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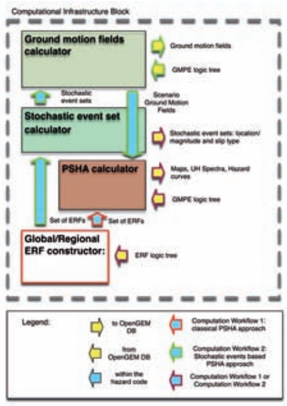

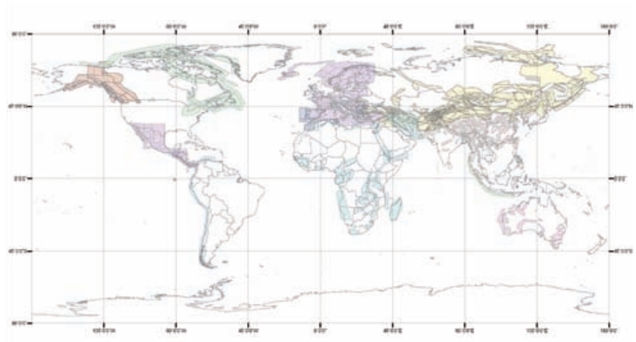

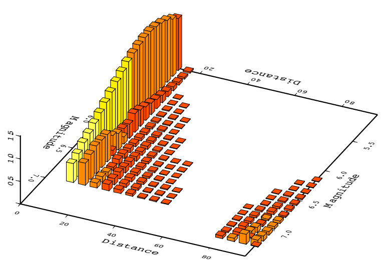

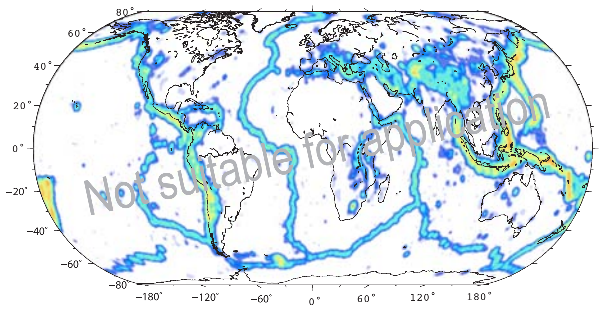

GEM1 Hazard: Description of Input Models, Calculation Engine and Main Results

By M. Pagani[1], D. Monelli[1], H. Crowley[2], L. Danciu[1], E. H. Field[3], S. Wiemer[1], D. Giardini[1]

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www.globalquakemodel.org

ABSTRACT

This document provides an overview of the PSHA input models collected during GEM1, of the engine used to perform PSHA calculations, and the methods and criteria adopted for computing a proof-of-concept global hazard map.

The GEM1 PSHA input repository contains seventeen national or regional models and one global model based on a smoothed seismicity approach. The oldest models were developed in the context of the GSHAP project, ended at the end of the 1990s; the most recent models are the ones prepared by the USGS-NSHM project for South America and a global smoothed seismicity model specifically produced for GEM1. In terms of geographical coverage the gathered models cover almost all the globe; the only missing regions are the Caribbean, the area around Papua-New Guinea and the Pacific Islands. These areas will hopefully be updated soon in the context of Regional Initiatives. In terms of information content, a relevant part of the PSHA input models is based on area sources while a minority uses fault sources. All the models but the Japanese and the model for the New Madrid Zone in the eastern US incorporate a time independent Poissonian model. Least but not last, epistemic uncertainties are taken into account by just some models, usually the most recent ones, and frequently treated as aleatory in the calculations.

The hazard engine, created on top of OpenSHA and fully integrated with it, accepts a set of standardized source typologies characterized by a time-independent occurrence model. At present, the seismic source typologies specified are: area, grid, fault and subduction sources. The engine calculates hazard following the procedure proposed by Field et al. [2003]. It accepts PSHA input models accounting for epistemic uncertainties in the definition of the Earthquake Rupture Forecast (ERF, in some cases also called the seismicity occurrence model) and epistemic uncertainties related to the definition of the Intensity Measure Relationships (widely known as Ground Motion Prediction Equations). The engine can generate a set of stochastic event sets representative of a given time span (just by sampling an ERF) and associate to each generated event a ground-motion field, with the possibility of accounting for the spatial correlation of ground motion. This feature will be of particular interest for future risk applications. The current version of the engine was successfully tested using almost all the PSHA input models contained in the GEM1 repository.

GEM1 developed an ad-hoc methodology to pre-process, compute and assemble the collected PSHA input models to create a first preliminary and patched set of seismic hazard maps covering the globe. The procedure adopted follows three main steps. In the first step we translate the original PSHA input into a common data model, in the second step we calculate the hazard using the standardized representation, finally, in the third step, we assemble the results to provide – as much as possible – homogenized products. We believe important to stress that, because of the heterogeneity of PSHA input models, the results obtained represent just a starting point in view of the final GEM goal of becoming “the uniform, independent standard to calculate and communicate earthquake risk worldwide”. Indeed, the exercise of creating a global hazard map in the context of GEM1 was meant to be a proof of concept more than a real attempt to already create a global, uniform, and reliable seismic hazard model.

Keywords: PSHA, input models, seismic hazard, hazard calculation engine, global seismic hazard;

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The GEM1 hazard team owes its gratitude the GEM1 Model Advisory Group (MAG) who provided a precious guidance, and gave assistance for improving the current report.

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1 The PSHA Input Models Collection

The creation of a suite of PSHA input models was a primary task for the GEM1 hazard team. The compilation of a comprehensive group of models covering different regions of the world was twofold: firstly to capture the current state-of-the-art in seismic hazard modelling at a global scale, and secondly to create a preliminary global seismic hazard model.

1.1 Overview

The GEM1 PSHA input model collection includes eighteen fairly heterogeneous models. The majority consists of national or regional models developed by national agencies or within international projects. The oldest models prepared within the GSHAP project, date back to the 1990s, whereas the most recent are the South America model, produced by the United States-National Seismic Hazard Mapping program (hereinafter USGS-NSHMP) in collaboration with the Centro Regional de Sismologia para América del Sur (hereinafter CERESIS) and the global smoothed seismicity model specifically prepared within GEM1.

Each model is implemented for specific software. In this regard, five models were created directly by the USGS-NSHMP or computed using their suite of codes, two models were developed for Crisis, one grounded on a modified version of Frisk88, one on EQRM and the remaining part were computed with proprietary codes or not clearly specified software (see **Table 1.1** for a more comprehensive description of the collected models).

In terms of source typologies, ten models contain area sources, seven contain grid sources and nine fault sources. Three models use area sources together with fault sources whereas five models combine faults sources with gridded seismicity. None of the models but the ones prepared by the NSHMP contains specialized sources for subduction environments (see **Table 1.2** for a more complete description).

The explicit inclusion of epistemic uncertainties is very inhomogeneous (see **Table 1.3**). Epistemic uncertainties are taken into account in the NSHMP-based models, in the Crisis models (Central America and Mexico), and in the Canada model. To keep calculation efficient and fast, epistemic uncertainties in the calculations are frequently considered as aleatoric.

Table 1.1 List of PSHA input models in the GEM1 collection.

Model #	Geographic area covered by the model	Organization providing the model	Contact person	Model format	Additional info
1	Africa	GSHAP			It contains a set of regional GSHAP models: sub-saharian Africa and Ibero-Maghreb models. We also included the Eastern Maghreb, Western Africa and Israel GSHAP models.
2	Alaska	USGS	M. Petersen	USGS format	Report available at: http://earthquake.usgs.gov/research/hazmaps/
3	Australia	Geoscience Australia	T. Allen	EQRM	Details of zones in Gaull (1990) Recurrence parameters from updated catalogue
4	Canada	Canada Geological Survey	S. Halchuk	GscFrisk	Report available at: http://earthquakescanada.nrcan.gc.ca/hazard-alea/OF4459/index-eng.php
5	Central America	Norsar	C. Lindholm	CRISIS	This model was developed within an international cooperation project called RESIS II.
6	Europe	GFZ-SHARE	G. Grünthal		This is a preliminary model for Europe developed by GFZ.
7	India	USGS-IIT	K. Jaiswal	USGS format	See also Jaiswal and Sinha [2007].
8	Iran	GSHAP			The model can be downloaded from the GSHAP website (http://www.seismo.ethz.ch/GSHAP/index.html)
9	Japan	J-SHIS	H. Fujiwara		The ASCII input files were kindly provided by P. Somerville (see also http://www.j-shis.bosai.go.jp/).
10	Mexico	UNAM	M. Ordaz	CRISIS	
11	New Zealand	GNS Science	M. Stirling		The model in the repository is proprietary. There's an updated model currently under development within OpenSHA. See also: http://www.gns.cri.nz/services/risk_assess/index.html
12	Northern Eurasia	GSHAP			The model can be downloaded from the GSHAP website (http://www.seismo.ethz.ch/GSHAP/index.html)
13	South America	USGS	M. Petersen	USGS format	This is an unpublished model developed by the USGS for the whole South American continent.
14	South East Asia	USGS	M. Petersen	USGS format	This model comprehends two originally separated models for Indonesia and Thailand
15	South East Asia	GSHAP			The model can be downloaded from the GSHAP website (http://www.seismo.ethz.ch/GSHAP/index.html)
16	Turkey	EMME/Koeri	K. Sesetyan		See Demircioglu et al. [2007] for model details
17	USA	USGS	M. Petersen	USGS format	Model available at: http://earthquake.usgs.gov/research/hazmaps/
18	Global Smoothed seismicity	ETH	J. Zechar		

Table 1.2 Typologies of sources contained in the PSHA input models collected.

Model #	Area covered by the model	Source typology			
		Area sources	Grid sources	Fault sources	Note
1	Africa	YES	NO	NO	
2	Alaska	NO	YES	YES	
3	Australia	YES	NO	NO	Each synthetic event modelled as a dipping plane with dimensions based on magnitude
4	Canada	YES	NO	YES	Cascadia subduction source is modelled deterministically
5	Central America	YES	NO	NO	
6	Europe	YES	NO	NO	
7	India	NO	YES	NO	A zonation is used to specify m_{max} values
8	Iran	YES	NO	NO	
9	Japan	NO	NO	YES	Some sources have a time dependent occurrence model
10	Mexico	YES	NO	NO	
11	New Zealand	NO	YES	YES	
12	Northern Eurasia	YES	NO	YES	
13	South America	NO	YES	YES	
14	South East Asia [USGS]	NO	YES	YES	
15	South East Asia [GSHAP]	YES	NO	NO	
16	Turkey	YES	NO	YES	The model also includes background sources
17	USA	NO	YES	YES	
18	Global smoothed seismicity	NO	YES	NO	
	TOTAL	10/18	7/18	9/11	

Table 1.3 Summary table of logic-trees contained in the PSHA input models in the GEM1 collection.

Model #	Area covered by the model	Logic tree	
		ERF	GMPE
1	Africa	NO	NO
2	Alaska	YES	YES
3	Australia	NO	NO
4	Canada	YES	NO
5	Central America	NO	YES
6	Europe	NO	NO
7	India	NO	YES
8	Iran	NO	NO
9	Japan	NO	NO (?)
10	Mexico	YES	NO
11	New Zealand	NO	NO
12	Northern Eurasia	NO	NO
13	South America	YES	YES
14	South East Asia [USGS]	YES	YES
15	South East Asia	NO	NO
16	Turkey	NO	NO
17	USA	YES	YES
18	Global smoothed seismicity	NO	n.a.
	TOTAL	6/18	6/18

2 A Unified PSHA Input Data Model

2.1 Description

The collection of PSHA input models described in the previous chapter was used as a representative sample of the current state-of-the-art. Despite the variety of formats used for model description, starting from this set we derived a data model able to represent all the gathered models; this data model contains the following seismic source typologies:

- Area source
- Grid source
- Fault source
- Subduction source.

All source typologies share the following assumptions:

- The seismicity temporal occurrence model follows a Poisson process
- Annual rates of occurrence for discrete intervals of magnitude describe the seismicity occurrence properties; usually evenly spaced intervals of 0.1 units are used. This description admits flexibility and generality; indeed, this unique representation allows the description of several diverse analytical magnitude-frequency distributions.

The four source typologies share some basic common properties; in adherence with this, the hazard calculator contains a "parent" class (called `GEMSourceData`) that includes general properties and methods. This class was later on extended into child classes to store typology-specific information.

A set of common parameters is defined for all source typologies:

- `Id` – Source identifier (for example, it can be the unique id used in the GEM database)
- `Name` – Source name (for example, the name of one source in the Mexico PSHA input model is "Baja California intraplaca norte")
- `tectReg` – Tectonic region type associated with the source. Once a - tectonic region to GMPE - mapping is defined, the engine calculates hazard using for each seismic source the appropriate ground motion prediction equation. The tectonic regions used in the current implementation are:
    - Active shallow tectonic region
    - Stable continental region
    - Subduction interface region
    - Subduction intraplate region
    - Volcanic region

In the following, we give a short description of each single source typology.

2.1.1 Area Sources

Area sources are, by far, the commonest typology used in the GEM1 PSHA input model collection. Area sources generally represent regions exhibiting the same seismotectonic regime and seismicity occurrence features. In PSHA, area sources are often modelled assuming that the seismicity is homogenously distributed over their extent. Is common use that, for each area, the occurrence parameters are calculated by processing the subset of events (from regional, national or international catalogues) occurred within the polygon. This procedure frequently creates a trade off between the need for small areas, so as to guarantee homogeneity in the underlying seismogenic process, and the necessity for large area sources so as to select large sets of events and – therefore – reliably compute the seismicity occurrence parameters.

In the scientific community is widely accepted that area sources correspond to the crudest seismic source model, nevertheless, their use is still quite frequent because of the lack of information needed to consistently define more accurate representations of seismic sources and of the corresponding seismogenic process. One major criticism to area sources is the subjectivity implicitly assumed in the definition of their geometry; this is, indeed, one of the main motivations that fostered the development of grid models.

In the GEM1 seismic hazard engine, the information used to describe area sources is collected into the `GemAreaSourceData` class. These are the main fields this class contains:

- `Reg` –The geographic region of pertinence for the modelled area i.e. the polygon bordering the area source. It corresponds to an array of locations described in terms of latitude, longitude [decimal degrees]
- `magfreqDistFocMech` – The seismicity occurrence model defined as a collection of discrete magnitude-frequency distributions each associated with a focal mechanism. Through this object is possible to specify the properties of one or many tectonic trends (or faulting families) and consequently reduce the degree of uncertainty related to the distribution of possible seismic sources within an area.
- `aveRupTopVsMag` – This field corresponds to an array containing two columns and *n* rows. It specifies the depth to the top of rupture for discrete intervals of magnitude. The example in the table below shows that magnitudes between 6.0 and 6.5 have a depth to the top of rupture equal to 5.0 km whereas the top of rupture for magnitudes above 6.5 is at the topographic surface.

Magnitude	Depth to the top of rupture [in km]
6.0	5.0
6.5	0.0

- `aveHypoDepth` – The average hypocentral depth [in km]. This depth is used for all the point ruptures considered in the calculation. These ruptures correspond to the ones with magnitude lower than the minimum value contained in the `aveRupTopVsMag` array.

2.1.2 Grid Sources

Grid sources can be considered as a PSHA source model alternative to area sources since they both try to represent distributed seismicity. Grid sources usually derive from the application of seismicity smoothing algorithms [Frankel, 1995; Woo, 1996]. The use of these algorithms carries some advantages compared to area sources, indeed, (1) they remove most of the unavoidable degree of subjectivity due to the definition of the geometries and (2) they define a seismicity spatial pattern that is, usually, more similar to reality. Nevertheless, some smoothing algorithms require the a-priori definition of some setup parameters that expose the calculation to a certain partiality level.

