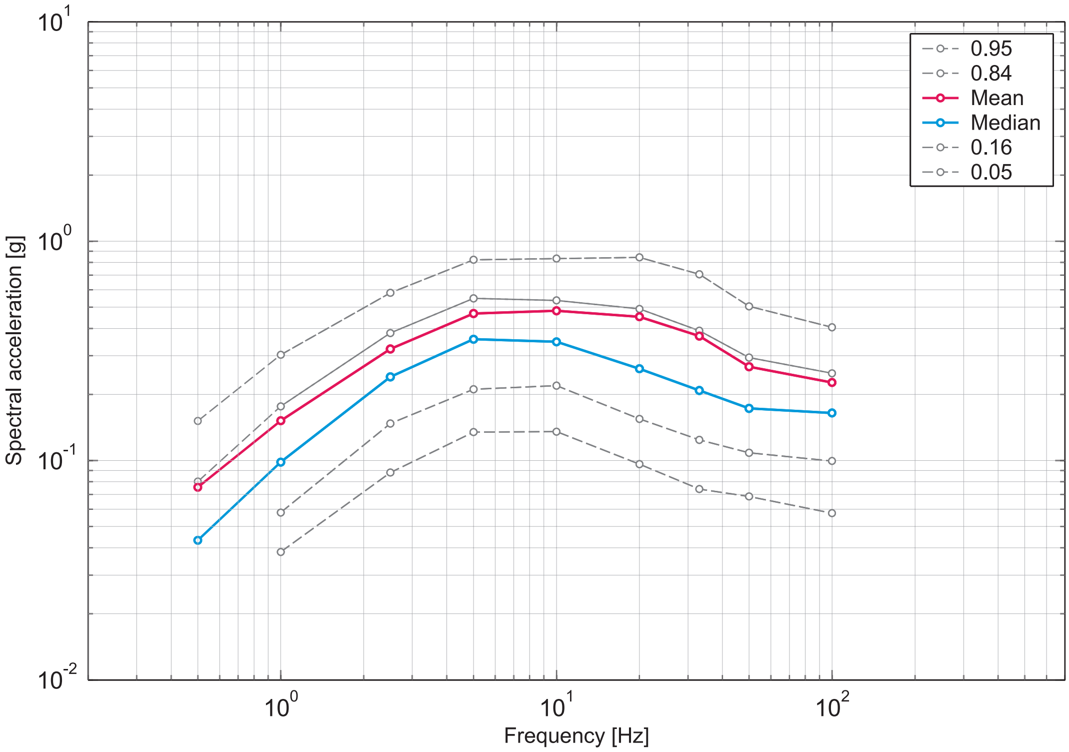

Fig. 8-3: Beznau, horizontal component, rock, surface, uniform hazard spectra for an annual probability of exceedence of 1E-04 and 5 % damping

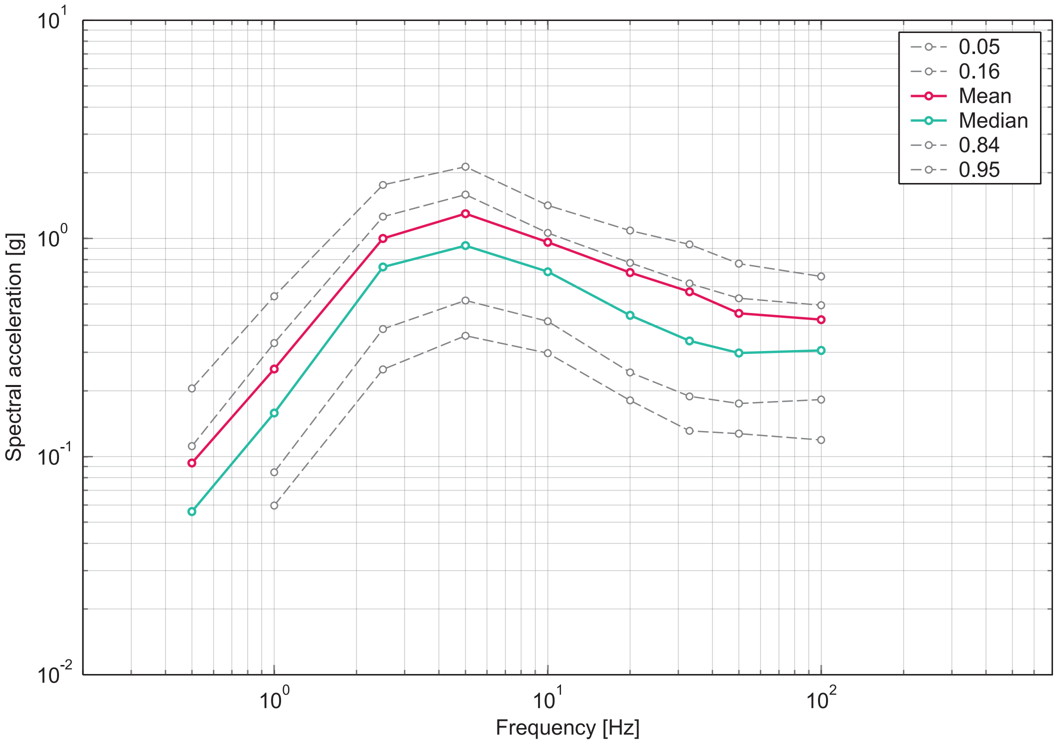

Fig. 8-4: Beznau, horizontal component, soil, surface, uniform hazard spectra for an annual probability of exceedence of 1E-04 and 5 % damping

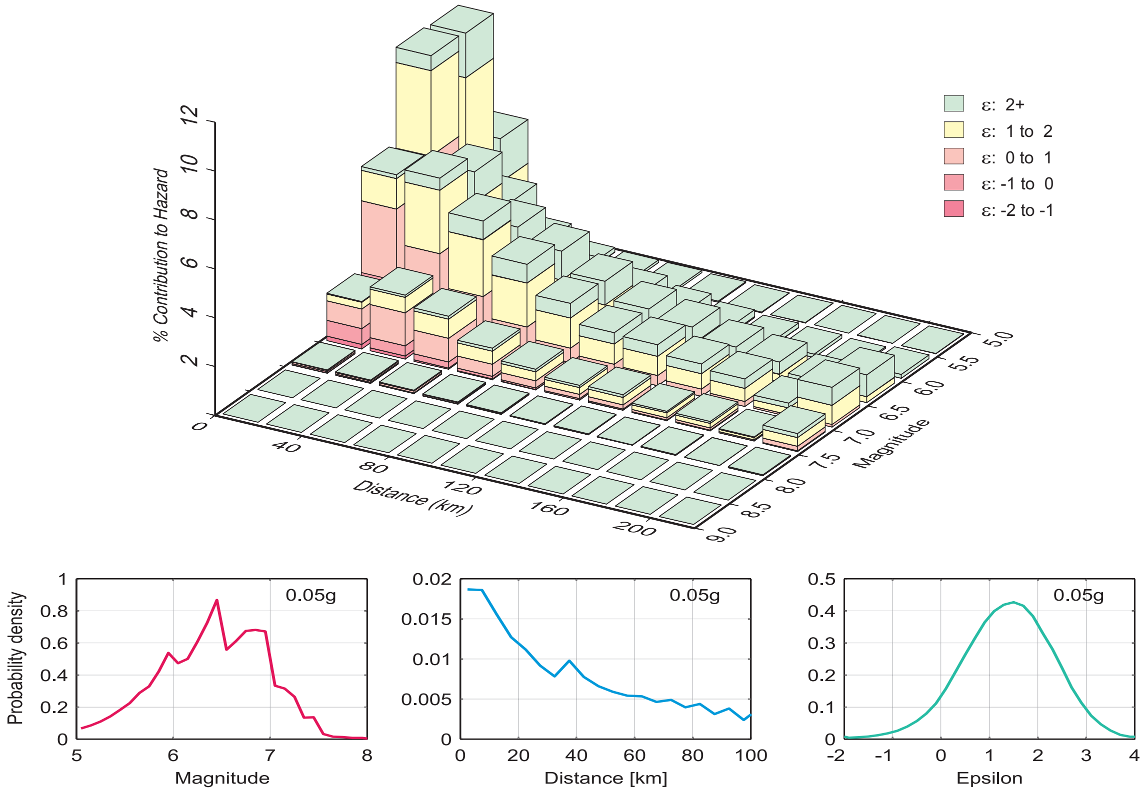

Fig. 8-5: Beznau, horizontal component, rock, surface, hazard deaggregation by magnitude, distance and epsilon for ground motion level 0.05 g, 0.5 Hz

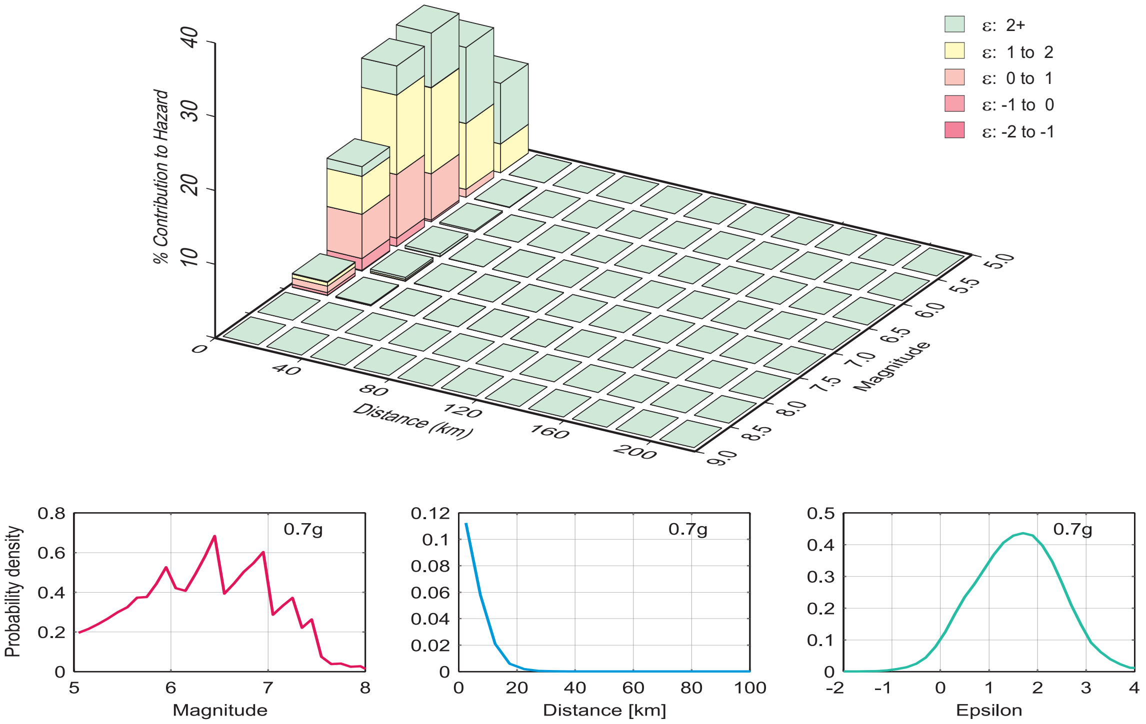

Fig. 8-6: Beznau, horizontal component, rock, surface, hazard deaggregation by magnitude, distance and epsilon for ground motion level 0.7 g, PGA

8.1.2 Gösgen

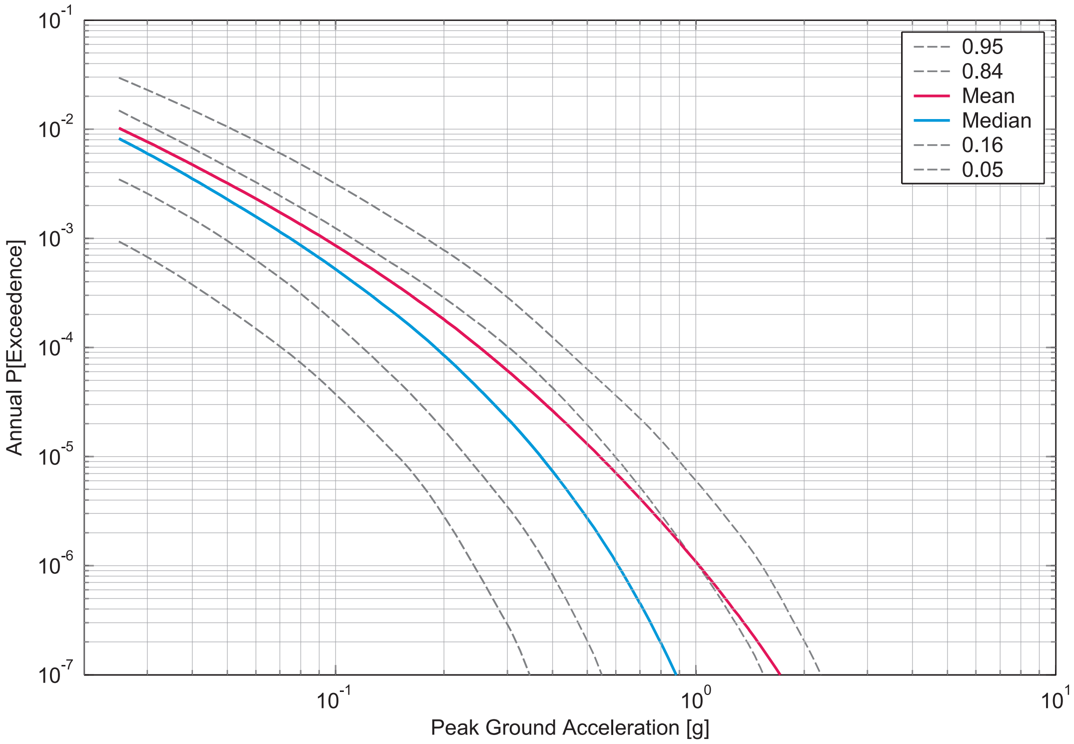

Fig. 8-7: Gösgen, horizontal component, rock, surface, mean hazard and fractiles, PGA

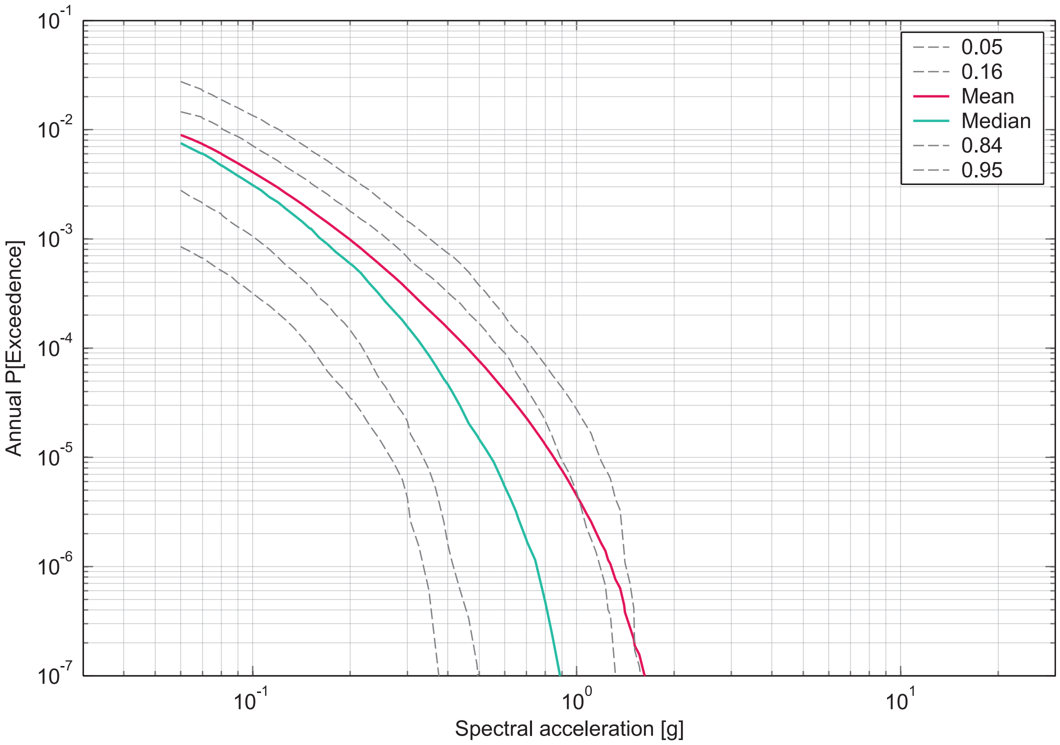

Fig. 8-8: Gösgen, horizontal component, soil, surface, mean hazard and fractiles, PGA

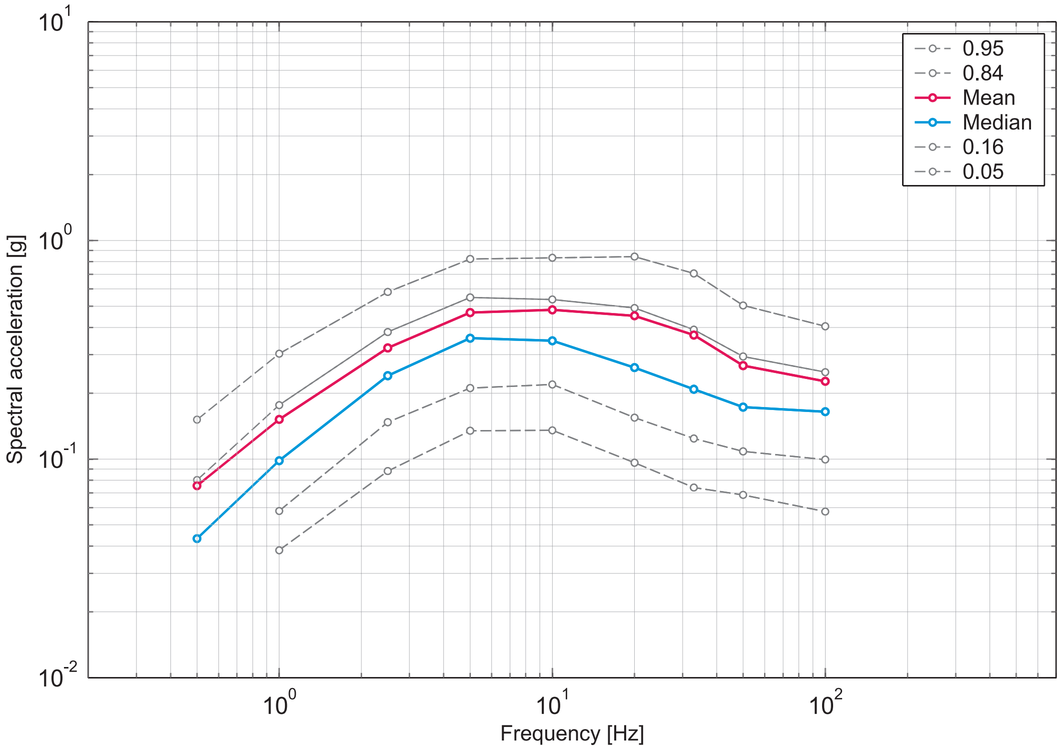

Fig. 8-9: Gösgen, horizontal component, rock, surface, uniform hazard spectra for an annual probability of exceedence of 1E-04 and 5 % damping

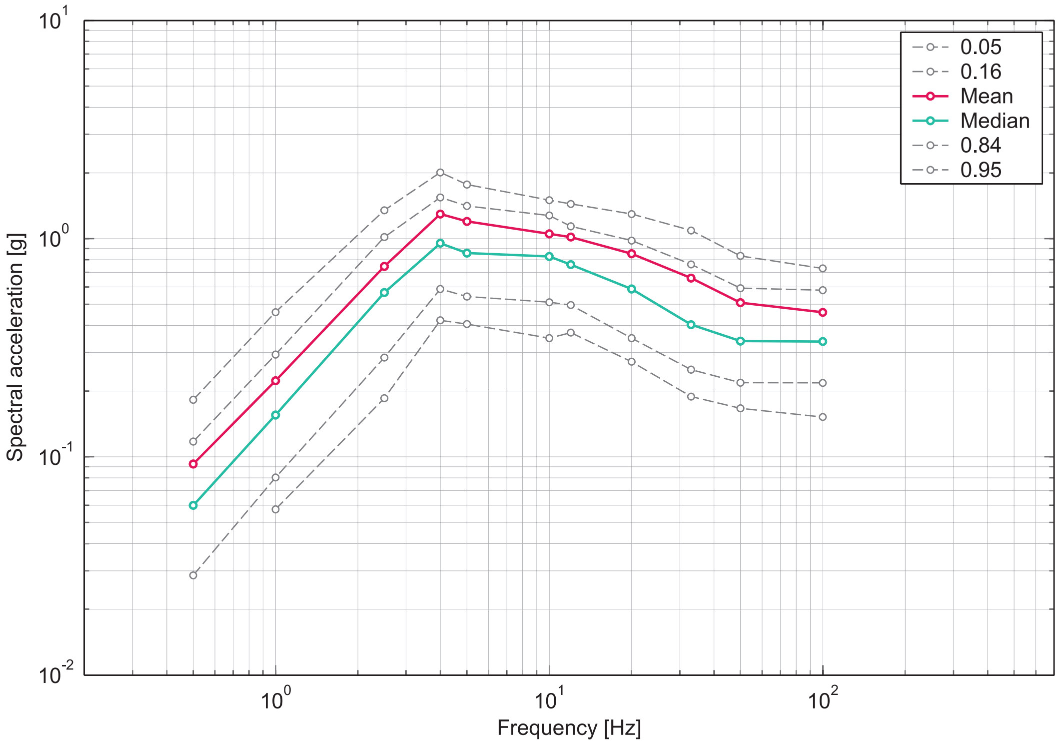

Fig. 8-10: Gösgen, horizontal component, soil, surface, uniform hazard spectra for an annual probability of exceedence of 1E-04 and 5 % damping

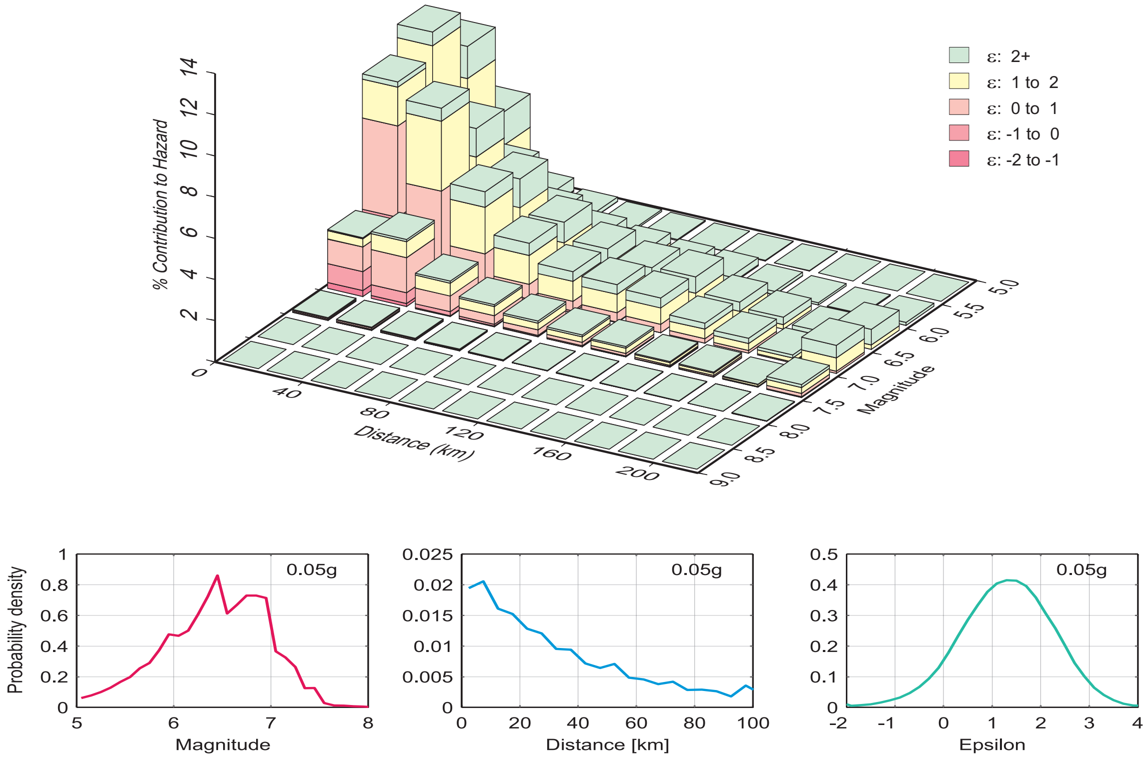

Fig. 8-11: Gösgen, horizontal component, rock, surface, hazard deaggregation by magnitude, distance and epsilon for ground motion level 0.05 g, 0.5 Hz

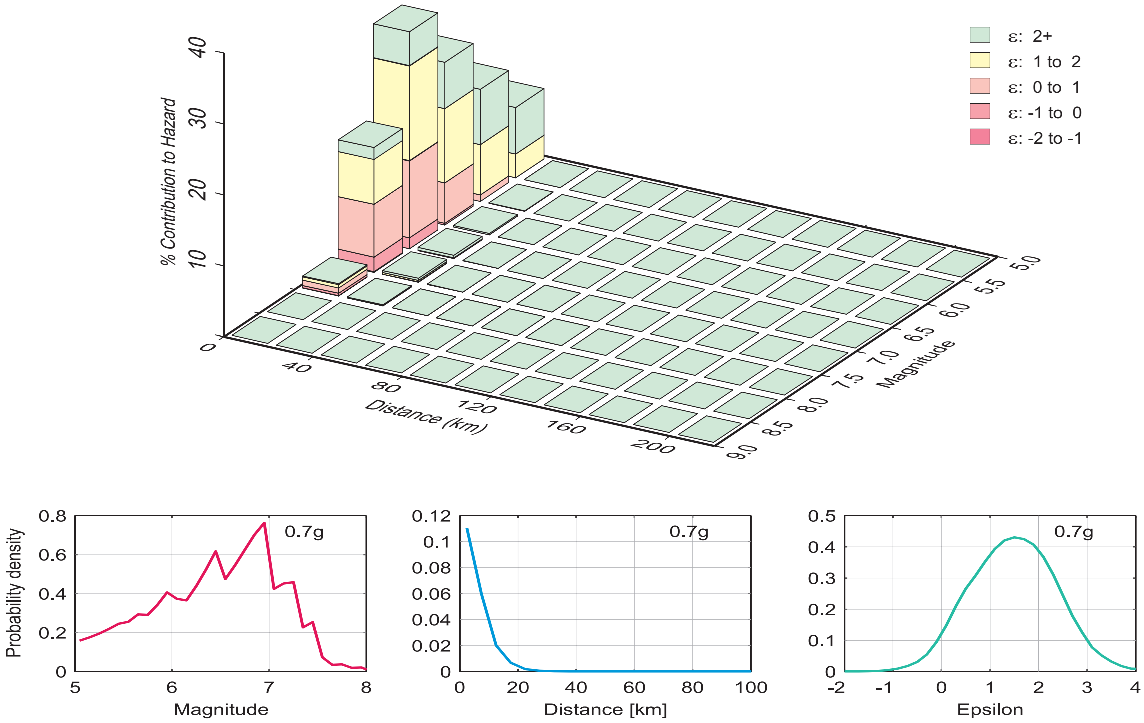

Fig. 8-12: Gösgen, horizontal component, rock, surface, hazard deaggregation by magnitude, distance and epsilon for ground motion level 0.7 g, PGA

