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Methodology and main results of seismic source characterization for the PEGASOS Project, Switzerland

Kevin J. Coppersmith [1], Robert R. Youngs [2] & Christian Sprecher [3]

Key words: PEGASOS, seismic source characterization, seismic hazard

ABSTRACT

Under the direction of National Cooperative for the Disposal of Radioactive Waste (NAGRA), a probabilistic seismic hazard analysis was conducted for the Swiss nuclear power plant sites. The study has become known under the name "PEGASOS Project." This is the first of a group of papers in this volume that describes the seismic source characterization methodology and the main results of the project. A formal expert elicitation process was used, including dissemination of a comprehensive database, multiple workshops for identification and discussion of alternative models and interpretations, elicitation interviews, feedback to provide the experts with the implications of their preliminary assessments, and full documentation of the assessments. A number of innovative approaches to the seismic source characterization methodology were developed by four expert groups and implemented in the study. The identification of epistemic uncertainties and treatment using logic trees were important elements of the assessments. Relative to the assessment of the seismotectonic framework, the four expert 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. In defining seismic sources, the expert teams used a variety of approaches. These range from large regional source zones having spatially-smoothed seismicity to smaller local zones, to account for spatial variations in observed seismicity. All of the teams discussed the issue of identification of feature-specific seismic sources (i.e. individual mapped faults) as well as the potential reactivation of the boundary faults of the Permo-Carboniferous grabens. Other important seismic source definition elements are the specification of earthquake rupture dimensions and the earthquake depth distribution. Maximum earthquake magnitudes were assessed for each seismic source using approaches that consider the magnitudes of observed earthquakes within analogous tectonic regions. All four expert teams used the PEGASOS earthquake catalogue for estimating earthquake recurrence parameters. This catalogue was developed by the Swiss Seismological Service and provided all historical and instrumental events in a uniform moment magnitude. The teams evaluated alternative declustering approaches and used available historical data to assess catalog completeness as a function of location, magnitude, and time period.

1 Introduction: Overview of the Swiss Seismic Hazard Analysis PEGASOS Project

Although Switzerland is generally considered to have a low to moderate level of seismicity, the Swiss Federal Nuclear Safety Inspectorate (HSK) identified seismic hazard as a potentially significant contributor to the risk at four Swiss nuclear power plant sites (Mühleberg, Gösgen, Beznau, and Leibstadt). The HSK also identified the need to update the seismic hazard analyses at the sites and requested that the Swiss electric utilities conduct a probabilistic seismic hazard analysis (PSHA) following Senior Seismic Hazard Analysis Committee (SSHAC) Level 4 expert elicitation methodologies (SSHAC 1997; Budnitz et al. 1998). A SSHAC Level 4 study involves a structured approach to capturing the range of views of the larger technical community through formal expert assessment. Under the direction of National Cooperative for the Disposal of Radioactive Waste (NAGRA), a probabilistic seismic hazard analysis (PSHA) was conducted for the Swiss nuclear power plant sites. The study has since become known under the name 'PEGASOS Project' (**P**robabilistische **E**rdbeben-**G**efährdungs-**A**nalyse für KKW-**S**tand-**O**rte in der **S**chweiz) (NAGRA 2004).

The objective of the project was to assess the relevant earthquake-induced ground motions at the building foundation levels of the four sites, which would be used subsequently for probabilistic safety analyses. A formal expert elicitation process was used, including dissemination of a comprehensive database, multiple workshops for identification and discussion

[1] Coppersmith Consulting, Inc., 2101 N. California Blvd., Suite 290, Walnut Creek, CA, USA. E-mail: kcoppersmith@earthlink.net
[2] AMEC Geomatrix, 2101 Webster St., 12th Floor, Oakland, CA, USA. E-mail: bob.youngs@AMEC.com
[3] Sprecher Consulting GmbH, Zürich, Switzerland. E-mail: christian.sprecher@bluewin.ch

of alternative models and interpretations, elicitation interviews, feedback to provide the experts with the implications of their preliminary assessments, and full documentation of the assessments. The study brought together experts from all over Europe. Four teams consisting of three experts conducted the seismic source characterization (subproject SP1), five individual experts addressed ground motion characterization (subproject SP2), and four experts characterized the site response (subproject SP3). The seismic hazard calculations were conducted as part of subproject SP4. The entire study was subject to participatory peer review by an HSK Review Team, which monitored and provided feedback on the procedural and technical aspects of the project, as well as provided a review of the final report.

The major results of the work of the four expert groups (EG1a, b, c, and d) involved in seismic source characterization (subproject SP1) are presented in this volume (Schmid & Slejko 2008; Burkhard & Grünthal 2008; Musson et al. 2008; Wiemer et al. 2008). This paper summarizes the integrated results of the assessments across all four expert teams.

2 Principal Steps taken during the implementation of project PEGASOS

This section describes the general approach implemented by the PEGASOS project for eliciting the evaluations of the experts.

Development of 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 organization and management of the entire project. The Project Plan was submitted to the 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 assure that the project goals were achieved. The Project Plan identified the Technical Facilitator/Integrators (TFIs) for the three subprojects. Following the guidance given in SSHAC (1997), the TFIs are responsible for facilitating the interactions among the experts and for integrating their assessments into a final result.

Selection of Experts. The PMT established criteria for the selection of experts. 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. The SP1 teams were interdisciplinary and each included a seismologist, geologist, and seismotectonics expert (Table 1).

Table 1. SP1 Expert Teams.

Expert Group	SP1 Expert	Affiliation	Expertise
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

Data Compilation and Dissemination. The compilation and distribution of pertinent data, including published reference material, began early and continued throughout the project. 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. Key issues included the spatial stationarity of seismicity, the relationship between the location and rates of small-magnitude earthquakes and the locations and rates of large-magnitude events, the potential activity of known faults, and the cause and structural association of the 1356 Basel earthquake. The workshop provided the basis for the first data delivery to the experts. At various times during the course of the project, the project honored 134 data requests, including a number of potential field geophysical maps, a uniform seismicity catalogue, and geologic maps of various scales.

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 (individuals with specialized knowledge and datasets) participated from a variety of organizations, 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 a fourth workshop 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 the project, which provided an opportunity to review the entire project, the hazard results, and sensitivity analyses. In addition to the total of five 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 specialized 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 provided 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.