Grid source models are implemented in the GEM1 hazard engine simply as set of point sources. The following parameters are required:

- `hypoMagFreqDistAtLoc` –The seismicity occurrence rates for discrete intervals of magnitude for the distinct possible faulting systems. Conceptually, this object is similar to the `magfreqDistFocMech` parameter previously described while commenting area sources.
- `aveRupTopVsMag` – Same parameter as for Area sources;
- `aveHypoDepth` – Same parameters as for Area sources;

2.1.3 Fault Sources: Shallow Faults and Subduction Faults

Fault sources are by far the most rigorous way to describe seismic sources. However, their correct definition in terms of geometry and recurrence parameters necessitate an amount of information currently available only in areas with clear surface evidences of faulting activity and high seismicity rates (e.g. California, Japan). In the GEM1 source data model there are two fault source typologies; the first is normally used to describe simple shallow faults while the second one, in general, is used to model subduction interface faults. In the following we give a short description of the parameters characterizing these two typologies, which differ mostly in the way the fault surface geometry is described.

In the `GEMFaulSourceData` class, the following are the fields used to describe a shallow fault source:

- `mfd` – The discrete magnitude-frequency distribution (usually an interval width of 0.1 units of magnitude is used).
- `trc` – The fault trace given as a set of geographical locations (latitude, longitude)
- `dip` – Average dip angle (follows the Aki-Richards convention) [degrees]
- `rake` – Rake angle (follows the Aki-Richards convention) [degrees]
- `seismDepthLow` –The lower seismogenic depth i.e. the lowest limit of the seismogenic interval on the fault surface [in km]

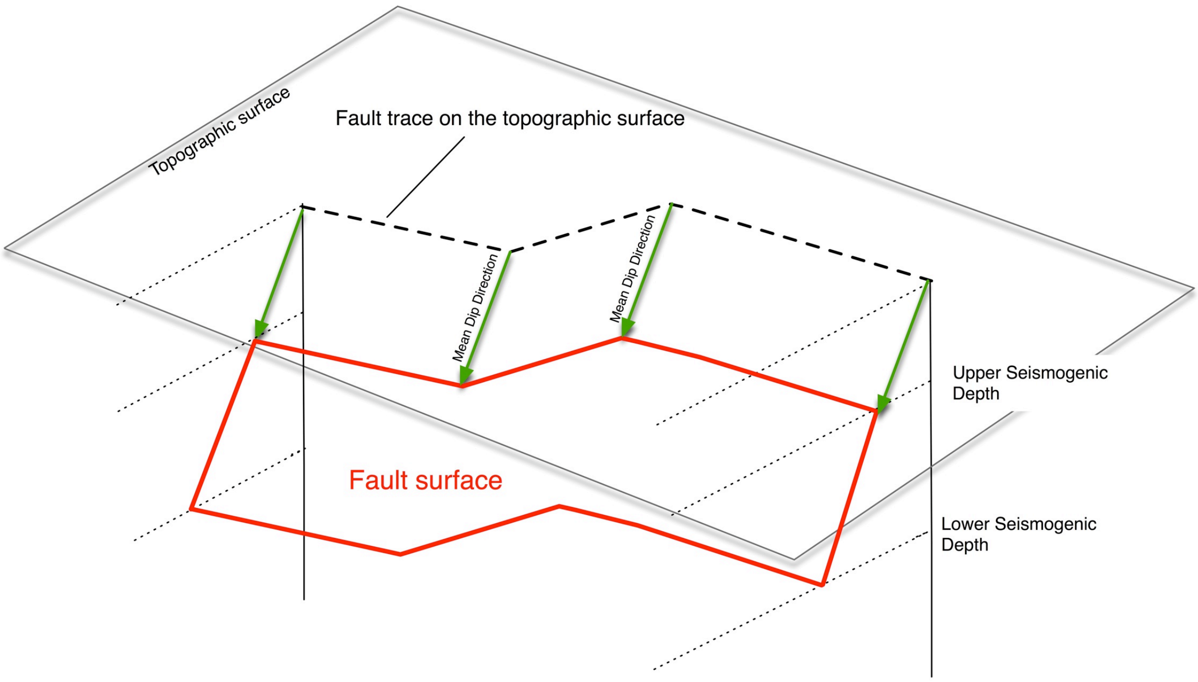

Figure 2.1 Schematization of a simple fault. The black dashed line is the fault trace at the surface. The red curves are the borders of the fault surface. The green arrow shows the dip angle. On the right side of the picture the seismDepthLow and the seismDepthUpp are appropriately placed.

- `seismDepthUpp` – This is the upper limit of the seismogenic interval [in km]
- `floatRuptureFlag` – Flag used to specify if ruptures are assumed to float over the fault surface or cover the whole fault surface.

In the `GEMSubductionFaultSourceData` class, the following fields are defined:

- `mfd` – The discrete magnitude-frequency distribution (usually an interval width of 0.1 units of magnitude is used).
- `topTrace` –The upper trace of the subduction fault - it corresponds to a set of locations defined in terms of latitude, longitude and depth.
- `bottomTrace` –The bottom trace delimiting the subduction fault surface - it corresponds to a set of locations defined in terms of latitude, longitude and depth.
- `rake` –The fault rake (follows the Aki-Richards convention)
- `floatRuptureFlag` – Flag used to specify if ruptures are assumed to float over the fault surface or cover the whole fault surface.

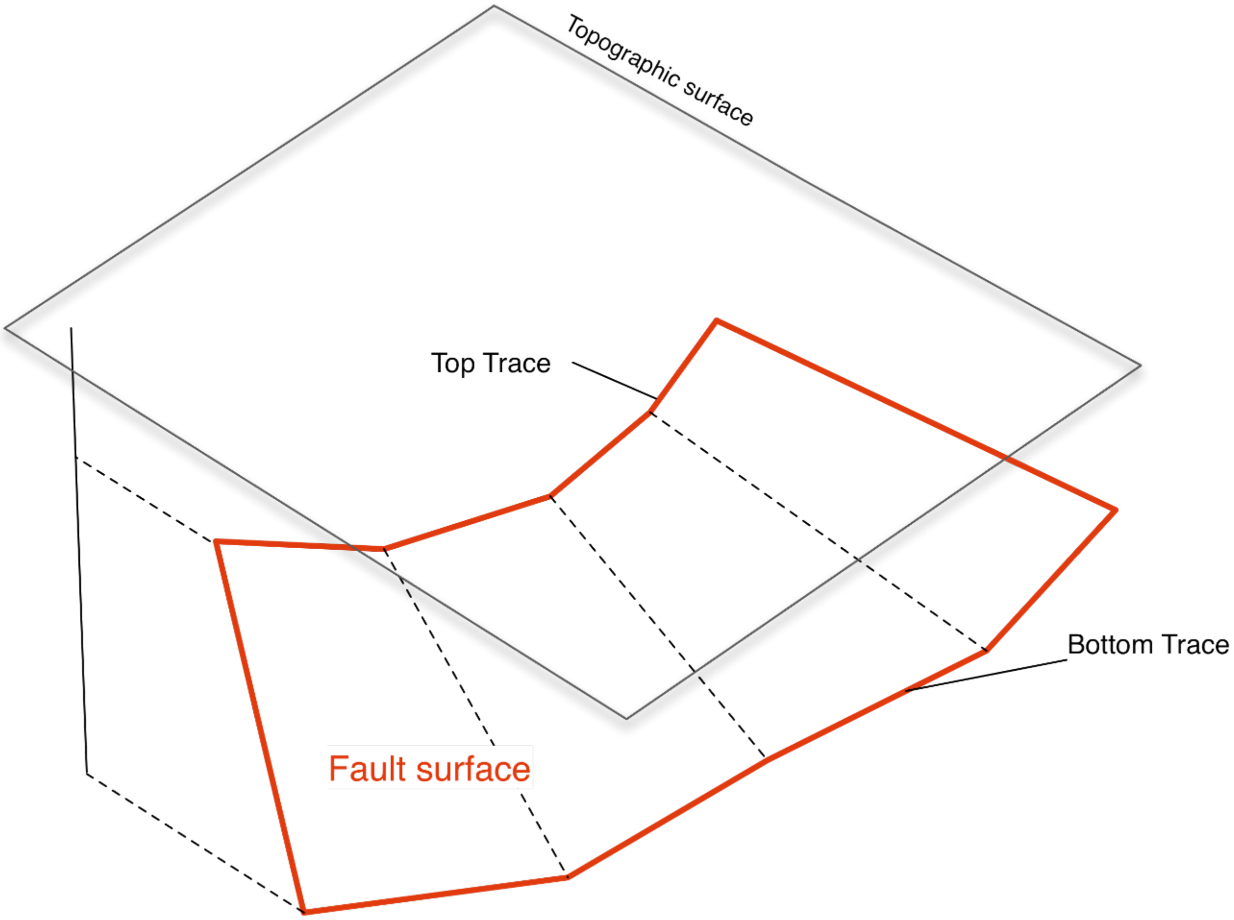

Figure 2.2 Schematization of a subduction fault.

2.2 PSHA Input Models: Their Representation in GEM1

After collecting and characterizing seismic sources in a homogeneous manner, the next step in the creation of the PSHA input was the organization of sources into a hazard model. For convenience, in the GEM1 hazard engine all the models were organized into a logic tree structure (in this case the reference class is the `GemLogicTree`). Note that in the engine, for each PSHA input model we defined two distinct logic trees: one for the creation of the ERF and one relative to IMRs (better known as GMPEs).

2.2.1 ERF Logic Tree

In case of a simple input model, i.e. a model that does not account for epistemic uncertainties, the information describing seismic sources is grouped into an array of `GEMSourceData` objects. The size of this array will correspond exactly to the number of sources included in the model.

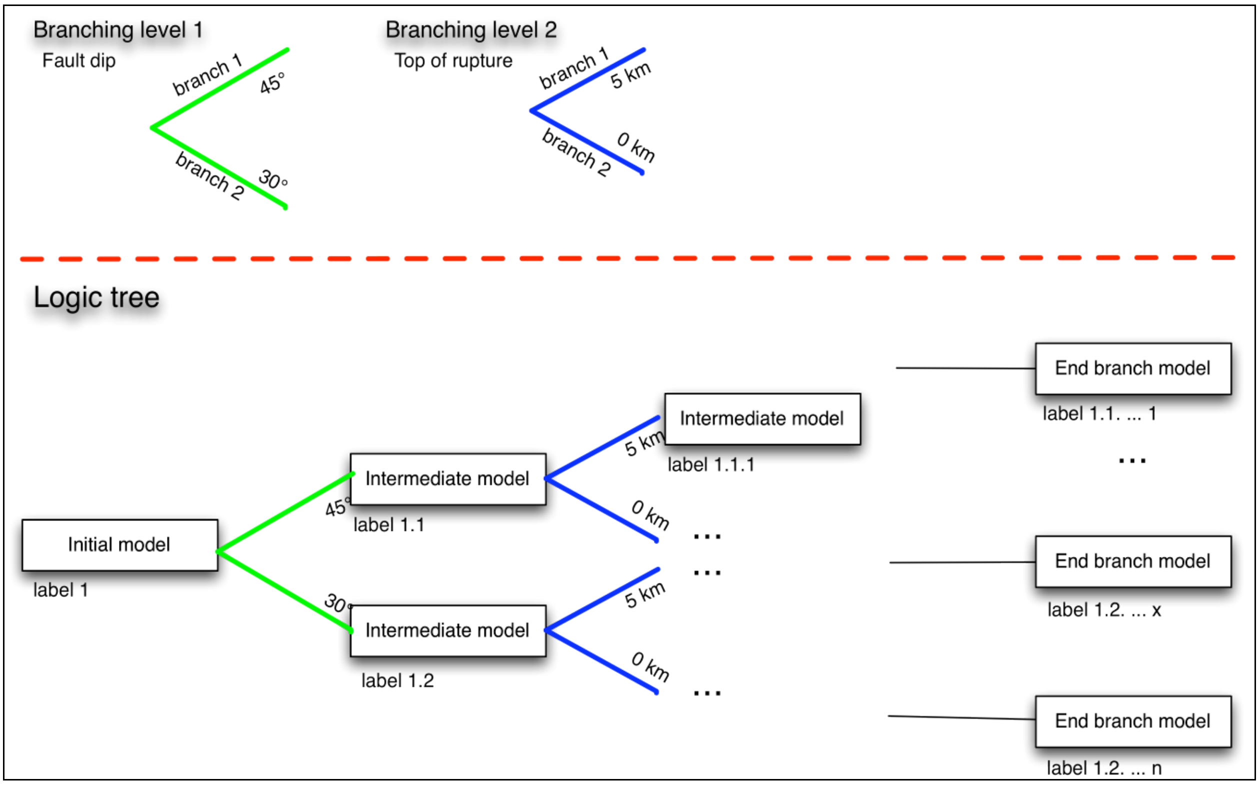

Figure 2.3 Example of the structure of a logic tree as used in the GEM1 seismic hazard engine. The upper part of the figure shows the definition of some branching levels used in the creation of the logic tree. The lower part of the figure shows the structure of the logic tree obtained by combining the initial PSHA input model and the branching level defined as represented in the upper part of the figure.

In the case of more complex models, i.e. models that account for epistemic uncertainties related to the creation ERF, in the GEM1 seismic hazard engine there exists a data structure capable to fully describe the structure of the logic tree (in the current version of the engine we do not support logic trees with branching levels with uncorrelated branches). For calculation purposes, the logic tree data structure we defined simply stores one `GEMSourceData` array for each end branch of the logic tree (note that this is a situation peculiar to GEM1 where indeed PSHA input models were already available and not created on purpose).

Figure 2.3 shows an example of the GEM1 logic tree structure. As it's evident in the figure, the central element used to describe the structure of a logic tree is an object called branching level. Each branching level contains one or more branches, every single one characterized by a parameter value (e.g. the dip angle) and a weight. In the example of **Figure 2.3** we put two branching levels, one accounting for epistemic uncertainties related to fault geometries the other used to specify two possible depths of the top of rupture. Within our logic tree model the defined branching levels can be combined whatsoever so as to create the desired tree structure (for an example, see the lower part of **Figure 2.3**).

2.2.2 IMR Logic Tree

In parallel with the definition of the ERF logic tree, the GEM1 seismic hazard engine provides the option of creating a logic tree to account for epistemic uncertainties related to IMRs (Intensity Measure Relationship i.e. Ground Motion Prediction

Equation). In this case, there will be a hash map of IMRs associated to each end branch of the logic tree; each hash map contains as many IMRs as the number of Tectonic Regions considered in the model. This data structure maps the correspondence between each Tectonic Region and each IMR i.e. given a source belonging to a specified tectonic region, by means of this mapping the hazard calculation engine is capable to use the appropriate IMR to compute the hazard at the site.

Table 4.1 shows an example for the content of such hash map of IMRs; it can be noticed that this table describes the two end branches of a very simple logic tree. The difference in the properties of the end branches is just in the IMR used for seismic sources belonging to active shallow tectonic regions.

3 The GEM1 Seismic Hazard Engine: Main Components and Calculation Workflow Description

The GEM1 seismic hazard engine is organized into packages. **Figure 3.1** shows a screenshot of a portion of the IDE tool (Eclipse, see also [2]) used by the hazard team for programming the engine; in particular, the figure shows the main structure of the package containing the classes composing the engine. The computational core is contained in the `calc` package, the `data` package includes the original ASCII input files of the PSHA input models collected so far, the `results` package groups the output ASCII files whereas the `local`, `commons`, and `util` packages contain general classes helpful for the calculation engine.