8.1.3 Leibstadt

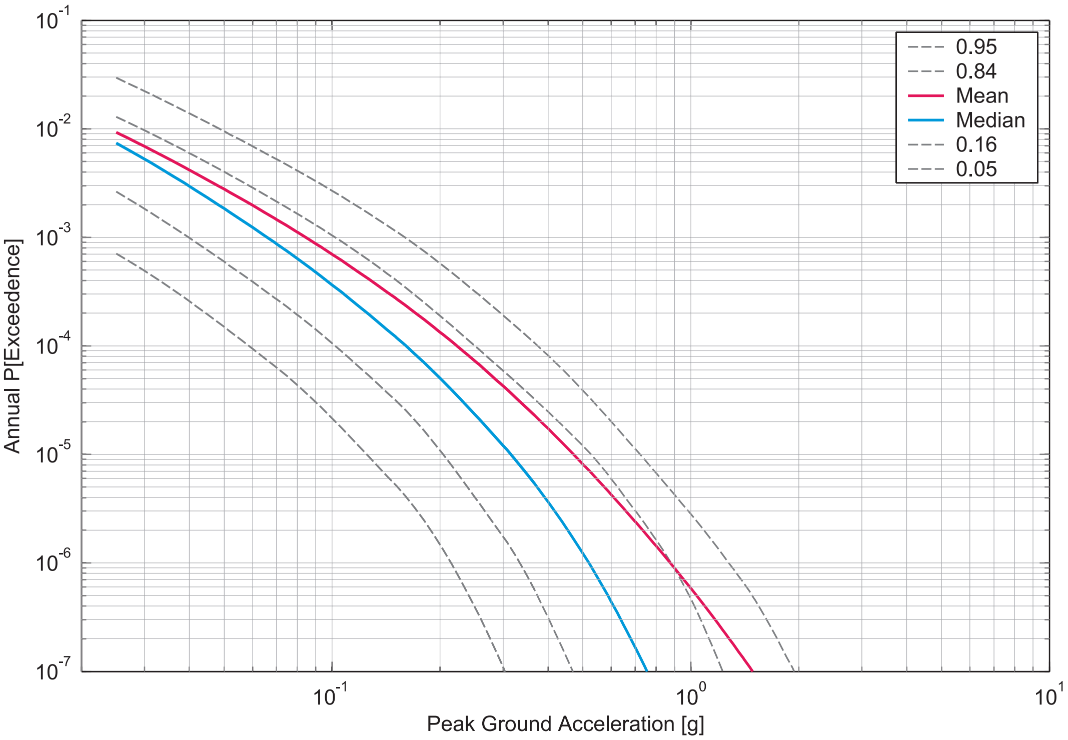

Fig. 8-13: Leibstadt, horizontal component, rock, surface, mean hazard and fractiles, PGA

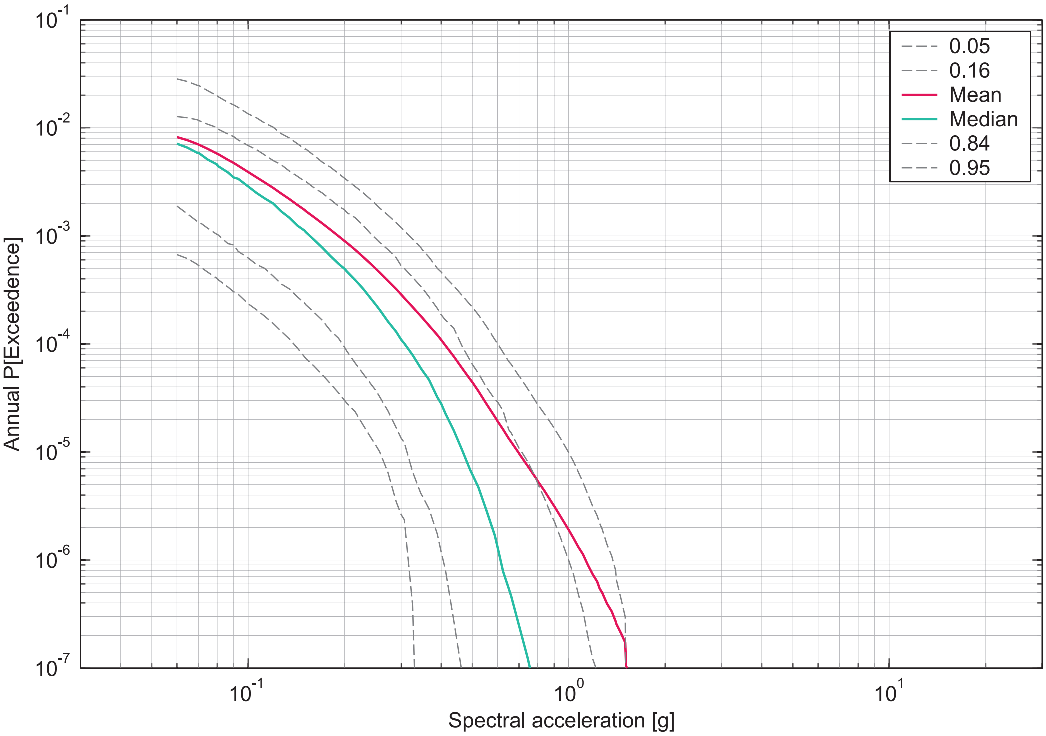

Fig. 8-14: Leibstadt, horizontal component, soil, surface, mean hazard and fractiles, PGA

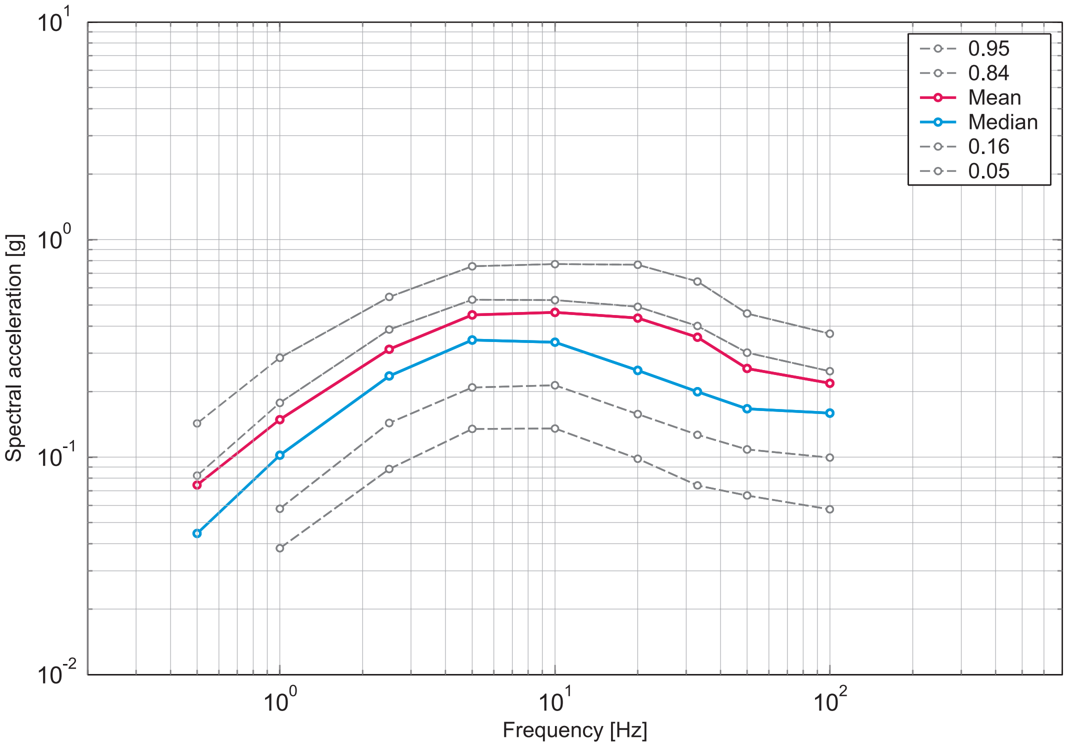

Fig. 8-15: Leibstadt, horizontal component, rock, surface, uniform hazard spectra for an annual probability of exceedence of 1E-04 and 5 % damping

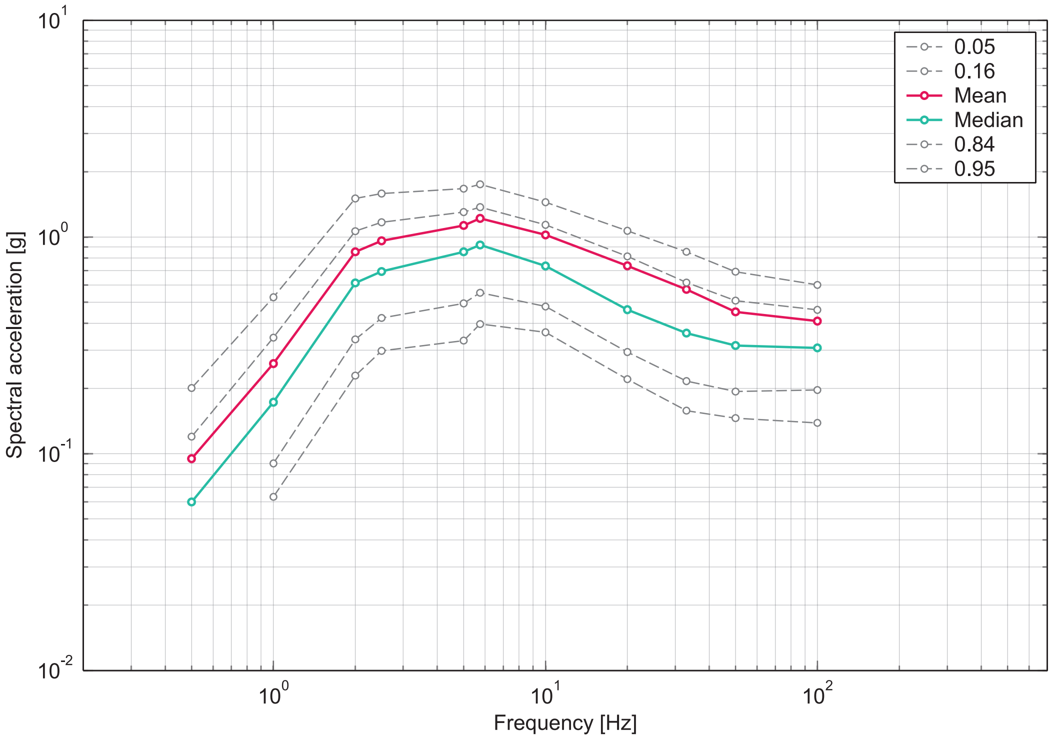

Fig. 8-16: Leibstadt, horizontal component, soil, surface, uniform hazard spectra for an annual probability of exceedence of 1E-04 and 5 % damping

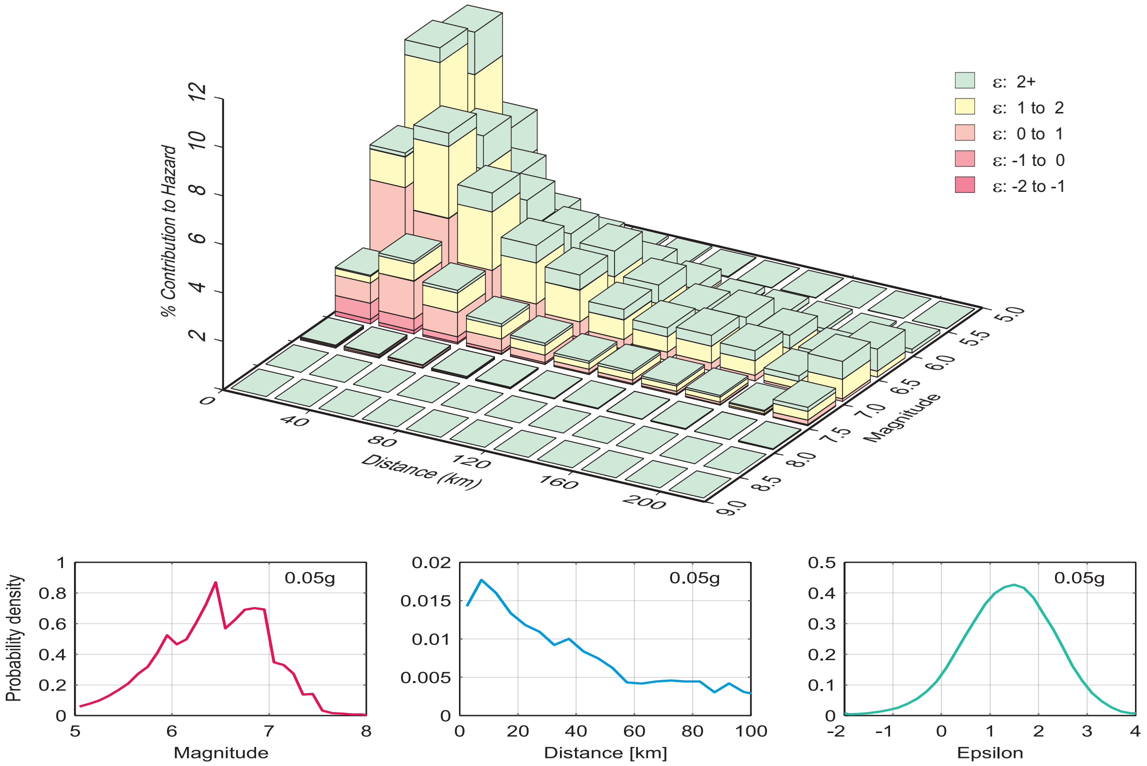

Fig. 8-17: Leibstadt, horizontal component, rock, surface, hazard deaggregation by magnitude, distance and epsilon for ground motion level 0.05 g, 0.5 Hz

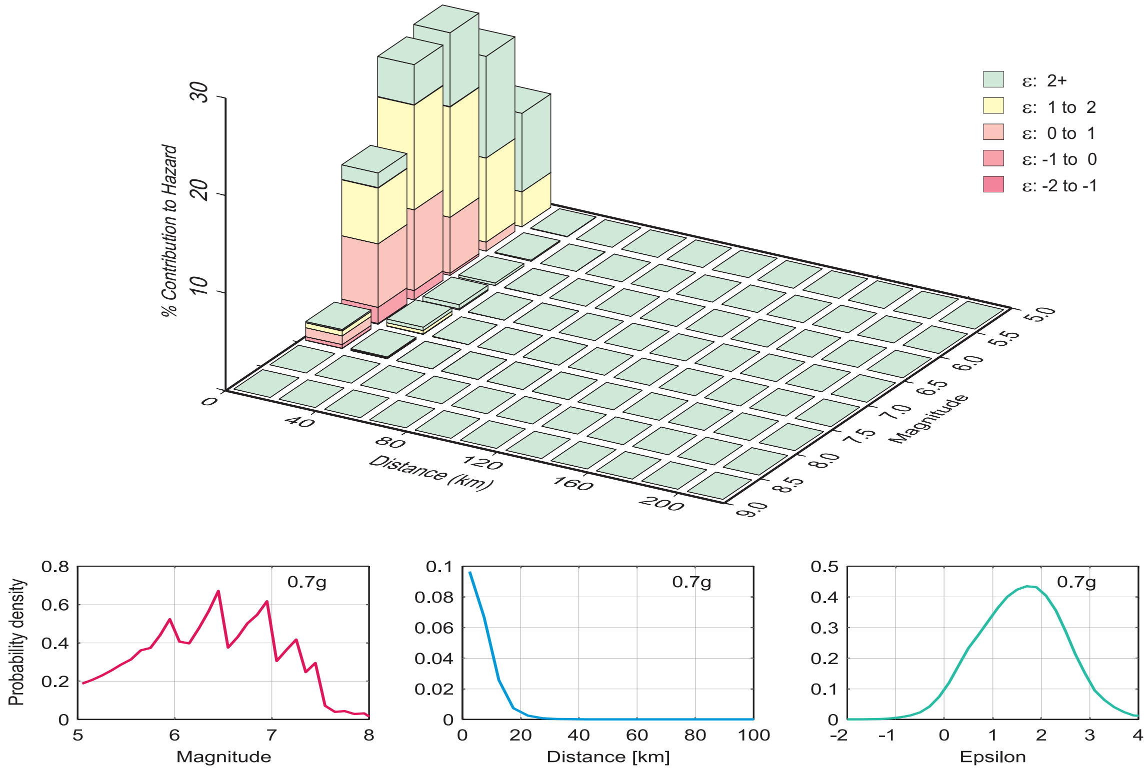

Fig. 8-18: Leibstadt, horizontal component, rock, surface, hazard deaggregation by magnitude, distance and epsilon for ground motion level 0.7 g, PGA

8.1.3 Mühleberg

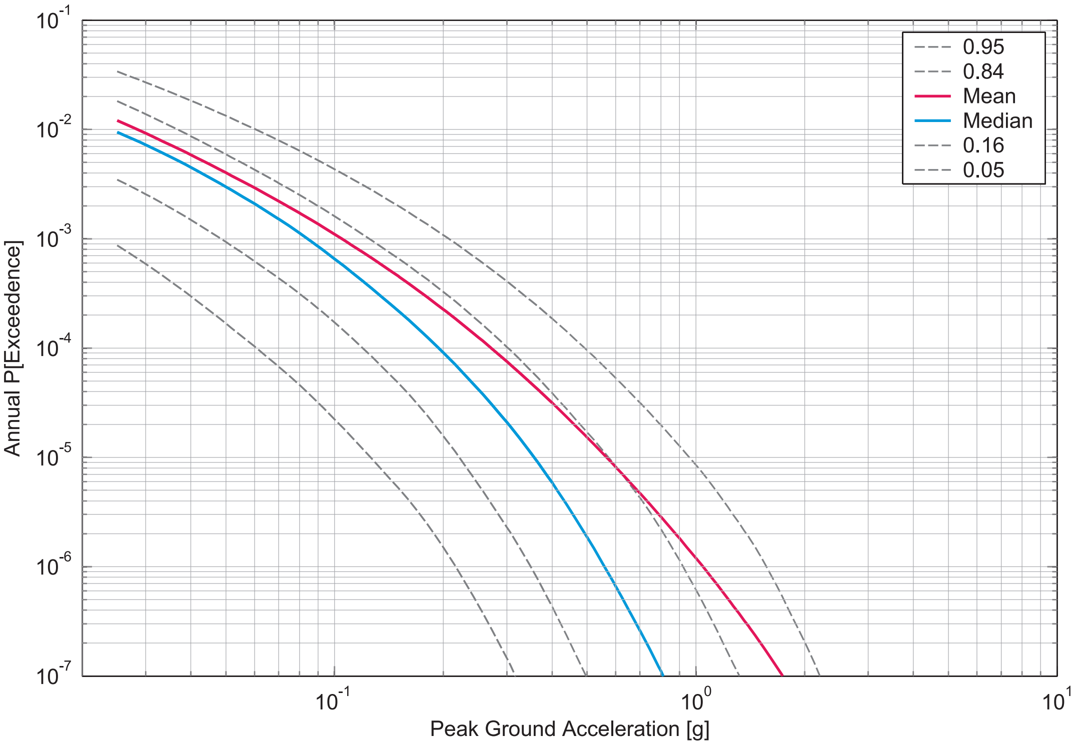

Fig. 8-19: Mühleberg, horizontal component, rock, surface, mean hazard and fractiles, PGA

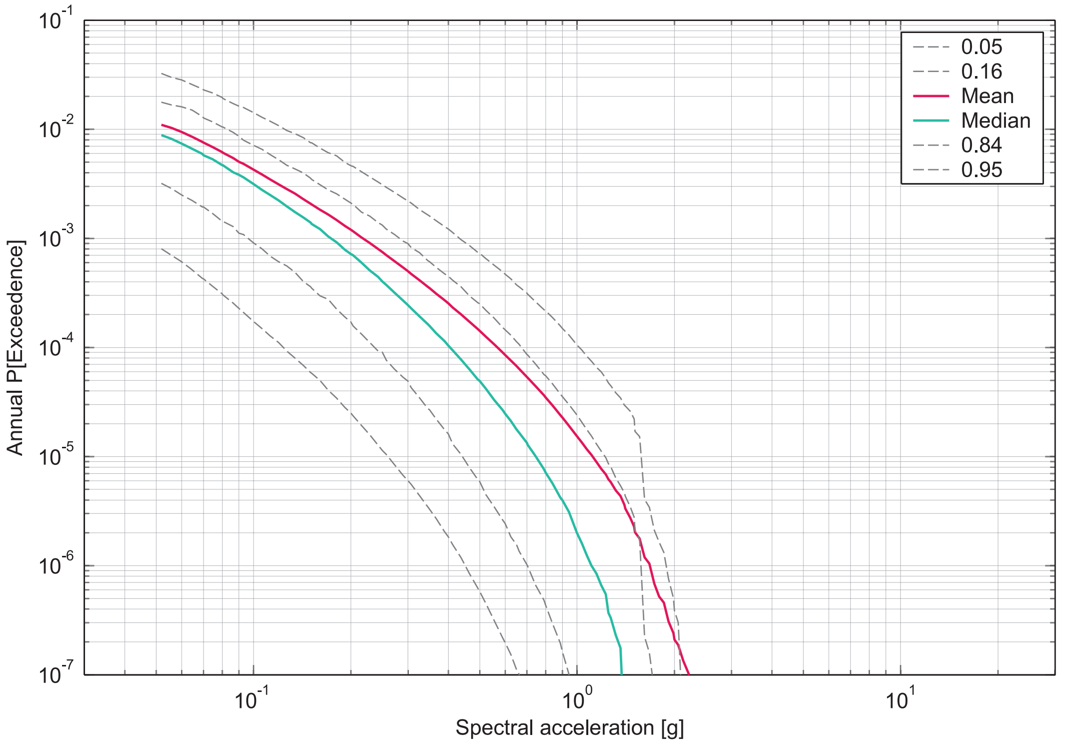

Fig. 8-20: Mühleberg, horizontal component, soil, surface, mean hazard and fractiles, PGA

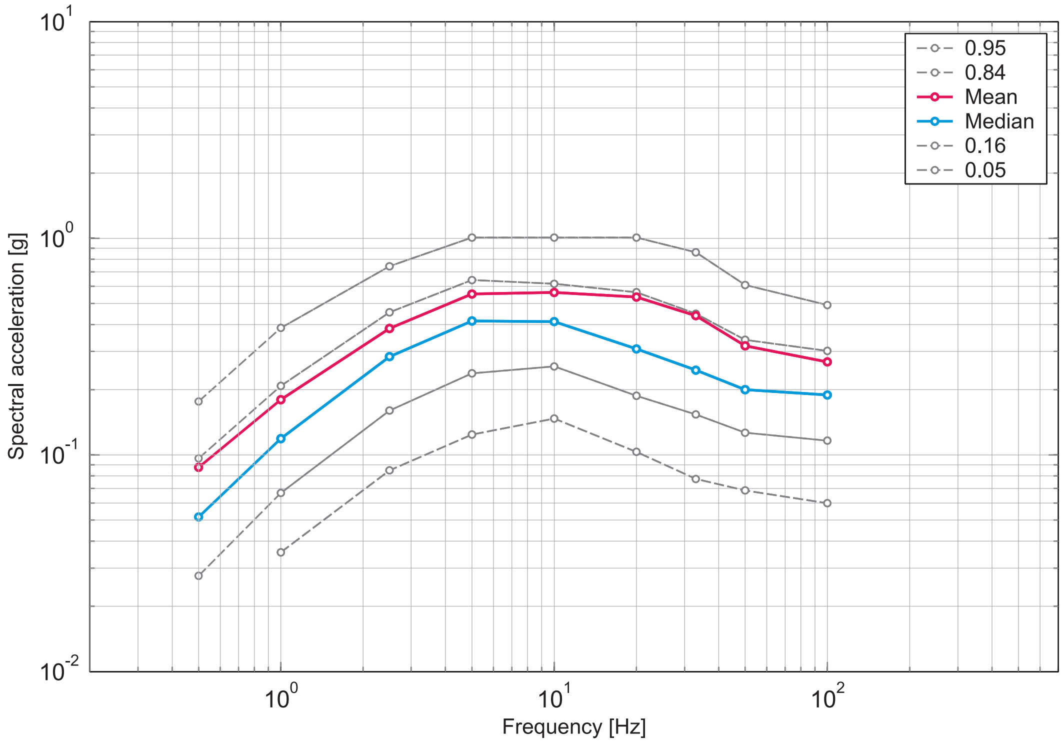

Fig. 8-21: Mühleberg, horizontal component, rock, surface, uniform hazard spectra for an annual probability of exceedence of 1E-04 and 5 % damping

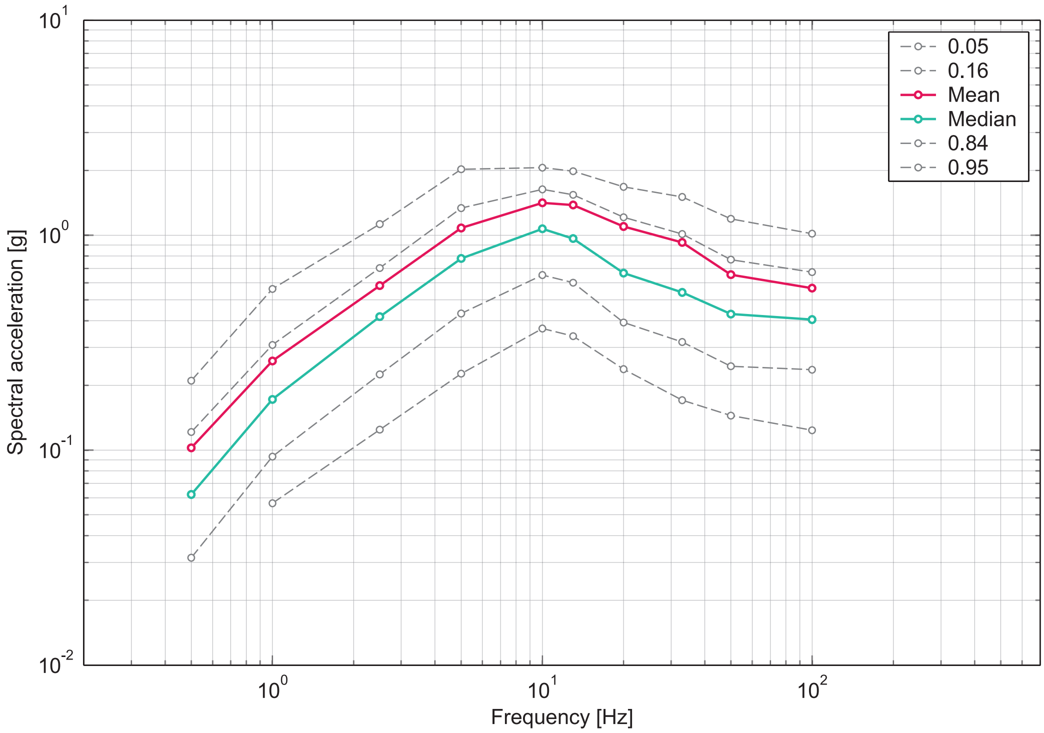

Fig. 8-22: Mühleberg, horizontal component, soil, surface, uniform hazard spectra for an annual probability of exceedence of 1E-04 and 5 % damping