Feedback of Preliminary Results. Following the elicitation interactive meetings and the completion of preliminary evaluations, feedback workshops were held for each of the three subprojects. 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 under a facilitated and structured environment, were encouraged to make sure that alternatives were understood and uncertainties were being appropriately addressed. For example, facilitated discussions occurred related to the potential activity of the Reinach fault and to the Permo-Carboniferous faults within the Molasse Basin. 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. For example, assessments of maximum magnitudes for the host source zones for the sites were found to be important contributors to the uncertainty in hazard at most sites.

Preparation of Hazard Input Documents. Once the experts 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. The draft HID was reviewed by each expert to ensure that it was accurate, signed by the expert, and then passed on to the hazard calculations team (subproject SP4). This process ensured that the expert assessments were properly and accurately passed along to the hazard calculations team.

Finalization 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. 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 Elicitation Summaries 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 were provided in the final report (NAGRA 2004) are the fundamental input to the PEGASOS PSHA.

3 Source Characterization Methodology

Seismic source characterization 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. In some cases, the approach taken by a particular Expert Group (EG1a, b, c, or d) will be described. In specifying their models and parameters, the teams identified both aleatory variabilities (randomness in the earthquake process that includes physical attributes not modeled) and epistemic uncertainties (uncertainty due to lack of knowledge in the models of the earthquake process).

3.1 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 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 of Hypocenters per Unit Area

Traditionally, the maximum magnitude, b-value, and annual rate of hypocenters 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 variability 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 de-coupled. 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 which is the horizontal distance to the surface projection of fault rupture.

For the purposes 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 hypocenters 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 hypocenter. Two approaches are available for the case where the hypocenter is within the source but the closest point from the rupture to the site is not within the source (see Figure 1). In the 'strict' ap-

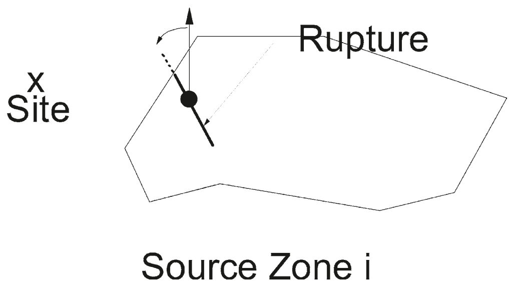

Fig. 1. Treatment of rupture-site-zone geometry when the earthquake is located near a source boundary.

proach, 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 approaches, some choosing the strict 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. This distribution is assumed to apply to small events (with negligible source dimensions) and is modified for the effect of magnitude-dependent rupture dimensions. This approach is based on the following two assumptions: (1) hypocenters occur on the deepest fraction T of the earthquake rupture, and (2) the normalized distance from the bottom of the rupture to the hypocenter is uniformly distributed between 0 and T. The value of T is specified by each team and is a percentage of the total width of the seismogenic zone. These assumptions are used to calculate a weighting function that represents the probability that a certain combination of hypocentral depth and magnitude is realizable (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 normalizing the probability so that the sum of probabilities is unity. Figure 2 illustrates the weighting functions and resulting magnitude-dependent depth distributions. In the "loose" approach, the rupture is allowed to extend past the source boundary for the purposes of computing the minimum distance to the site. In the "strict" approach, the rupture is truncated at the source boundary.

3.2 *Fault Sources*

The geometry of fault sources is represented in three dimensions by a fault trace, a dip angle, and minimum and maximum

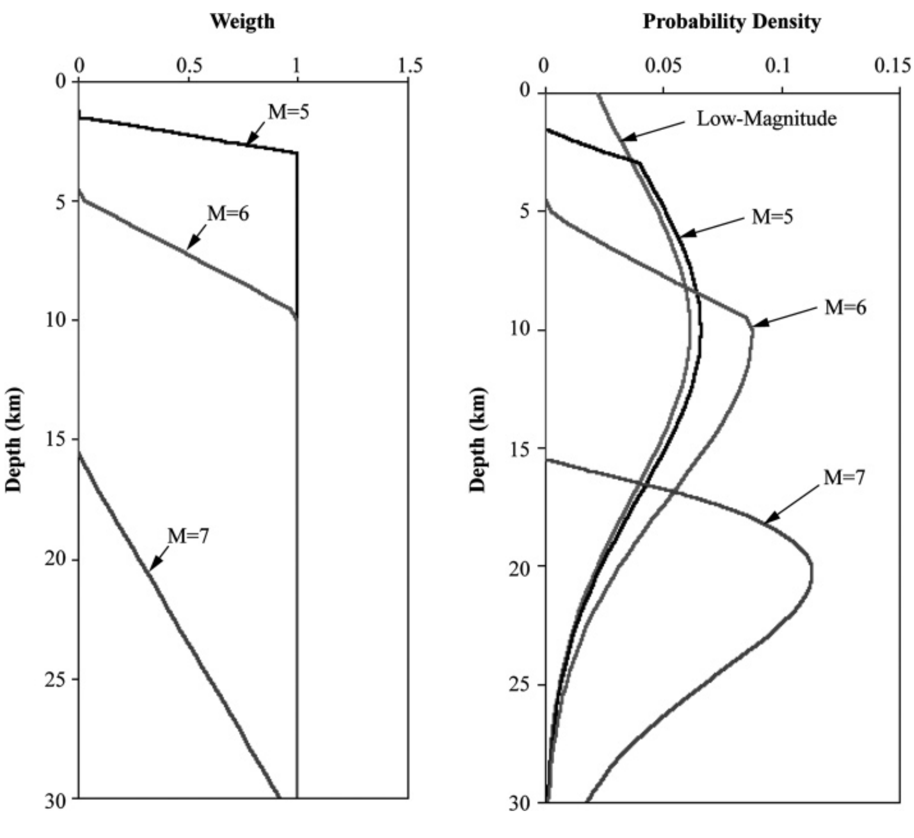

Fig. 2 Weighting functions and magnitude-dependent depth distributions for T = 0.5 (weighted approach).

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, 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

When earthquakes are modeled as occurring on faults in the hazard analysis, the length of the fault rupture is magnitude-dependent. The length is calculated using an empirical relationship between magnitude and the logarithm of rupture length. If the calculated rupture length exceeds the total length of a mapped fault or the source zone, it is truncated.

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.

3.3 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 and is associated with an attenuation equation.

3.4 Epistemic Uncertainty in Seismic Source Characterization

The PSHA methodology and software employed in the PEGASOS study allows each SP1 team to define its own source-characterization logic tree. The following discussion illustrates the common features of these logic trees.