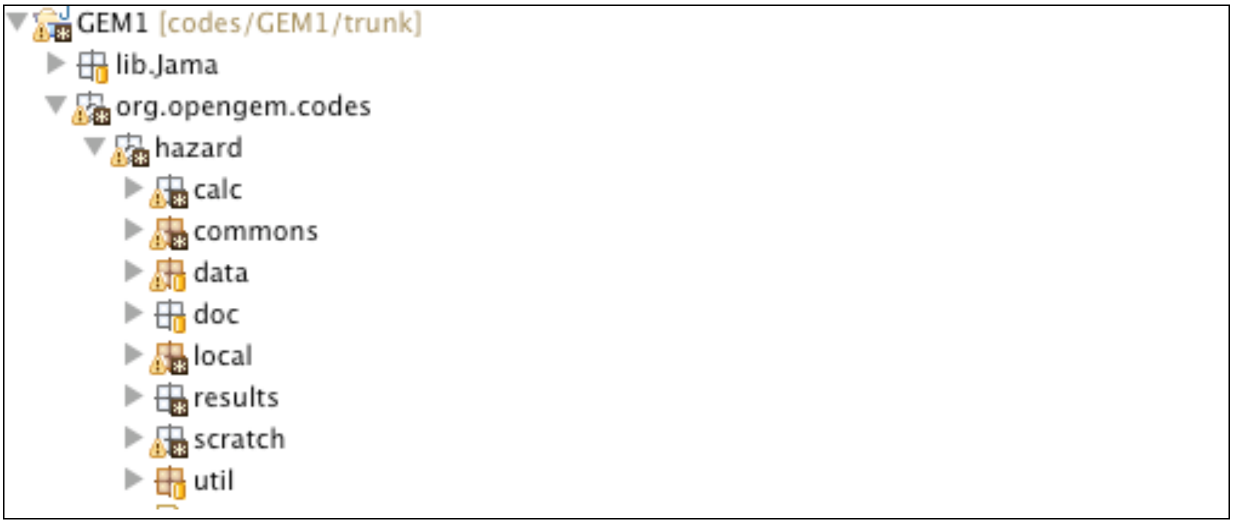

Figure 3.1 Main package structure of the GEM1 seismic hazard engine project

Entering into a major detail, the `calc` package is furthermore organized into sub-packages; **Figure 3.2** shows the structure of sub-packages. The real calculation core resides in the `GemHazardCalculation` package. `GemModelData`, `GemModelParser` and `GemLogicTree` are packages pertinent to the storage of the information needed to describe a PSHA input model.

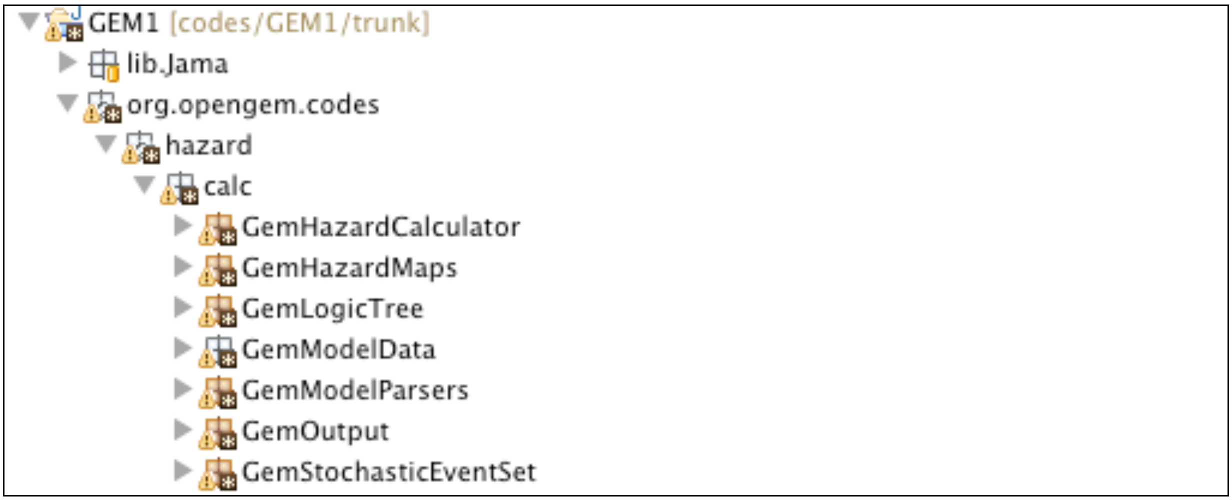

Figure 3.2 `Calc` package: sub package structure description

3.1 An Example of Calculation Workflow

Let's consider a very simple PSHA model, whose original information is made available as an ASCII input file, and let's go through the calculation workflow needed to obtain typical hazard results (note that these are the typical circumstances for the GEM1 hazard team). In particular, we want to use this model to calculate seismic hazard curves for an investigation time of 50 years in a specified area covered by the PSHA input model.

The first step in the hazard calculation workflow is to create a parser class i.e. a piece of code capable to read the information contained in the original ASCII input file and to convert it in a format compatible with the GEM1 seismic source data model. In more detail, the parser processes and transfers the information describing each source in the input file to the fields of the appropriate source typology class. In case the model is residing in a database (DB) instead of an ASCII input file, the parsing process can be simply substituted by a query. In either case, the final result of this initial step is an array of `GEMSourceData`. In the GEM1 seismic hazard engine, for convenience, we represent all the models using a logic tree data structure; in the case we're currently considering, the ERF logic tree will have a single branch (1.0 weight) within one single branching level.

Immediately after the creation of the source data array and the ERF logic tree, it is necessary to create the IMR logic tree. In case all seismic sources belong to the same tectonic region and epistemic uncertainties are not considered the logic tree will simply require one IMR.

Additional information required to execute the calculation is the set of sites of interest (i.e. list of sites where hazard curves have to be calculated), and the type of expected results (e.g. the intensity measure type PGA, PGV, SA, …, the probability of exeedence for hazard maps (2%, 10%) in the given time period). Once the engine receives this information the calculation is performed without any additional supervision.

In case of a model based on a logic tree, the engine will generate as many hazard curves files as the number of end branches (given that in this preliminary version we do not support branching levels containing uncorrelated branches) plus mean hazard curves computed using the information in the logic tree structure and, if requested, mean hazard maps.

4 Implementing the GEM1 Hazard Model: An Introduction

After putting together a suite of PSHA input models and preparing a data model capable to describe them in an unified fashion the ultimate GEM1 hazard tasks included (1) the representation of the collected PSHA input models into the unified PSHA input model (see Section 3) and (2) the implementation of the GEM1 "patchy" global hazard model. We underline that the creation of a global hazard model in the context of GEM1 was expected to be a proof-of-concept exercise more than a real attempt to create a reliable and homogeneous product.

Figure 4.1 shows a diagram of the workflow followed to perform hazard calculations; the common modus operandi incorporated three main steps. The first step was the representation of the PSHA input into the GEM1 standardized input data model, the second was the calculation of hazard using the GEM1 hazard calculator, and finally the assembling of results.

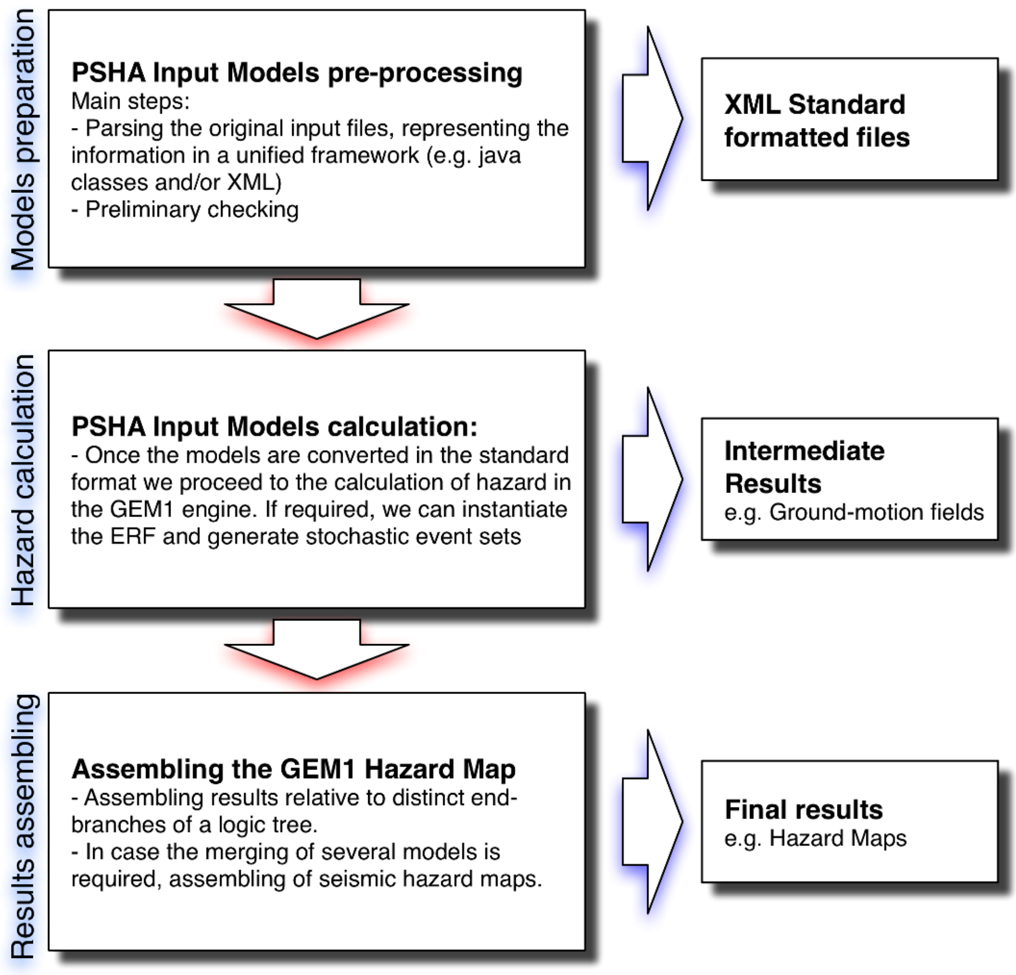

Figure 4.1 GEM1 global model calculation workflow and results provided.

In major details, these are the main steps forming the workflow:

- We converted 14 of the original PSHA input models available in the GEM1 repository (see Chapter 1) into a standard representation. The conversion process, strongly dependent on the format of the original files, was completed on a single model basis; in practice, we created customized Java codes, called parsers, capable to read the original ASCII input files and create the necessary Java objects so as to appropriately store in a standardized fashion the information describing seismic sources.

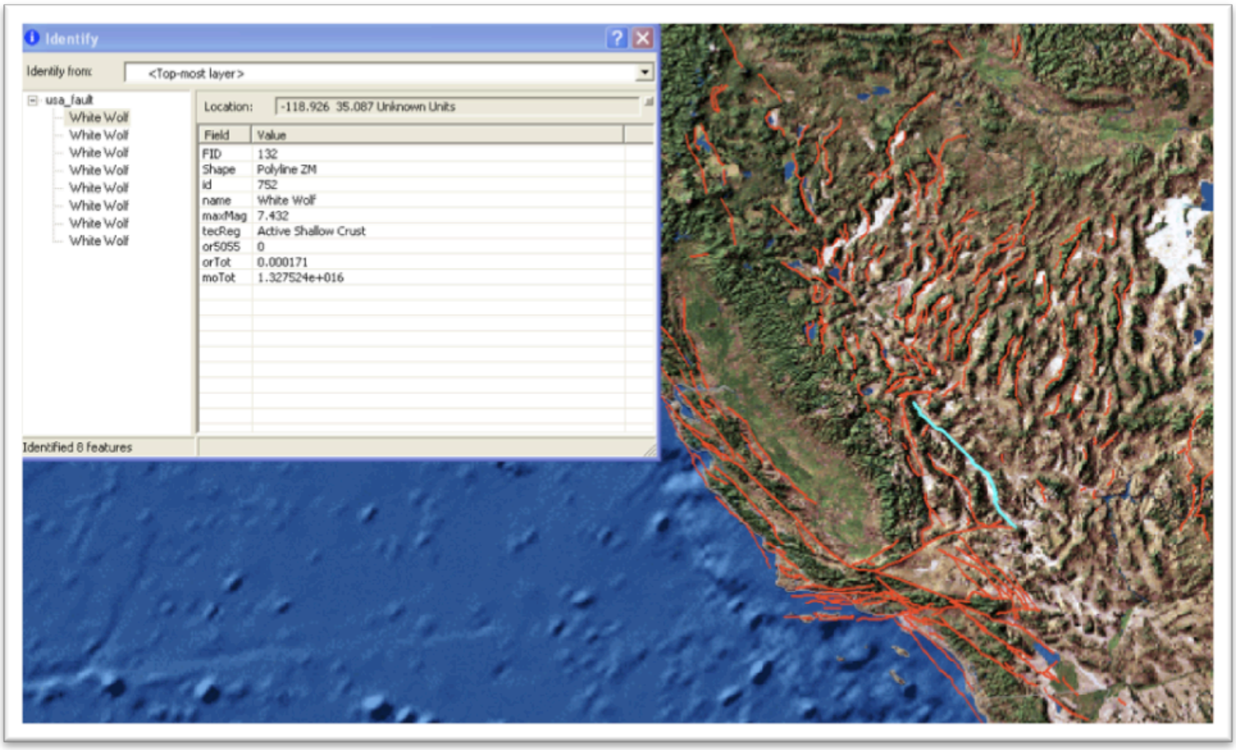

Figure 4.2 Screenshot of the NSHMP 2008 WUS faults as represented into a GIS. The window in the upper left corner shows the properties associated to the selected fault (i.e. the cyan lineament in the right part of the figure).

- Having the models available in a standard format prompted the creation of tools for their inspection and preliminary verification. Currently we have tools to convert PSHA input models into files readable by Geographic Information Systems and common plotting tools such as the Generic Mapping Tool [3]. **Figure 4.2** shows an example of the information parsed from the NSHMP 2008 Western United States PSHA Input model as represented in a Geographic Information System. The visual inspection of source geometry and the look up of their properties proved to be a useful tool for better understanding the input models and for a preliminary checking of the information parsed.
- For each PSHA input model we provide the hazard engine with the corresponding unified representation collectively with typology and characteristics of the results required (i.e. a set of standardized calculations settings).
- The hazard code computes hazard and gives results (note that the computation time ranged between a few hours and some days, depending on the complexity of the PSHA input model – i.e. number and size of sources – and the size of the investigated area). In most of the cases we computed hazard curves for PGA considering an investigation time of 50 years. To demonstrate the capability of the engine to deal with models accounting for epistemic uncertainties, we calculated hazard using a very simple logic tree for IMRs. In particular, we used two alternative suites of GMPEs with elements as indicated in the table below [see also Douglas et al., 2009].

Table 4.1 Description of the two end branches of the GMPE logic tree.

End-branch 1.1 – weight 0.5	IMR for active shallow tectonic regions	Boore and Atkinson (2008)
	IMR for stable continental regions	Atkinson and Boore (2006)
	IMR for subduction sources	Zhao et al. (2006)

end-branch 1.2 – weight 0.5	IMR for active shallow tectonic regions	Chiou and Youngs (2008)
	IMR for stable continental regions	Atkinson and Boore (2006)
	IMR for subduction sources	Zhao et al. (2006)

- To get the definitive products (e.g. mean hazard maps for PGA with 10% probability of exceedance in 50 years) we post-processed partial results obtained at the previous point. The first post-processing step was the calculation of mean hazard maps from hazard curves; the second was meant to be the combination of different hazard maps to create a single global hazard map.