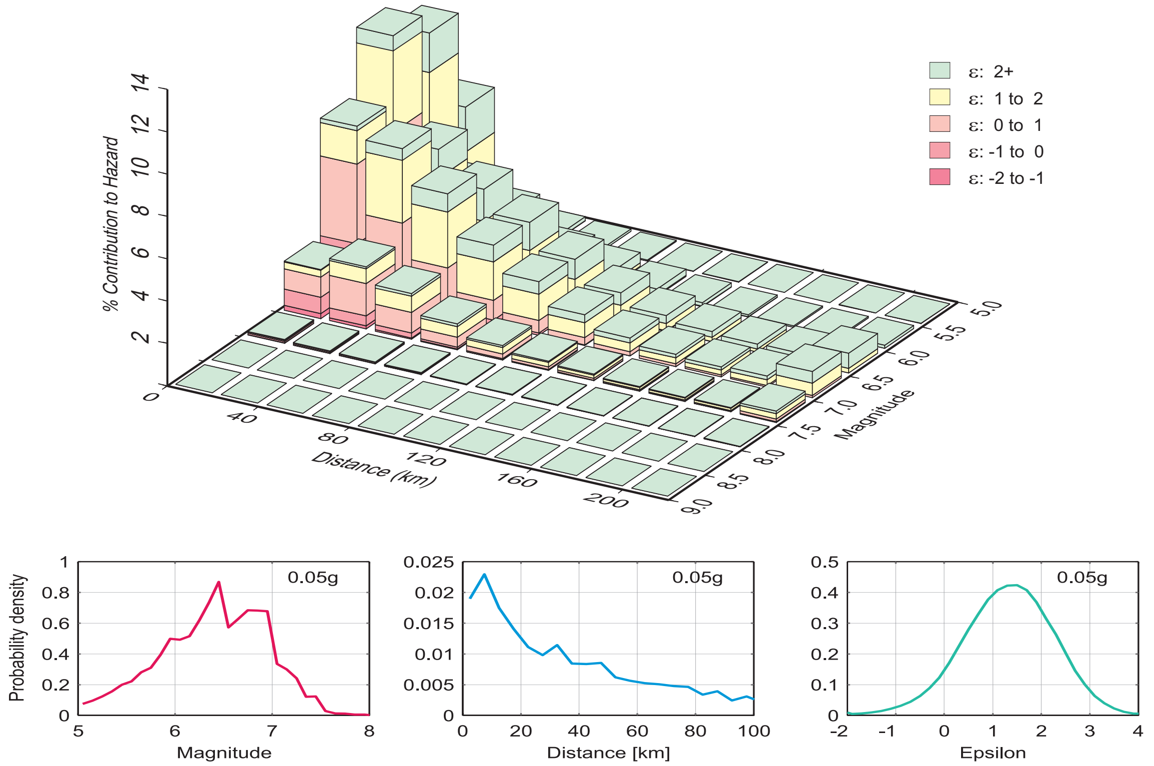

Fig. 8-23: Mühleberg, horizontal component, rock, surface, hazard deaggregation by magnitude, distance and epsilon for ground motion level 0.05 g, 0.5 Hz

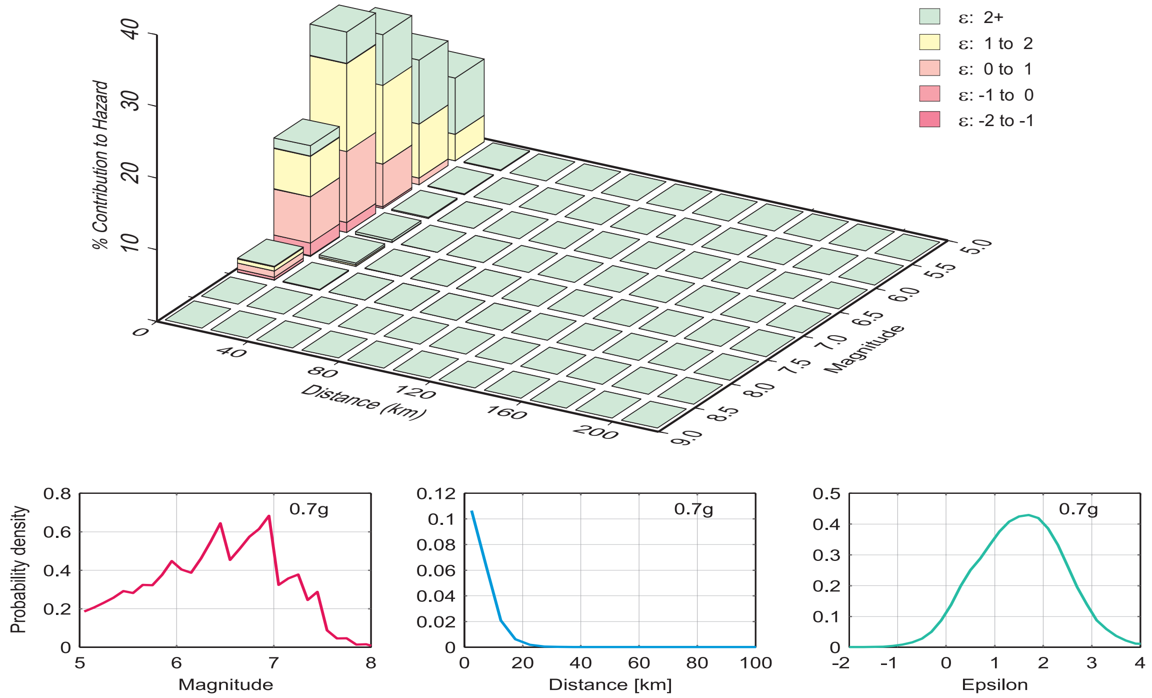

Fig. 8-24: Mühleberg, horizontal component, rock, surface, hazard deaggregation by magnitude, distance and epsilon for ground motion level 0.7 g, PGA

8.2 Sensitivity Results

More than the hazard curves, the sensitivity results provide insights into the effect (or lack of effect) of different model parameters on the computed seismic hazard and its uncertainty. They also provide a consistency check for the experts and hazard analysts. Volume 2 of this report contains a complete set of figures, from which a few examples for the Beznau site are extracted and discussed here.

8.2.1 Contributions of Significant Sources

In accordance with the deaggregation figures described above, the following figures show that the SP1 seismic source zones that provide the largest contribution to seismic hazard are sources located close to the site (see section 4.4.2 for maps of the source zones). Often the host seismic source – the source within which the site is located – is the dominant source in terms of contribution to seismic hazard. This is valid here for PGA, but sections 2.6, 3.6, 4.6 and 5.6 of Volume 2 show that this is also the case for spectral accelerations at all frequencies. Figures 8-25 through 8-28 show the 10 seismic sources with the strongest contributions to the total rock hazard for PGA at Beznau, for the four SP1 expert teams. Note that the hazard curves shown on these figures are weighted mean hazard, such that the sum of the hazard curves equals the total mean hazard. Thus, a seismic source that can produce a high hazard if active, but with a low probability of activity, may have a lower contribution to the total mean hazard than an always active source with lower hazard potential. For example, for the EG1b team, Beznau lies within the small-scale source AE02 or, alternatively, within the large-scale source AE. As shown on Figure 8-26, the weighted mean frequency of exceeding 0.1 g for source AE02 is about four times higher that that for source AE. This difference corresponds to the difference in weights assigned to the two zonation alternatives, 0.8 to small-scale sources and 0.2 to large-scale sources. For the EG1a team, sources E3a and E3b are alternative models for the host zone for Beznau. For team EG1c, zones BLAF and NSPG are the alternative models for the host zone; and for team EG1d zones E and E-NRG are alternative models for the host zone. The results for team EG1c show that the distant, more active BASL (Basel) source is the largest contributor at low ground motion levels. But for the probability levels of primary interest to evaluating the plant safety (less that ~10^{-4}), the host zone is the largest contributor to the hazard.

8.2.2 Effect of the Upper Limit Ground Motion Estimates

SP2 as well as SP3 have assessed the maximum possible ground motion on rock and on soil respectively. The truncation of the hazard results at these values of maximum ground motion has been systematically applied during the hazard computations (weight of 1). However, to be able to investigate how the rock and soil seismic hazard would have looked like without taking into account these physical limits, a no-truncation scenario with a negligible weight of 1E-05 has also been considered that now allows the sensitivity of the seismic hazard results to this upper limit ground motion truncation to be shown.

Figure 8-30 shows this sensitivity for Beznau, PGA on the seismic rock hazard. Both the truncation of the tails of the distribution of residuals in the SP2 ground motion models and the absolute upper bounds specified by the SP2 experts as functions of magnitude and distance are considered (or not considered) here. The effect of truncation is significant, even at low ground motion amplitudes. The effect is seen at low ground motions because the maximum ground motion is given as a function of magnitude and distance rather than a single global maximum value. As shown in chapter 5, SP2 experts Bungum and Scherbaum have the strong truncation effects, but the other three experts do not. The average effect shown in Figure 8-30 reflects a weighting of 2/5 with strong truncation and 3/5 with weak truncation.

Figure 8-31 shows the sensitivity to upper limit soil ground motion truncation for Beznau, PGA on the seismic soil hazard. Only the effect of the SP3 upper limit soil ground motion truncation

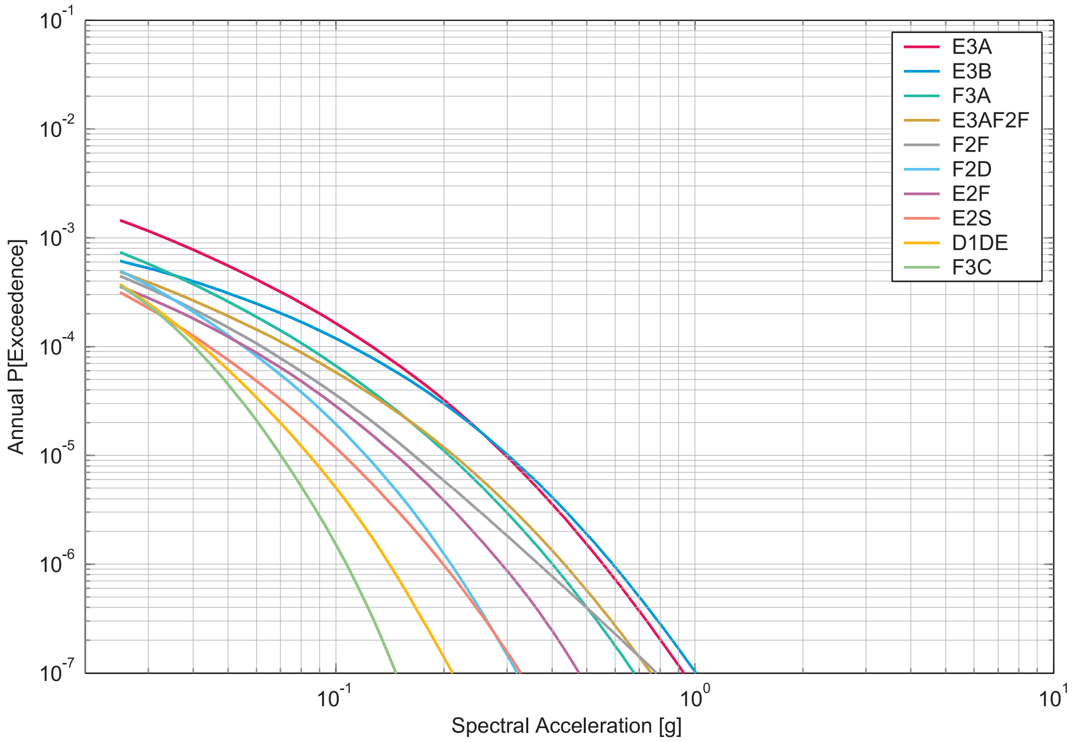

Fig. 8-25: Beznau, horizontal component, rock, surface, 10 largest source contributions to mean hazard, EG1a, PGA

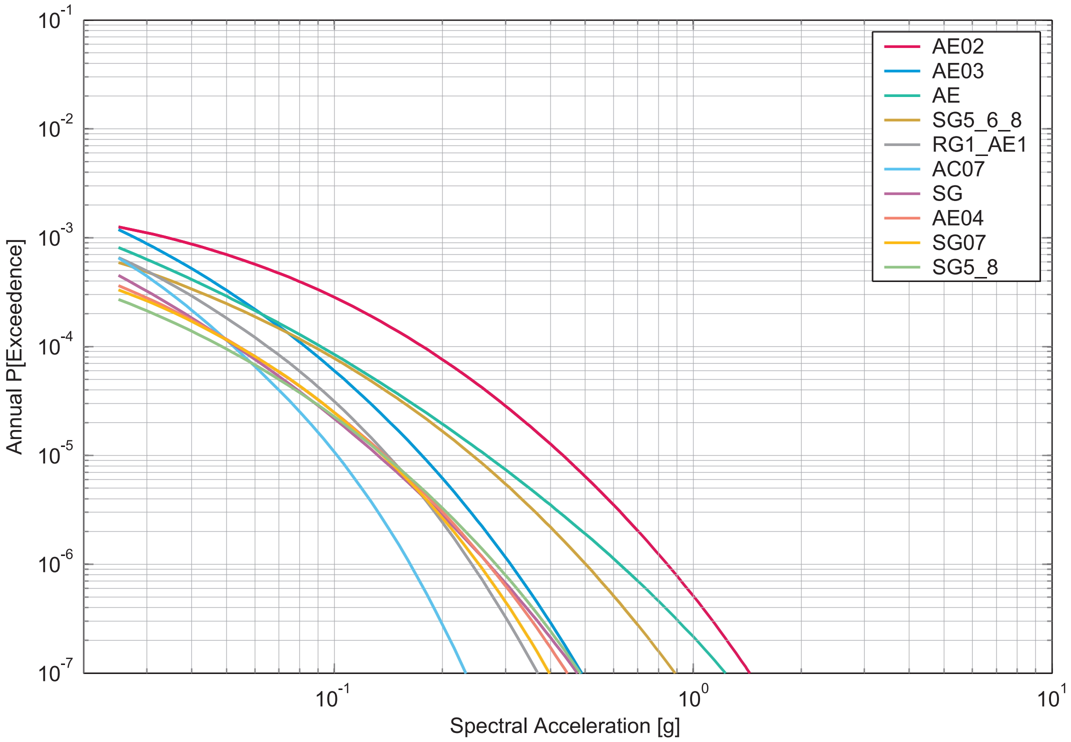

Fig. 8-26: Beznau, horizontal component, rock, surface, 10 largest source contributions to mean hazard, EG1b, PGA

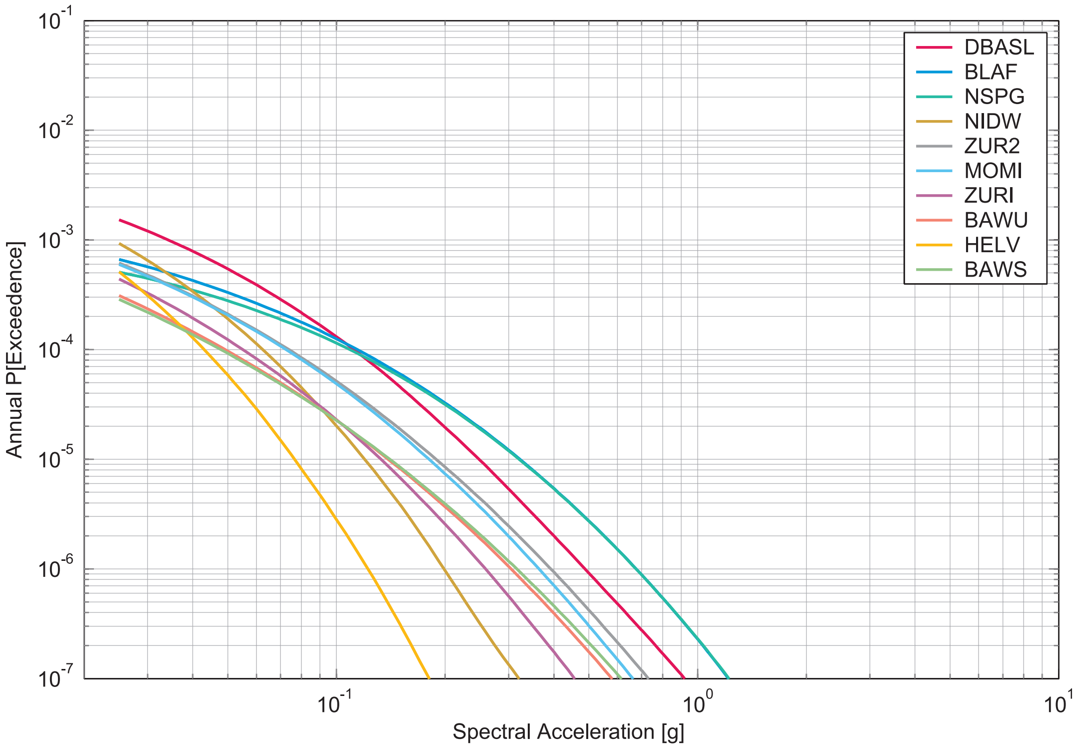

Fig. 8-27: Beznau, horizontal component, rock, surface, 10 largest source contributions to mean hazard, EG1c, PGA

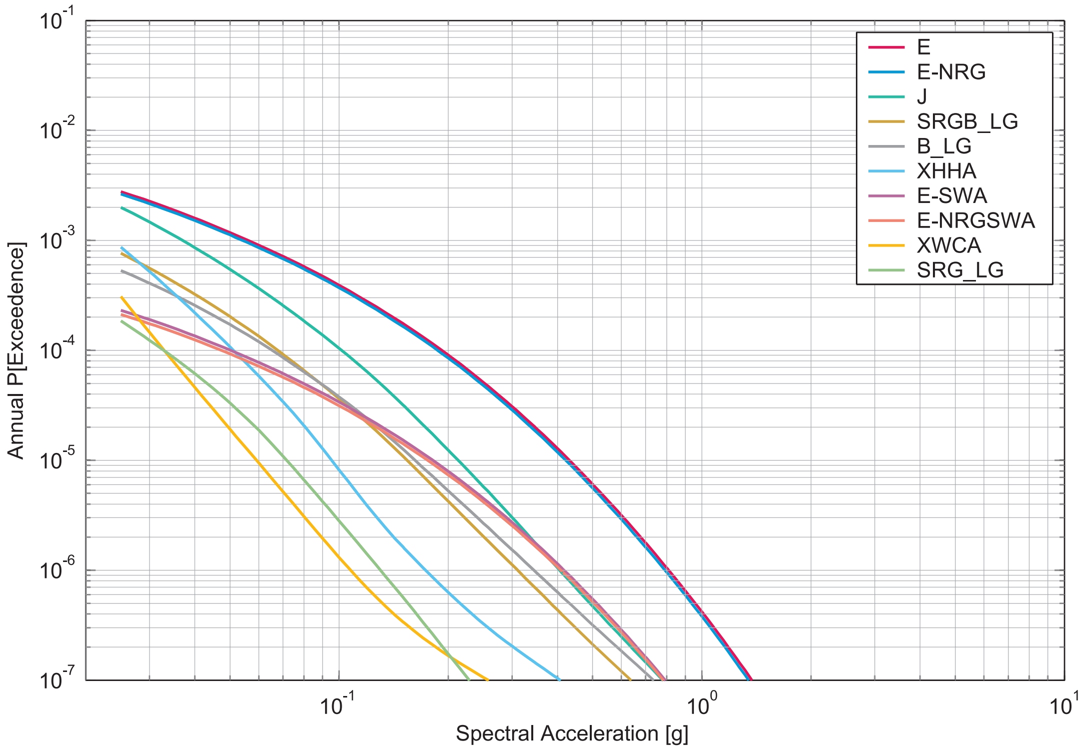

Fig. 8-28: Beznau, horizontal component, rock, surface, 10 largest source contributions to mean hazard, EG1d, PGA

is considered here (both curves rely on the truncated rock hazard results). The effect of truncation is also significant, but clearly only for ground motion amplitudes larger than 1 g. Unlike the effect of the SP2 upper limit rock ground motion truncation, which progressively increases with increasing ground motion amplitude, the effect of the SP3 soil ground motion truncation starts abruptly and leads to a discontinuity of the soil hazard fractiles that is easily observable in the seismic soil hazard figures of section 8.1. The truncation effect for soil is seen only at the low probability levels because the SP3 experts' truncation models were on the maximum ground motion that the soil could transmit rather than a maximum ground motion for each magnitude and distance as used by the SP2 experts.

8.2.3 Expert-to-Expert Comparisons

Figure 8-32 compares the total mean rock hazard obtained using the individual seismic source characterisation (SP1) expert teams' models for PGA at Beznau. These results and the results of Volume 2 (section 2.8) show a good degree of consistency among the mean estimates of the expert teams, with usually less than a factor of three in exceedence probability between the lowest and highest expert group's estimate. The results presented in section 8.1 show that the hazard for peak ground acceleration is dominated by moderate magnitude events at nearby locations. The relative order of the mean hazard estimates for Beznau by the four SP1 teams follows the relative order of the predicted mean annual frequency of earthquakes ≥ M 5 within 25 kilometres and 50 kilometres of the site shown on Figure 4-64. Similarly, the order of the hazard curves for the four SP1 expert teams for the Mühleberg site (Figure 5-8.2 in Volume 2) is consistent with the order of the predicted mean recurrence rates shown on Figure 4-65. The results presented in Volume 2 show that the variation in mean hazard between the four SP1 expert teams is larger for spectral accelerations at low frequencies than they are at higher frequencies. This is probably due in part to differences in the assessments of maximum magnitude as the larger earthquakes are more important contributors the hazard for low frequency ground motions that for high frequency ground motions.

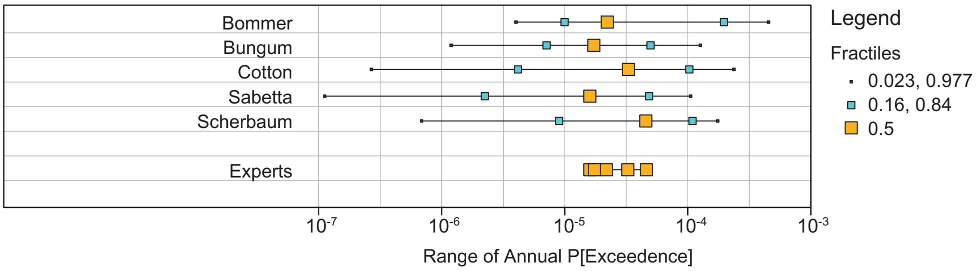

Fig.8-29: Sensitivity diagram showing the sensitivity of the rock hazard to the uncertainty in the median ground motion estimates of the five SP2 experts

The horizontal bars in the upper part of the figure connect the hazard values arising from the 0.028, 0.16 0.5, 0.84, and 0.978 fractiles in median ground motion estimates (see section 5.3.3.1). The 0.5 fractiles are repeated in the lowest row. Beznau, PGA = 0.3 g, combination of the SP2 models with the EG1b model.

Gösgen is the site with the highest degree of consistency among the mean estimates of the expert teams, whereas the other three sites show more or less the same expert-to-expert uncertainty (see Volume 2, Figures 2-8.2, 3-8.2, 4-8.2, and 5-8.2). The larger differences at the two northern sites is likely due to differences in how the four SP1 teams modelled the transition from the Alpine Foreland to Southern Germany and the larger differences at the Mühleberg site are likely due to differences in how the expert teams modelled seismic sources near Fribourg.

Figure 8-33 compares the mean rock hazard curves obtained by the five SP2 experts for PGA at Beznau (using the seismic source models of all four SP1 expert teams). The expert-to-expert uncertainty is larger than in SP1 but smaller than the within-expert uncertainties. Figure 8-29 further illustrates this point. It shows the sensitivity of the rock hazard to the epistemic uncertainty in the median ground motion estimates of the five individual SP2 expert models as compared to their five median estimates, for Beznau, and a PGA of 0.3 g [17]. Not surprisingly, this confirms in the hazard space what had already been observed in the ground motion space (see e.g. Fig. 5-20).

This demonstrates that the larger uncertainties resulting from the SP2 models are not due to different interpretations by the experts. There is agreement between the five SP2 experts that there is large uncertainty in the rock ground motion in Switzerland given the information available during the PEGASOS Project. Figure 8-34 shows the sensitivity of the total soil hazard at surface to the site effects charcterisation (SP3) experts and their models, for PGA at Beznau. These results, and the results of Volume 2 (section 2.8), show a good degree of consistency among the mean estimates. At low frequencies, this consistency is also high until a ground motion of 1 to 2 g is reached, above which it decreases due to the differences in the upper limit soil ground motion models (see e.g. Volume 2, Figure 2-8.5). For the example shown in Figure 8-34, Pecker's model leads to the largest soil ground motions at higher probabilities, but it leads to the lowest soil ground motions at low probabilities. This reflects that Pecker's model had the smallest maximum PGA values (see chapter 7) of all of the SP3 experts.

8.2.4 Sensitivity to Depth Levels

The sensitivity of the PGA hazard to the depth of embedment is shown on Figure 8-35 for Leibstadt and on Figure 8-36 for Mühleberg.

For the Leibstadt site, the soil ground motion is similar at all three embedment levels. The reason for this lack of sensitivity to embedment depth occurs because the soil profile at Leibstadt has a depth of 90 m to rock and it has a large velocity contrast at 50 m depth. The gradient in the top 10 m is not steep. Therefore, the amplification due to the top 10 m of the soil profile is small compared to the amplification of the total profile. The non-linearity of the site response can also been seen in Figure 8-35. At higher probability levels, there is about a factor of 2 amplification of the soil motion relative to the input rock motion, but this amplification is reduced at lower probability levels (higher ground motion levels). At low probability levels, the soil PGA is only 10 – 20 % larger than the rock motion.

For the Mühleberg site, there is a large effect of embedment depth on the hazard. This occurs because the soil profile at Mühleberg has a strong gradient in the top 10 m with a high velocity contrast at 9 m depth. Although the depth to rock (V_s = 2000 m/s) is greater than 200 m, the top 9 m has a strong effect on the amplification due to the layer at 9 m depth. For embedment depths greater than 9 m, the amplification from this layer is removed. In contrast to the Leibstadt site, the non-linearity at Mühleberg is not strong. The amplification at higher probability levels is about a factor of 2. This amplification remains nearly constant at lower probability levels. The reduction in the amplification at probability levels of 1E-6 or less reflect the maximum ground motion effects.

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[17] This sensitivity is shown for the combination of the five SP2 expert models with the EG1b model, representative of the SP1 models. The epistemic uncertainty has been removed from the EG1b model.