The first group of logic-tree variables, called "global" variables, are those that affect multiple seismic sources. 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, maxi-

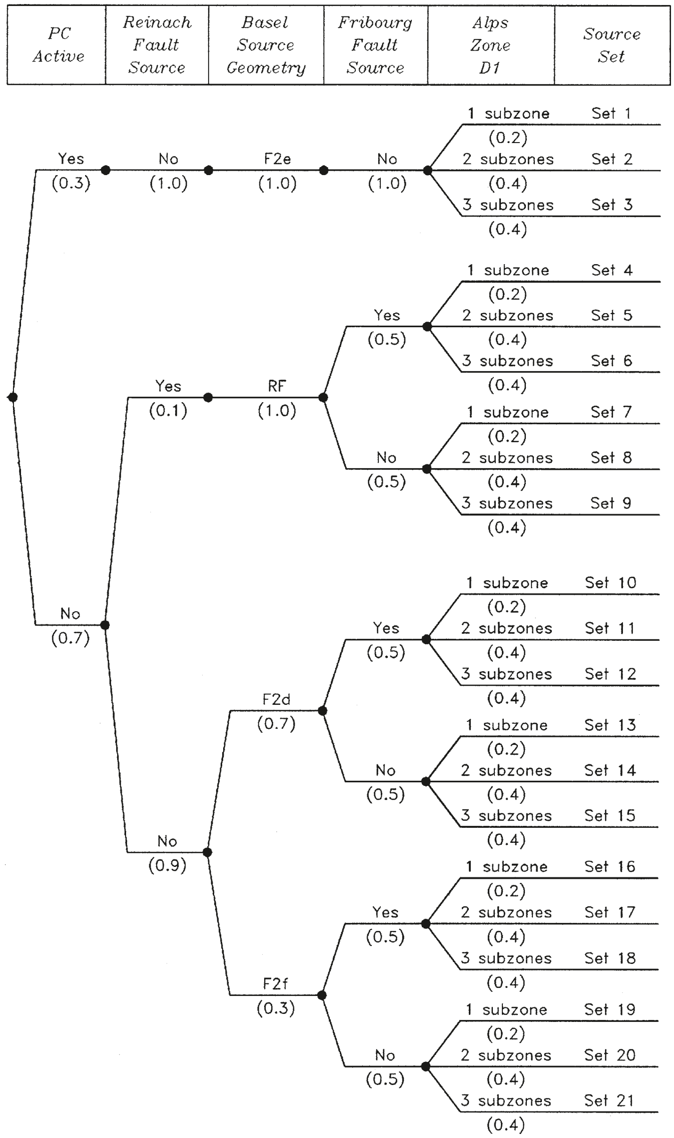

Fig. 3. Logic tree for expert team EG1a, as an example of capturing epistemic uncertainties in seismic source characterization using a logic tree.

mum magnitudes, etc.) are quite flexible. Global variables may be sub-divided into two main categories, as follows:

– 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., alternative zonation approaches of team EG1b, Burkhard & Grünthal (2008); 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 of the various seismic sources. Figure 3 illustrates the logic tree for seismic source zonation used by team EG1c (Schmid & Slejko 2008).

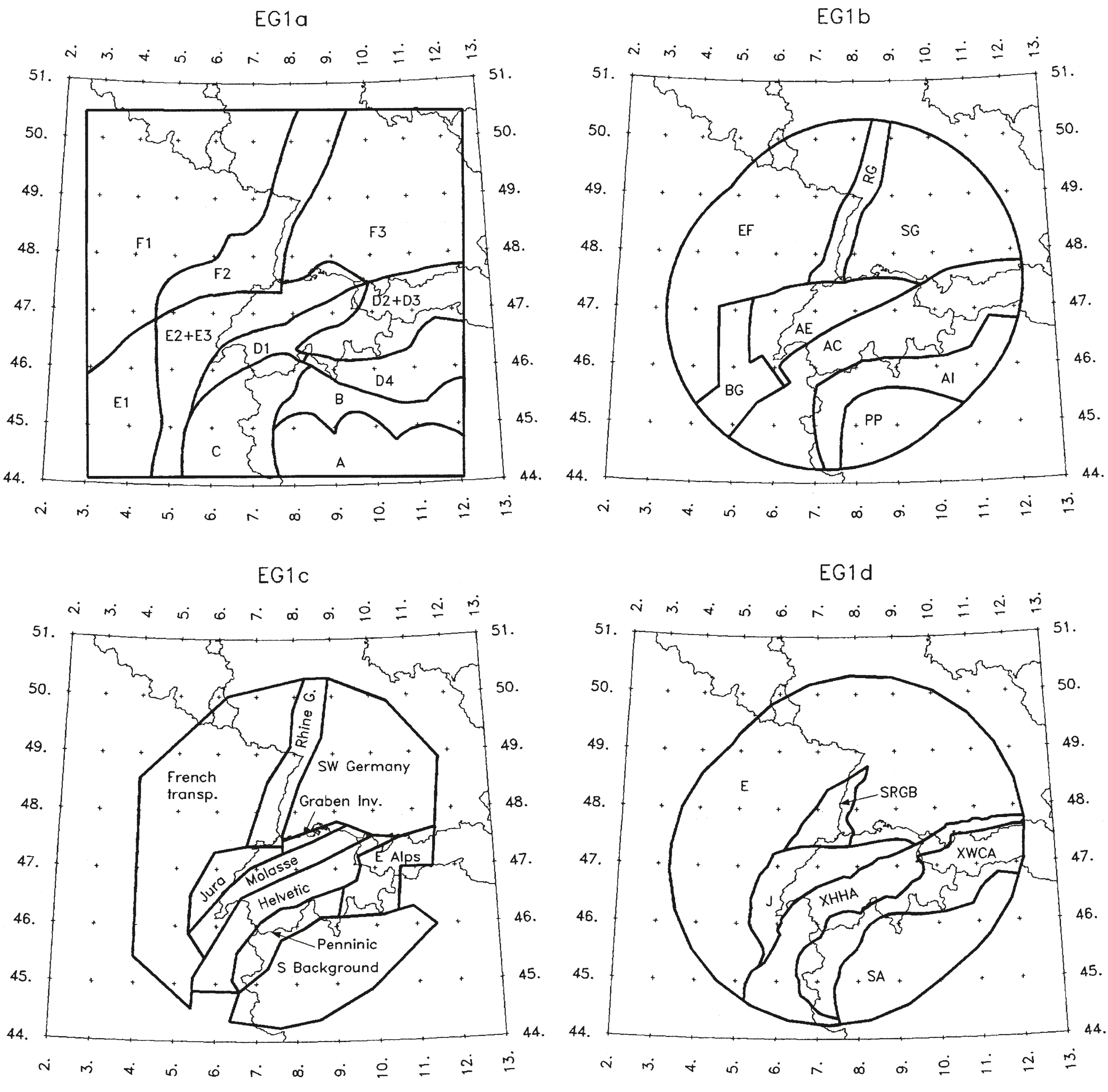

Fig. 4. Comparison of the primary seismotectonic regions developed by the four SP1 Expert Teams EG1a, b, c, and d.