  Despite the considerable time invested in understanding and homogenizing the collected models, without doubts there are still differences between results provided by overlapping – or adjacent – models due to the original information used, the methods followed to identify sources and, the procedures adopted to derive seismicity parameters. These differences inevitably generate problems and inconsistencies in areas where the hazard depends on several models. Contrary to our first intentions and according to the GEM1 Model Advisory Group suggestions provided in November 2009 we delayed the testing of procedures related to the combination and harmonization of hazard maps so as to derive authoritative global seismic hazard maps.

The final GEM1 hazard results consist of probabilistic seismic hazard maps and site-specific hazard results (e.g. seismic hazard curves). In some cases, in addition to PGA we calculated maps for spectral acceleration Sa (referred to some periods) using multiple probabilities of exceedance (e.g. 10% and 2% probability of exceedance in 50 years), however, we did not consider this exercise of particular relevance for demonstrating the capabilities of the GEM1 seismic hazard engine.

In addition to the classical PSHA computation procedure, we implemented tools for the creation of risk specific products. In particular we developed:

- Codes capable to sample the ERF and generate stochastic event sets,
- Tools for the calculation of scenario ground-motion fields that accounts for the spatial correlation of ground motion,
- Tools for the computation of seismic hazard curves and seismic hazard maps in terms of (instrumental) intensity.

All these applications were of particular relevance for strengthening the connections between the GEM1 seismic hazard and the seismic risk engines.

5 PSHA Input Models Pre-Processing

The PSHA input model pre-processing step was a fundamental phase in the calculation of the GEM1 seismic hazard products. During this stage, we converted the models from their original format into a common representation with the clear ambition to create a uniform and standardized data set. The availability of a standardized data set of PSHA input models was the initial and unavoidable step for an effective usage of the developed seismic hazard engine and, subsequently, for the creation of standard tools to inspect and visualize the information contained in the models.

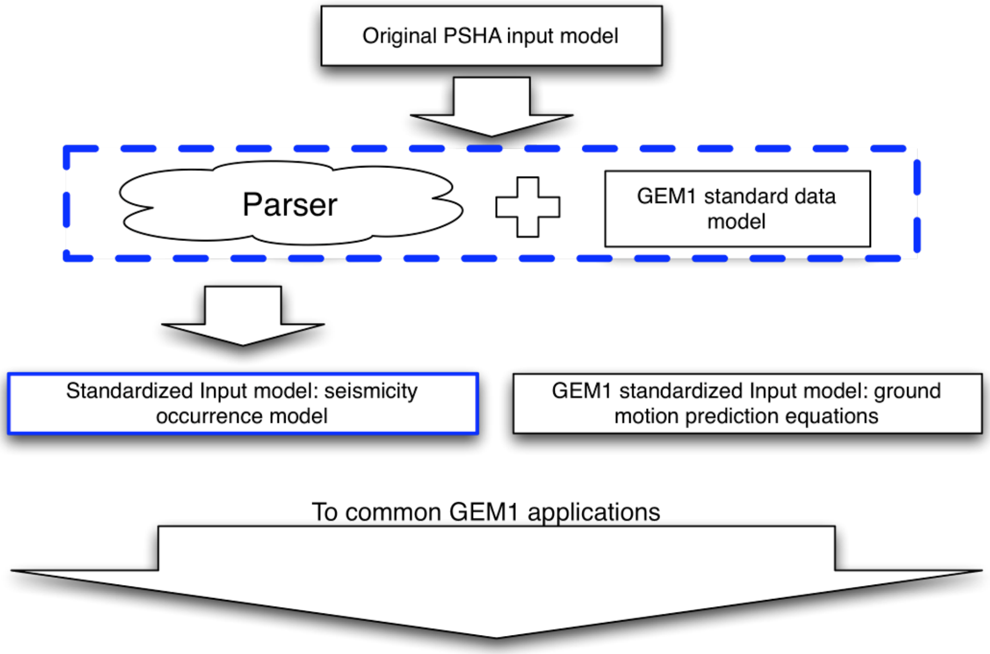

Figure 5.1 Description of the standardization process of PSHA input models.

Figure 5.1 shows the process adopted to create a harmonized collection of PSHA input models. The figure also makes clear the idea to separate the PSHA input component describing the seismicity occurrence model (i.e. the information needed to instantiate the ERF) from the one specifying the characteristics of ground motion prediction equations.

With regard to the part relative to GMPEs, since the first phases of the project it was decided to apply the same set of GMPEs to all the PSHA input models gathered in the GEM1 repository. As a consequence, while parsing the ASCII input files we decided to skip the parts describing this information.

5.1 Description of the Model Pre-Processing Procedure

Schematically, these are the steps we followed to pre-process the PSHA input models:

1. Model comprehension
2. Parser programming
3. Model inspection
4. Model storage

5.1.1 Model Comprehension

During this initial phase we collected and organized the information received from the data providers (data and possible documentation); the goal was to understand the structure of the provided PSHA input models (e.g. the source typologies adopted, their properties and – were applicable – the structure of the logic tree) and to map it into the GEM1 hazard data model. The time necessary to understand a PSHA input model depended on its complexity and on the quality and quantity of documentation and examples available. Usually the documentation isn't public and it is frequently intended to describe the results of the analysis and not to make the models reproducible. In some cases further interactions with the data providers were necessary. **Figure 5.2** contains a diagram that ideally represents what has been done to create parsers.

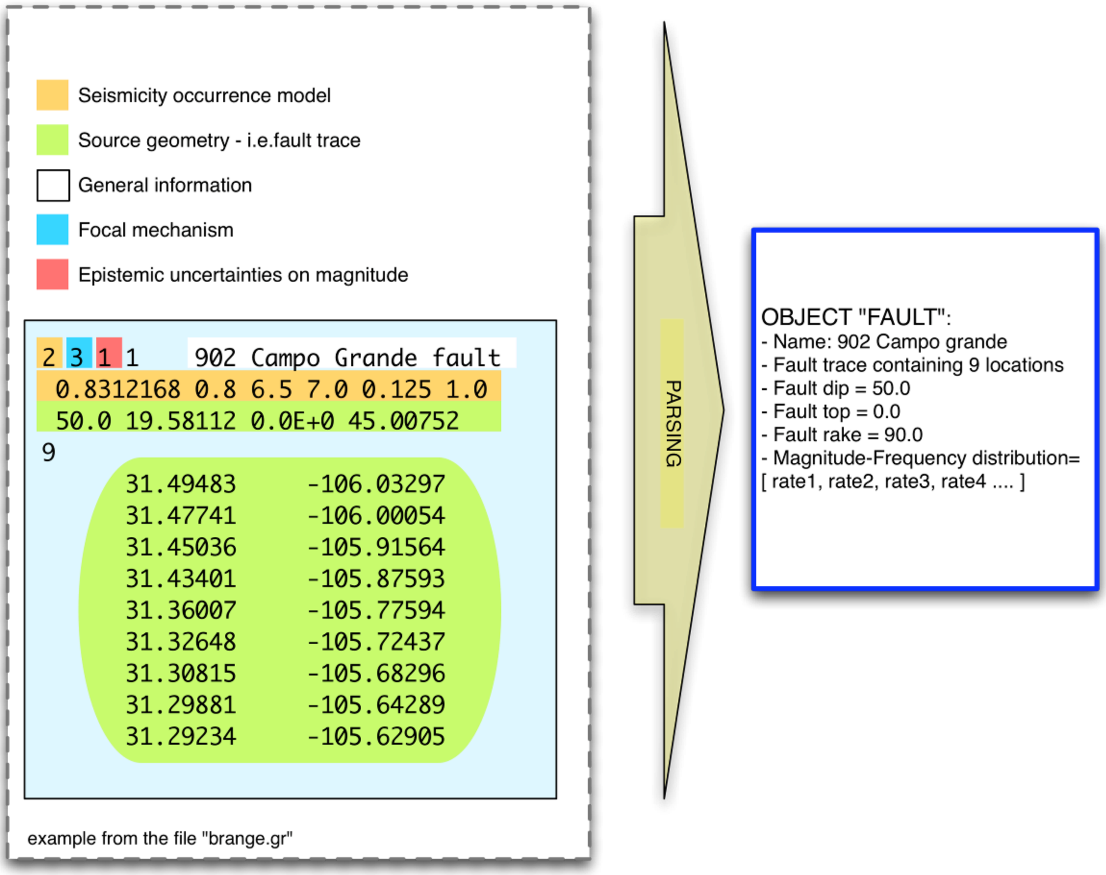

Figure 5.2 Conceptual diagram exemplifying the parsing procedure. The left side of the picture shows the description of one fault contained in the "brange.gr" file of the USGS-NSHMP 2008 model; the background colours make evident the main types of information provided (see also the associated legend). The right side of the picture exemplifies the standard representation of the information as provided by the parser.

5.1.2 Parser Programming

In this phase we created codes capable to read the original ASCII files and to convert their content from its initial format into the GEM1 standard; different implementation strategies were adopted depending on the characteristics and formats of the input models. In some cases, one class was sufficient to read the original information and create the standardized representation of input. In some other cases, several classes were necessary to read and store the original information; as an example, more than one model had the geometry of sources stored in a shapefile and seismicity occurrence parameters stored in a separate ASCII file. In these cases, we had to create one class to read and store the geometries, one to read and store the seismicity parameters and one class to accept the objects instantiated with the two previous classes so as to create the final standardized representation.

5.1.3 Model Inspection and Checking

This is a very important step that, unfortunately, we were only partially able to implement during GEM1. The verification of the models was done by reading the information in the input file and by inspecting the content of shapefiles created (see for instance **Figure 4.2**).

In a more general perspective, this is a list of possible checks that we're planning to implement in the next phases of the project. This is to make sure that:

1. The created models are in agreement with their original version. Some possible options:
   - Comparison between the seismicity rates predicted by the standardized models and the original ones. This procedure was extensively applied to the NSHMP USGS 2008 model with the aim to create at least in one case a wholly tested analysis.
2. The models created agree with basic prescriptions (e.g. a fault with m_{max}=7.5 cannot be associated to a fault trace with a length of a few kilometres). Here are some specific examples:
   - For all the sources:
     - Verify if the value of scalar seismic moment rate released per unit of area (M_w>5) is within a predefined range.
   - For area sources, check if:
     - The geometry of each source can accommodate a rupture whose magnitude corresponds to m_{max} (NOTE: this checks holds just in cases where the rupture cannot extend outside the source boundary – i.e. area source boundaries are "impermeable". In cases were the rupture can extend outside, the percentage of rupture outside the fault surface must be taken into account.)
     - Polygon geometry is correct
     - Area sources contained in the same model do not overlap (unless explicitly stated)
   - For magnitude-frequency distributions, verify if:
     - The b_{GR} is included in a predefined range (e.g. 0, 2.0)
   - For fault sources, check if:
     - The fault trace isn't too irregular (e.g. it does not contain right angles)
     - The fault trace is compatible with the maximum magnitude value indicated for the source.
3. The differences between the models created and the information obtainable from global databases are moderate (e.g. the GSHAP model for South East Asia contains maximum values of magnitude that are not consistent with current evidences). Some possible tests:
   - For all source typologies:
     - Is the focal mechanism compatible with the general trend provided by global datasets (e.g. Harvard CMT)?
   - For area sources and grid sources:
     - Which are the differences between the seismicity occurrence rates provided by the models and the ones derived from a global catalogue?

6 GEM1 Hazard Computation Engine and the Implemented Calculation Methodologies

During the first part of the project the seismic hazard team created a sandbox with several PSHA codes in order to appraise and evaluate the PSHA software currently used worldwide by the scientific community (see Danciu et al., 2010). A clear overview of the state-of-the-art in the discipline was the essential prerequisite to the creation of a comprehensive proposal about the ideal features of the final GEM1 hazard engine.

Figure 6.1 offers a schematic view of the GEM1 hazard engine outlining its main inputs and outputs.

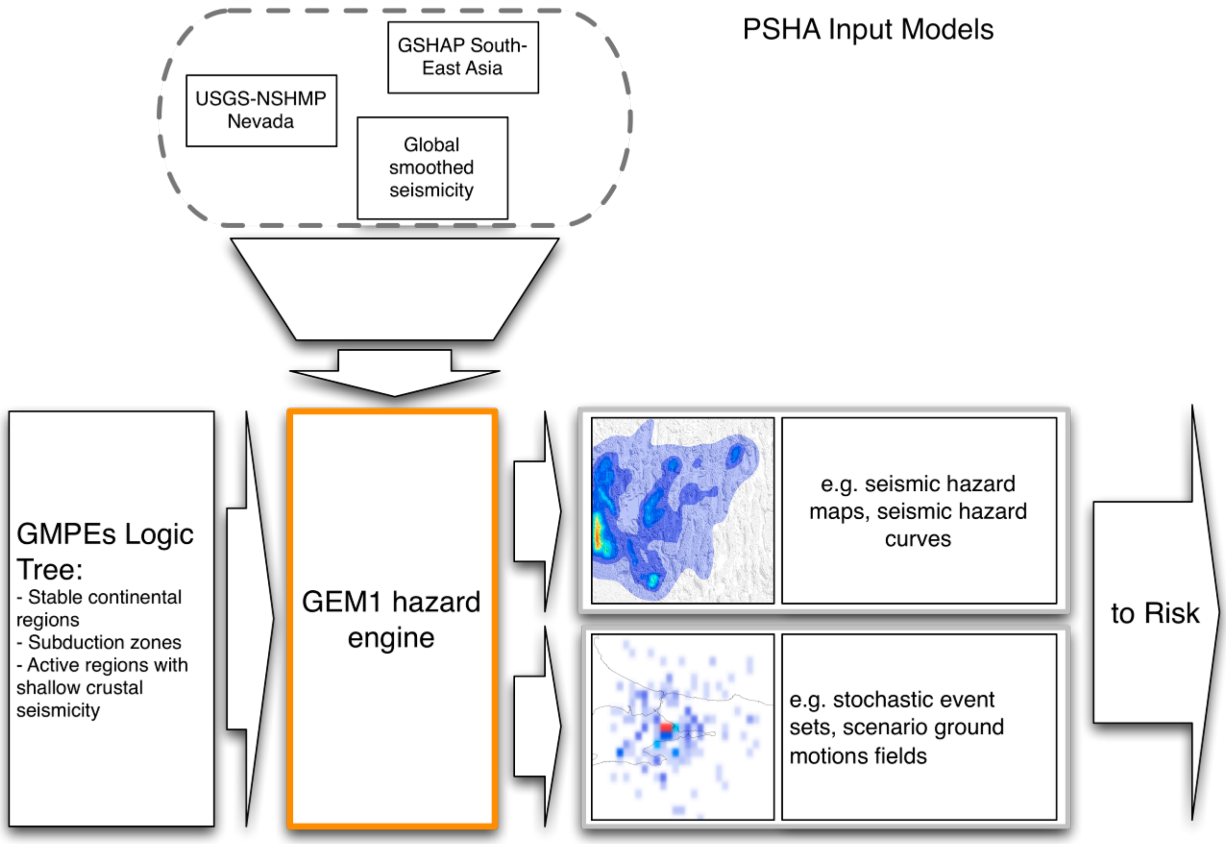

Figure 6.1 Schematic representation of the GEM1 hazard engine.