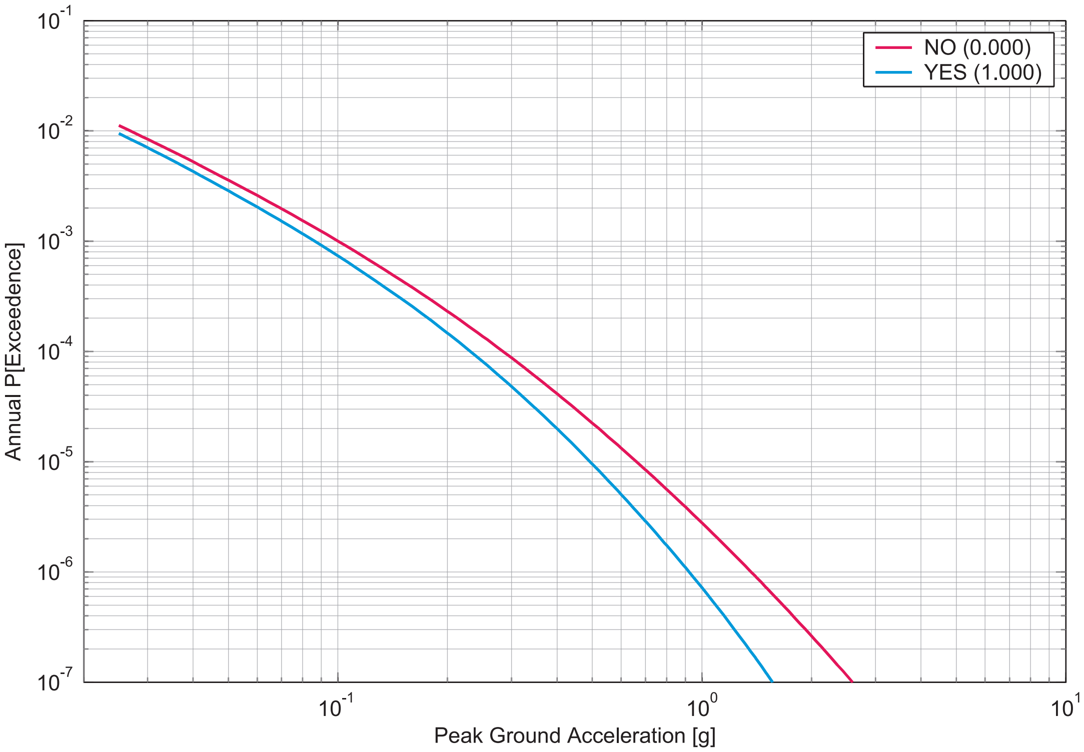

Fig. 8-30: Beznau, horizontal component, rock, surface, mean hazard with and without upper limit GM / upper tail truncation, PGA

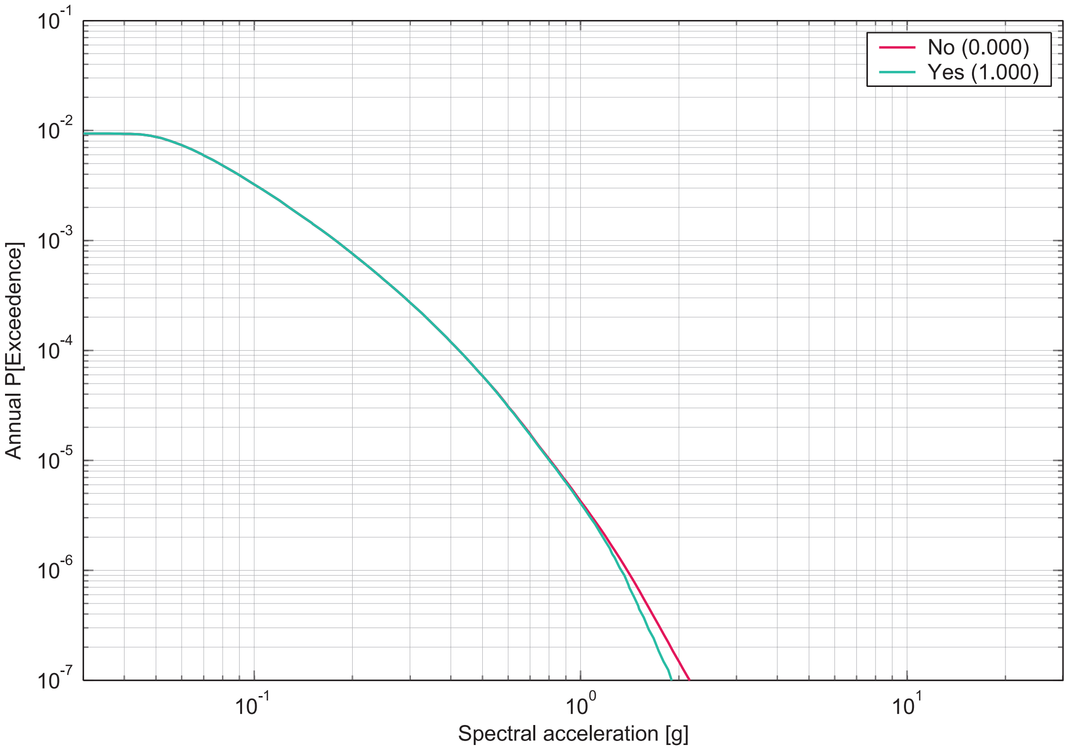

Fig. 8-31: Beznau, horizontal component, soil, surface, mean hazard with and without SP3 upper limit GM truncation, PGA

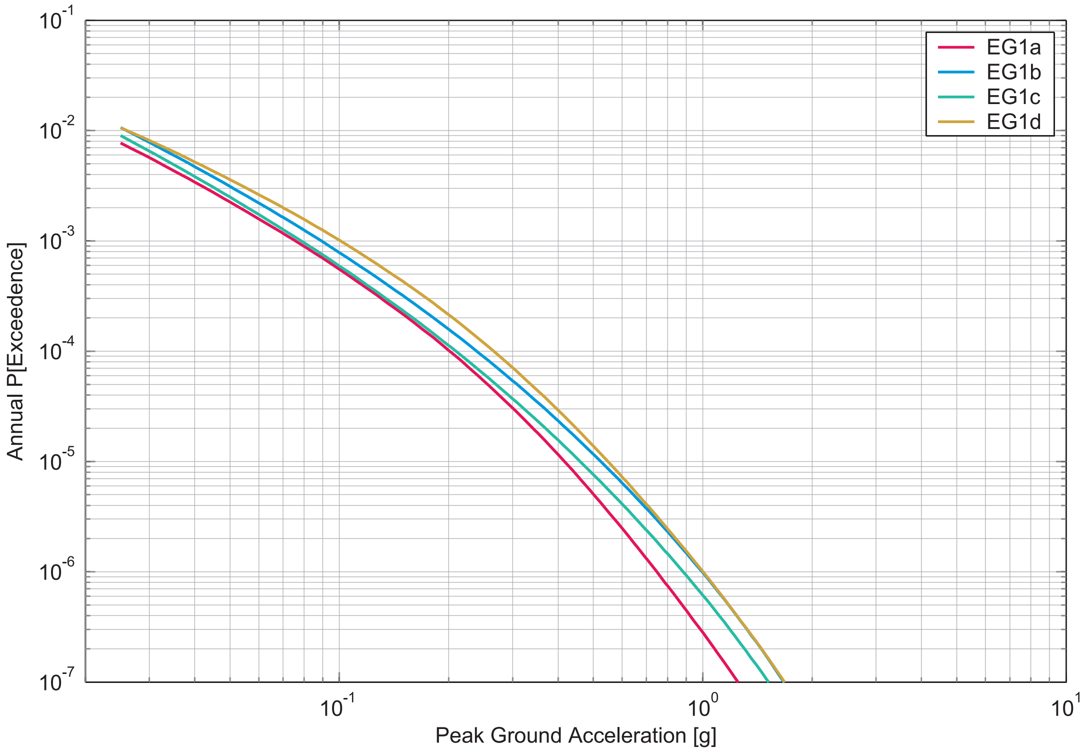

Fig. 8-32: Beznau, horizontal component, rock, surface, mean hazard of the four SP1 expert groups, PGA

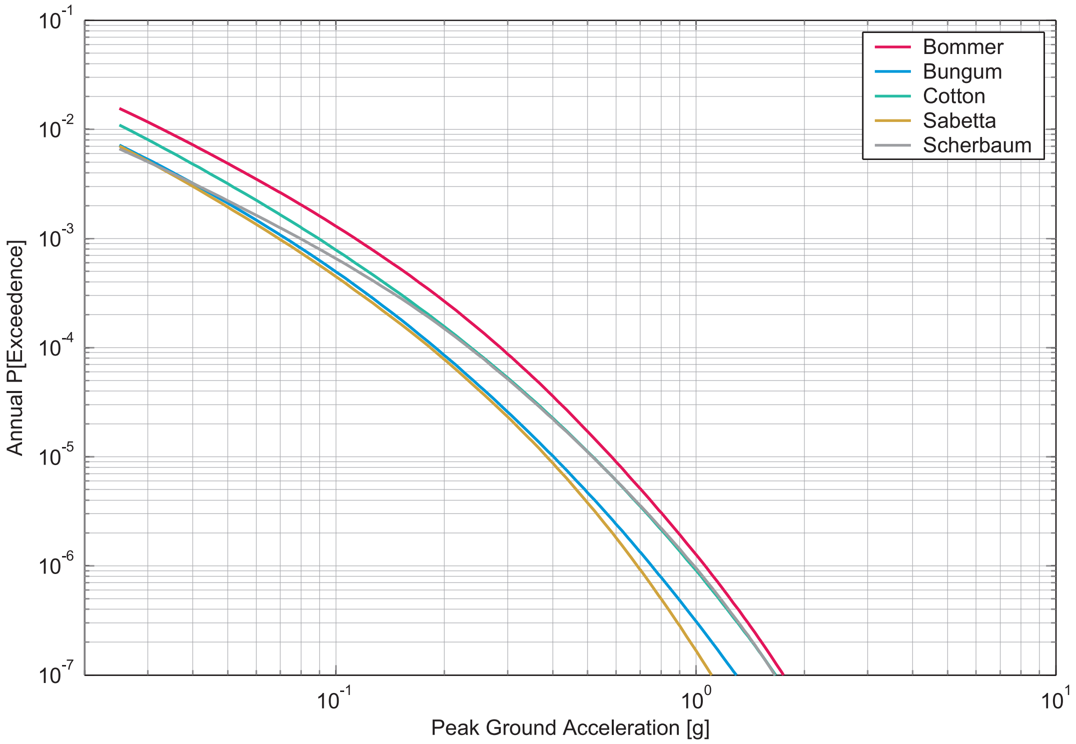

Fig. 8-33: Beznau, horizontal component, rock, surface, mean hazard of the five SP2 experts, PGA

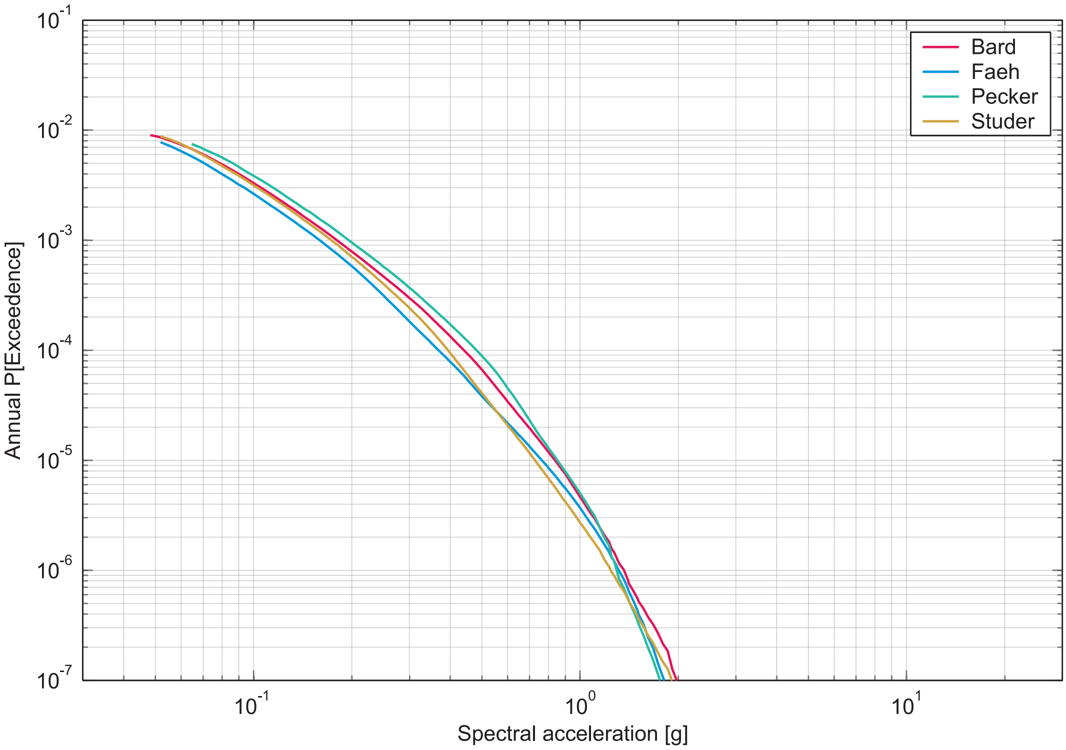

Fig. 8-34: Beznau, horizontal component, soil, surface, mean hazard of the four SP3 experts, PGA

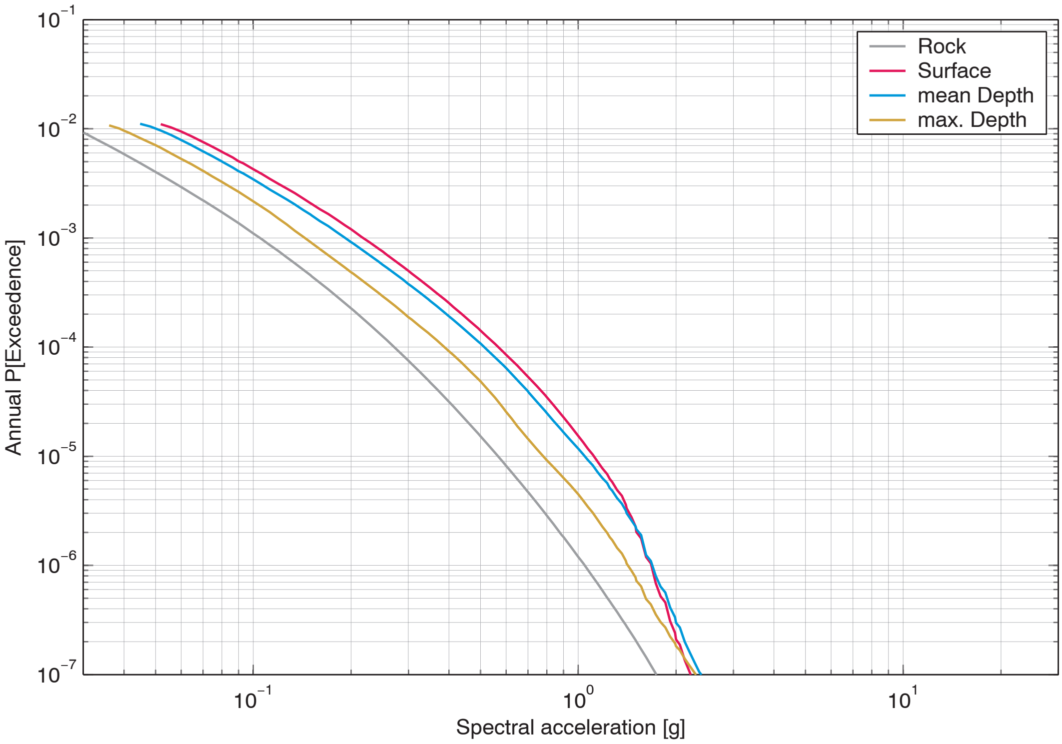

Fig. 8-35: Leibstadt, horizontal component, soil, surface, mean hazard of the four depth levels, PGA

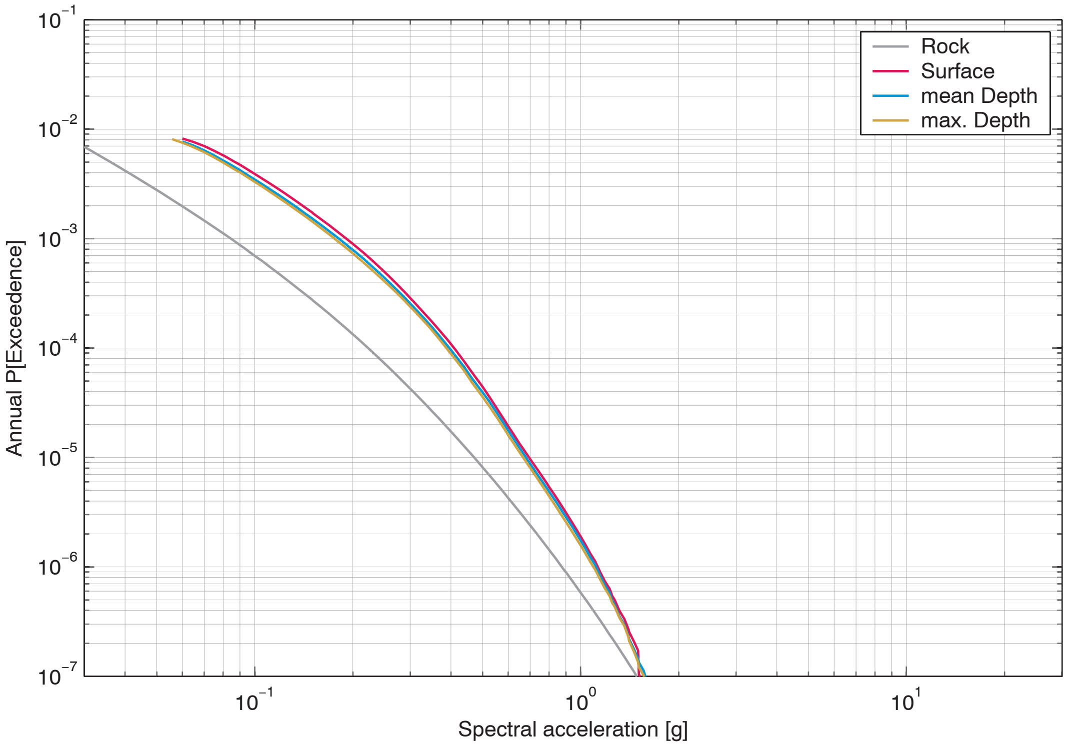

Fig. 8-36: Mühleberg, horizontal component, soil, surface, mean hazard of the four depth levels, PGA

8.3 Contributions to Total Epistemic Uncertainties

Figures 8-37 and 8-38 summarise the SP1 contributions to the uncertainty in rock hazard for 1 Hz spectral acceleration and a ground motion amplitude of 0.15 g, as well as for PGA and 1 g, using the results for Beznau. The first row shows the epistemic uncertainty associated with the differences between the mean hazard for the SP1 expert groups. Below this, all the global tree variables are shown for each of the four SP1 models. The total epistemic uncertainty (including both SP1 and SP2) is shown at the bottom of the figure. The points shown on the right-hand side indicate the mean hazard derived from each individual group of branches, associated with the values of that variable, while their colour reflects the weights assigned to these values. For example, the first row in Figure 8-37 can be interpreted as a vertical cross-section in Figure 8-32 (at 1 g). In addition to the global tree variables of the four SP1 expert groups, two source variables (M_{max} and recurrence) for the two sources with the highest contribution to hazard for each team are also shown.

In Figures 8-37 and 8-38, the mean hazard values of the individual SP1 expert groups have been renormalised to the overall mean rock hazard. Logic tree variables that SP4 trimmed for that site appear without bullets (e.g. EG1b's SWAB_ALB_ZON – alternative models for the Swabian Alps source zone). When sorting and grouping the logic tree branches to compute sensitivity to a logic tree variable, branches often have to be grouped into an additional category that is not linked to the values of this variable (e.g. the smoothing kernel parameters for branch tips not associated with spatial smoothing). This category is not shown as bullets in these figures since it is not relevant to the investigated variable; the weights of the other categories are renormalised to sum to unity. The absence of this group of branches (and the fact that even dominating sources may not be active in all zoning scenarios) explains the fact that, for a few variables, all the bullets post on the same side of the overall mean. It should be noted that a variable with two equally weighted branches at a certain distance from each other may contribute more to the total epistemic uncertainty that another variable with a larger number of more distant branches but with lower weights on the far sides.

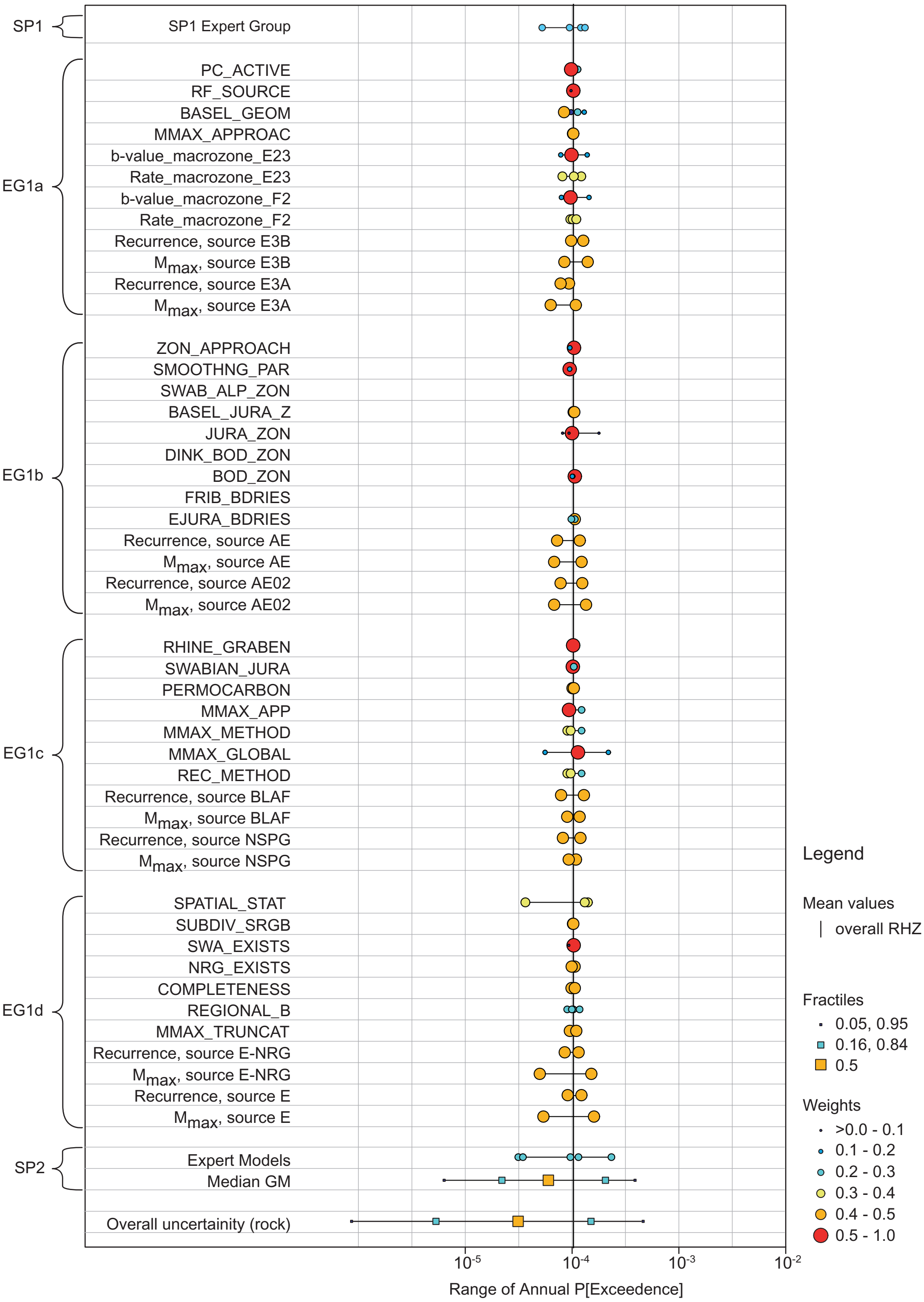

Fig. 8-37: SP1 contributions to the uncertainty in rock hazard for 1 Hz spectral acceleration and a ground motion amplitude of 0.15 g; Beznau site

Figures 8-37 and 8-38 show that the largest contribution from the SP1 models to the rock hazard uncertainty is the maximum magnitude. For EG1d, the variable SPATIAL_ STAT (alternative degrees of spatial stationarity/seismicity smoothing – see section 4.4.2 and Figure 4-26) also has a large relative contribution to the rock hazard uncertainty. The comparison of the contributions of the SP1 models to the total rock hazard uncertainty shown at the bottom of these figures indicates that the epistemic uncertainty in the ground motion models has a much larger contribution to the rock hazard uncertainty than does the uncertainty in the SP1 models. This is a typical result in PSHA studies that include a full treatment of epistemic uncertainty.

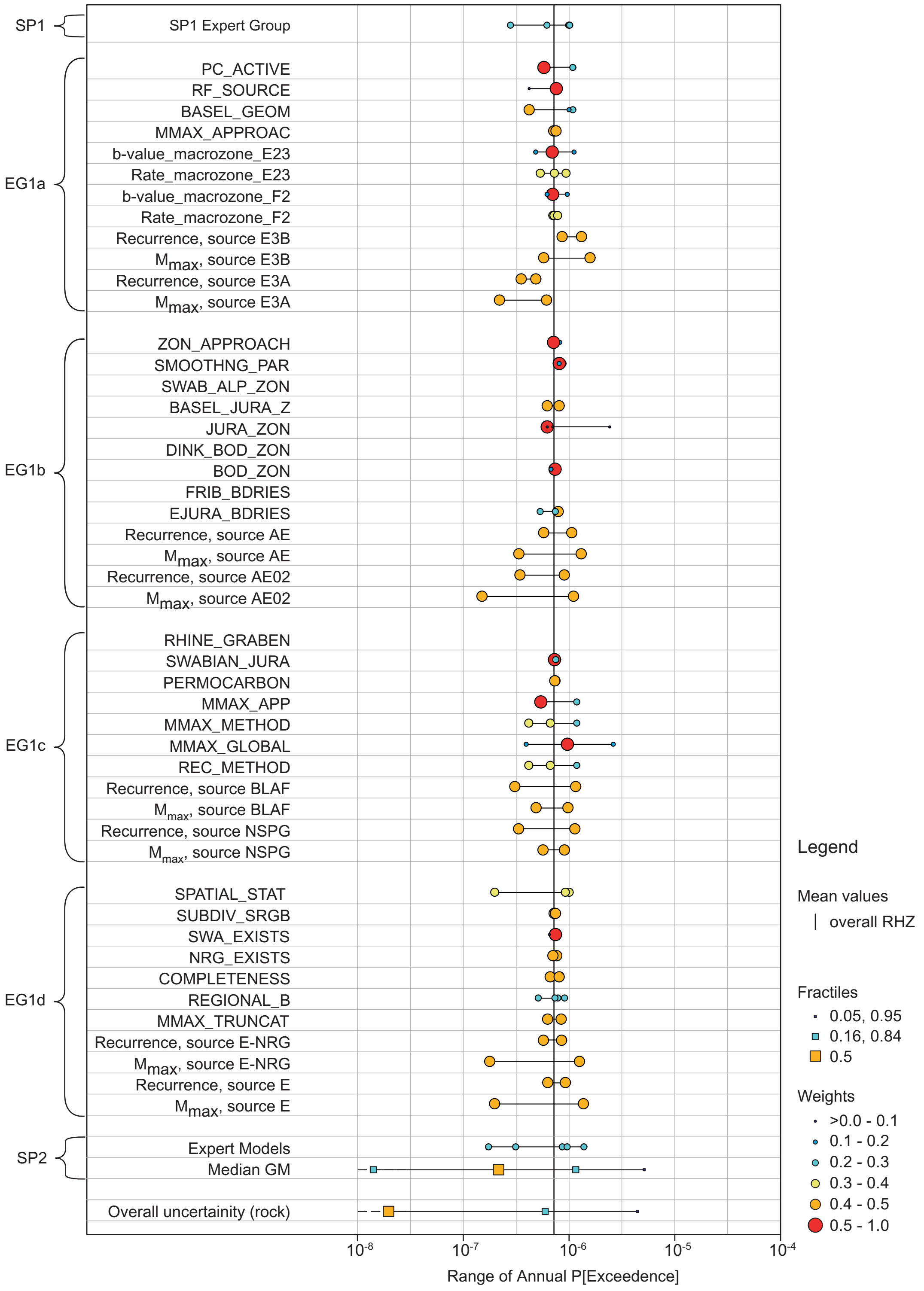

Fig. 8-38: SP1 contributions to the uncertainty in rock hazard for PGA and a ground motion amplitude of 1 g; Beznau site

Figures 8-39 and 8-40 show similar sensitivity histograms for SP2 based on similar ground motion parameters (1 Hz with 0.15 g and PGA with 1 g). For the sake of economy, only one set of source models (EG1b) was used for the rock hazard computations. In these figures, the epistemic uncertainty in the SP2 models is not shown for the physical branches in the logic tree, but rather for the branches of the composite model (median ground motion, aleatory variability of the ground motion and maximum ground motions). Squares associated with composite model parameters represent the 0.05, 0.16, 0.50, 0.84 and 0.95 fractiles for the median ground motion and its aleatory variability, rather than the direct weights on the branches as was the case for SP1.