– Variables related to the calculation of source parameters. Examples of these include the catalog to use, catalog-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. The dependence of these variables on the global variables is specified by the SP1 teams. Multiple, alternative values of these variables represent the conditional epistemic uncertainty in the source parameters, given the values of the global variables.

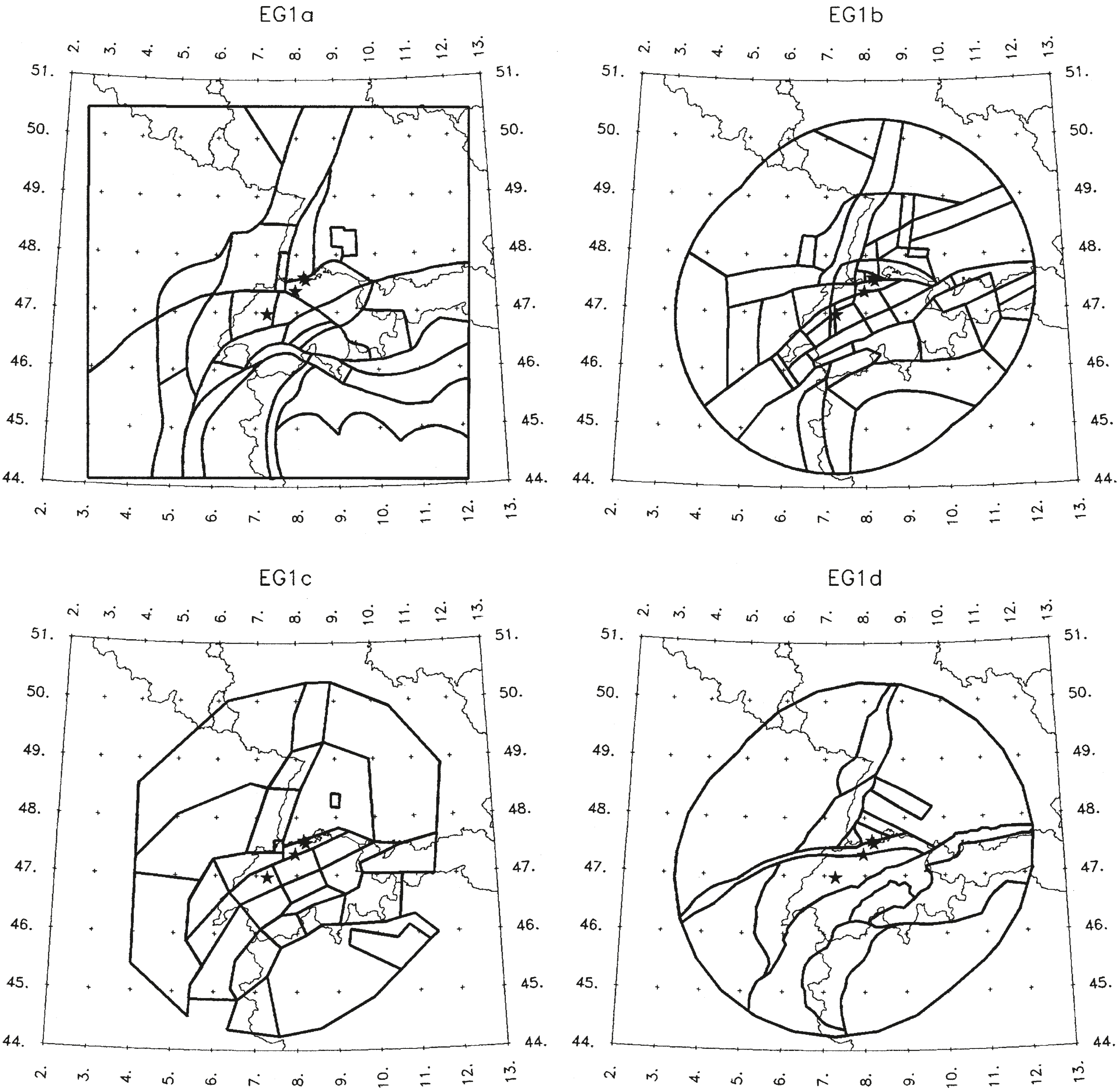

Fig. 5. Comparison of the most detailed seismic source definition developed by the four SP1 Expert Teams EG1a, b, c, and d. The stars show the locations of the four NPP sites.

4 Summary of Seismic Source Characterization Expert Assessments

In this section we present a comparison of the seismic source characterization developed by the four SP1 Expert Teams. Descriptions of the individual team models are given in Schmid & Slejko 2008, Burkhard & Grünthal 2008, Musson et al. 2008 and Wiemer et al. 2008 (this volume).

4.1 Seismotectonic Framework

The SP1 Expert Teams EG1a, b, c, and d 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 compares the primary seismotectonic regions identified by the four teams. There was general agreement among

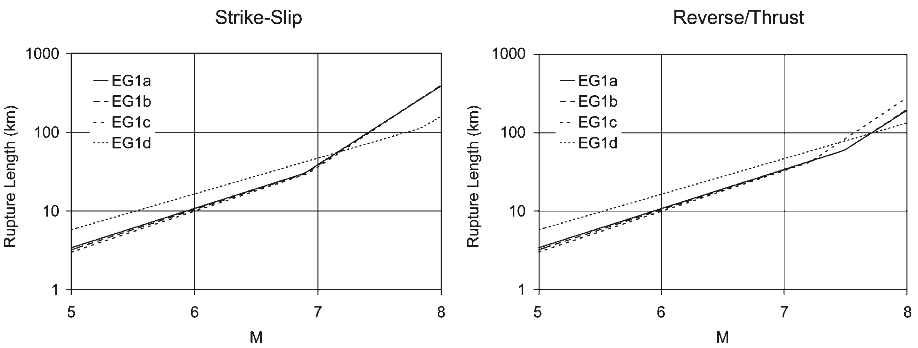

Fig. 6. Comparison of relationships between mean rupture length and earthquake magnitude specified by the four SP1 Expert Teams for northern Switzerland.

the four SP1 Expert Teams on the general seismotectonic framework for the region and the four expert 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.