As represented in the figure above, the GEM1 seismic hazard engine is able to calculate hazard using the classical approach as well as to generate stochastic event sets and scenario ground-motion fields.

6.1 GEM1 Hazard Computation Engine

The diversity of input hazard models and the miscellany of outputs, advocated the design of a hazard computation engine adaptable and upgradable. **Figure 6.2** shows a simplified schema of the GEM1 hazard computation engine. The content of this image isn't that different from the one of **Figure 6.1**, however, in this picture we emphasize the distinct computation workflows and the strong interactions between the computation components and the data storage components, thus giving emphasis to the concept of computational infrastructure. For the sake of clarity, the workflow based on the stochastic event set and the ground-motion field calculators was created in a prototypal version and tested using only a few PSHA input models. The relevance of this computation workflow was slightly decreased in the course of GEM1, but it's clear that in case of future risk applications it will result in an extremely useful tool.

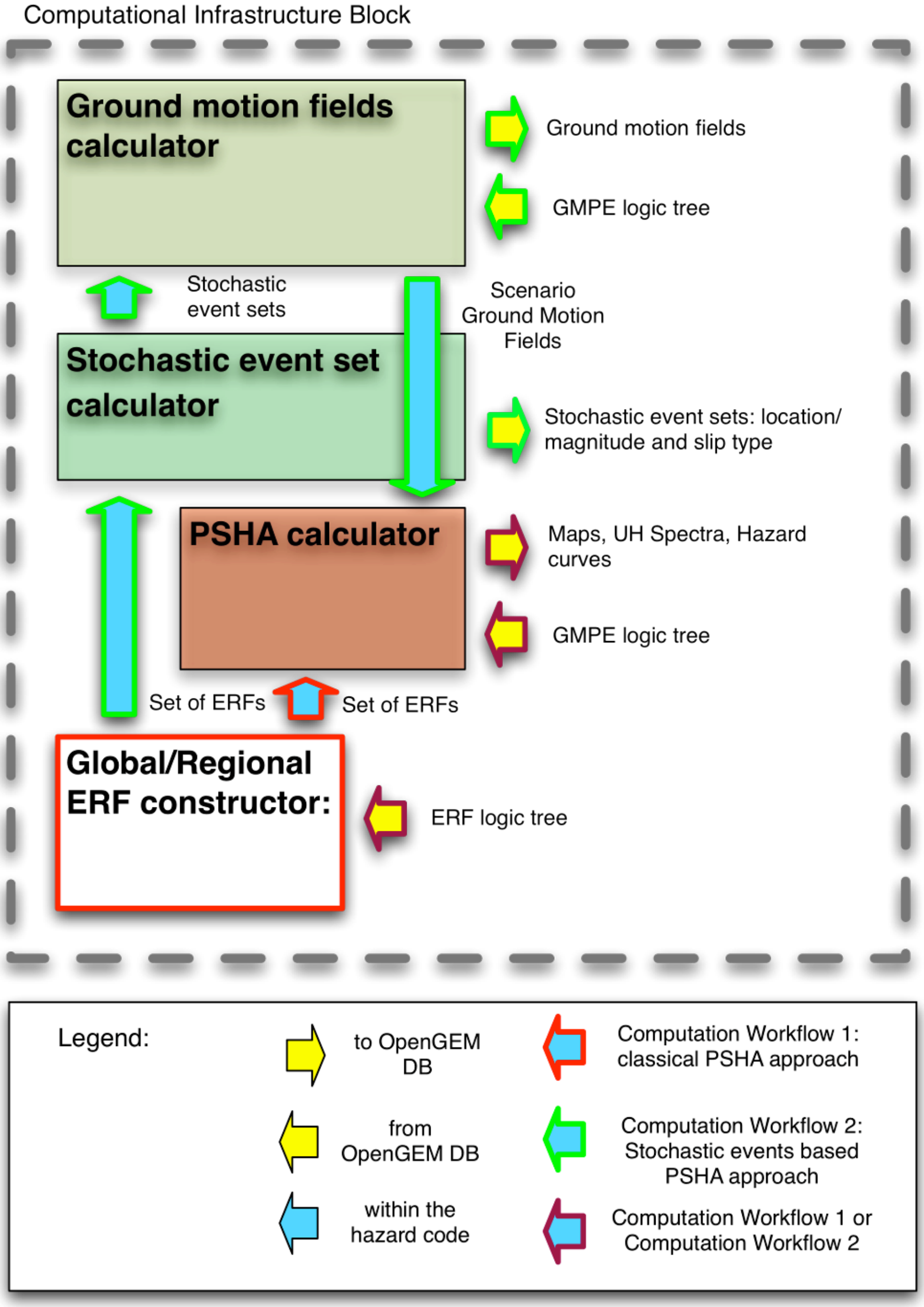

Figure 6.2 GEM1 seismic hazard engine block diagram. The arrow indicates the information flow; their filling colour evidences if the flow is between components of the engine (cyan) or between the computational infrastructure block and the OpenGEM system (yellow). The arrow border colour indicates the computation workflow the information exchange belongs (e.g. green indicates the hazard computation workflow based on stochastic event sets).

The implementation of a hazard engine – as much as possible flexible and expandable – and its integration with the whole infrastructure were among the most distinctive elements of the GEM1 project. It has to be acknowledged that a substantial part of the engine flexibility derived by the use of OpenSHA (based on an object oriented programming paradigm).

6.2 Standard Calculation Settings

In addition to the use of standardized seismic source typologies we believe important to underline some supplementary elements of standardization that were introduced in the calculations:

- We used a constant minimum magnitude value equal to 5.0 (M_W). In the literature it's well known the influence of m_{min} on the final results [see for example Musson, 2009]; the use of a regional dependent m_{min} would impede the creation of globally comparable results. The value of m_{min} adopted in GEM1 was just a convenience choice. The value of the minimum value of magnitude to be adopted will be extensively reconsidered in the next phases in strong connection with the risk component.
- A unified GMPE logic tree for the whole globe that associates GMPEs to seismotectonic environments. In GEM1, due to the limited time available, we considered a very simple logic tree (see also **Table 4.1**) considering the outcomes of the work of Douglas et al. [2009] and the review of this work completed by some MAG members.
- Further standard parameters used in the calculation:

- Area grid spacing:	0.1 degrees
- Area rupture type:	point source
- Grid rupture type:	point source
- Fault grid spacing:	2.5 km
- Fault rupture offset:	5.0 km
- Fault mag-area scal. relationship:	Wells and Coppersmith [1994]
- Rupture aspect ratio:	1.0
- Rupture floating method:	along strike and along dip
- Subduction fault grid spacing:	10 km
- Subduction fault rupture offset:	10 km
- Subduction fault mag-area scal. relationship:	Wells and Coppersmith [1994]
- Subduction ruptures aspect ratio:	1.0
- GMPE truncation:	3.0 sigmas

6.2.1 Accounting for Site Conditions

Two are the key approaches proposed in the PSHA literature to account for site conditions. The first method requires the modification of the GMPE functional so as to include a part accounting for local site conditions. In this regard, the parameter commonly adopted to characterize local soil conditions is the average shear wave velocity measured along the soil column between the topographic surface and -30m (the common symbol used to identify this quantity is $V_{S,30}$). Most of the recently developed GMPEs calculate the ground motion by taking into account the $V_{S,30}$ parameter [Douglas, 2003, 2004, 2006, 2008; Douglas et al., 2009].

The second methodology is a site-specific scheme that allows detailed calculations of the hazard for sites of relevant importance [Bazzurro and Cornell, 2004; Baturay and Stewart, 2003]. Generally, it requires a more complete description of the soil column and, consequently, it can be applied just to a limited number of points; the results it provides are more accurate than the ones obtainable with the previous methodology.

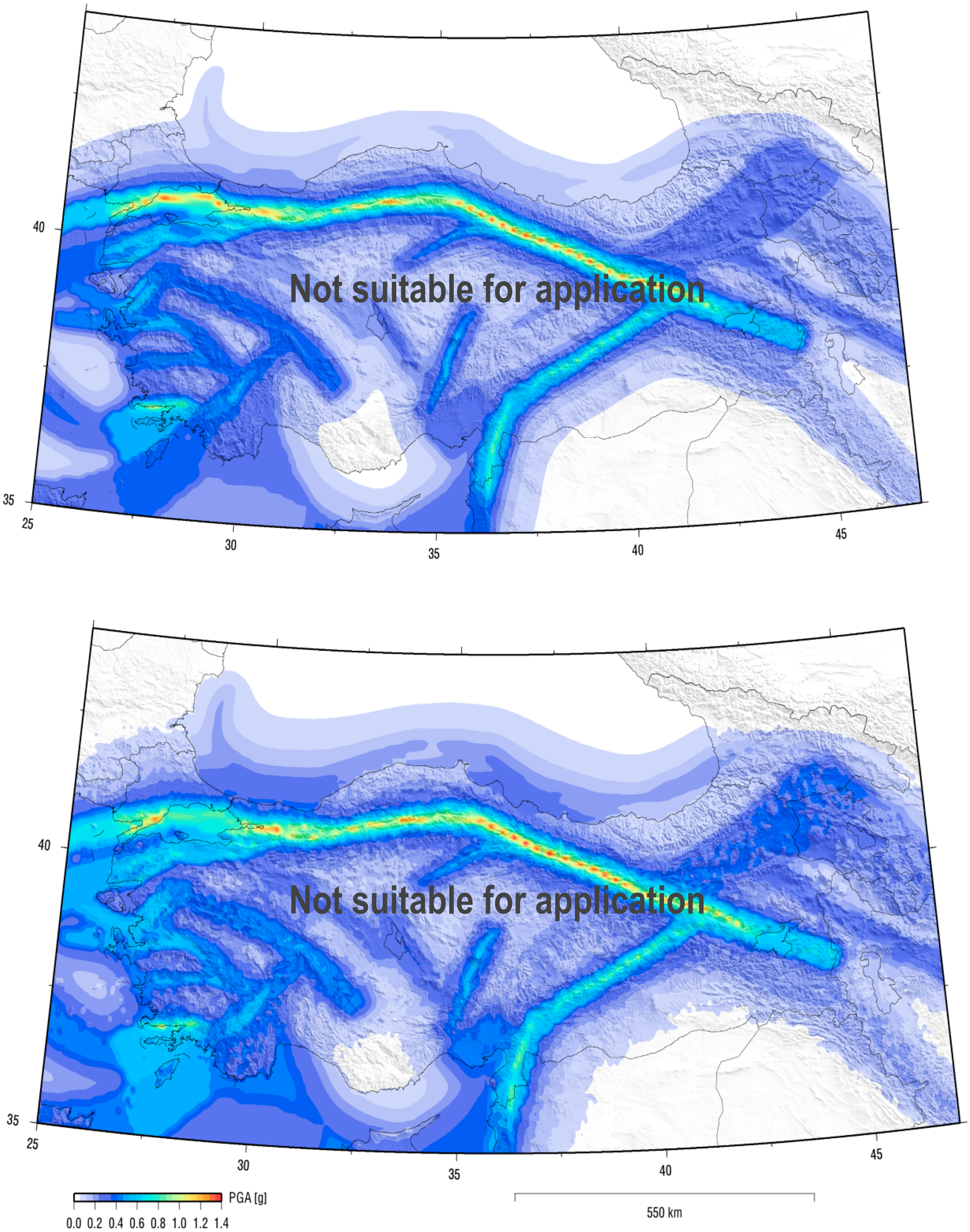

Figure 6.3 Seismic hazard map - PGA with 10% probability of exceedance in 50 years for Turkey. (Upper panel) ground motion computed on a reference soil characterized by a $V_{S,30}$=760m/s (Lower panel) ground motion computed taking into account local soil conditions (the Vs,30 is derived by using the topography proxy of Wald and Allen [2007]). Values of ground motion in the areas covered by the sea shouldn't be considered.

Within GEM1 we did some tests using the first methodology; in these cases the values of $V_{s,30}$ adopted were computed using the topography proxy proposed by Wald and Allen [2007] (see also [1]). **Figure 6.3** shows a comparison between two hazard maps expressed in terms of the PGA with 10% probability of exceedance in 50 years and computed, in one case, by assuming a standard value of Vs30 equal to 760 m/s, and in a second case, by using site dependent Vs30 values obtained by applying the Wald and Allen [2007] topographic proxy. It can be noticed that the map in the lower panel – i.e. the one including local soil conditions – exhibits a less regular pattern. A slight increase in the hazard is evident by comparing the hazard in the basins located in the upper right part of the lower panel with the hazard computed for the same area on a reference soil (upper panel of **Figure 6.3**).

6.2.2 Dealing with Uncertainties

Modern probabilistic seismic hazard analyses distinguish between aleatoric and epistemic uncertainties. Epistemic uncertainties are commonly accounted in the analysis through the use of logic trees. As already mentioned, in GEM1 we treated independently the seismicity occurrence model – and the potential logic tree associated – from the GMPEs logic tree (for an example see **Figure 6.4**).

With regard to the implementation of the earthquake rupture forecast, we tried to reproduce the models by limiting as much as possible potential changes. As a consequence, we created logic trees only in cases were the model was originally based on such a data structure. Following the suggestions of the MAG, for the sake of simplicity, most of the logic trees where trimmed by considering epistemic uncertainties as aleatoric.

On the contrary, we treated homogeneously epistemic uncertainties related to GMPEs by simply applying the same logic tree structure to all the PSHA input models take into account (see **Table 4.1**).

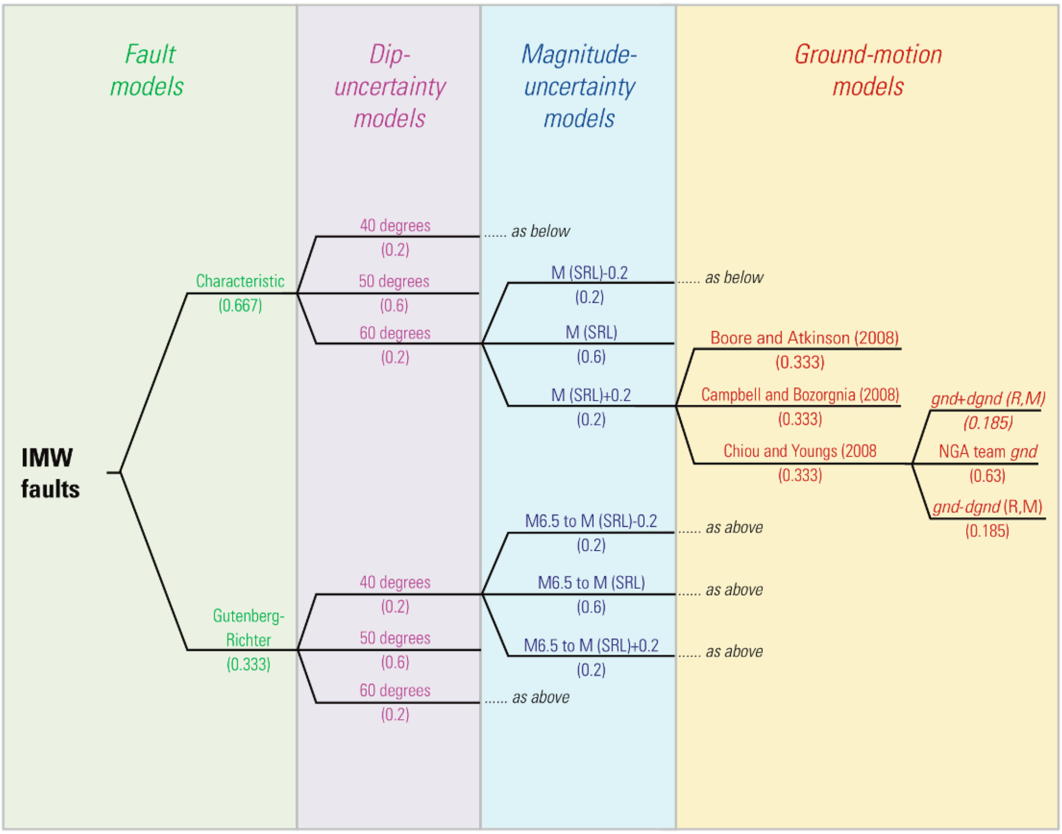

Figure 6.4 Example of a logic tree structure (taken from Petersen et al. [2008]). The first three branching-levels represent the part of the logic-tree relative to the creation of the seismicity occurrence model while the latest two describe the portion of the logic tree relative to GMPEs.