The SP2 sensitivity histograms illustrate that the highest contribution to the total uncertainty arises from the median ground motion models for all five SP2 experts. This large uncertainty from the median ground motion models is an expected result and reflects the key issue that faced the SP2 experts: do the low ground motions observed for small magnitude earthquakes in Switzerland imply that the ground motions from large magnitude earthquakes in Switzerland will also be lower than in other parts of Europe? Until progress is made on this issue, there will remain a large epistemic uncertainty in the rock motions which will dominate the epistemic uncertainty in the rock hazard.

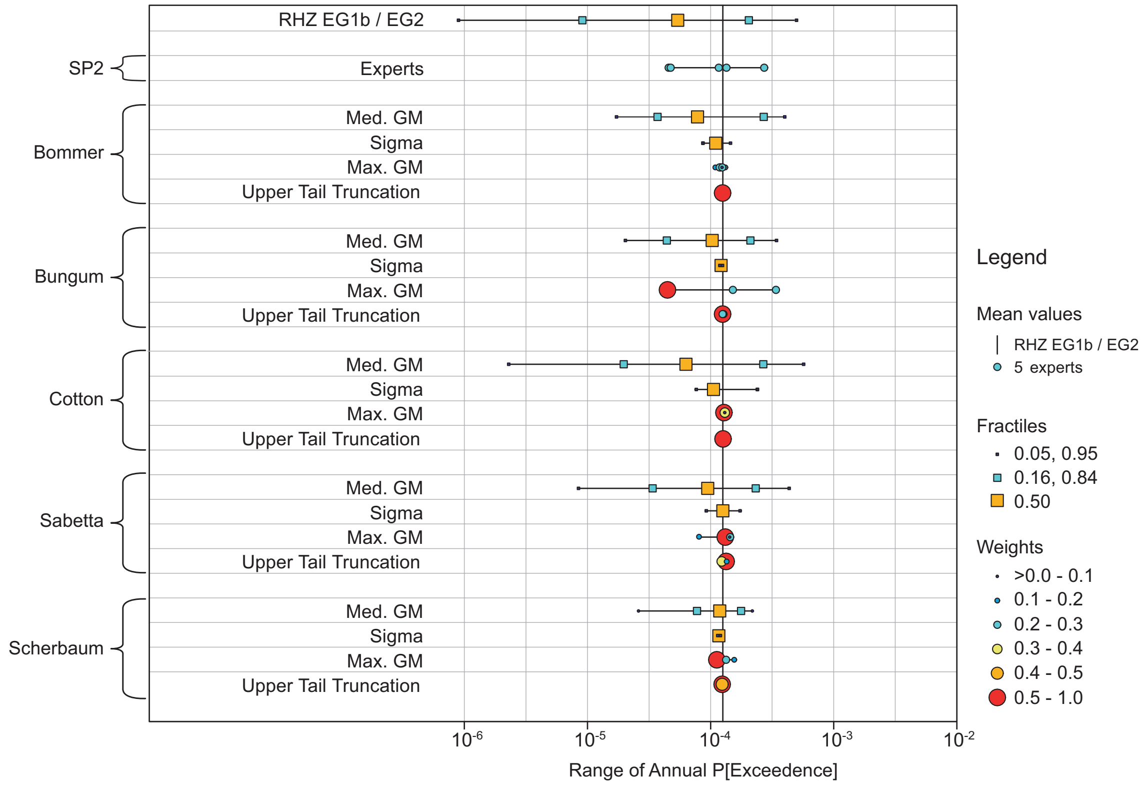

Fig. 8-39: SP2 contributions to the uncertainty in rock hazard[18] for 1 Hz spectral acceleration and a ground motion amplitude of 0.15 g; Beznau site[19]

Figures 8-41 and 8-42 show soil hazard sensitivity histograms for Beznau and again the same two ground motion parameters (1 Hz with 0.15 g and PGA with 1 g). Note that the ground motion amplitudes now refer to the soil hazard. The accelerations of the underlying rock hazard

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[18] Only one set of source models (EG1b) has been used to compute the rock hazard (RHZ) in this figure. The results are therefore not directly comparable to Fig. 8-37.

[19] Only the median and the 5th and 95th fractiles are shown for the SIGMA variables. This is a consequence of the SP2 tree trimming that decreased the symmetry of the median-sigma distribution (see *Toro 2004b, TP4-TN-0395*). The same applies to Fig. 8-40.

are thus lower: approximately 0.09 g for the '1Hz, 0.15g' case and approximately 0.74g for the 'PGA, 1g' case. As was the case for SP2, the epistemic uncertainty in the SP3 models is not shown for the physical branches in the logic tree, but rather for the branches of the composite model (median amplification, aleatory variability of the amplification and maximum soil ground motions).

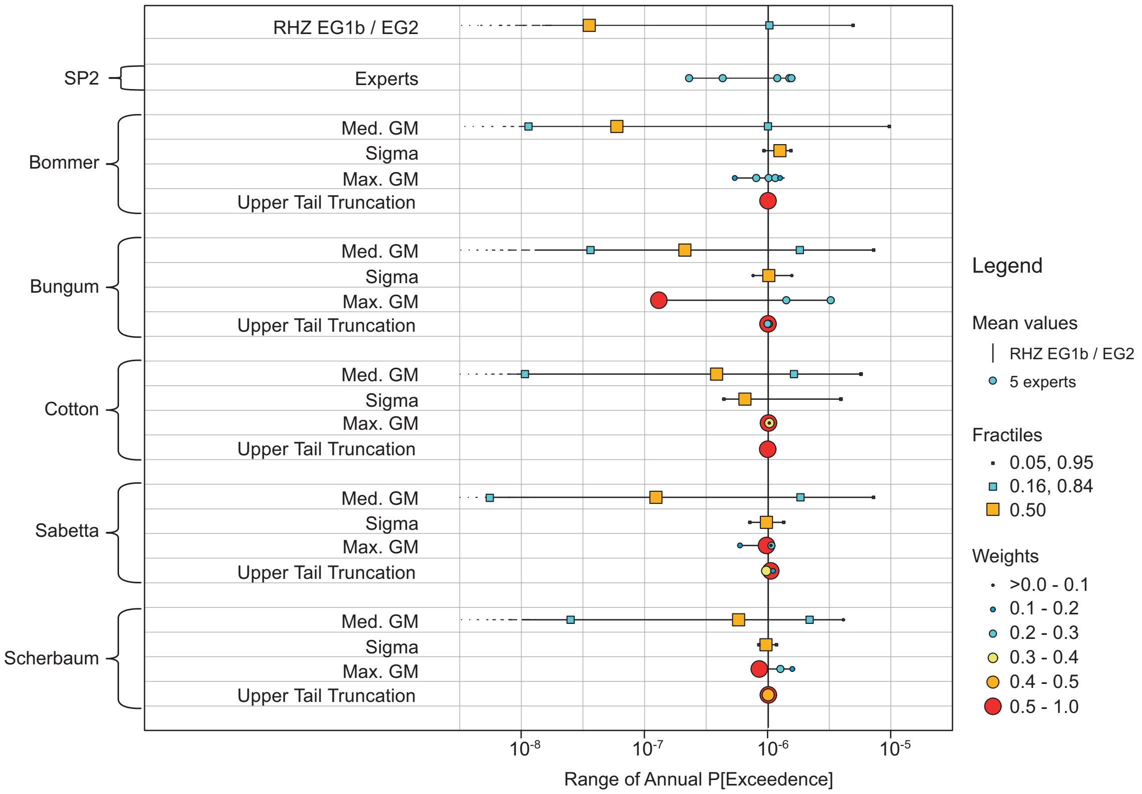

Fig. 8-40: SP2 contributions to the uncertainty in rock hazard[20] for PGA and a ground motion amplitude of 1 g; Beznau site

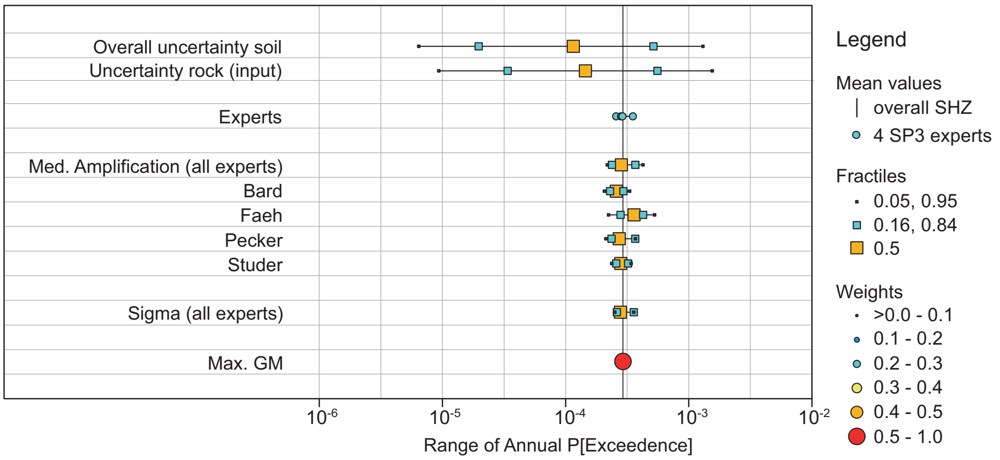

Fig. 8-41: SP3 contributions to the uncertainty in soil hazard for 1 Hz spectral acceleration and a ground motion amplitude of 0.15 g; Beznau site

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[20] Only one set of source models (EG1b) has been used to compute the rock hazard (RHZ) in this figure. The results are therefore not directly comparable to Fig. 8-38.

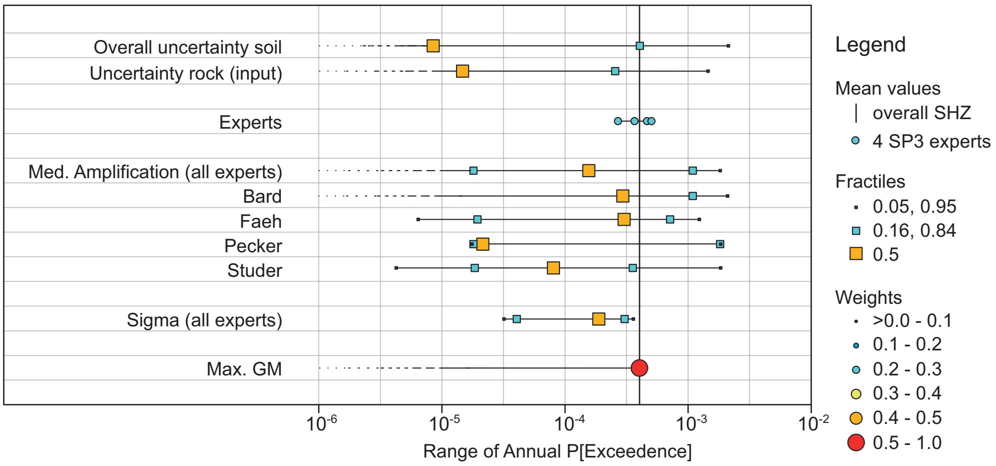

Fig. 8-42: SP3 contributions to the uncertainty in soil hazard for PGA and a ground motion amplitude of 1 g; Beznau site

The line at the bottom of Figures 8-41 and 8-42 shows the uncertainty arising from the various maximum ground motion truncation parameters. This uncertainty is zero in the '1Hz, 0.15g' case, since the maximum ground motion spectra do not yet cut into the results. In the 'PGA, 1g' case, 4.3% of the results are truncated, as indicated by a horizontal line towards low exceedence probabilities.

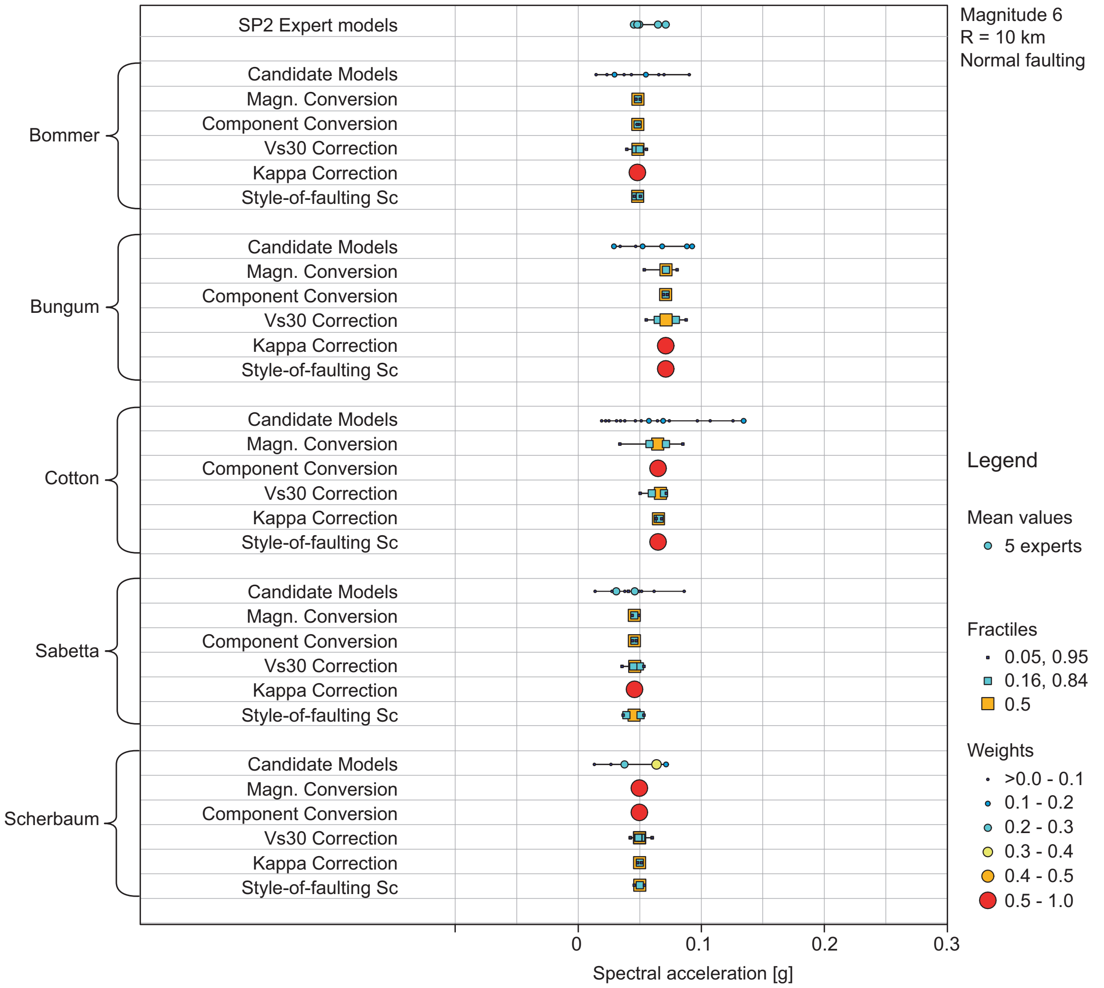

Fig. 8-43: Contributions of the SP2 logic tree branches to the median ground motion by expert for 1 Hz spectral acceleration, M = 6, R =10 km and normal style of faulting

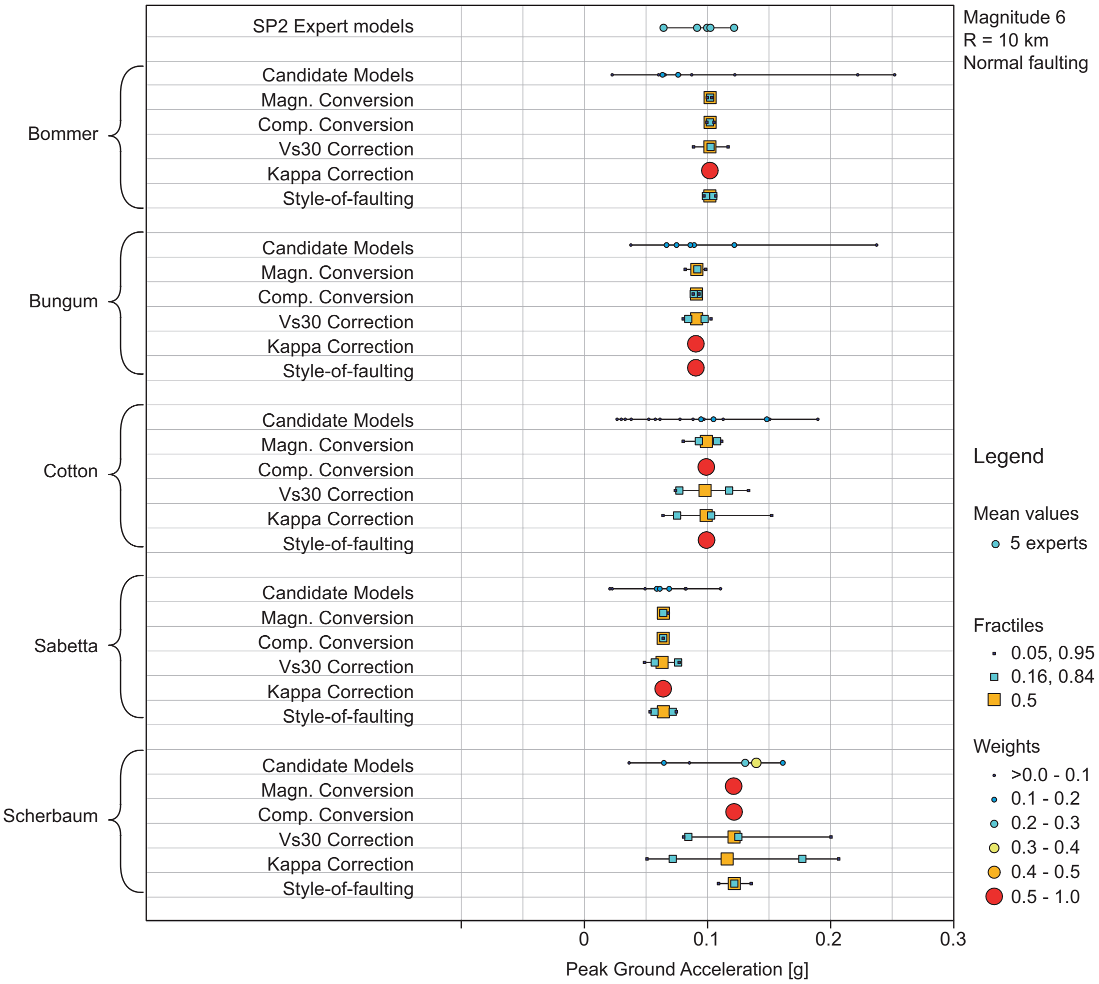

Fig. 8-44: Contributions of the SP2 logic tree branches to the median ground motion by expert for PGA and a ground motion amplitude of 1 g. Magnitude 6, distance of 10 km and normal style of faulting

The soil hazard sensitivity figures show that, for low amplitudes (Figure 8-41), the most significant contribution to the overall uncertainty in SHZ comes from the rock hazard. The uncertainty of the rock hazard is as large as two orders of magnitude, whereas the SP3 contributions make up less than 0.5 order of magnitude. However, this pattern is quite different for high accelerations ('PGA, 1g' case in Figure 8-42). At short periods and high ground motion levels, the SP3 models are significant contributors to the overall uncertainty in the soil hazard, although the uncertainty from SP3 is still lower than that from the rock hazard.

A disadvantage of using the composite model approach is that it obscures the physical branches of the logic tree in the hazard uncertainty sensitivity study. We can gain insights into the controlling physical branches by showing the contributions to the median ground motion uncertainty and median site amplification uncertainty for the controlling earthquakes. Here, we have used a magnitude 6 normal faulting earthquake at a distance of 10 km. For the SP2 sensitivity, we examine the ground motion models uncertainty for 1 Hz spectral acceleration and for PGA. For SP3, we examine the amplification factor models uncertainty for 5 Hz (resonance frequency at Beznau) spectral acceleration at Beznau and Leibstadt.

Figure 8-43 and 8-44 show the contributions of the SP2 physical branches to the median ground motion. In the 1 Hz case (Figure 8-43), the candidate models are the dominant contributors to uncertainty, with some contributions from the V_{s30} correction. In the PGA case (Figure 8-44), the candidate models are still dominant, but the V_{s30} and kappa corrections are also large contributors for Scherbaum and Cotton. These two experts relied more heavily on these corrections in their models.

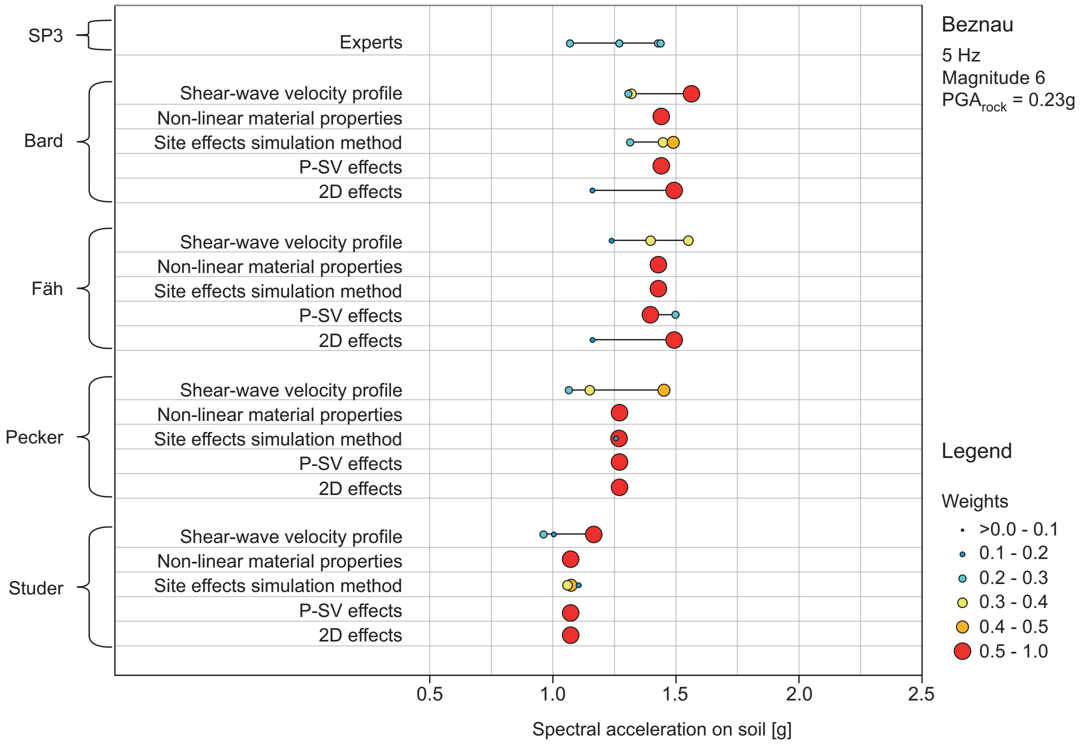

Fig. 8-45: Contribution of the SP3 logic tree branches to the median amplification at 5 Hz; for magnitude 6 and PGA$_{rock}$ = 0.23g; Beznau site

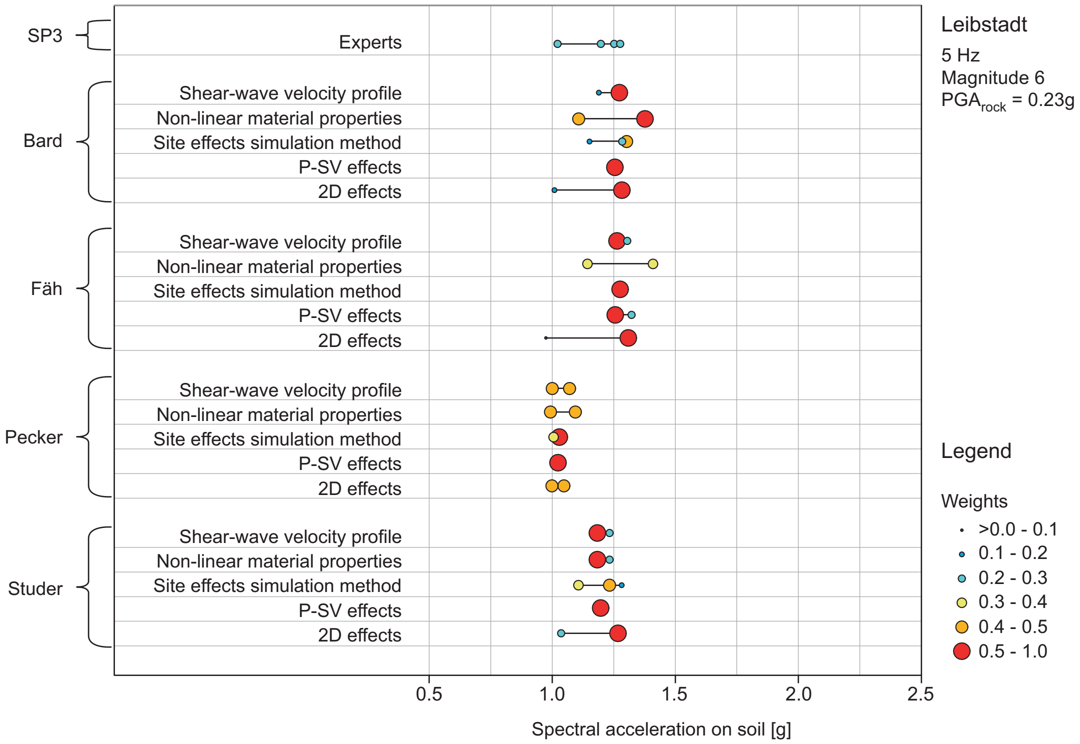

Fig. 8-46: Contribution of the SP3 logic tree branches to the median amplification at 5 Hz; for magnitude 6 and PGA$_{rock}$ = 0.23g; Leibstadt site

In SP3 (Figures 8-45 and 8-46), the major sources of uncertainty are the shear wave velocity profiles at Beznau and the non-linear material properties at Leibstadt for all four SP3 experts. These two sources of uncertainty could be reduced by additional geotechnical investigations. Other sources of uncertainty, e.g. the consideration of two-dimensional effects, vary significantly and depend on the expert's evalation of the importance of the effects. In Bard's and Fäh's models, the uncertainty due to 2-D effects is generally a significant contributor to the overall uncertainty, but it is not a significant contributor in the models of Pecker and Studer, except in the case of Leibstadt for Studer.

Conclusions

The expert-to-expert variability in seismic rock hazard is smaller for SP1 and SP3 than for SP2. All are small compared to the total uncertainty. This means that the within-expert variability exceeds the expert-to-expert variability, which indicates that the individual experts (or expert teams) have satisfactorily captured the range of uncertainty in the informed technical community. It also demonstrates that the computed hazard is not sensitive to the selection of the experts, implying that the results are robust and similar results would be expected if different experts had been selected.