4.2 *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) 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 with three levels of spatial smoothing. They also introduce some additional subdivisions of the larger seismotectonic elements. Figure 5 shows the maximum level of individual source zone definition developed by the four SP1 Expert Teams.

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 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 the team did not include specific source elements to represent them.

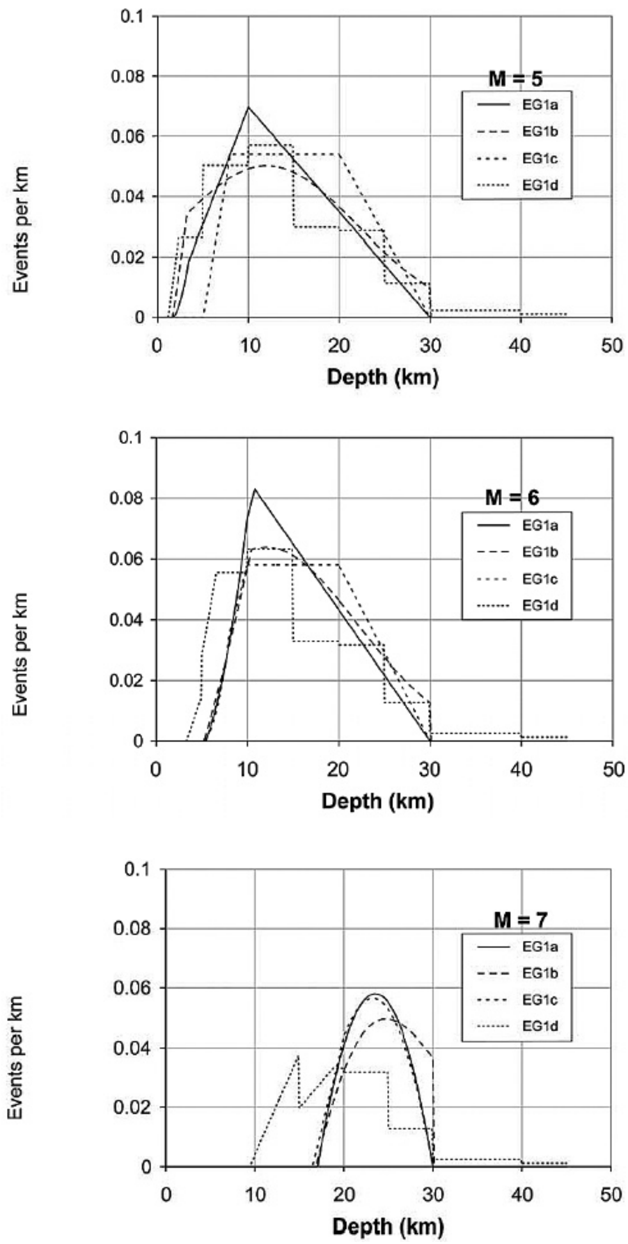

Fig. 7. Comparison of earthquake hypocenter depth distributions specified by the four SP1 Expert Teams for northern Switzerland.

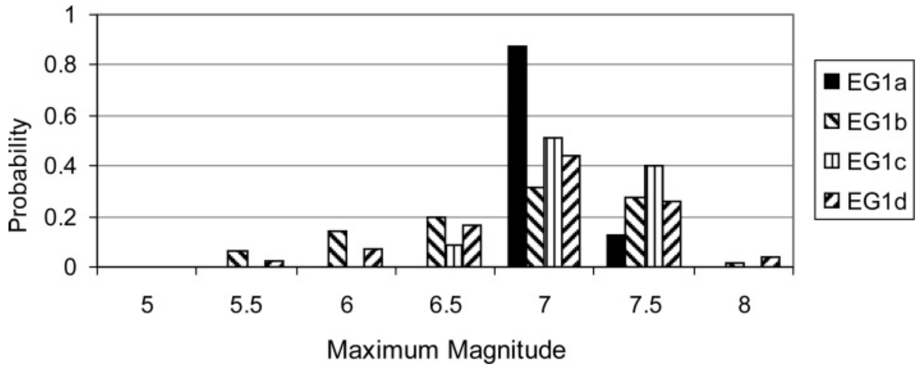

Fig. 8. Comparison of maximum magnitude distributions developed by the four SP1 Expert Teams for the Basel region.

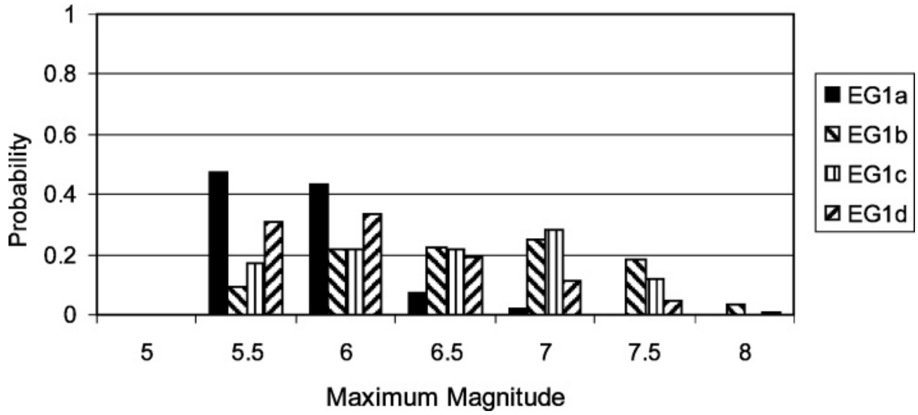

Fig. 9. Comparison of maximum magnitude distributions developed by the four SP1 Expert Teams for the Fribourg region.