6.3 Seismic Hazard Calculation based on the GEM1 Global Smoothed Seismicity Model

The global seismicity model used in GEM1 was generated using the TripleS algorithm; for a more detailed description we refer the reader to Appendix A (see section A.18). In the context of our project this model was of particular interest for testing the hazard engine in case of global scale calculations.

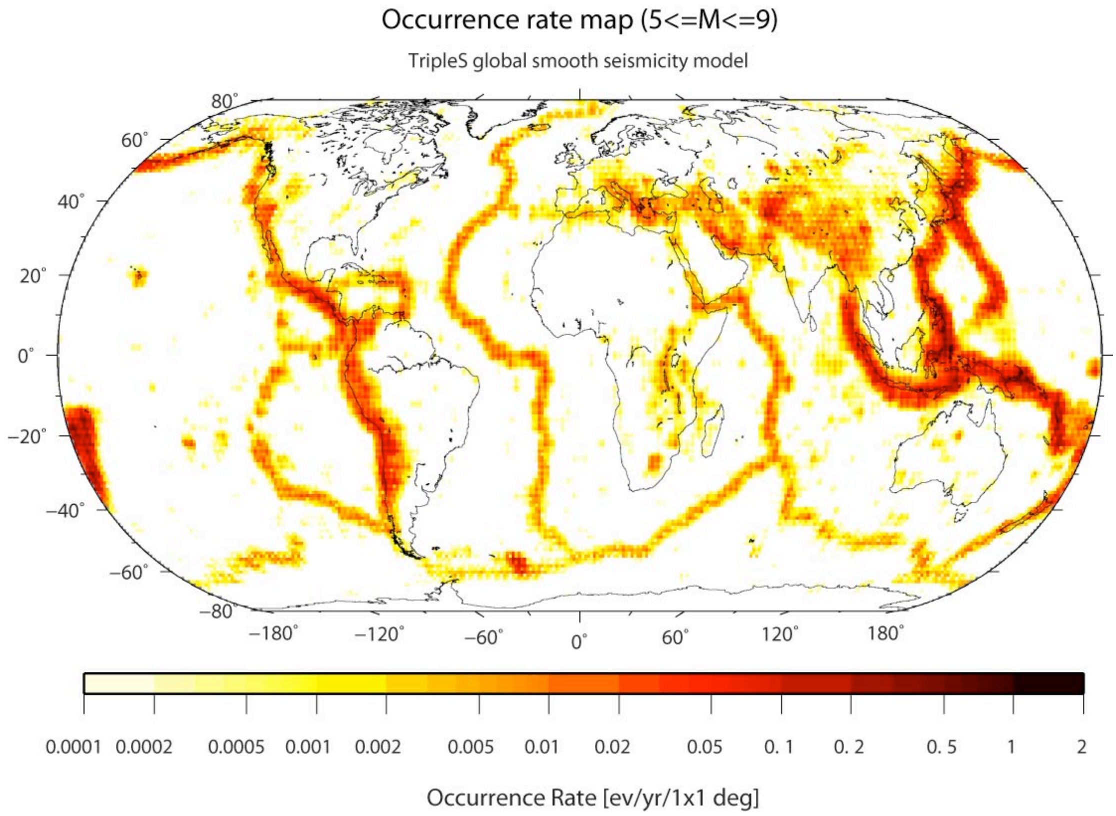

Figure 6.5 Total cumulative rate per grid cell from the global smoothed seismicity model.

The global smoothed seismicity model provides earthquake annual occurrence rates for grid cells of 1 by 1 degrees. Rates are assumed to follow a Gutenberg-Richter magnitude frequency distribution with b_{GR} value equal to 1. The minimum moment magnitude is 5. The total cumulative rate for each grid cell over the entire globe is shown in **Figure 6.5**.

Occurrence rates have been obtained by considering events in a depth range of 0-30 km. We therefore assumed events to be associated mainly to shallow active or shallow stable continental regions. The tectonic region type associated to each grid cell has been determined by using the tectonic regionalization of GMPEs proposed for GEM1 [Douglas et al., 2009] and presented in Figure 6-7.

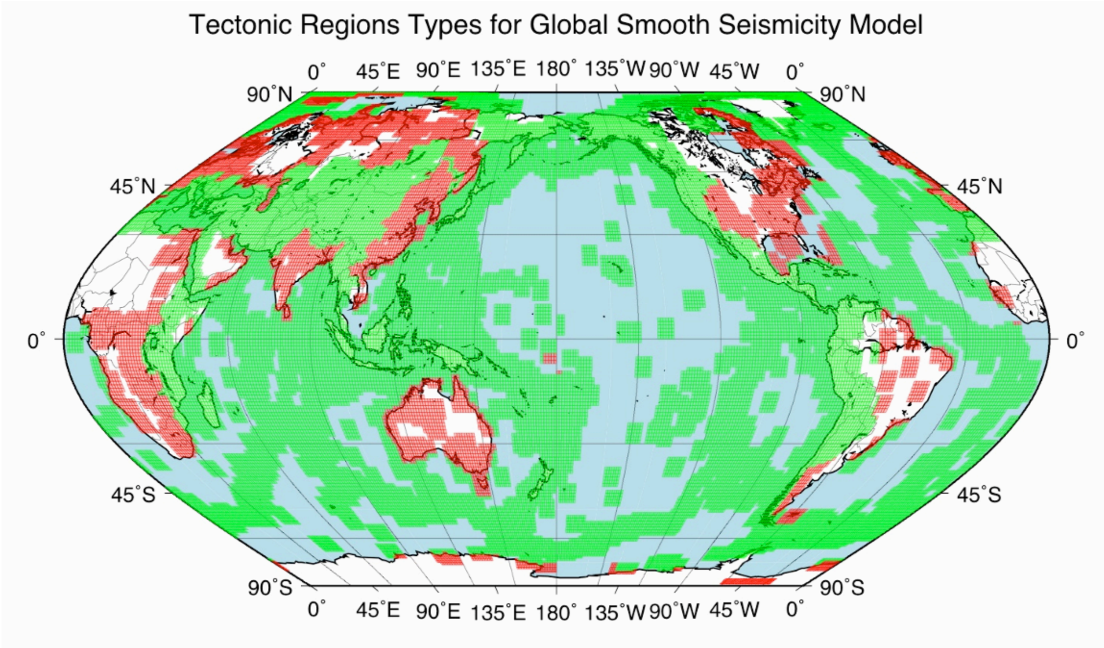

Figure 6.6 Tectonic regions types (green->shallow active, red->shallow stable continental) for each grid cell as derived by the GMPEs regionalization proposed in GEM1.

We calculated hazard curves for PGA (with 3 sigma truncation) on a 0.5 by 0.5 degree grid over the entire globe. We used two GMPEs for shallow active sources [Boore and Atkinson 2008, and Chiou and Youngs 2008, both with equal weight] and only one for stable continental sources [Atkinson and Boore 2006]. At each grid node earthquakes are treated as point sources. Under these conditions the calculation took about 52 hours on a 30 CPUs machine. In **Figure 6.7** we show the computed PGA with 10% probability of exceedance in 50 years.

This calculation is clearly not useful for any reliable estimate of seismic hazard. The model takes into account mostly shallow seismicity, therefore neglecting almost all the seismicity associated with subduction zones. The catalogue has not been declustered and therefore hazard values can be over-estimated. The model provides only earthquake occurrence rates and no data about predominant focal mechanism(s), which is required for modelling large magnitude earthquakes (where the point source approximation is clearly no longer valid and spinning the rupture over all possible strike angles may not be realistic). Despite the limits in the validity of the obtained hazard estimates, the model proved to be a valid benchmark for evaluating the performances of the GEM1 hazard engine for global-scale calculations. The example presented here is very simple (sources treated as points, logic tree with at maximum only two GMPEs, hazard curves calculated on a low resolution grid), and nevertheless the calculation time is of the order of two days and fully exploiting a 30 CPUs machine. We foresee that under more realistic conditions hazard estimates for the entire globe (oceans comprised) could be very demanding, therefore requiring an efficient calculator able to use large scale computing facilities in order to make the calculation feasible.

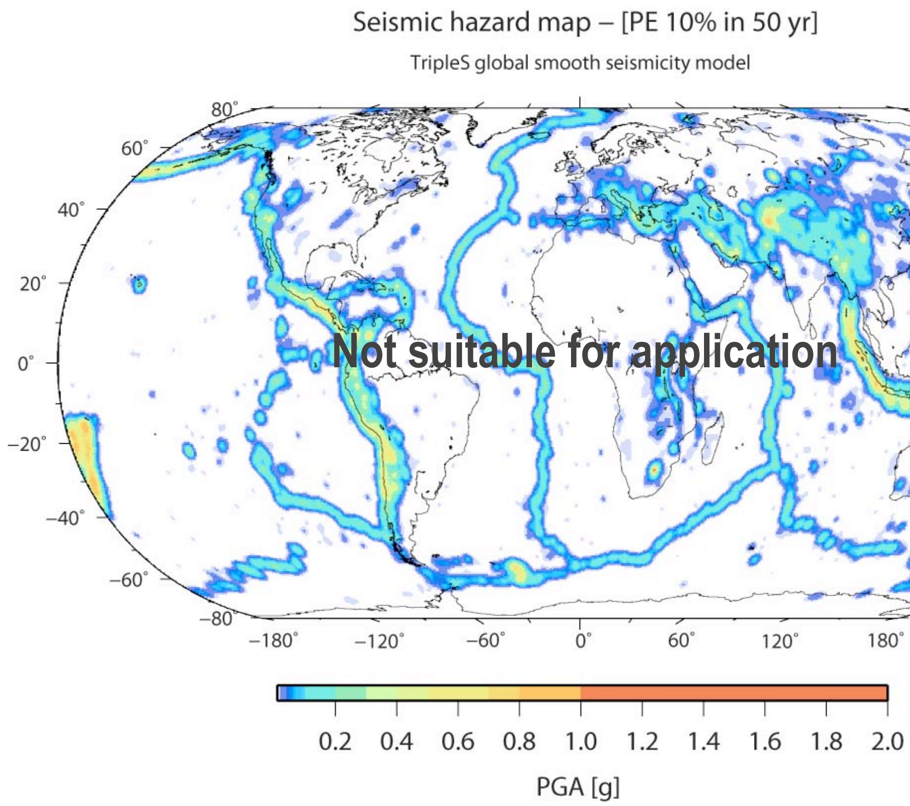

Figure 6.7 Hazard map (10% probability of exceedance in 50 years) as derived from the global smoothed seismicity model.

7 Seismic Hazard Maps Assembling

7.1 Assembling Maps Representing Diverse Outcomes of the same PSHA Input Model

The calculation of the mean hazard curves and hazard maps is completed though a post-processing procedure that works on a standardized repository object. The methods that complete this step are part of the GEM1 seismic engine and are usually applied automatically at the end of the calculation. Note that the calculation of weights and mean results is done automatically using the standardized description of the logic trees for ERF and IMRs. The rightmost panel in **Figure 7.1** shows an example of the final result obtained in the case of the Western United States.

In some cases this post-processing procedure was applied successively on the ASCII files used to store intermediate results with the aim to expand the set of final results (e.g. obtaining mean seismic hazard maps for additional probabilities of exceedance).

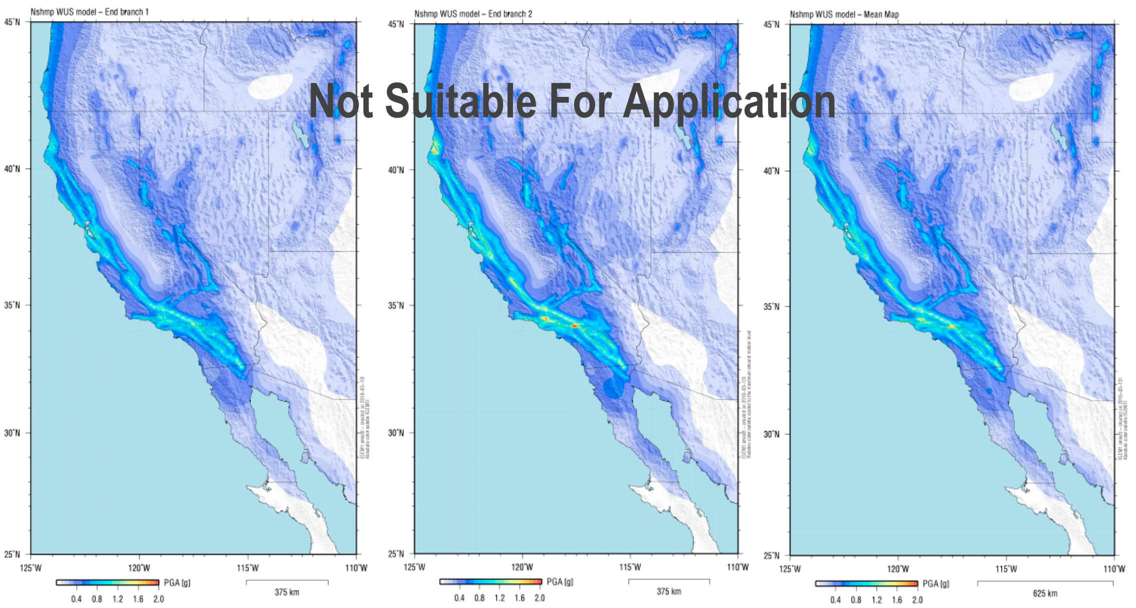

Figure 7.1 Example of mean hazard map calculation for the Western US model. Left and central panels represent hazard maps for the two end-branches of the IMR logic tree (i.e. Boore and Atkinson [2008] (left panel), Chiu and Youngs [2008] middle panel). Right panel shows the mean hazard map.

7.2 Assembling Maps coming from Distinct PSHA Input Models

In this section we specify the procedures so far conceived to create homogenized global hazard results (e.g. Maps, Hazard curves, Uniform Hazard Spectra, Disaggregation). As previously anticipated, in GEM1 we did not focus on experimenting possible solutions for merging distinct maps so as to create a unique homogenous seismic hazard map. The following description is just a proposal to be accurately evaluated and tested in the future.

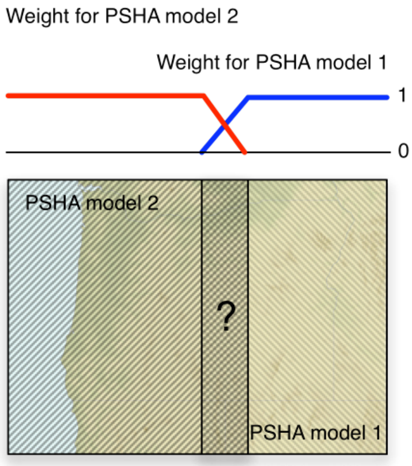

Figure 7.2 Diagram descriptive of the possible fusion methodology on the overlapping part of two adjacent maps.