8.4 Summary and Discussion

8.4.1 Principal Contributors to Uncertainty in Hazard

The uncertainty in the rock ground motion models contributes more to the rock hazard uncertainty than the uncertainty in the source models. The large uncertainty in rock ground-motion amplitudes illustrated by Figure 5-20, is a feature of all five SP2 expert models, and is primarily due to the wide range of candidate ground motion models (European, eastern US, western US, and Japanese crustal) which the SP2 experts considered to be potentially applicable to Switzerland. This range of models reflects the tectonic environment in Switzerland which could be interpreted as a stable continental region or as an active plate boundary. The limited Swiss strong motion-data are not sufficient to narrow down the set of candidate models. (To a lesser degree the same issue affected the maximum magnitude interpretations of the SP1 experts – should the study region be considered part of stable continental crust or part of a zone of transition to plate boundary conditions).

A frequently encountered dilemma in regions with little ground motion data is how to reconcile local data (and the models derived from these data) with the data, models and insights obtained from other regions where more data are available. It is tempting to argue that local data are more relevant and should be given much more weight; on the other hand one should be aware of at least two potential problems. The first is that the data are from much smaller magnitude earthquakes than those of engineering relevance. The second is purely statistical: small sample sizes imply a high statistical uncertainty.

The SP2 experts were well aware of this issue, and gave it considerable thought when they formulated their interpretations and models. They concluded that there was not a strong technical basis for ground motions in Switzerland being significantly smaller than in other areas in Europe. The ground motion data from the M 4.8 St. Dié earthquake supports this evaluation; these ground motions are significantly higher than the predictions by Swiss-specific models developed from weak motion data.

In summary, the most important contributor to uncertainty in seismic hazard is uncertainty in the rock ground motions, followed by uncertainty in site response and then uncertainty in source characterization. This situation is common of hazard results in regions with limited strong-motion data. Yucca Mountain is one example of a site with ground motion uncertainty contributing most to the uncertainty in seismic hazard (CRWMS M&O. 1998).

8.4.2 Comparison with Previous Hazard Studies for the Swiss NPPs

The resulting hazard curves from the PEGASOS study lead to a much larger hazard than previous site-specific studies at the four sites (Basler & Hofmann 1984 / 1989 / 1991 / 1996). For example, the PGA corresponding to the median hazard at 10^{-4} annual probability of exceedence range from 1.7 to 2.7 times larger. This increase was to be expected because the previous hazard studies did not include the aleatory variability of the ground motion in the hazard calculation in the way considered to be correct in modern studies. These studies were conducted between 1984 and 1996. In the 1970s and early 1980s, it was common practice to conduct PSHA studies without including the ground motion variability. This situation was partly a consequence of this variability being ignored in Cornell's original paper (Cornell, 1968) that developed the fundamental approach basis for PSHA. In the US, the national hazard maps developed by the USGS in 1982 did not include the ground motion variability either.

A later publication by Cornell (Cornell, 1971) includes the effect of aleatory variability in ground motions and calls this effect important. By the late 1970s and the 1980s, this key missing component in the PSHA method was widely recognised and, by the 1990s, the standard practice was to include the effect of ground motion variability in the computation of the hazard integral. In the USA, site-specific and generic seismic hazard studies for nuclear power plants performed in the 1980s included the effect of aleatory variability in ground motions (e.g. Pacific Gas and Electric Company 1988; Bernreuter et al. 1989; EPRI 1989). The national hazard maps, developed by the USGS since 1990, include ground motion variability and resulted in increased hazard as compared to the previous maps. The same is true in Europe, e.g. for the new seismic hazard map of metropolitan France, for which values of the aleatory variability (σ) between 0.58 and 0.67 have been used (Martin et al. 2002).

Today, it is no longer accepted practice not to explicitly include the aleatory variability of the ground motion in a PSHA or to treat this variability as epistemic.

In the previous Swiss site-specific studies, PGA hazard curves were obtained by considering 36 combinations of input parameters ('element combinations'). This 36 end-branch logic tree resulted from 2 source models, 2 recurrence relationships, 3 upper bound magnitudes and 3 GM attenuation relationships. The ground motion variability was not included in the calculation of the hazard integrals associated with the 36 end-branches, but the authors did include a discussion of the aleatory variability of the ground motion attenuation relations. Aleatory variability in the ground motion was treated as an epistemic uncertainty and the method chosen to introduce it in the results was to subdivide each one of the 36 basic hazard curves into three hazard curves; the first two with their amplitudes scaled by $\exp[\pm\sigma]$[21] and 25% of the original weight and the third left unscaled with 50% of the original weight[22]. This approach, however, only broadens the distribution of the hazard, while it leaves the median virtually unchanged. It leads to a non-conservative result for the median hazard and has no effect towards compensating for the non-inclusion of the aleatory ground motion variability in the hazard

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[21] In the application of their approach, the authors of the previous studies made an error in their calculations. They noted that the standard deviation of the peak acceleration is about 0.7 natural log units (Basler & Hofmann 1984). They further noted that the alternative attenuation relations and source parameters used resulted in a standard deviation on the median PGA of about 0.2 natural log units. Their conclusion was that the 0.7 value included both epistemic uncertainty and aleatory variability and they therefore decided to remove the median PGA epistemic uncertainty contribution contained in the 0.7 value. This they tried to achieve by subtracting the epistemic standard deviation of 0.2 from the total standard deviation of 0.7, resulting in an aleatory variability of about 0.5 (the actual value used was 0.47). Because these two uncertainties are independent, the correct approach would have been to subtract the variances (squares of the standard deviations). Subtracting the variance (i.e. 0.7^2 - $0.2^2)^{1/2}$ would have reduced the total of 0.7 to an aleatory part of 0.67 (i.e. a very small reduction). The proper use of this corrected σ value in the calculation of the hazard integrals leads to a significant increase of the median hazard (see Figures 8-47 and 8-48).

[22] This approach is equivalent to transforming each of the original attenuation equations into three separate equations such that the leading coefficients (c_1) of the new attenuation equations are equal to $c_{1,original}\pm\sigma$ and $c_{1,original}$. and the new weights are 25%, 25%, and 50% of the original weight, respectively.

integrals. The final median hazard results are still equivalent to the results that would have been obtained with zero ground motion variability ($\sigma = 0$).

It is well known that including the ground motion variability will greatly increase the hazard at low probability levels. To investigate this effect, the Basler & Hofmann (1984) calculations for Beznau were replicated, using the complete set of Basler & Hofmann (1984) input models. The first calculations were set up with a ground motion aleatory variability (σ) of 0. They provide a good match to the old results (within 10% in median amplitudes for a given exceedence probability), as shown in Figure 8-47. The next set of calculations was performed by using a σ value of 0.67 (see footnote). Median results from these calculations are shown in Figure 8-47, which also shows the PEGASOS rock and soil results for Beznau.

Figure 8-47 shows that if a σ value of 0.67 is used for the aleatory variability of the peak acceleration, the calculated median hazard is comparable to the corresponding median hazard from the PEGASOS results.

The SP2 experts assessed smaller values for the aleatory variability of the peak acceleration, as shown in Figure 5-22. A representative value for earthquakes in the M5-M7 range and at a distance of 10 km is 0.25 log base 10 units, which corresponds to 0.58 natural log units.

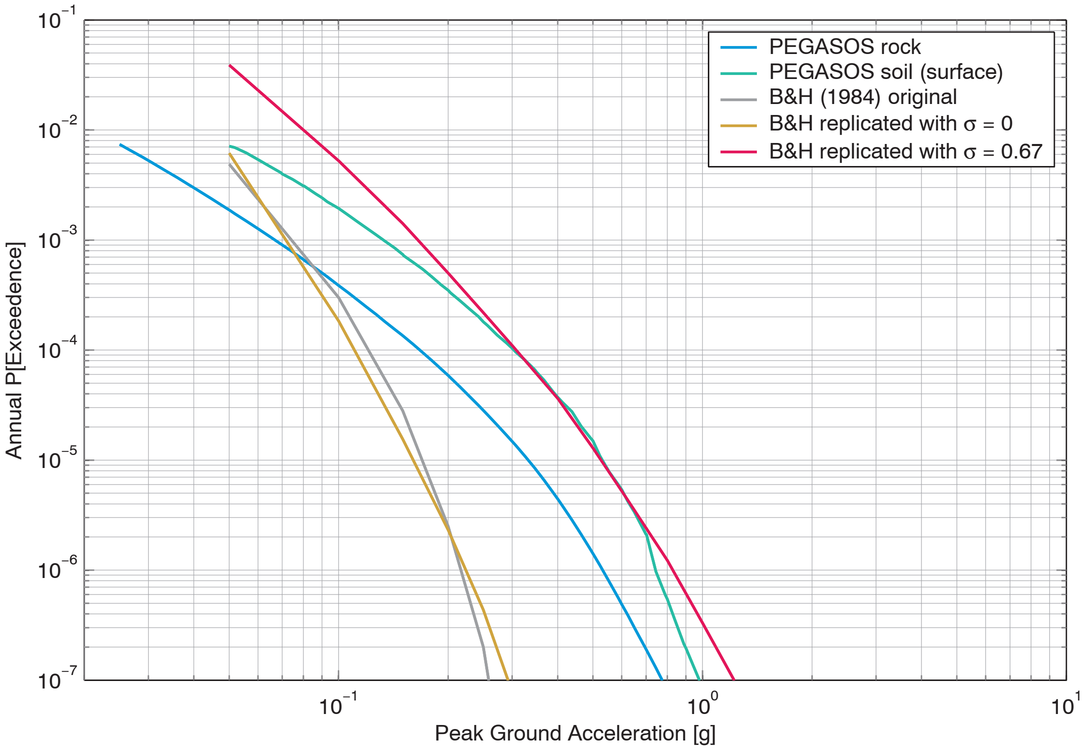

Fig.8-47: Effect of including the aleatory ground motion variability in the previous hazard studies for the Swiss NPP sites. The example shown is the median of the PGA hazard for Beznau (Basler & Hofmann 1984)

To produce this comparison, the 1984 Basler & Hofmann calculations were replicated, with the original input models, using σ values of 0 and 0.67 respectively. The results are plotted together with the corresponding PEGASOS soil and rock hazard curves.

Most of the previous studies used ground motion attenuation relations for generic site categories (e.g. soil, rock) and did not include site-specific soil response, as was done in the PEGASOS study. A notable exception is the 1996 Basler & Hofmann study for Leibstadt which did consider a soil effect. It was derived from SHAKE calculations for a 40-45 m layer of unconsolidated sediments, resulting in an estimated amplification factor of 1.4 for the median PGA at 10 m depth (Basler & Hofman 1996). This constant amplification factor was applied to the Beznau rock hazard, which was considered to be applicable also in Leibstadt due to the small spatial separation of only a few kilometres. The resulting median soil hazard curve is shown in Figure 8-48. Again the results were replicated by applying the constant soil amplification factor of 1.4; first to the $\sigma = 0$ and then to the $\sigma = 0.67$ median curves of the Beznau site. A comparison with the corresponding median rock and soil hazard of this study in Figure 48 shows that the PEGASOS soil results are actually significantly lower than the $\sigma = 0.67$ corrected results of Basler & Hofmann (1996).

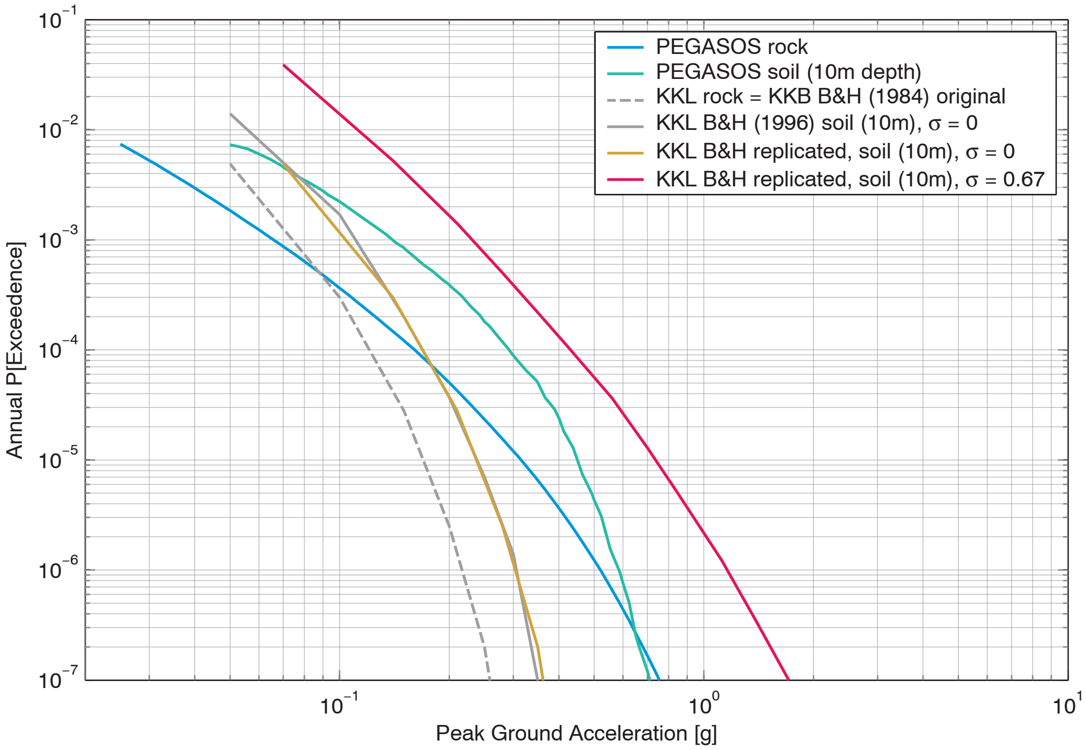

Fig.8-48: Example of a previous Swiss hazard study with site-specific soil response. The example is the median of the PGA hazard for Leibstadt at 10 m depth (Basler & Hofmann 1996)

The 1996 Basler & Hofmann results for Leibstadt were obtained by multiplying the Beznau (rock) PGA amplitudes with a constant soil amplification factor of 1.4. Curves for $\sigma = 0$ and $\sigma = 0.67$ are compared with the corresponding PEGASOS soil results for the depth level -10 m.

On the basis of these comparisons, one must conclude that the principal cause of the differences between the PEGASOS results and previous site-specific study results is the fact that previous studies did not properly include the ground motion aleatory variability in the hazard calculations. Although the above results were obtained for Beznau and Leibstadt only, this conclusion also applies at the other two sites. Even if most of the previous studies did not include site-specific soil response, the resulting (corrected) hazard results are very similar to the PEGASOS soil results. The inclusion of the ground motion aleatory variability alone is sufficient to explain the apparent large differences in the results.

8.4.3 Hazard Levels and Uncertainty Ranges

The PEGASOS hazard levels are similar to those that are found for other areas with low to moderate seismic activity. For example, the peak rock accelerations corresponding to a mean hazard of 10^{-4} at the four Swiss NPP sites range from 0.23 – 0.27 g, as compared to peak accelerations for hard rock (~3000 m/s) of 0.1 – 0.4 g for much of the eastern US (excluding the New Madrid and Charleston regions). The range of peak accelerations in Fig. 8-49 was obtained from the rock hazard curves available on the United States Geological Survey's National Seismic Hazard Mapping Project web site. The published data were for firm rock conditions (760 m/s) and were adjusted to hard rock conditions using the hard rock to firm rock site amplification factor of 1.52 employed by the USGS to create the hazard maps using hard rock attenuation relationships. These values are comparable to those obtained in the PEGASOS study and can be considered typical for stable continental regions with comparable levels of seismic activity.

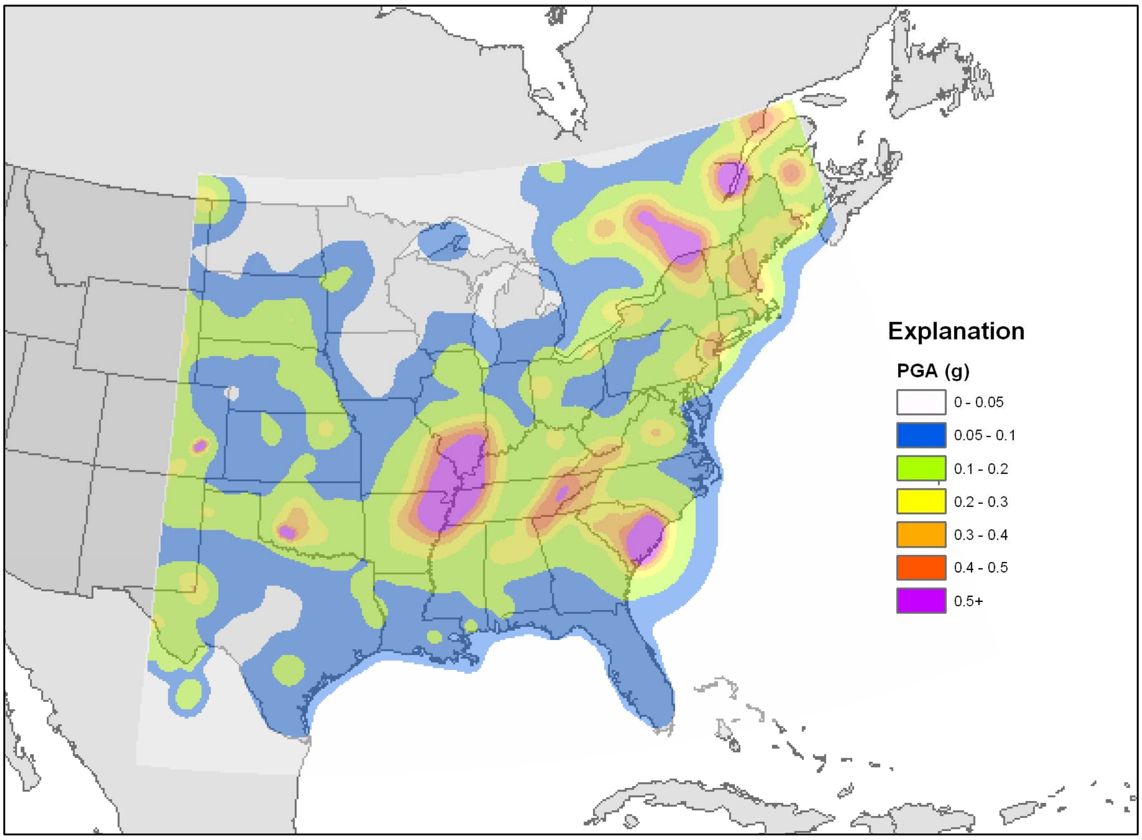

Fig.8-49 Contours of peak ground acceleration on hard rock in the central and eastern United States for an annual probability of exceedence of 10^{-4}

The results were obtained from the USGS National Seismic Hazard Mapping Project web site (http://eqhazmaps.usgs.gov), output file USPGADEC.HAZ. The tabulated hazard curves were converted from firm rock (V_S = 760 m / sec) to hard rock (V_s ~ 3000 m/sec) by dividing the ground motion amplitudes by the amplifycation factor of 1.52.

For all four sites, the mean hazard curve is near the median hazard at low ground motion levels and it is close to the 85th fractile for probability levels of 1E-5 to 1E-6. This increase in the fractile corresponding to the mean hazard with decreasing probability level is common in hazard. It reflects the increasing skewness of the hazard distribution as the ground motion level increases. The size of the uncertainty in the rock hazard is also fairly typical for regions with significant ground motion model uncertainty. For example, the 16th to 84th fractile range of the PGA hazard on rock at a mean probability level of 1E-4 corresponds to a factor of 20. For comparison, the 15th to 85th fractile from the PSHA study for the proposed US nuclear waste repository at Yucca Mountain, Nevada, corresponds to a factor of 30. Yucca Mountain lies in a transition region between California and the Basin and Range interior of the western United States, and there is significant uncertainty in the characteristics of Basin and Range earthquake ground motions. In the central and eastern United States, where there is limited ground motion data but the tectonic environment is well known and extensive ground motion modelling studies have been conducted, the 16th to 84th fractile typically represents a factor of 5 to 10 in probability.

For the Beznau and Leibstadt sites, the range of the uncertainty in the soil PGA hazard at the 1E-4 probability level is smaller than the range from the rock PGA for the same probability level. This reduction of the PGA hazard uncertainty when the site response in incorporated is typical for sites with significant non-linear site response. The higher rock ground motions have smaller amplifications than the lower rock ground motions. This tends to reduce the range of the ground motions. In contrast, for Mühleberg, the uncertainty range for the soil hazard is similar to the uncertainty range for the rock hazard. This is expected since the site response for Mühleberg is close to linear until the maximum soil ground motions have a significant effect.

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TP1-ASW-0022	PLFBAD Youngs
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TP1-CAT-0003	Giardini, D.: PEGASOS Earthquake Catalogue v. 31.01.2002.
TP1-CAT-0004	Final PEGASOS Earthquake Catalogue v. 31.03.2002.
TP1-STR-0001	Geological / Tectonic Composite Layer with GTÜ350.
TP1-STR-0002	Geological / Tectonic Composite Layer with GTÜ500.
TP1-STR-0003	Fault layer.
TP1-STR-0004	Mohorovic Discontinuity.
TP1-STR-0005	Elevation GIS layer.
TP1-STR-0006	Reflection Seismic Lines layer.
TP1-STR-0007	Topography Layer.
TP1-STR-0008	Map of Base Mesozoic – Nagra OPA 3-D area.
TP1-STR-0009	Map of Base Mesozoic – Nagra OPA 97 area.
TP1-STR-0010	Map of Base Mesozoic – Nagra USM East area.
TP1-STR-0011	Map of Base Mesozoic – Nagra USM West area.
TP1-STR-0012	Map of Top Basement – Western Switzerland.
TP1-STR-0013	Subsurface information on the Mettauer and Mandacher faults (compilation).

TP1-STR-0014	Heat Flow Map of Switzerland.
TP1-STR-0015	Thermal and Sulfur Springs.
TP1-STR-0016	Aeromagnetic Total Field Layer.
TP1-STR-0018	Bouguer Anomaly Layer.
TP1-STR-0019	Total Horizontal Gradient of Upward Continued Bouguer Anomaly Layer.
TP1-STR-0020	Faults in Base Mesozoic across N. Switzerland (> 7 km length).
TP1-SUP-0045	EG1d Model: Gaussian smoothed 'a' values incorporating uncertainty, 6 filter radii.
TP1-SUP-0046	EG1b Model: Gaussian smoothed 'a' values by zone. 3 filter radii.
TP1-SUP-0049	EG1b Model: EPRI Mu distributions using 8 large zones and 23 smaller zones.
TP1-SUP-0051	EG1d Model: Revised regional b-value calculations.
TP1-SUP-0053	EG1c Model: Results of least-squares fitting recurrence modelling.
TP1-SUP-0054	EG1c Model: N & beta distributions computed using least squares fitting.
TP1-SUP-0055	EG1a Model: Mmax and Recurrence.
TP1-SUP-0056	EG1d Model: Source Model Recurrence Calculations.
TP1-SUP-0057	EG1d Model: EPRIMMax Computations.
TP1-TEC-0002	In-situ stress measurements.
TP1-TEC-0003	Inversion of focal mechanisms.
TP1-TEC-0004	National Uplift and Subsidence Layer.
TP1-TEC-0005	Nagra Uplift and Subsidence Layer.
TP1-TEC-0006	Macroseismic field data of eq. in Baden-Württemberg.
TP1-TEC-0007	Maximum Intensity Map (N. Pavoni).
TP1-TEC-0008	Maximum Intensity Map (E. Rüttener).
TP1-TEC-0010	Final Fault Plane Solutions Layer.
TP2-ASW-0006	Excel Worksheet to assist the SP2 expert elicitations.
TP2-ASW-0009	Fortran code to compute and Matlab script to plot residuals for empirical attenuation models.
TP2-SUP-0001	Numerical simulations of GM for finite extent sources (preliminary results).
TP2-SUP-0002	Estimation of the ground motion upper limit in Switzerland, based on the Empirical Source Time Function Method simulating broad-band strong ground motions – Final results.
TP2-SUP-0003	Numerical Simulations for Evaluation of Median and Upper Limit Ground Motion in Switzerland.
TP2-SUP-0031	H / V ratio computation for 20 European sites.
TP2-SUP-0036	Determination of input parameters for the stochastic simulation of strong ground motion for Switzerland.

TP2-SUP-0037	Madariaga, R. 2002: Assessment of feasibility of kinematic fault models used for upper limit ground motion evaluations for the pegasos project.
TP2-SUP-0038	Forward modelling, PSS inversion, DB comparison.
TP2-SUP-0039	Resiudal Computations.
TP2-SUP-0040	Residuals as a function of epicentral distance for GMs recorded at short JB distances.
TP2-SUP-0041	Normal probability plots of residuals of selected empirical attenuation relations with more than 1000 recordings.
TP2-SUP-0042	Derive coefficients for the missing frequencies of the candidate models.
TP2-SUP-0043	M 5.5 & M 7 numerical simulations for evaluation of median and upper limit GM in Switzerland.
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TP2-SUP-0048	Computation of spectra in TP2-WAF-0008.
TP2-SUP-0050	Sensitivity Analysis on Upper Tail Modification of the Ground Motion Distribution for Switzerland.
TP2-SUP-0052	KNET and Berge magnitudes and distances for each data point used by Lussou et al. 2000.
TP2-SUP-0058	Small magnitude CA ground motion data.
TP2-SUP-0061	Computation of scaling factors for 20 profiles.
TP2-SUP-0064	Computation of scaling factors for three "realistic" rock profiles.
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TP3-SUP-0008	Shear wave velocity profiles for the four sites.
TP3-SUP-0011	15 scaled time histories.
TP3-SUP-0012	1-D numerical models of site effects using time histories and SHAKE.
TP3-SUP-0013	1-D numerical models of site effects using the Random Vibration Theory (RVT).
TP3-SUP-0014	Comparison between TP3-SUP-0013 (RVT) and TP3-SUP-0012 (Time Histories) runs.
TP3-SUP-0015	Comparison of amplification factors at the four NPP sites, different material sets, shaking levels.
TP3-SUP-0018	M 5 and M 7 SHAKE time histories for the 4 NPP's.
TP3-SUP-0019	Amplification factors for Surface, Outcropping and Total Motions Computed using the RVT Method.
TP3-SUP-0020	Superseded Amplification factors computed using the RVT-method with soil randomisation.
TP3-SUP-0021	Superseded One dimensional site response analysis with soil profiles as defined in TP3-TN-0166.

TP3-SUP-0022	Non-linear Site Response Analyses for Beznau, Gösgen and Leibstadt.
TP3-SUP-0023	2-D Sh Computations for the Leibstadt nuclear power plant site. Amplification factors in the low and high strain cases.
TP3-SUP-0024	Spectral Amplification for SH- and PSV-waves at sites Beznau, Gösgen and Leibstadt.
TP3-SUP-0025	Superseded two dimensional modelling of SH-wave amplification.
TP3-SUP-0026	Gösgen NPP, True non-linear site response analysis.
TP3-SUP-0027	Superseded Visualisation and Comparison of RVT and SHAKE Results.
TP3-SUP-0028	Additional one dimensional site response analysis for M 5 and 7 earthquakes.
TP3-SUP-0032	Two dimensional modelling of SH-wave amplification.
TP3-SUP-0033	One dimensional site response analysis with soil profiles as defined in TP3-TN-0166.
TP3-SUP-0034	Amplification factors computed using the RVT-method with soil randomisation.
TP3-SUP-0035	Visualisation and Comparison of RVT and SHAKE Results.
TP3-SUP-0047	Site Response Analyses considering Cyclic Mobility Effects for Two sites (Beznau and Gösgen) in Switzerland.
TP3-SUP-0059	Development of scaling factors to account for the differences in definitions of reference rock between SP2 and SP3.
TP3-SUP-0060	Evaluation of maximum ground motions for each of the 4 sites.
TP3-SUP-0062	Additional Nonlinear Site Response Analyses for Beznau and Gösgen at a high shaking level considering cyclic mobility effects.
TP3-SUP-0063	Evaluation of maximum ground motions.
TP3-SUP-0069	Additional SHAKE computations at depth.