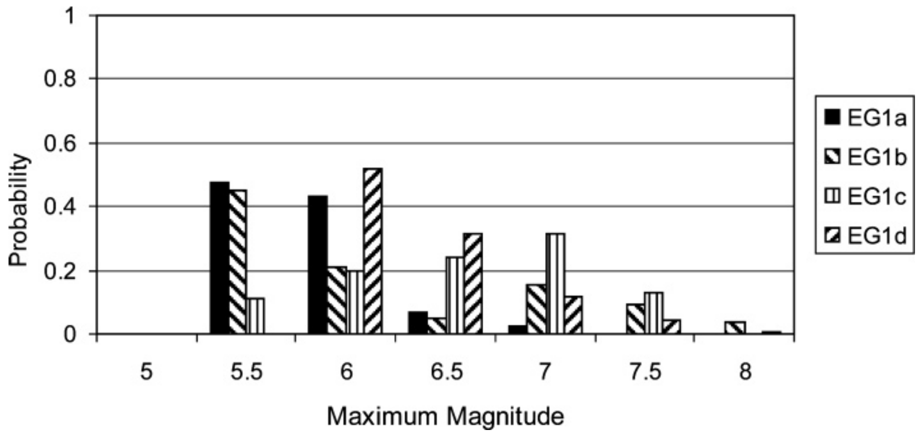

Fig. 10. Comparison of maximum magnitude distributions developed by the four SP1 Expert Teams for northern Switzerland near the border with Germany.

Other important seismic source definition elements are the specification of earthquake rupture dimensions and the earthquake depth distribution. Figure 6 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 term 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 mag-

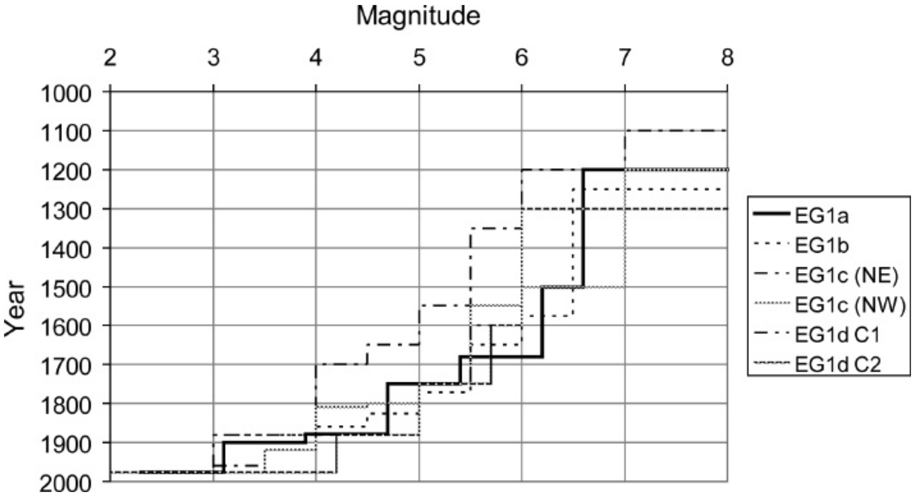

Fig. 11. Comparison of earthquake catalogue completeness estimates for northern Switzerland developed by the four SP1 Expert Teams for northern Switzerland.

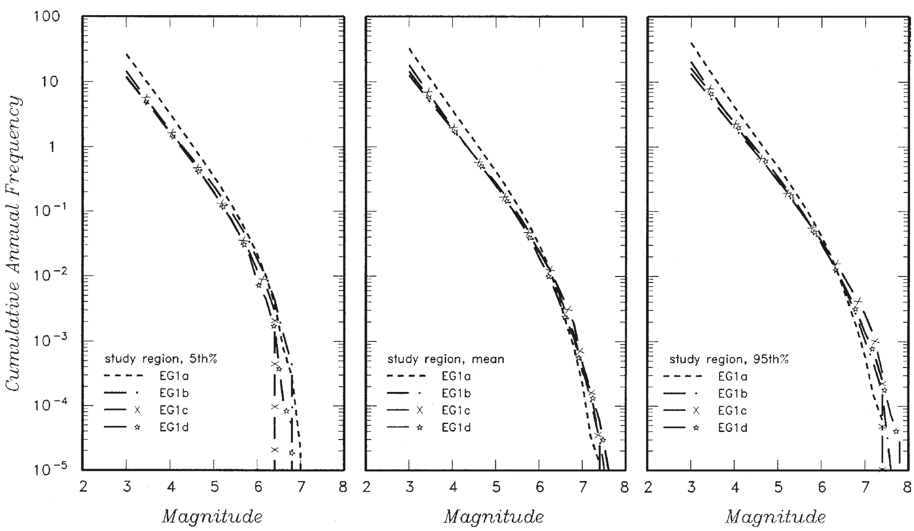

Fig. 12. Comparison of predicted earthquake recurrence rates for the region covered by each Expert Team's seismic source model.

nitudes, 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).

Figure 7 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. 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-to-width aspect ratio of 2.5 : 1.

4.3 Maximum Magnitude

All of the expert teams used the "EPRI" approach for assessing maximum magnitude (Johnston et al. 1994). 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 expert teams used either solely the extended-crust prior distribution or a mixture of the extend- and non-extended crust priors (depending on location) developed in the Bayesian analysis in Johnston et al. (1994).