In the following we specify for most of the possible situation the solution adopted in order to obtain the global hazard maps:

- Area not covered by a regional or national model

  POSSIBLE SOLUTION: Use the hazard maps based on smoothed seismicity

- Area covered by two or more models (National or Regional) + smoothed seismicity models:
  - Area at the border between two models (e.g. United States – Canada border).

    POSSIBLE SOLUTION: This case is open to different solutions depending on the type of results needed. One possible option would be to have a final hazard map as much as possible smooth. In this case a simple method could be to use a weighted average over the area where the two maps overlaps. **Figure 7.2** demonstrate the distribution of weights (the lines blue and red) to be adopted in order to smoothly fuse the two hazard maps. Note that this example presumes that the reliability of the two maps is the same.

    A second solution tends to compute a final map corresponding to a patch of distinct maps each one fully representative of the hazard within its territory. For example, in this case we will truncate the map for the United States computed with the USGS model at the border and abruptly on the opposite side we'll plot the model computed using the Geological Survey of Canada PSHA input model.

  - Large areas with more than a model available.

    POSSIBLE SOLUTION: In this case, we can use a weighted average to obtain a single hazard map. Eventually, alternative fusion operators can be implemented (e.g. instead of computing a weighted average we can derive a conservative map based on the maximum value). To note that, independently on the fusion operator adopted, it will be necessary to fix a criterion to weight the reliability of each PSHA input model (and consequently of the derived PSHA maps).

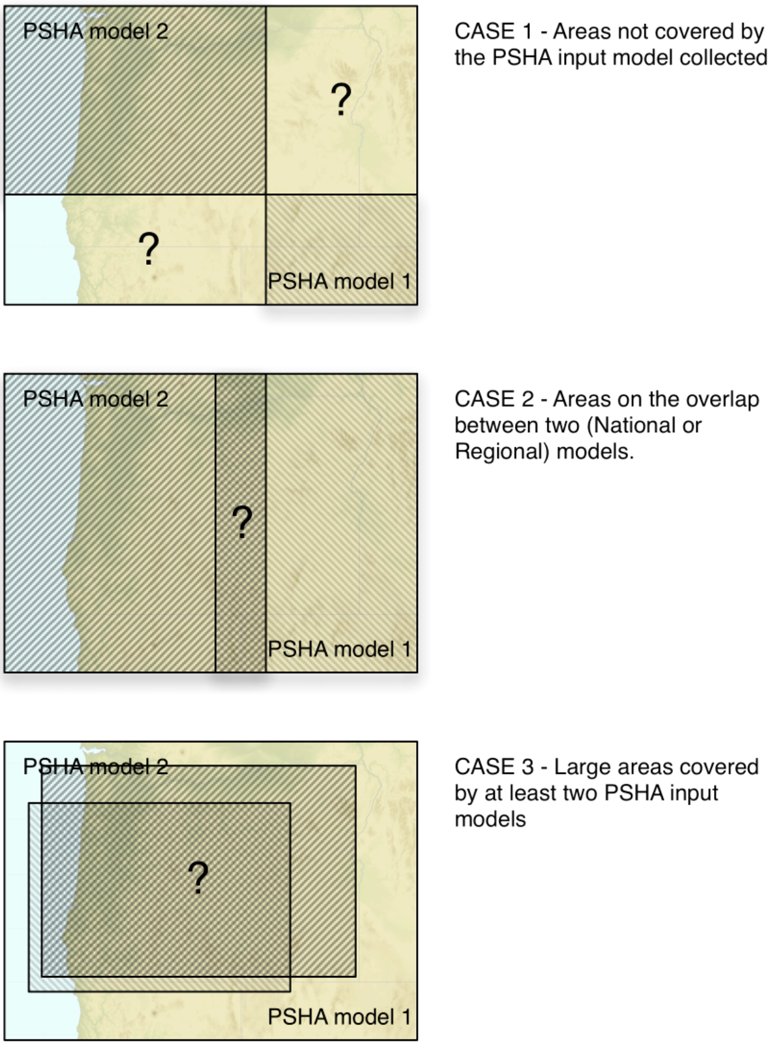

Figure 7.3 Description of the possible cases to be solved when assembling the global hazard map.

As an example of merging hazard results, we present in **Figure 7.4** the hazard map (for 2% probability of exceedance in 50 yr) obtained by applying a weighted average of hazard curves for the following models: South America, Central America, Mexico, US.

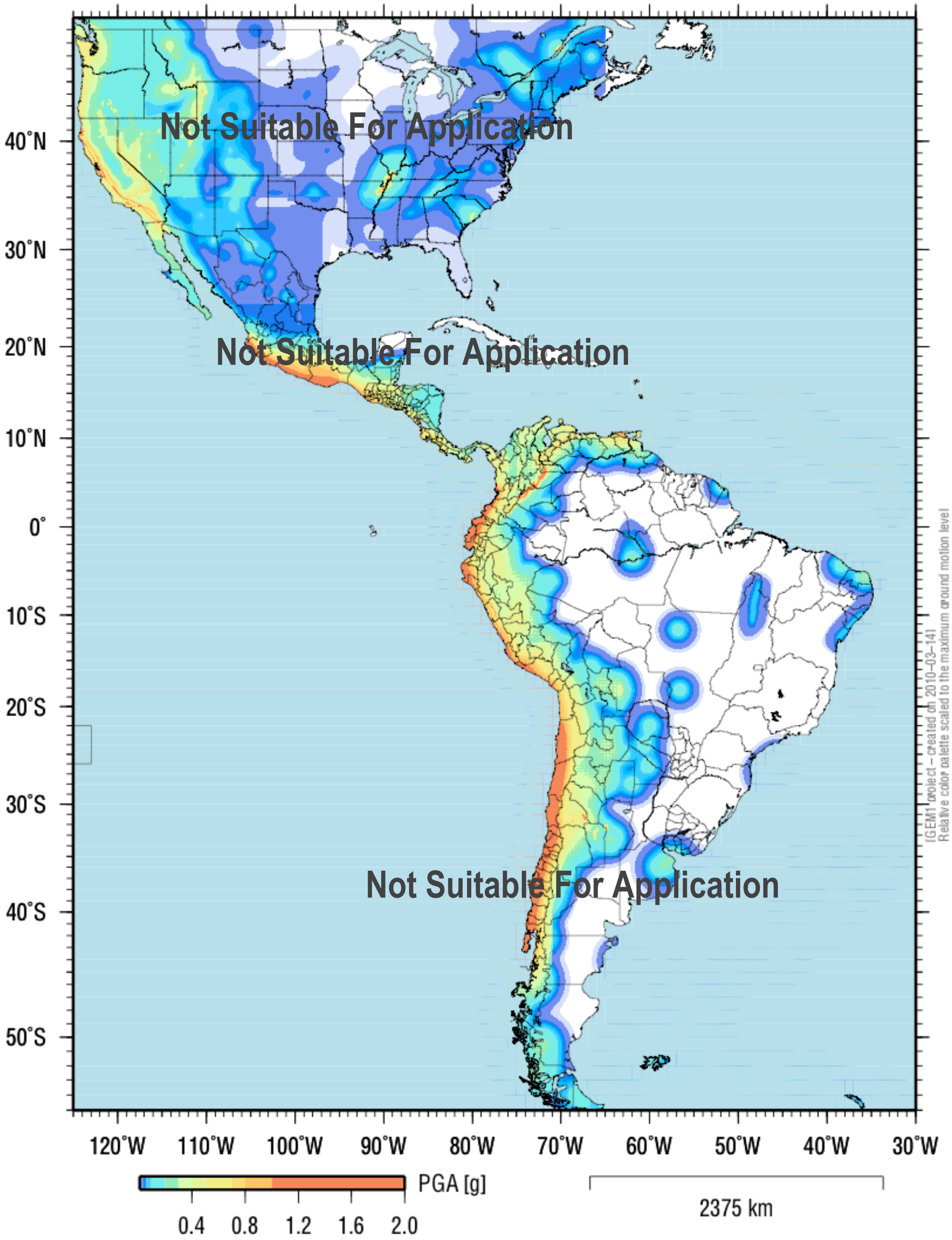

Figure 7.4 Seismic hazard map (PGA with 2% probability of exceedance in 50 years) obtained by merging the results of the South America, Central America, Mexico and, US models.

8 Main Results Achieved

8.1 Standard Hazard Products

We computed PSHA maps [characterized by 10% and 2% probability of exceedance in 50 years] for most of the models contained in the GEM1 PSHA input model repository. In particular we worked on the following models:

- Africa
- Australia
- Canada
- Central America
- Europe
- Iran
- Mexico
- Northern Eurasia
- South America
- South East Asia [GSHAP]
- South East Asia [USGS]
- Turkey
- Conterminous Unites States
- Global smoothed seismicity model

Some models were temporary not included in the calculations: Japan, New Zealand and peninsular India. In the case of Japan, we started the implementation a parser capable to read the dataset of rectangular faults but extra time is needed to complete the process of converting this model into our standard representation (note that the Japan model includes a subset of sources with a time dependent occurrence model). The India model calculation was delayed simply for convenience; indeed, India (especially the northern part) was already covered by another regional model created in the framework of the GSHAP project. Given the importance and interesting aspects of the model for the peninsular part, we're planning to calculate hazard for peninsular India in the next few months. In the case of New Zealand, the PSHA input model currently available is a proprietary model; we did not calculate hazard using this model because we thought it was advisable to avoid any possible problem.

Main products created:

- Hazard maps computed on a reference bedrock [available for all the models taken into account]
- Hazard maps including local site conditions ($V_{S,30}$ derived from topography using the proxy of Wald and Allen [2007]) [available just for some models – see for example **Figure 6.3**]

Site-specific products computed for all the PSHA input models:

- Hazard curves (PGA and investigation time equal to 50 years) [available for all the models]
- Seismic hazard disaggregation (M-D-ε) [just some tests so far performed] - **Figure 8.1** shows an example of the disaggregation for the city of San Jose (Costarica) computed using the Central America model. The disaggregation shows the contributions to the PGA with 10% probability of exceedance in 50 years.

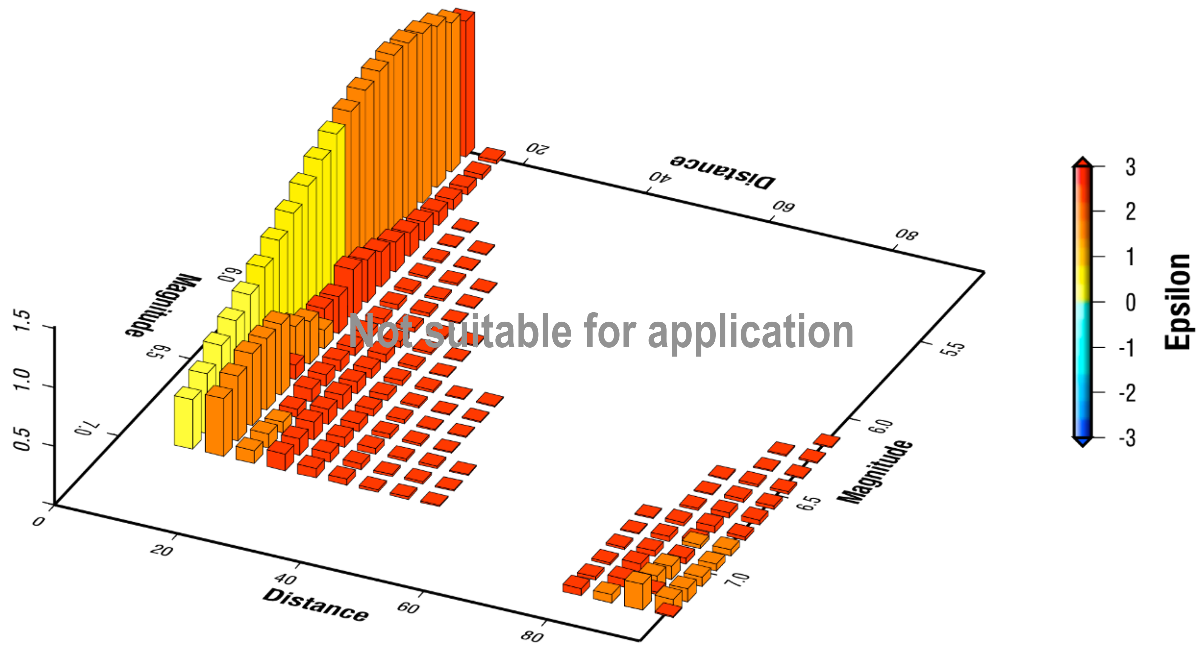

Figure 8.1 Seismic hazard disaggregation for the PGA with 10% probability of exceedance in 50 years - City of San Jose (Costa Rica).

8.2 Risk Specific Products

Seismic hazard results computed for use in risk calculations:

- Intensity hazard curves [available for all the models computed] – These were used in the GEM1 risk engine for the calculation of losses.
- Intensity hazard maps - **Figure 8.2** shows an example of a hazard map for Central America in terms of the instrumental intensity with 10% probability of exceedance in 50 years.
- Sets of stochastic events and sets of ground motion fields representative of the seismicity generated by the sources included in one PSHA input model [just tested for the Marmara region]

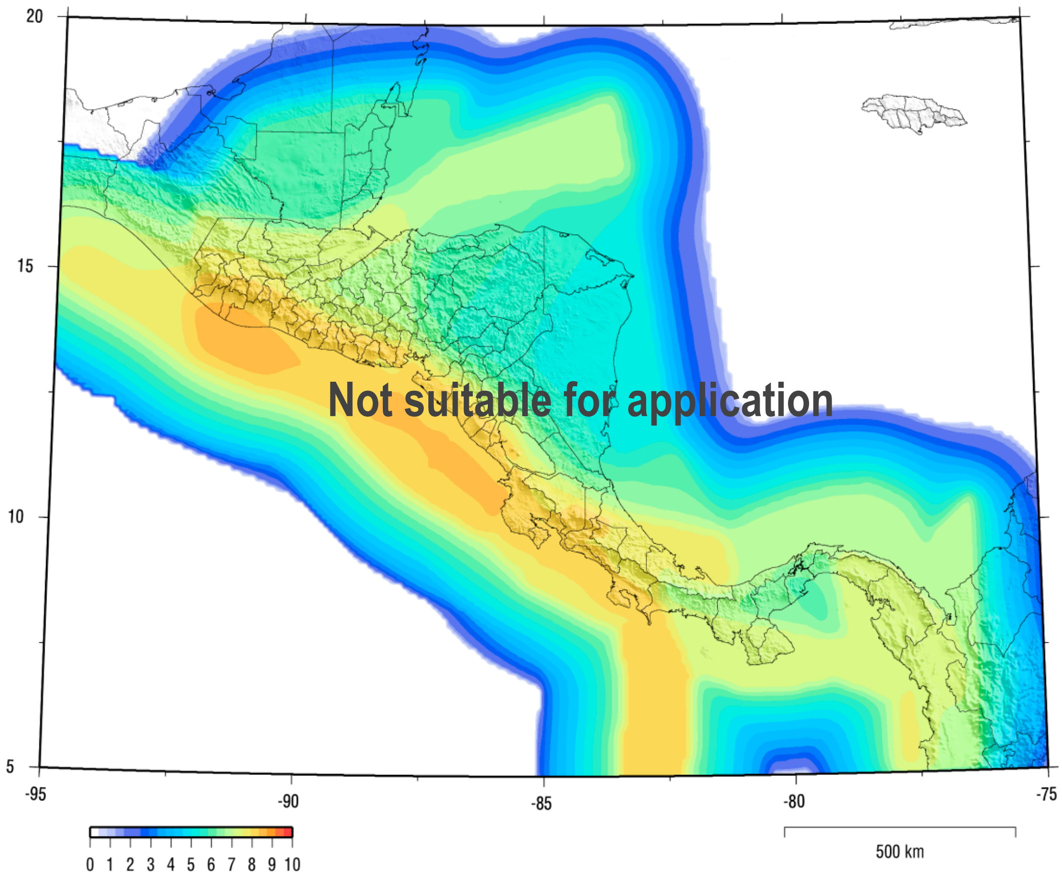

Figure 8.2 Seismic hazard map: Instrumental intensity with 10% probability of exceedance in 50 years.