APPENDIX 1 QA GUIDELINES, REV. 03 (PMT-TN-0402)

Unterausschuss Kernenergie der Ueberlandwerke (UAK)
UAK Sekretariat, c/o Atel CH-4601 Olten

QA - GUIDELINES

Probabilistische Erdbeben-Gefährdungs-Analyse für die KKW-StandOrte in der Schweiz (PEGASOS)

Rev. 03
14. Januar 2004

Table of Contents (see page numbers at the bottom of the page)

Table of Appendices

QA Procedures for the PEGASOS Project

A1 Scope

This procedure describes the Quality Assurance requirements to be applied to documents, data and computations for the PEGASOS Project .

The QA guidelines are set up apriori and the PMT may revise these guidelines as the project evolves.

A2 Processes Subject to QA Procedures

A2.1 Management of Project Documents

2.1.1 Definition of Project Documents

The term Project Document is used to describe any form of written record, produced or consulted in the context and for the purpose of the Project, that is likely to be needed for a complete reconstruction of the Project history, the Project results and the background and reasoning which led to important Project decisions. Project documents can be produced and archived in electronic and / or paper form.

2.1.2 Project Document Language, Format & Style

Project Documents shall be written in English whenever readability / accessibility by the whole of the Project team or the expert groups is a prerequisite. In other cases German is also permissible as a language for Project Documents.

A consistent format / style is to be used for the creation of Project Documents. This PEGASOS format standard is described by Formatting Example Documents in lieu of sets of formatting rules. Such fomatted templates shall be provided by the CMD. Standard setting Formatting Example Documents are:

PMT-TN-0118 Workshop Summary WS-1
PMT-TN-0130 Agenda WS-2 / SP1

2.1.3 Categories of Documents

Classified Documents are documents of considerable importance for the Project work. (e.g. reports, memorandums, technical notes, minutes of meetings and workshops, correspondence etc.). Such documents are to be entered into the Document Administration DB under a predefined Identifier Code and number (see 0). They are easily retrievable from the DB by searching for the document type or the document origin designation, or upon request to the CMD, any other criteria such as e.g. the author.

Non-classified Documents are documents of less importance for the Project work, in particular documents that are not deemed essential for the traceability of Project results or Project decisions (e.g. short personal Email messages etc.). They are primarily meant as an efficient, informal means for communication within the Project. In general, such documents shall be registered as non-classified documents but the registration is at the discretion of the author. If the author decides to have the documents registered, they shall be entered into the *Memo Administration DB* without an Identifier Code (see 0). The only applicable search criterion for such items is the date. Upon request, the CMD can base a search on author, date or the content of a document.

2.1.4 Registration of Classified Project Documents

Classified Documents are to be registered by the author, by the first receiver in the case of outside surface mail or by the Project staff member promoting its inclusion in the Document Administration DB. Registration requires assigning an Identifier Code with a running number (to be obtained from the CMD), filling out an electronically stored *Document Archiving Form* (AF, see App.2) and transmitting the document together with the AF to the CMD (by Email or, in the case of paper documents by mail).

The Identifier Code for Classified Documents consists of three alphanumeric segments (keys), separated by hyphens. The first key designates the origin of the document, the second the document type and the third is a 4-digit running number (starting at 1 for each document type) which is assigned by the CMD. The following document origin and document type codes are currently in use (list may be expanded):

1. Key	*Document Origin*	*2. Key*	*Document Type*	*3.Key*
PMT	Project Management Team	AN	Administrative Note	xxxx
QA	Quality Assurance	ES	Elicitation Summary	xxxx
RW	Accounting	EI	Elicitation S. Input	xxxx
TP1	Subproject 1	GR	Graphic Document	xxxx
TP2	Subproject 2	KS	Correspondence	xxxx
TP3	Subproject 3	PF	Project Planning File	xxxx
TP4	Subproject 4	RE	Invoice	xxxx
RDZ	Comp. Modelling & Database C.	RF	Reference Publication	xxxx
DBK	Data Procurement & Compilation	SB	Final Report	xxxx
EG1	Expert Group 1	SP	Meeting Minutes	xxxx
EG2	Expert Group 2	TB	Technical Report	xxxx
EG3	Expert Group 3	TN	Technical Note	xxxx
EXT	External (from outside the Project)	VG	Viewgraph	xxxx
HSK	HSK Review team	VT	Contract / Order	xxxx
UAK	Project Sponsors (Licensees)	ZB	Progress Report	xxxx

The following are examples of Identifier Codes to clarify the above:

PMT-TN-0143:	Project Management Team, technical note Nr. 143
TP2-RF-0053:	Subproject 2, reference publication Nr. 53

The filename of all Classified Documents starts with Identifier Code followed by a blank and the document name. For example:

PMT-TN-0156 QA-Guidelines.doc

For entry into the Document Administration DB the AF together with the Classified Document have to be forwarded to the CMD's (archiving) E-mail address pegasos@proseis.com. In the case of paper documents, only the AF is sent as an Email attachment while the document itself is sent by surface mail. To allow automatic filing, the E-mail message must contain in the E-mail subject line the word PEGASOS followed by a blank and the document's Identifier Code. For example:

(Email subject line): PEGASOS PMT-TN-0134

2.1.5 Registration of Non-classified Documents (PEGASOS MEMO design.)

In general, all E-mail messages of any importance to the Project should be registered as Non-Classified Documents. To do this, Emails (with or without attachments) have to show the words PEGASOS MEMO: followed by a blank and the memo's title in the subject line and must be copied to pegasos@proseis.com (note: this just initiates automatic filing in the Memo Administration DB but does not mean that the content of the E-mail will necessarily be known to Proseis or Proseis staff). The following is an example of the two features ensuring automatic E-mail registration:

(E-mail copy line): pegasos@proseis.com
(E-mail subject line): PEGASOS MEMO: New Dates for SP1 Interactive Meetings

Papers documents to be registered in the Non-Classified category should carry the PEGASOS MEMO designation (but no Identifier CodE) and should be forwarded to the CMD by FAX or surface mail.

2.1.6 Archiving of Project Documents

All Project Documents shall be safely archived (Classified Documents together with their AFs) at the CMD for at least 12 months after the Project has been completed (submission of the Final Report to the regulating authority). After this time the Project Document database shall be handed over to the Project Sponsors (NPP licensees).

2.1.7 Availability and Requisition of Project Documents

Project Documents shall be made available to the Project Sponsors, the Project Management Team and the HSK Review Team (HSK-RT) without restriction. All other members of the Project Team and the experts shall have unlimited access to the classified technical Project documentation (categories RF, TB, TN, ES see 0 above) and the Non-classified Documents (PEGASOS MEMOs).

The CMD shall publish lists of the Project Document Database on the PEGASOS internet homepage (http://www.pegasos.ch/). These lists are to be updated at least once every calendar month and can be used for ordering electronic or paper copies of Project Documents from the CMD.

A2.2 Management of Project Data

2.2.1 Definition of Project Data

The term *Project Data* refers to all data that have or may have direct influence on the numerical results of the Project. This includes hazard input data (expert elicitation results), data on which hazard input is based and the software used for hazard computations. To decide on the inclusion or non-inclusion of a dataset in the *Project Data DB,* the following criteria can be applied:

The entirety of the Project Data must be comprehensive enough to allow a reconstruction of all numerical results arising from the Project.

The Project Data must guarantee traceability and reproducibility of all computations back to the level of Basic Data (outside data as they were originally accepted and entered into the Project Data DB).

2.2.2 Project Data DB

App.1 shows the general structure of the Project Data DB and delineates the flow of information from the level of Basic Data level to the final, site specific soil hazard results. Individual DB sub-units (boxes) are designed to hold different types of data, each type with its own designation (second key of the Identifier Code, see 0 below) and its own data type specific QA requirements (s. coloured dots in App.1). The colour of the dots indicates that the corresponding DB entries have to be checked by an Independent Technical Reviewer (green), by an Expert or Expert team (blue) or by a reviewer of the SP4 Hazard Computations Subproject (red).

2.2.3 Identification (Designation) of Project Data

Project Data sets are to be registered in the Project Data DB by CMD staff at the request of the subproject manager in charge. Upon registration a three-key alphanumeric Identifier Code and an electronic *Project Data Archiving Form* (PF, see App.3) shall be assigned to each Project Dataset. Once a Project Dataset is registered at the CMD, the subproject manager shall be notified and supplied with copies of the filled out PF.

The Identifier Code for Project Data consists of three alphanumeric items (keys), separated by hyphens. The first key relates to the subproject which created the Project Data set or assumes responsibility for it (source subproject). The second key indicates the type of data or the sub-unit of the Project Data DB where the dataset shall be stored (note that the second key for Project Data has 3 letters whereas a 2 letter second key is assigned to Project Documents). The third is a 4-digit fiducial number, starting at 1 for each data type described with the second key.

The following keys for the origin and type of Project Data are currently in use (list may be expanded):

1. Key	*Origin of Project Data*	*2. Key*	*Type of Data (Project Data DB unit)*	*3.Key*
TP1	Subproject 1	CAT	Earthquake Catalogue DB	xxxx
		STR	Structural Geology DB	xxxx
		TEC	Seismotectonic DB	xxxx
TP2	Subproject 2	EAT	Empirical Attenuation Relations DB	xxxx
		WAF	GM and Wave Form DB	xxxx
TP3	Subproject 3	SIG	Site Geology DB	xxxx
		GTC	Geotechnical DB	xxxx
TP1/2/3	Subproject 1/2/3	SUP	Support Computations DB	xxxx
		EXA	Expert Assessments DB	xxxx
		EXM	Expert Models DB	xxxx
		HID	Hazard Input Documents DB	xxxx
TP4	Subproject 4	RIF	Rock Hazard Input Files DB	xxxx
		RHZ	Rock Hazard Computations DB	xxxx
		SIF	Soil Hazard Input Files DB	xxxx
		SHZ	Soil Hazard Computations DB	xxxx
		HSW	Hazard Software DB	xxxx
		ASW	Auxiliary Software DB	xxxx

The following are examples of Project Data DB Identifier Codes:

TP1-CAT-0003:	Third version of the PEGASOS Earthquake Catalogue (TP1)
TP2-WAF-0004:	Baden Württemberg SM records and assoc. parameters (TP2)

2.2.4 Release of Project Data

Project Data that are to be used outside the subproject from which they originate (source subproject), either for preliminary or final hazard computations or for any other purpose have to be released by the Project Manager (PM). The PM will release Project Data sets for general use at the request of the source subproject or, alternatively at the request of the first user outside of the source subproject. This will be done after consulting with the source Subproject Manager, verifying that all required QA-checks have been performed and after carefully considering the intended use and the likelyhood of the data being soon outdated by a later releases (anticipated lifespan).

Preliminary Data can be released for an open-ended or for a limited period of time. The latter is the case, if the preliminary nature of the dataset is known at the time of the release. An originally unlimited release can be withdrawn, if the dataset is superseeded by a later, improved aequivalent or at the end of the period of *Preliminary Hazard Computations.*

Project Data to be used as input for the *Final Hazard Computations* shall be explicitly designated as *Final Data* on the accompaning Project Data Archiving Form (see 2.2.3).

2.2.5 Archiving of Project Data

Project Data shall generally be stored in electronic format in Project Data DB (see 2.2.2). Parts of the Basic Data category (see topmost row of subunits in App.1) will be linked to a GIS (Geographic Information System). If data are only available as paper records, the data shall be stored in their original form, unless they have been digitized by the Project, in which case the digital record shall be added under the same designation.

Safe storage of all Project Data (datasets accompanied by their PFs) has to be maintained at the CMD for at least 12 months after the Project has been completed (submitting the Final Report to the regulating authority). After this time the Project Data DB will be handed over to the Project Sponsors (NPP licensees).

2.2.6 Availability and Requisition of Project Data

Being the principal basis for their assessments, subproject-specific Project Data shall be put at the disposal of the respective experts for use within the PEGASOS Project only. Released data will be made available to all experts according to the provisions in Section 2.2.4. In addition, the Project Sponsors, the Project Management Team, and the HSK-RT shall all have unlimited access to Project Data.

The CMD will publish listings describing the contents of the Project Data DB on the PEGASOS internet homepage (http://www.pegasos.ch/). These lists are to be updated at least once every calendar month. Whenever important data becomes available, these updates will be done more frequently to reflect this.

Experts wishing to order Project Data in electronic or paper format for their Project work, should adhere to the data requisition rules as outlined in Project Database Report of their subproject (Roth (2002a) for SP1, Smit et al. (2002) for SP2 and Farrington (2002) for SP3).

A2.3 Acceptance and Entry of Basic data into the Project Database

2.3.1 Acceptance of Basic Data

An *Independent Technical Review* (ITR) will be made of all data sets submitted before the data are entered into the Project Database. The ITR shall be performed by a reviewer competent in the technical area covered by the data set. The reviewer may not be the originator of the data set being reviewed. The qualifications of the reviewers will be determined by the PMT. The ITR is not intended to verify the numerical accuracy of the each entry in the data set, but the ITR shall be of sufficient depth to establish the general acceptability of the data set. If errors are found that require correction, the data sets shall be returned to the originators for correction. The corrected data sets will be subjected to another ITR.

2.3.2 Entry of Basic Data

Entry of the data into the Project Database will be subjected to an *Independent Check* (IC). The IC will be made by a person other than the person that originally entered the data, but may be an employee of the same company.

a) For data sets that are submitted as electronic files, at least 1 % of the entries or 50 entries whichever is smaller shall be checked. The checked entries shall be statistically distributed over the entire dataset.
b) For data sets submitted on paper, 100 % of the entries shall be checked.

2.3.3 QA-Certification

A QA-certificate for Basic Data acceptance and DB entry (see form App.4) shall be submitted for every set of Basic Data that is entered into the Project Database to document compliance with the above provisions. This form will be signed by the reviever of the data set and by the person who checked the entry into the Database.

A2.4 Supporting Computations on Behalf of the Experts

The Project may ask the TFI teams, the CMD or external contractors to carry out computations requested by the experts (Supporting Computations, SUP).

2.4.1 Software

Software used in Supporting Computations is not subject to the software verification requirements in Section 2.10.

2.4.2 Documentation

A Report (Technical Note) must be prepared to document the computations. The Technical Note must adequately describe the computations for evaluation by the experts. As a minimum, the documentation shall include the following:

a) Purpose of the computation
b) Description of the methods used
c) Names and version numbers of computer programs used
d) Descriptions of assumptions and input parameters

2.4.3 Independent Technical Review

An Independent Technical Review (ITR) shall be made of the Supporting Computations. A reviewer competent in the technical area covered by the computation shall perform the ITR. The ITR may not be done by the person who performed the computations, but the reviewer may be an employee of the same company or institution where the computations were carried out. The computation originator shall determine a qualified reviewer.

The ITR shall include checks on the summaries of the computation results such as tables and plots included in the Technical Note. If errors are found, the Technical Note shall be revised to the originator for correction. The revised Technical Note will then be checked again until all errors have been eliminated.

2.4.4 QA-Certification

A QA-certificate for Supporting Computations (see form App.5) shall be submitted to document the Independent Technical Review that has been carried out on the computations. This form has to be signed by the person who performed the computations and the independent reviewer.

A2.5 Development of Expert Models

2.5.1 Definition of the Expert Model

An *Expert Model* (EXM) consists of a set of alternative quantitative models of the parameters considered by each subproject (SP1: source characterisation, SP2: rock ground motion attenuation, or SP3: site response). The *Model Logic Tree,* which is an integral part of the Expert Model, describes the structure of this set of alternatives, the relationship between the models and the weight assigned to each of them. The ultimate subdivisions of the Model Logic Tree are referred to as *Branch Tip Models*. A single Expert Model is developed by each individual Expert (SP2 and SP3) or each Experts Group (SP1) who are acting as virtual experts.

2.5.2 Expert Assessments

Expert Assessments (EXA) are preliminary and / or incomplete descriptions of Expert Models in the form of numerical values, maps, tables, logic trees, text, etc. Expert assessments may or may not become input for the final version of the Expert Models. The term also covers other expert elicitation products which may become significant in the later stages of the Project.

2.5.3 Computations made by the Experts

In developing their models, the experts may make computations on their own. These computations are not subject to the requirements of Section 2.4. They shall, however, be subjected to a peer review in the form of expert interactions. This peer review is conducted by the other experts in the corresponding subproject and takes place during the workshops. It will be documented by the Workshop Summaries. Separate documentation of the peer reviews is not required.

2.5.4 Plotting and Computational Support

Experts may ask for plotting or computational support while they are developing and completing their models. If this support is granted, the work shall be carried out according to the experts' precise instructions and under their personal supervision by a contractor of their choice (incl. the CMD). This type of work for individual experts or expert groups in the model development phase is not subject to the requirements of Section 2.4. Experts remain fully responsible for all aspects of their models incl. the correctness of computations carried out on their behalf.

2.5.5 Elicitation Summary

Supported by the TFI team, each Expert or Expert Group shall prepare an *Elicitation Summary* (ES) that provides a detailed description of the Expert Model with all its variations and with the technical basis for the decisions made in its development. There will be one ES per Expert (SP2 and SP3) or one for each Expert Group (SP1).

A2.6 Conversion of Expert Models into Hazard Computation Input

2.6.1 Hazard Input Document

Based on the expert elicitations, the Elicitation Summary or a draft of the ES, the TFI team shall prepare a *Hazard Input Document* (HID). The HID parameterises the Expert Model in terms of the inputs required for the hazard computationResponsability for preparing the HID lies with the TFI who willl rely on the competence of the *Hazard Software Specialist* within his TFI team. This specialist is knowledgeable of the capabilities and limitations of the selected hazard computation software package (e.g. FRISK88M) and knows all its possibilities and limitations.

The first task in preparing the HID is to propose and describe the best possible parameterisation of the Expert Model. The second task is to ensure that the HID contains all subproject specific computation input that is required by the hazard software.

The software must not limit the freedom of the experts. If important aspects of the Expert *Model* cannot be acceptably parameterised due to limitations of the hazard computation software in use, then the responsible TFI shall notify the *Project Manager*. He will then determine if the hazard software needs to be modified (see Section 2.8.2).

The HID includes a Model Logic Tree which graphically summarizes the Expert Model and allows one to trace the origin of each of the Branch Tip Models.

2.6.2 Review of the Hazard Input Document

The experts shall review the Hazard Input Document to ensure that the parameterisation of their Expert Model accurately reflects their interpretation. If the translation of the ES or a draft ES into the HID requires abstractions or interpretations, the TFI team must demonstrate to the expert’s satisfaction that these interpretations are consistent with the intended characterisation of the Expert Model.

If the experts do not agree that the HID accurately represents their Expert Model, the HID will be returned to the TFI team for corrections. The corrected HID shall then again be reviewed by the experts until all concerns are satisfied.

2.6.3 QA-Certification

A QA-Certificate for Hazard Input Documents (see form App.6) shall be submitted together with each HID to furnish proof of completeness and expert approval. The form shall be signed by the TFI responsible for the proposed HID-parameterisation of the Expert Model and by the experts (all the experts in the case of a SP1 Expert Group), who thereby indicate their acceptance.

A2.7 Hazard Software Input Files

2.7.1 Rock Hazard Input Files

Rock hazard Input Files (RIF) for the rock site hazard software (FRISK88M) shall be prepared by SP4 using HIDs of source- and ground motion Expert Models. No interpretations of the HIDs shall be permissible while developing the RIF. If the information contained in a HID is not complete or if it is not compatible with the input requirements of the rock hazard software, the HID will be returned with the relevant comments to the TFI team responsible for preparing the HID. The TFI team shall then revise the HID. The revised HID shall again be be reviewed and QA-certified according to the provisions in Section 2.6.3.

2.7.2 Soil Hazard Input Files

Soil Hazard Input Files (SIF) for the soil site hazard software shall be prepared by SP4 using the corresponding HIDs and the results from the rock site hazard computations (see Section 2.8.5). If a HID is found to be incomplete, the same rules as in the case of the Rock hazard Input Files shall apply (see Section 2.7.1 above).

2.7.3 Pinch Points

SP4 may introduce at some levels of the logic tree algorithmic grouping of logic tree branches (pinching), provided that such *Pinch Points* have negligible effect on the calculated total hazard and its uncertainty. Section 2.9 (and references therein) specify the permissible differences in hazard.

2.7.4 Review of the Hazard Input Files

An Independent Check shall be made for each Hazard Input File (RIF or SIF). The IC will cover 100 % of the entries in the RIF or SIF. In the case of Hazard Input Files used to compute Rock Hazard at more then one site, the entries into the RIF need to be checked for one site only.

In addition to checking the RIF or SIF entries, the IC shall also verify that no interpretations were made in developing the RIF or SIF. The IC shall be conducted by a qualified person from a different company than the originator of the Hazard Input Files. There are two contractors for the hazard computations: Contractor 1 ('leading contractor') and contractor 2 ('reviewing contractor'). If a RIF or SIF originates from a person at contractor 1, then a person at contractor 2 shall conduct the IC and vice-versa.

2.7.5 QA-Certification

A QA-certificate for for Rock or Soil Hazard Input Files (see form App.7 and form App.8) shall be submitted with each RIF or SIF to document the Independent Checks that have been carried out on the Hazard Input Files. These forms have to be signed by the originator of the RIF or SIF and by the person who carried out the IC.

A2.8 Hazard Computations

2.8.1 Master Logic Tree

A *Master Logic Tree* will be prepared by the *Extended Management Team* (EMT) before the *Final Hazard Computations* can be performed. The Master Logic Tree will serve as a master plan showing the way in which the Expert Models will be combined.

2.8.2 Software

Software used for the hazard computations shall be verified according to Section 2.10, with the exception of FRISK88M or other software that has been previously verified by a recognized authority. If the software is modified during the Project (for example to meet the requirements of non-standard forms of Expert Models) then the modified software shall be verified again.

2.8.3 Hazard Computations

The hazard computations will be conducted by SP4. Each computation will be one item in the Rock Hazard Computations (RHZ) or in the Soil Hazard Computations (SHZ) database (see App.1). A computation will contain the RIF or SIF, if relevant the intermediate files, and the output files. It will also include the version number of the software code.

2.8.4 Preliminary Hazard Computations

Expert requests for *Preliminary Hazard Computations* (mainly sensitivity checks) will be addressed to the corresponding TFI teams, which after examination, will pass them to SP4. This is to avoid duplication of computations or incomplete datasets to be forwarded.

2.8.5 Final Hazard Computations

The Master Logic Tree shall define the final *Rock Hazard (RHZ) and Soil Hazard (SHZ) Computations*. No interpretations by SP4 are allowed. The ground motion levels, spectral frequencies and fractiles at which the computations are made shall be taken from the Project Plan specifications.

2.8.6 Independent Check of Preliminary and Final Hazard Computations

For at least 5 percent of the Hazard Computations, an independent hazard computation contractor (contractor 1 and 2, see 0) shall perform the computations in parallel, using the same RIFs or SIFs. If differences in the computed hazard are found, representatives of the two companies will meet to identify the reasons for such differences and take the necessary corrective action. After the differences are corrected, the hazard computations shall be repeated.

2.8.7 Reporting

The output from the hazard computations will be reported in terms of tables and plots. They are not part of the hazard computations. The tables and plots for the Preliminary Hazard Computations used for sensitivity studies are not subject to an Independent Check (IC). For the final hazard computations, an IC will be made for all tables and plots.

2.8.8 QA-Certification

A QA-Certificate for Rock or Soil Hazard Computations (see form App.9 and form App.10) shall be submitted to document the Independent Checks that have been carried out on the hazard computations. These forms have to be signed by the person at one of the two hazard computation contractors who performed the leading computation, and by the independent reviewer of the other hazard computation contractors who performed the comparative computations.

A2.9 Algorithmic Pinching

2.9.1 Definition of Pinching

Computational considerations sometimes make it necessary for SP4 to introduce Pinch Points when calculating the total seismic hazard. This reduction of the total number of branches is called *Algorithmic Pinching* and is considered to be an algorithmic decision. Pinching by SP4 shall only be performed if it can be shown that it has no significant effect on the total seismic hazard. The purpose of Pinching is to allow the hazard computations to be performed within reasonable time using available computational resources.

2.9.2 Primary Accuracy Criteria

To ensure that the accuracy of the total hazard results is maintained, Pinching shall meet the following *Primary Accuracy Criteria* on the acceptable errors in the results:

Acceptable errors in the mean and standard deviation of total seismic hazard: 3 %, which translates into approximately 1 % error in ground motion amplitude.

Acceptable errors in the 0.50, 0.85, and 0.95 fractiles of seismic hazard: 10 % if the fractile is underestimated and 20 % if the fractile is overestimated.

2.9.3 Technical Basis for the Pinching Rules

The Primary Accuracy Criteria are generic. Depending on the type of Pinching, different Operational Criteria are applied that give specific technical guidance on how to implement Pinching. The Operational Criteria are easy to check on a routine basis and assure that the Primary Criteria are being met (see TP4-TN-0394 for the technical basis). Three different categories of Pinching are identified. They are described in the next sections (2.9.4 to 2.9.6).

2.9.4 Moment-Based Pinching.

Moment-Based Pinching is the process of replacing a number of conditional branches in a source's logic tree with a one, two, or three equivalent branches, while conserving the mean hazard and possibly some higher moments of the hazard distribution.

To test compliance with the Operational Criteria, checking computations shall be conducted at two differents frequencies and three different amplitudes. After completion the SP4 analyst shall examine the mean hazard results by source and determine if the Operational Criteria given in App 11, and the criteria on the standard deviation, are being met. Each RHZ and SHZ relying on Pinching shall contain the relevant intermediate or output files of these test runs, based on which the compliance with the Operational Criteria can be reconstructed.

2.9.5 Tree Trimming

The SP4 analyst may modify the global logic tree for the sake of efficiency, provided that the error introduced by this modification is within the tolerable errors given by the Primary Accuracy Criteria. Possible cases of such a *Tree Trimming* may arise if one or more branches of the logic tree have very low weights or if a few global branches produce nearly identical hazard results. Branches can then be eliminated or grouped into one representative branch, their weight being redistributed.

The SP4 analyst shall perform sensitivity computations at the same two different frequencies and three different amplitudes as for Moment based Pinching (see 0) to confirm that the Primary Accuracy Criteria on the mean and standard deviation are being met. These calculations need only consider those sources affected by the global branches being considered for Tree Trimming. For the sake of computational efficiency, this sensitivity analysis can be performed using only one representative attenuation equation for the appropriate frequency, in which case the tolerances should be reduced in half to compensate for possible effects that may arise when using all attenuation equations.

2.9.6 Mathematically Equivalent Trees

There are rare situations where the logic tree used as input to the rock hazard software may be transformed into a logic tree that is a *Mathematically Equivalent Tree* but is more efficient computationally.

2.9.7 Documentation

If the Operational Criteria for Moment based Pinching are met, no further documentation is required.

Where computations are necessary for demonstrating that the Primary Criteria are met, these computations shall be documented in a Technical Note. The Technical Note shall include results from all sensitivity analyses that were used to verify compliance with the Primary Criteria.

If neither the Operational nor the Primary Criteria are met, the computations shall be repeated using different Pinching options until either condition is met or the computations have to be performed without Pinching.