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

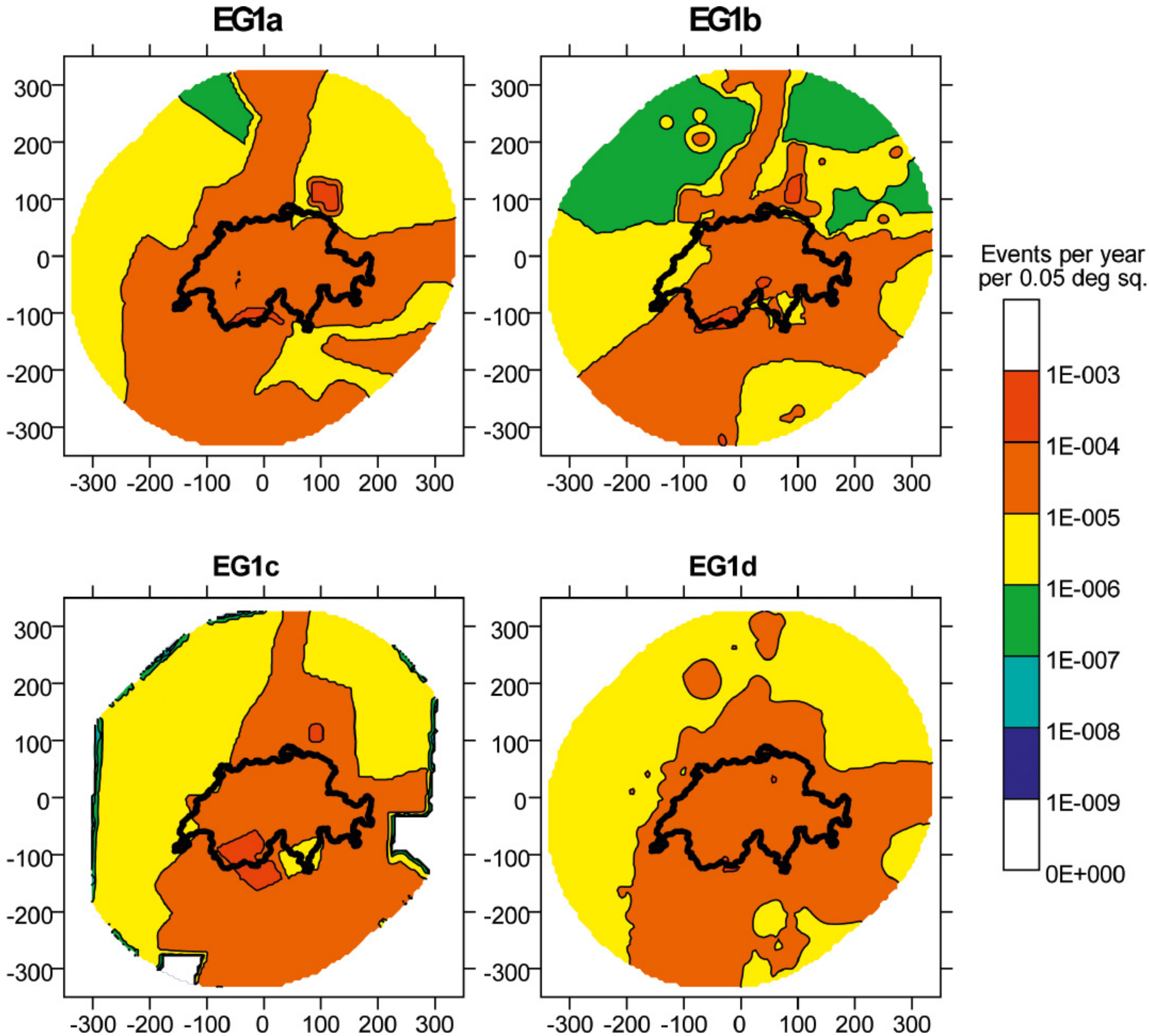

Fig. 13. Spatial distribution of the mean frequency of earthquakes with magnitudes ≥M 5. Units are earthquakes per year per 0.05° longitude × 0.05° latitude.

points were either source specific (teams EG1a and EG1b) or general (teams EG1c and EG1d). Figures 8, 9, and 10 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 one-half magnitude bins. The distributions show fairly close agreement for the Basel region, which included the 1356 earthquake. The differences are greater among the team's assessments for the other sources, due to the lack of a clear large-magnitude historical earthquake and different approaches taken by the teams to estimate maximum magnitudes.

4.4 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

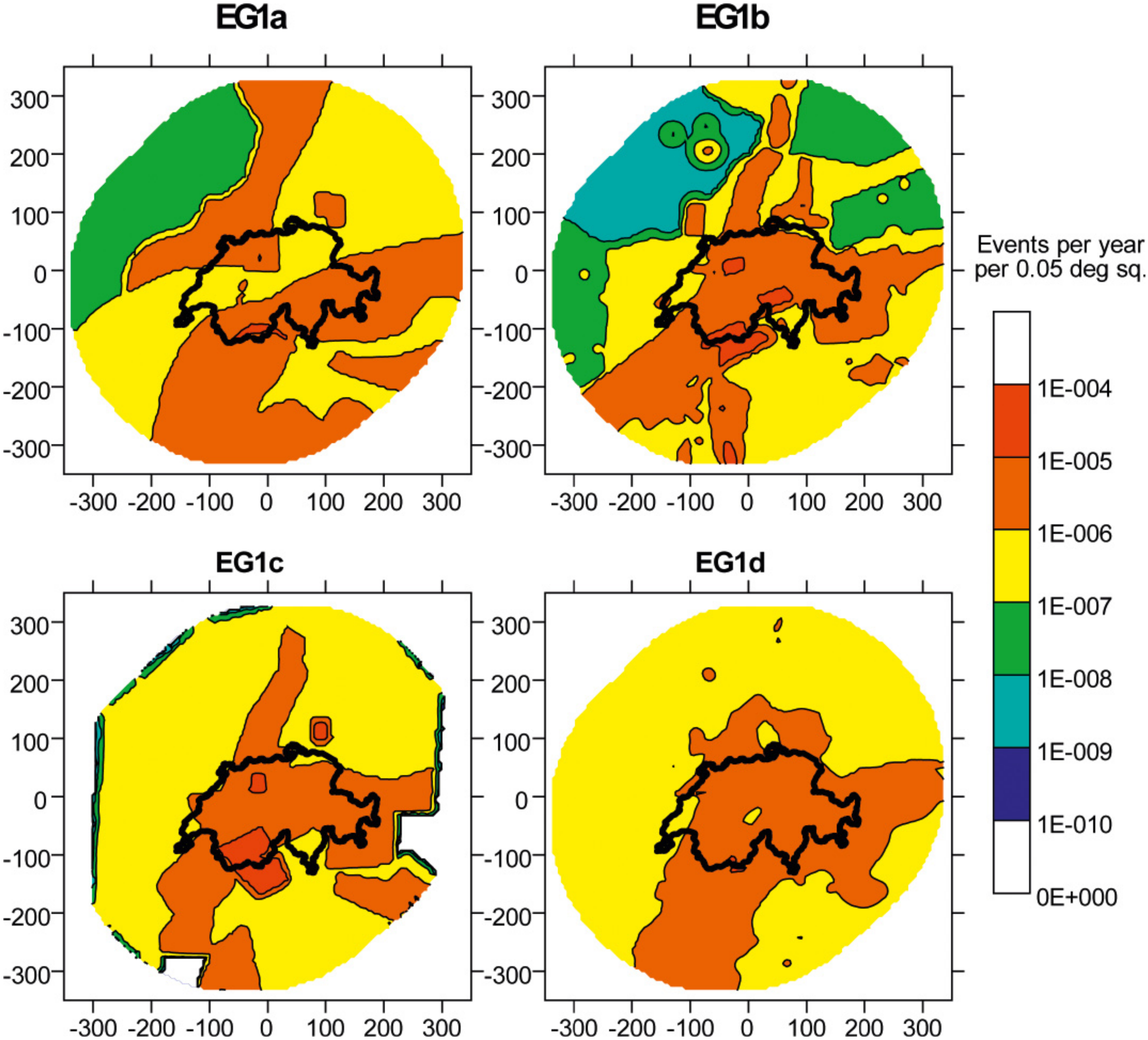

Fig. 14. Spatial distribution of the mean frequency of earthquakes with magnitudes ≥M 6. Units are earthquakes per year per 0.05° longitude × 0.05° latitude.

developed initial recurrence parameter estimates using the results of three declustering approaches.

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, 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 Expert Team developed estimates of catalogue completeness. Expert Teams EG1a, EG1b, and EG1d relied primarily on a version of "Stepp" plots to assess catalogue completeness, following the approach given by Stepp (1972). Expert Team EG1c combined this method with a historical analysis to develop estimates of catalogue completeness. Figure 11 compares the catalogue completeness estimates for northern Switzerland developed by the four teams. Expert Team EG1c

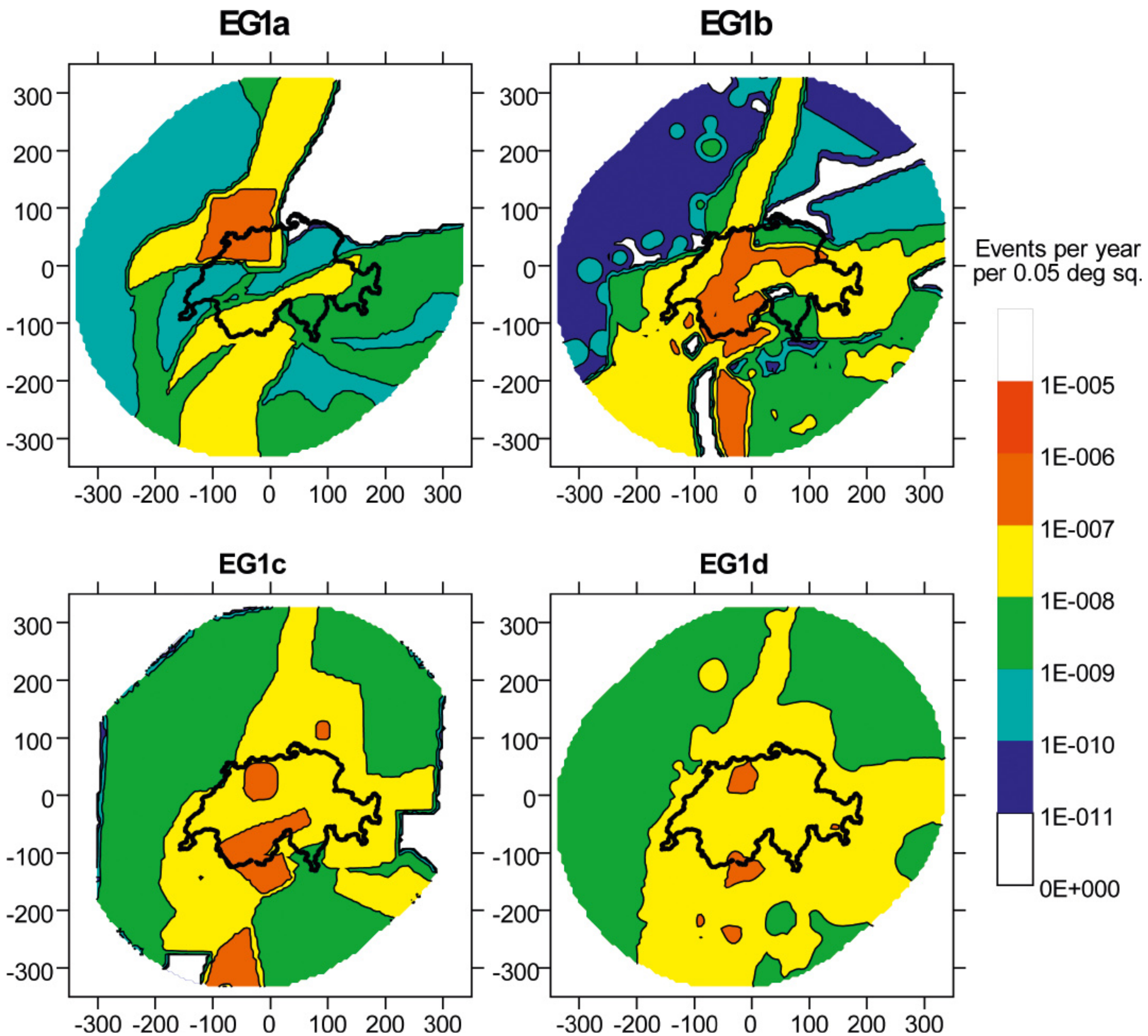

Fig. 15. Spatial distribution of the mean frequency of earthquakes with magnitudes ≥M 7. Units are earthquakes per year per 0.05° longitude × 0.05° latitude.

developed separate estimates for northwestern and northeastern Switzerland 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.

Earthquake Recurrence Estimates

All four expert teams used the truncated exponential mode to represent the earthquake recurrence for individual seismic sources. Distributions for earthquake recurrence parameters were developed primarily using the relative likelihood methods. The earthquake recurrence parameters were obtained using a maximum likelihood fit to the earthquake catalog data. Distributions for the earthquake recurrence parameters were then developed by computing the relative likelihood of a range of parameter values and then normalizing these relative like-

Table 2. 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}

lihoods to form a joint distribution for earthquake frequency and *b*-value.

Figure 12 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 2. Note that there are slight differences in the area covered by each model (Figure 4). The predicted recurrence rates and mean seismic moment rates are very similar.

Figures 13, 14, and 15 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 15 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, which is based on small-scale source zones with uniform spatial distributions of seismicity, and Team EG1d, which is based primarily on large-scale zones with spatial smoothing, produce very similar spatial distributions of the mean frequency of earthquakes.

5 Conclusions

The PEGASOS probabilistic seismic hazard project was conducted according to methodologies given in SSHAC (1997) for formal expert elicitations. Further, a number of enhancements were made to the methodology over previous studies that will serve to set a standard for future studies of this kind. A goal of the methodology is to capture uncertainties and to arrive at a representation of the views of the larger informed technical community. The seismic source characterization aspect of the project (SP1) was conducted by four interdisciplinary teams. The specific aspects of the seismic source models and the technical evaluations made by the SP1 teams are given in associated PEGASOS papers in this volume.

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This paper and others in the volume are dedicated to the memory of Dr. Martin Burkhard. Martin's warm personality and keen intellect will be missed by all who knew him through the PEGASOS project.

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