A2.10 Software Verification

2.10.1 Verification Documentation

Computer programs used for hazard computations shall be verified, with the exception of FRISK88M or other software that has been previously verified by a recognized authority. The verification shall be documented in a Technical Note and shall identify, as a minimum, the following*:*

a) Program name

b) Program version
c) Computer platform the program is designed to run on
d) Program author
e) Identification of individuals responsible for checking the software code executables
f) Verification methods used

Verification methods may include one or more of the following:

- Comparison with well documented examples in software manuals, textbooks or other scientific literature
- Comparison with outputs from other recognized, verified computer programs, or
- Comparison with outputs from alternate independent computation methods

The documentation shall also provide details of problems analysed and associated input and output data for any verification runs performed.

New versions of a computer program that has been previously verified by a recognized authority or by the PEGASOS Project shall be verified by performing tests that exercise and tests the modified or new capabilities of the program. Performance of the full set of tests used in the initial qualification shall not be required. The verification of new versions of the software shall be documented in a Technical Note.

Porting to another platform of a computer program that has been previously verified by a recognized authority or by the PEGASOS Project shall be verified by performing at least three of the tests used in the initial qualification. The verification of ported software shall be documented in a Technical Note.

A3 Supervision of QA Procedures

3.1 QA Audits commissioned by the PMT

To ensure that the QA procedures are implemented, the PMT will commission independent QA audits. An audit will verify that the required QA rules and provisions were followed by reviewing a subset of the data sets and computations. The audit may also include spot checks of the numerical values in data sets as well as checking that the required reviews were performed and the corresponding QA-certificates were properly filled out and signed.

Representative data sets and computation will be selected for audits. The selected data sets and computations should sample the range of activities for which QA is required: e.g. archiving of Project Documents and Project Data, acceptance of Basic Data into the Project Database, Supporting Computations, development of Hazard Input Documents and Hazard Input Files and the performance of Hazard Computations (see App.1).

3.2 QA Audits commissioned by the Regulator (HSK-RT)

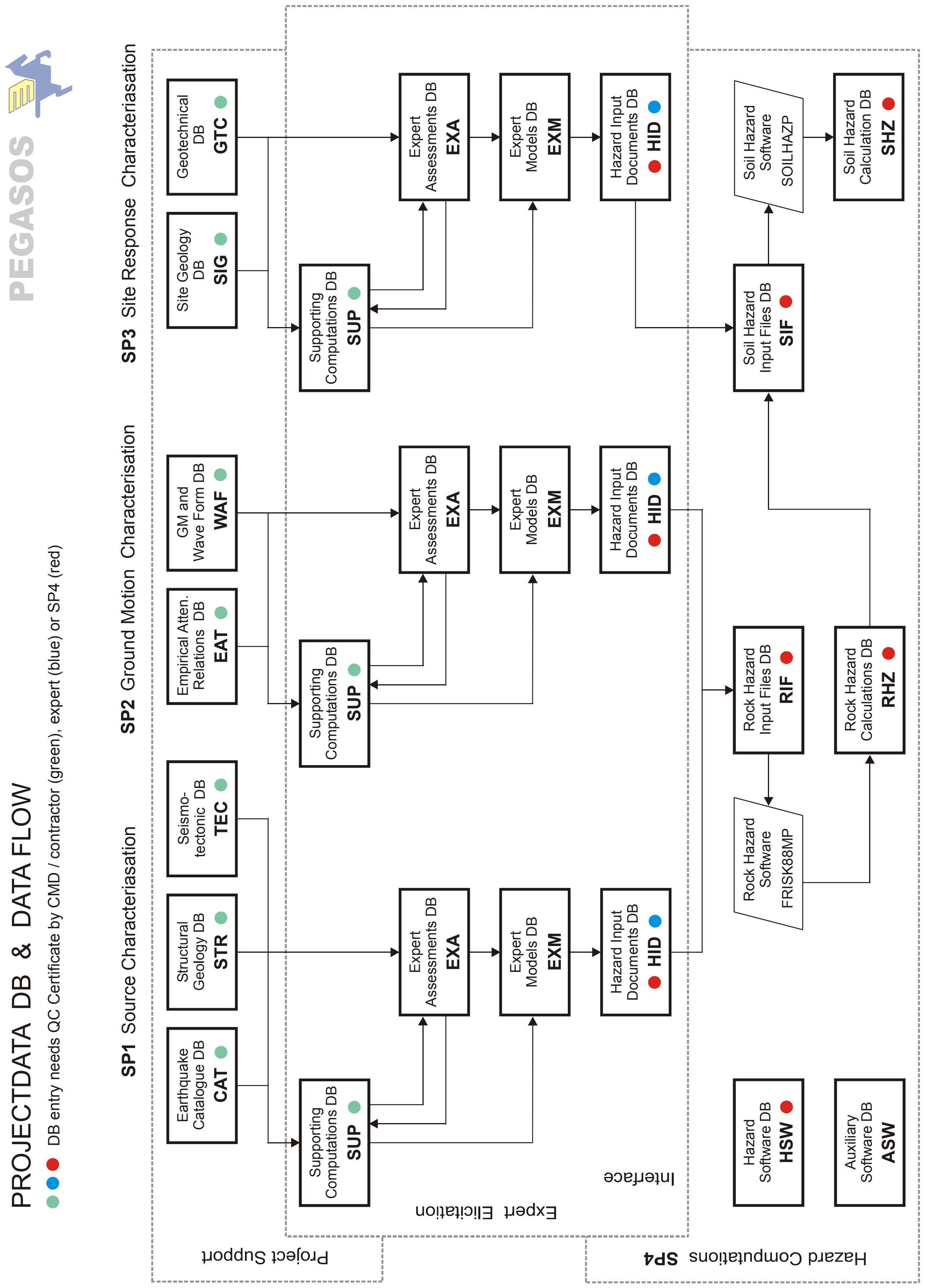
In addition to the QA audits commissioned by the PMT, the regulator (HSK) may decide to carry out its own independent QA audits. If this is the case, the PMT shall ensure that the HSK auditor is getting all the necessary support from the members of the PEGASOS Project Team.

Glossary of Terms

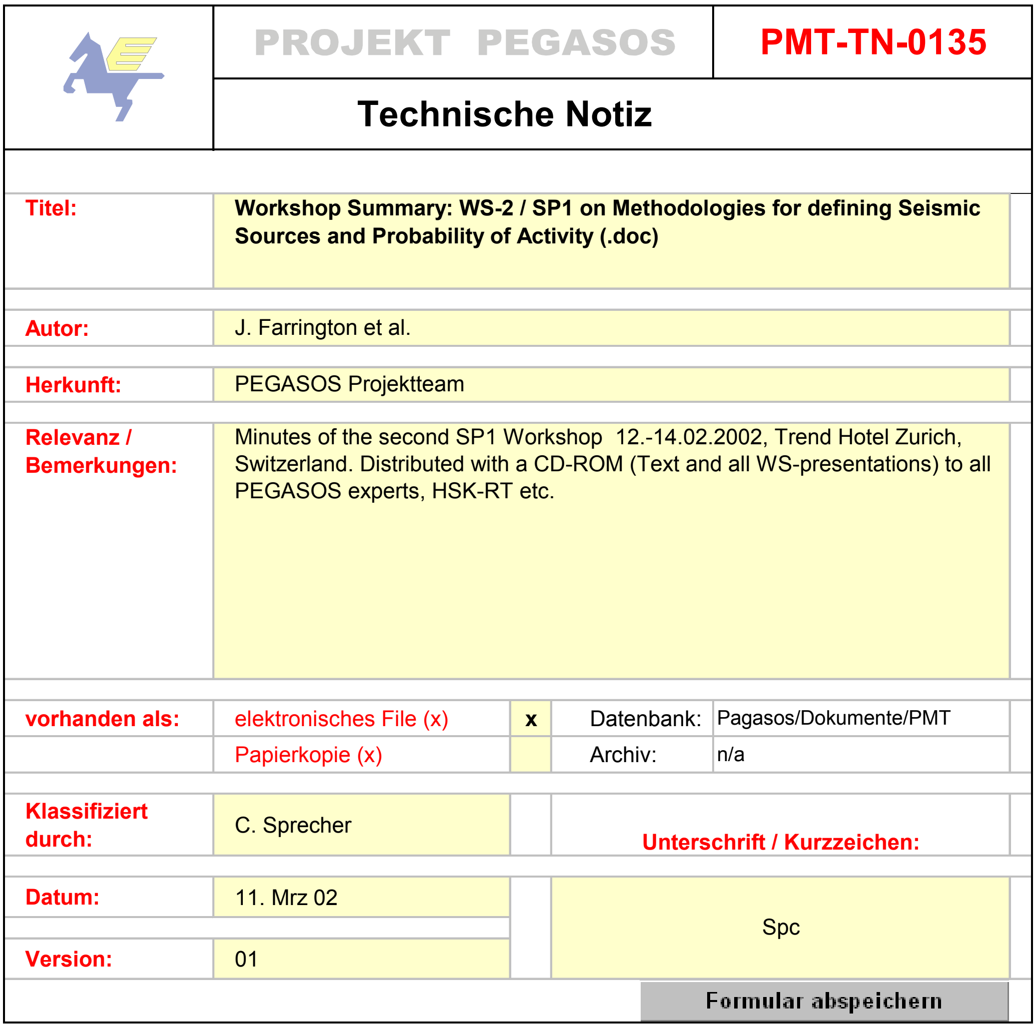
Term	Description / Definition
Basic Data	Outside data as they were originally accepted and entered into the Project Data DB
Branch Tip Model	Model that results from a single path through a logic tree.
Classified Documents	Important Document that is entered into the Project Document DB under an Identifier Code and accompanied by a AF
CMD	Computing-, Modelling- and Database centre
DB	Data Base
Document Administration DB	Listing of all Classified Project Documents
Document Archiving Form (AF)	Form used to archive Classified Documents
Elicitation Summary (ES)	Detailed description of the Expert Model (incl. the technical basis for decisions made)
Expert Assessment (EXA)	Preliminary and/or incomplete description of Expert Models or any other expert elicitation product
Expert Model (EXM)	Complete subproject specific PSHA input contribution by one expert (SP2 / 3) or one expert group (SP1)
Extended Management Team (EMT)	PMT plus the TFIs
Final (Project) Data	Project Data to be used as input for the Final Hazard Computations
Final Hazard Computation	Final computation of (site dependent) Rock or Soil Hazard (final Project results)
Formatting Example Documents	Specimen for the style & formatting of Project Documents
Hazard Input Document (HID)	The HID describes the Expert Model in terms of the inputs required for the hazard computation
Hazard Software Specialist	TFI-team member with specialist knowledge of the rock- (FRISK88M) and soil hazard software packages and their input requirements
HSK	Swiss Nuclear Regulatory Authority (Hauptabteilung für die Sicherheit der Kernanlagen)
HSK Review Team (HSK-RT)	(Participatory) Review team established by HSK
Identifier Code	Three-key alphanumeric code that uniquely identifies a Classified Project Document or an item in the Projectdata DB

Independent Technical Review (ITR)	Review of a data set or a computation by a person, other than the originator, who is competent in the relevant technical area
Master Logic Tree	Logic tree desciption of the set of Model Logic Trees for the Final Hazard Computation
Memo Administration DB	Listing of all Non-Classified Project Documents (PEGASOS MEMO)
Model Logic tree	Logic tree desciption of the full set of weighted alternatives included in the Expert Model
Non-classified Documents	Documents that are not considered to be essential for the traceability of Project results or Project decisions
Pinch Point	Point in the Logic Tree where Branch Tip Models are grouped into a smaller representative subsets including the appropriate weights
Preliminary (Project) Data	Non-final Project Data; can be used for Preliminary Hazard Computations by the originator subproject or, if released, throughout the Project
Preliminary Hazard Computations	Hazard input sensitivity tests orderd by the experts
Project	The PEGASOS project
Project Data	Data that are known to have or may have a direct influence on the numerical results of the Project
Project Data archiving form (PF)	Form used to archive Project Data (see App.3); indicates QA and Data Release status
Project Database	Includes the Project Document DB and the Project Data DB
Project Document	Any form of written record, that is likely to be needed to reconstruct history, results or the background of important Project decisions
Project Management Team (PMT)	Project Manager, Subproject Managers and two Project Consultants
QA-Certification	Completing and signing of a dedicated form (see App.4 to 10) to provide proof that the compulsory QA-procedures have been followed
Rock hazard Input File (RIF)	Input file for the rock site hazard software (FRISK88M) prepared for one or more sites by SP4 on the basis of source- and ground motion HIDs.
Soil hazard Input File (SIF)	Input file for the soil site hazard software prepared for one or more sites by SP4 on the basis of rock site hazard computations and site response HIDs
Supporting Computations	Computations requested by and carried out on behalf of the experts by the CMD or outside contractors (e.g. num. site response simulations)

App.1: Projectdata DB and Data Flow

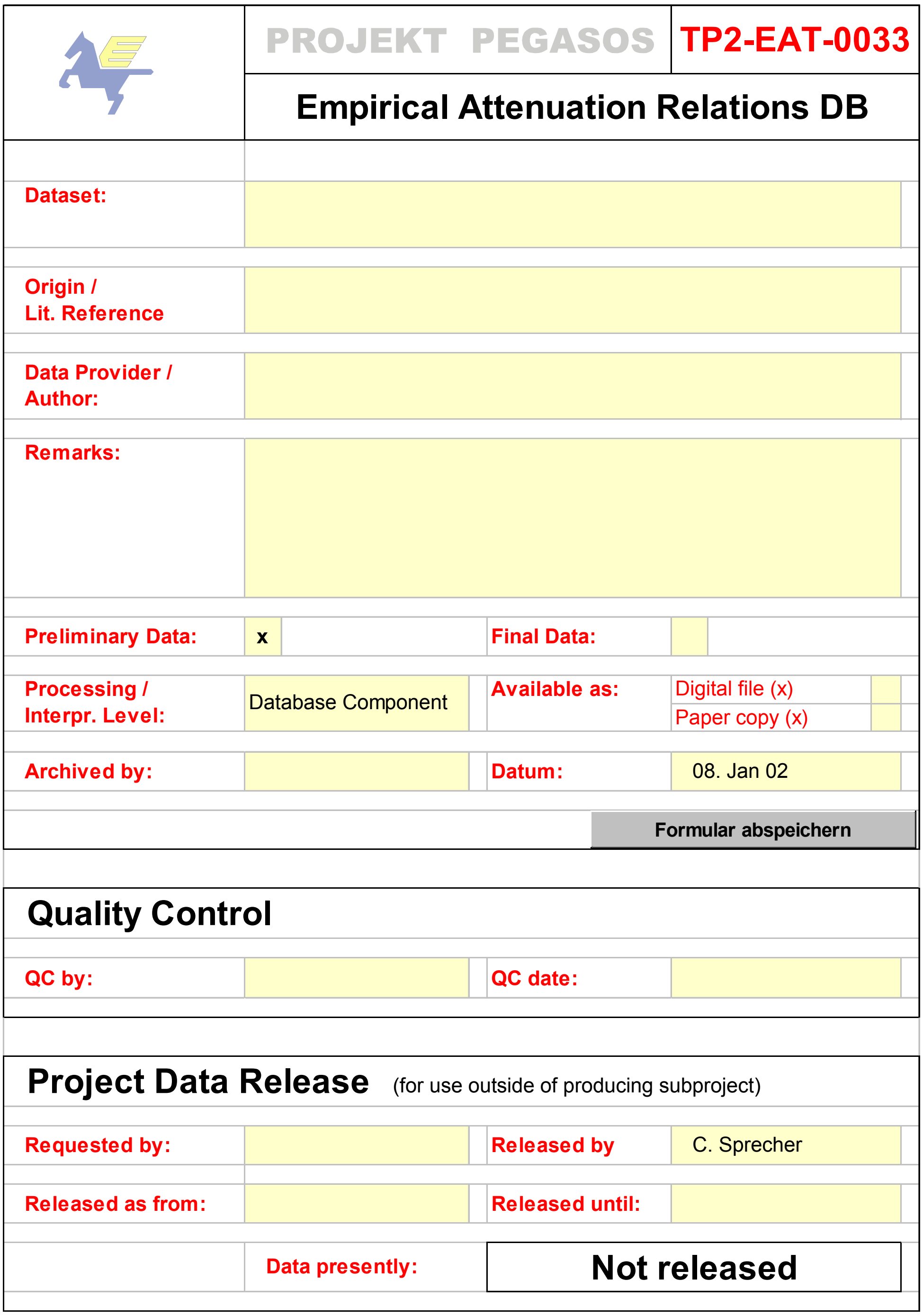


App.2: Project Document Archiving Form (PMT-AN-0147)



	PROJEKT PEGASOS			**PMT-TN-0135**
	Technische Notiz			
Titel:	**Workshop Summary: WS-2 / SP1 on Methodologies for defining Seismic Sources and Probability of Activity (.doc)**			
Autor:	J. Farrington et al.			
Herkunft:	PEGASOS Projektteam			
Relevanz / Bemerkungen:	Minutes of the second SP1 Workshop 12.-14.02.2002, Trend Hotel Zurich, Switzerland. Distributed with a CD-ROM (Text and all WS-presentations) to all PEGASOS experts, HSK-RT etc.			
vorhanden als:	elektronisches File (x)	x	Datenbank:	Pagasos/Dokumente/PMT
	Papierkopie (x)		Archiv:	n/a
Klassifiziert durch:	C. Sprecher		**Unterschrift / Kurzzeichen:**	
Datum:	11. Mrz 02		Spc	
Version:	01			
			Formular abspeichern	

App.3: Project Data Archiving Form (PMT-AN-0131)



PROJEKT PEGASOS **TP2-EAT-0033**

Empirical Attenuation Relations DB

Dataset:			
Origin / Lit. Reference			
Data Provider / Author:			
Remarks:			
Preliminary Data:	x	**Final Data:**	
Processing / Interpr. Level:	Database Component	**Available as:**	Digital file (x) Paper copy (x)
Archived by:		**Datum:**	08. Jan 02

Formular abspeichern

Quality Control

QC by:		**QC date:**	

Project Data Release (for use outside of producing subproject)

Requested by:		**Released by**	C. Sprecher
Released as from:		**Released until:**	
	Data presently:	**Not released**	

App.4: QA-Certificate for Basic Data acceptance and DB entry (QA-TN-0159)

QA Certificate	**PEGASOS PROJECT**

Acceptance and Entry of Basic Data into the Project DB

Data Set Designation:

Description:

Origin: ***Author:***

Published: ***Delivery date:***

Independent Technical Review (ITR):

PMT approved reviewer: ***Company:***

Description of acceptance checks performed (see 2.3.1 QA-Guidelines):

The undersigned reviewer declares that the Independent Technical Review carried out on the dataset has not revealed any errors and he recommends acceptance of the data set into the Project DB.

Signature:

Database Entry Checks:

Form of original data: ***Electronic:*** ☐ ***Paper:*** ☐ ***Entry date:***

Dataset entered by: ***Company:***

Independently checked by: ***Company:***

Description of (conversion-) and database entry checks performed (see 2.3.2 QA-Guidelines):

The undersigned has independently checked the entry of the above dataset into the Project-DB and declares that the stored data is equal or equivalent to the data as it was originally delivered.

Signature:

App.5: QA-Certificate for Supporting Computations (QA-TN-0286)

QA Certificate

PEGASOS PROJECT

Supporting Computations on Behalf of the Experts

Commissioning Subproject:

Expert / Expert Group:

Report (TN):

DB unit designation

Description:

Computations:

Computations carried out by:

Company:

Software code designation:

Date:

Signature:

Independent Technical Review (ITR)

Review carried out by:

Company:

Date:

Description of QA-checks (see 2.4.3 QA-Guidelines):

The undersigned declares that an Independent Technical Review carried out on the above mentioned computions has not revealed any faults or errors.

Signature:

App.6: QA-Certificate for Hazard Input Documents (QA-TN-0287)

QA Certificate	**PEGASOS PROJECT**

Hazard Input Document (HID)

Expert group:

HID designation:

Expert:

Expert Model (EXM)

HID parameterisation of Expert Model:

TFI:

Hazard Input Specialist of TFI-team:

HID based on Elicitation Documents: ☐

HID based on Expert Assessments (EXA): ☐

Remarks on the HID model parameterisation in terms of hazard computation input:

The undersigned Hazard Input Specialist confirms that this HID includes all required (subproject specific) input information for hazard computations. No further interpretations of this input will be required and no simplifications except Algorithmic Pinching according to paragraph 2.9 of the QA-Guidelines will be applied to convert this HID into hazard software Input Files.

Signature:

HID acceptance by the Expert / Expert Group:

Date of HID review by the Expert / Expert group:

HID accepted: ☐ ***HID not accepted:*** ☐

Reasons for non-acceptance of HID / Recommendations:

The undersigned Expert(s) accept(s) the parameterisation proposed in this HID as a faithful and adequate representation of his/their Expert Model. He/they confirm(s) that this HID is free of errors and agree(s) to its use as hazard computation input.

Signature Expert 1 / Expert:

Signature Expert 2:

Signature Expert 3:

App.7: QA-Certificate for Rock Hazard Input Files (QA-TN-0396)

QA Certificate | **PEGASOS PROJECT**

Rock Hazard Input File (RIF)

Hazard computation requested by (subproject or PMT):

Rock Hazard Softw. Version (HSW): ***RIF designation:***

Input / Sites

Seismic sources: EG1-HID- .... or TP1-HID- ....

Ground motion: EG2-HID- .... or TP2-HID- ....

Remarks: ***Sites:***

Beznau ☐
Leibstadt ☐
Gösgen ☐
Mühleber ☐

Compilation of Rock Hazard Input File

Source (SP1) Input & Intermediate Files	***Ground Motion (SP2) Input***
Part compiled by:	***Part compiled by:***
Company: ***Date:***	***Company:*** ***Date:***
Signature:	***Signature:***

QA-checks

Source (SP1) Input & Intermediate Files	***Ground Motion (SP2) Input***
Checks performed by:	***Checks performed by:***
Company: ***Date:***	***Company:*** ***Date:***

Description of QA-checks (see 2.7.1 QA-Guidelines) and remarks:

The undersigned reviewers declare that no interpretations have been necessary to convert the above HIDs into this RIF. All numerical values have been checked and were found to be correct. Algorithmic Pinching (if applied) conforms to the conditions layed down in section 2.9 of the QA-Guidelines.

Signature: ***Signature:***

App.8: QA-Certificate for Soil Hazard Input Files (QA-TN-0289)

QA Certificate

PEGASOS PROJECT

Soil Hazard Input File (SIF)

Hazard computation requested by (subproject or PMT):

Soil Hazard Software Version (HSW): ***SIF designation:***

Rock Hazard and Site Response Input

Beznau ☐ ***Rock Hazard Input: TP4-RHZ- ....***
Leibstadt ☐ ***Rock Hazard Input: TP4-RHZ- ....***
Gösgen ☐ ***Rock Hazard Input: TP4-RHZ- ....***
Mühleberg ☐ ***Rock Hazard Input: TP4-RHZ- ....***

Beznau ☐ ***Site response: TP3-HID- ....***
Leibstadt ☐ ***Site response: TP3-HID- ....***
Gösgen ☐ ***Site response: TP3-HID- ....***
Mühleberg ☐ ***Site response: TP3-HID- ....***

Compilation of Soil Hazard Input File *(leading computation contractor)*

SIF compiled by: ***Company:*** ***Date:***

Signature:

QA-checks *(reviewing computation contractor)*

Checks performed by: ***Company:*** ***Date:***

Description of QA-checks (see 2.7.2 QA-Guidelines) and remarks:

The undersigned reviewer declares that no interpretations have been necessary to convert the above HIDs into this SIF. All numerical values have been checked and were found to be correct. Algorithmic Pinching (if applied) conforms to the conditions layed down in section 2.9 of the QA-Guidelines.

Signature:

App.9: QA-Certificate for Rock Hazard Computations (QA-TN-0290)

QA Certificate | PEGASOS PROJECT

Rock Hazard Computation (RHZ)

Preliminary (Sensitivity) Rock Hazard Computation ☐ *Requested by Subproject / PMT:*

Final Rock Hazard Computation ☐

Rock Hazard Softw. Version (HSW): *RHZ designation:*

Input / Sites

Input (RIF)

Remarks:

Sites:

Beznau ☐

Leibstadt ☐

Gösgen ☐

Mühleberg ☐

Rock Hazard Computation (leading computation contractor)

Performed by: *Organisation:* *Date:*

Signature:

Comparative Computation (reviewing computation contractor)

Performed by: *Organisation:* *Date:*

Remarks / Observations:

The undersigned hazard computation reviewer declares that a comparative computation was carried out in parallel and that the results of the two computations were found to be identical.

Signature:

App.10: QA-Certificate for Soil Hazard Computations (QA-TN-0291)

QA Certificate | **PEGASOS PROJECT**

Soil Hazard Computation (SHZ)

Preliminary (Sensitivity) Soil Hazard Computation ☐ ***Requested by Subproject:***

Final Rock Hazard Computation ☐

Soil Hazard Software Version (HSW): ***SHZ designation:***

Input / Sites

Input (SIF)

Remarks:

Sites:

Beznau ☐
Leibstadt ☐
Gösgen ☐
Mühleberg ☐

Soil Hazard Computation *(leading computation contractor)*

Performed by: ***Organisation:*** ***Date:***

Signature:

Comparative Computation *(reviewing computation contractor)*

Performed by: ***Organisation:*** ***Date:***

Remarks / Observations:

The undersigned hazard computation reviewer declares that a comparative computation was carried out in parallel and that the results of the two computations were found to be identical.

Signature:

App.11: Operational Criteria for Moment-Based Pinching (from TP4-TN-0394):

Tab. A11-1: Maximum Acceptable Values of the Hazard Ratio r

COV	Maximum r (1-point pinching)	Maximum r (2-point pinching)	Maximum r (3-point pinching)
0.00	1.00	1.00	1.00
0.60	1.00	1.00	1.00
0.63	0.80	1.00	1.00
0.78	0.60	1.00	1.00
2.00	0.10	1.00	1.00
2.10	0.09	0.80	1.00
2.16	0.08	0.50	1.00
2.17	0.08	0.49	0.40
2.55	0.05	0.27	0.30
3.16	0.03	0.10	0.27
4.00	0.02	0.04	0.24
4.17	0.02	0.03	0.23
>5.00	0.02	0.03	0.20

r = Ratio between the mean hazard of a given source and the mean hazard of the dominant source (with the strongest contribution to total Hazard)

COV: Coefficient of variation (see TP4-TN-0282)

1-point pinching: Calculates the mean hazard from all conditional branches and replaces them with one branch located at the mean hazard and with a (conditional) weight of 1.0. Preserves the mean hazard (for the individual source, as well as for the total hazard).

2-point pinching: Calculates the mean and standard deviation of hazard from all conditional branches and replaces them with two branches located at the mean $\pm \sigma$ the hazard and with (conditional) weights of 1/2 each. Preserves the mean and standard deviation of the hazard (for the individual source, as well as for the total hazard).

3-point pinching: Calculates the mean, standard deviation, and skewness of hazard from all conditional branches and replaces them with three branches at properly selected locations, with weights of 1/6, 2/3, and 1/6. Preserves the mean, standard deviation, and skewness of the hazard (if the skewness is lower than 1.78 in absolute value).

Note:
1) The values for 1-point pinching are also constrained by the criteria on the standard deviation (see Equation 1 in TP4-TN-0282).
2) Moment-based pinching (using 1, 2, or 3 points) is permitted when $r < 0.006$, regardless of the COV.