9 Summary, Problems and, Perspectives

We believe GEM1 reached the goal of providing a fully functional prototype of the seismic hazard engine i.e. a proof of concept that demonstrates the potential capability of the hazard infrastructure to calculate seismic hazard globally following standardized procedures. It's fairly evident that a lot of issues remain to be investigated further and verified, possible errors removed and, plenty of things improved.

We designed the GEM1 seismic hazard engine and we integrated it in OpenSHA. This merge resulted in an amalgamation of the extensive set of tools available in this library with the GEM1 effort to create a prototypal standardized and authoritative PSHA code. In our opinion the results are certainly encouraging despite the need of additional work.

Our experience in GEM1 evidenced that PSHA input models currently adopted at a global scale do not differ substantially in terms of information used to perform calculations, as a consequence, nowadays we see many clear reasons to move toward a community based PSHA input data model. The products created within GEM1 could be a starting point for a broad and open discussion within the community that should result in a shared data model and a data exchange format. Some of the most evident advantages of such an option could be:

- Code interoperability
- PSHA homogenization
- Creation of a shared knowledge and common language. Moreover, we think this will foster a participated development of new PSHA methods and tools.

GEM1 did not work on implementing PSHA input models; accordingly, so far, potential tools for assisting in the creation of model were not developed nor designed. It's fairly evident that the definition of procedures and tools for the creation will be an essential step toward the creation of a really global homogeneous model. This and many other issues will be hopefully soon discussed among the MAG, the regional and the global initiatives.

9.1 Future Enhancements: Engine

The GEM1 seismic hazard engine is a first step in the development of a complete and powerful tool, as GEM will necessitate. Many are the enhancements and improvements foreseen; herein we list some among many:

- Improvement of calculation efficiency; accurate profiling of the implemented Java classes can be used to reveal possible bottlenecks in the calculation workflow. Currently, area source- and grid seismicity source-based models are associated with the largest computation times. More efficient implementations of these two source typologies and/or development of customized calculator could provide better performances.
- Development of a "suite" of basic tools that can be initially provided to the regional programs and creation of a user manual to enhance usability of the code.
- Enhance the disaggregation capabilities of the engine (currently we can disaggregate the contributions to a defined value of hazard in terms of magnitude, distance and ε)
- Improve ways of handling logic trees: Implementation of a Monte Carlo sampler for logic trees.

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1. Global Vs30 maps

Global Vs30 Map Server.

[Available at http://earthquake.usgs.gov/research/hazmaps/interactive/vs30/]

2. OpenSHA

Brief overview.

[Available at http://www.opensha.org/documentation/overview.html]

3. Generic Mapping Tool (GMT)

The website of the Generic Mapping Tool a largely used application for plotting spatial information within the Geophysical community.

[Available at http://gmt.soeast.hawaii.edu]

4. Resis II Project website

The website of Resis II Project

[Available at http://www.norsar.no/c-138-RESIS-II.aspx]

APPENDIX A Description of Input Models

A.1 Alaska

The Alaska input model was initially developed by the USGS - NSHMP in 1999 and subsequently revised in 2007.

Seismotectonic Settings

The Alaska model accounts for the seismicity generated by the convergence process (about 59 mm/yr according to Bird, 2003) currently active at the border between the Pacific plate (PA) and the North American (NA) one [Bird, 2003]. Seismicity is intense along the Aleutinian arc with hypocentral depths ranging between few kilometers and about 300 km and alongside the Alaska-Aleutinian megathrust (from the Aleutinian arc till south-central Alaska). Additional important seismogenic sources are: the Denali fault (in 2002 it generated a M_w 7.9 earthquake), and the system of right-lateral strike slip faults bounding the north-eastern part of the Pacific plate [Wesson et al., 2007; page 3].

Input Model Description

The Alaska input model (the most seismically active state of USA according to Wesson et al., 2007) is based on two source typologies in agreement with the USGS-NSHMP standards: fault sources, to describe both active crustal discontinuities with well know parameters and geologic structures connected to the Alaska-Aleutinian megathrust, and gridded seismicity, used to account for “uncharacterized and unrecognized faults” [Wesson et al., 2007].

Input Model Implementation

The model implementation follows the NSHMP PSHA software (see 0). A particular feature of the Alaska model is found for the Denali fault where the a_{GR} value is variable along the fault trace.

Distinct suites of GMPEs take into account particular source mechanisms and propagation paths. The model-summary table (see **table 4.1**) synthesizes the ground motion prediction equations adopted for distinct seismotectonic regions.

Table A.1 Alaska input model summary table

Seismotectonic environments incorporated in the model	- Subduction zone
Number of area sources contained in the model	None
Number of gridded seismicity sources contained in the model	The model we received do not contain grid sources. However, we read in the report that grid sources were used for calculations.
Number of fault sources contained in the model	8 crustal faults + 22 subduction faults
Logic tree/ epistemic uncertainty treatment	The model accounts for epistemic uncertainties about maximum magnitude and GMPEs (by averaging the contributions of multiple GMPEs – see Wesson et al. [2007] – page 14)
Ground motion prediction equations [see also Wesson et al., 2007; Table 2, page 22]	Thrust and transition faults: - Youngs et al. [1997] - interface - Sadigh et al. [1997] – used only when distance is less than 70 km
	Crustal faults: - Abrahamson and Silva [1997] - Boore et al. [1997] - Sadigh et al. [1997] - Campbell and Bozorgnia [2003]
	For smoothed seismicity, the GMPEs adopted are the same used for crustal faults. Source-site distances were corrected to account for source finiteness.
	Deep earthquakes (between 50 and 80 km): - Youngs et al. [1997] – intraslab with depth fixed at 60 km - Atkinson and Boore [2003]
	Deeper earthquakes (between 80 and 120 km): - Youngs et al. [1997] – intraslab with depth fixed at 90 km - Atkinson and Boore [2003]
Model minimum magnitude (M_W)	Not available in the report
R_{max}	Not available in the report
PSHA code used	USGS-NSHMP suite of codes

A.2 Africa

The PSHA input model for Africa currently available in the GEM repository incorporates regional models developed in the framework of the GSHAP project. These are:

- The model for the Ibero-Maghreb region (available on the GSHAP website at the following address: http://www.seismo.ethz.ch/gshap/iberomag/; see also Jimenez et al. [1999]).
- The model for the Eastern Maghreb region, including models of Libya and Egypt (model recovered from a GSHAP repository available at SED-ETH – Contact person: S. Sellami, ETH Zurich);
- The model for Israel (model recovered from a GSHAP repository available at SED-ETH – Contact person: S. Sellami, ETH Zurich);
- The model for Western Africa (model recovered from a GSHAP repository available at SED-ETH – Contact person: S. Sellami, ETH Zurich);

- The model for the East African Rift – also called Sub-Saharan (available on the GSHAP website at the following address: http://www.seismo.ethz.ch/gshap/earift/; see also Midzi et al. [1999]);

Seismotectonic Settings

The Africa hazard model covers the Africa (AF) and the Somalia (SO) tectonic plates. In this area, of particular relevance for seismicity generation is the rifting process active along the south-eastern part of the continent from Djibouti till South Africa, and the area involved in the collision process between Africa and Eurasia, located in the westernmost flank of the continent.

Seismicity is concentrated along the Rift Valley, the largest continental Rift system on Earth and in the Ibero-Maghreb region; additional seismic active areas are situated along the Benue Rift (Guinea Gulf area).

Within this model the strongest earthquakes occur in the northern part of the continent and principally in Algeria; seismogenic sources are also present along the Atlas mountain chain.

Input Model Description

The input model for Africa contains a total of 120 shallow area sources distributed as follows: 66 sources in the Ibero-Maghreb model, 3 sources for Libya, one source for Egypt, 22 sources for the Israel model, 22 sources for Eastern African Rift model, and 6 sources for Western Africa Model.

The seismicity temporal occurrence model is assumed to follow a Poisson process whereas the Magnitude-Frequency Distribution (MFD) of earthquakes is described in terms of a Gutenberg-Richter distribution (GR).

In the Ibero-Maghreb model the GR distribution is defined by means of the following parameters [Jimenez et al., 1999; page 1061]:

- Minimum (m_{min}) and maximum values (m_{max}) of magnitude.
- a_{mmin} value (corresponding to 10 to the annual rate – per unit of area - for magnitudes comprised between m_{min} and m_{max})
- b_{GR} value

This model doesn't take into account explicitly epistemic uncertainties.

For the Libya Model as well as for the Western African Model, the parameters that describe the GR distribution are the following:

- Minimum (m_{min}) and maximum values (m_{max}) of magnitude;
- An earthquake occurrence rate value (for magnitudes comprised between m_{min} and m_{max});
- The b_{GR} value

Epistemic uncertainties not taken into account.

The GR distribution for the Egypt and Israel models is described in terms of the following parameters:

- Minimum (m_{min}) and maximum values (m_{max}) of magnitude;
- a_{mmin} value
- b_{GR} value
- Uncertainties associated to a_{mmin} and b_{GR} parameters.

The seismicity parameters that describe the GR earthquake distribution within the East African Rift model are defined as follows:

- Minimum (m_{min}) and maximum values (m_{max}) of magnitude;
- Earthquake occurrence rate value (for magnitudes comprised between m_{min} and m_{max});
- β_{GR}-value

This model does not account for epistemic uncertainties.

Table A.2 Africa input models: summary table.

	Ibero-Maghreb	Libya	Egypt	Israel	East African Rift	Western Africa
Seismotectonic environments	Shallow active crust	Shallow active crust	Shallow active crust	Shallow active crust	Shallow active crust	Shallow active crust
Number of area sources contained in the model	66	3	1	22	22	6
Number of gridded seismicity sources	None	None	None	None	None	None
Number of fault sources	None	None	None	None	None	None
Logic tree/ epistemic uncertainty treatment	No	No	No	No	No	No
Ground motion prediction equations	Joyner and Boore [1981]	Joyner and Boore [1981]	Joyner and Boore [1981]	Joyner and Boore [1981]	Jonathan [1996] Twesigomwe [1997]	Joyner and Boore [1981]
Model minimum magnitude	4.0	4.5	4.5	4.5	4.5	3.75
PSHA code used	Seisrisk III	Seisrisk II	EQRISK	EQRISK	Seisrisk II	Seisrisk II

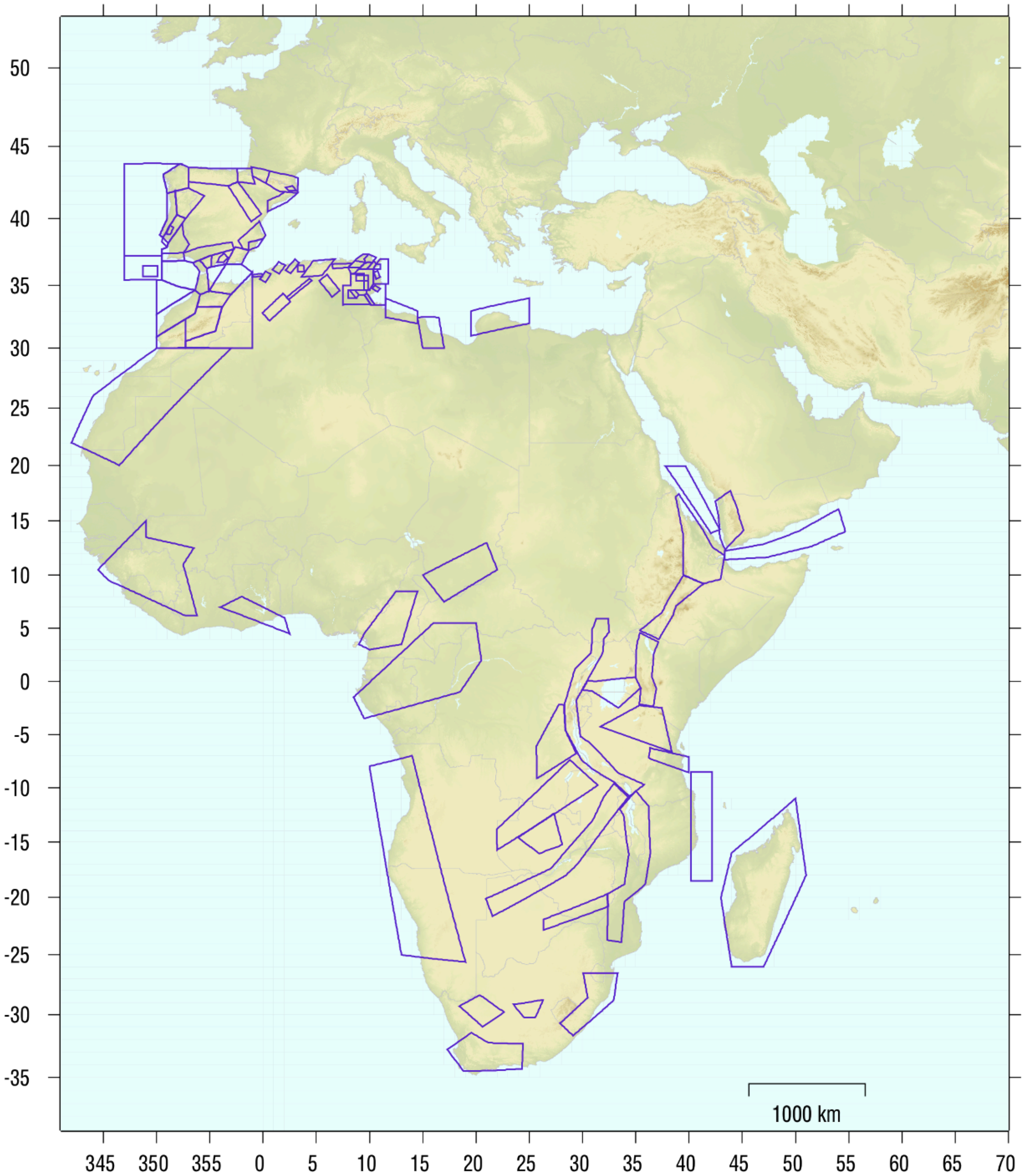

Figure A.1 Seismic sources contained in the Africa PSHA input models (Israel sources are not depicted).

A.3 Australia

The Australia model, prepared by Geoscience Australia, is a first round model covering the whole Australian territory.

Seismotectonic Settings

Australia is a large and stable craton where seismicity occurs rarely typically along ancient tectonic structures. On average there are two magnitude 5 earthquakes per year and one magnitude 6 every 5 years.

Input Model Description

The Australia input model contains 30 area sources accounting both for background seismicity and areas of concentrated seismic activity. **Figure A.2** shows position and geometry of the area sources contained in the Australia input PSHA model.

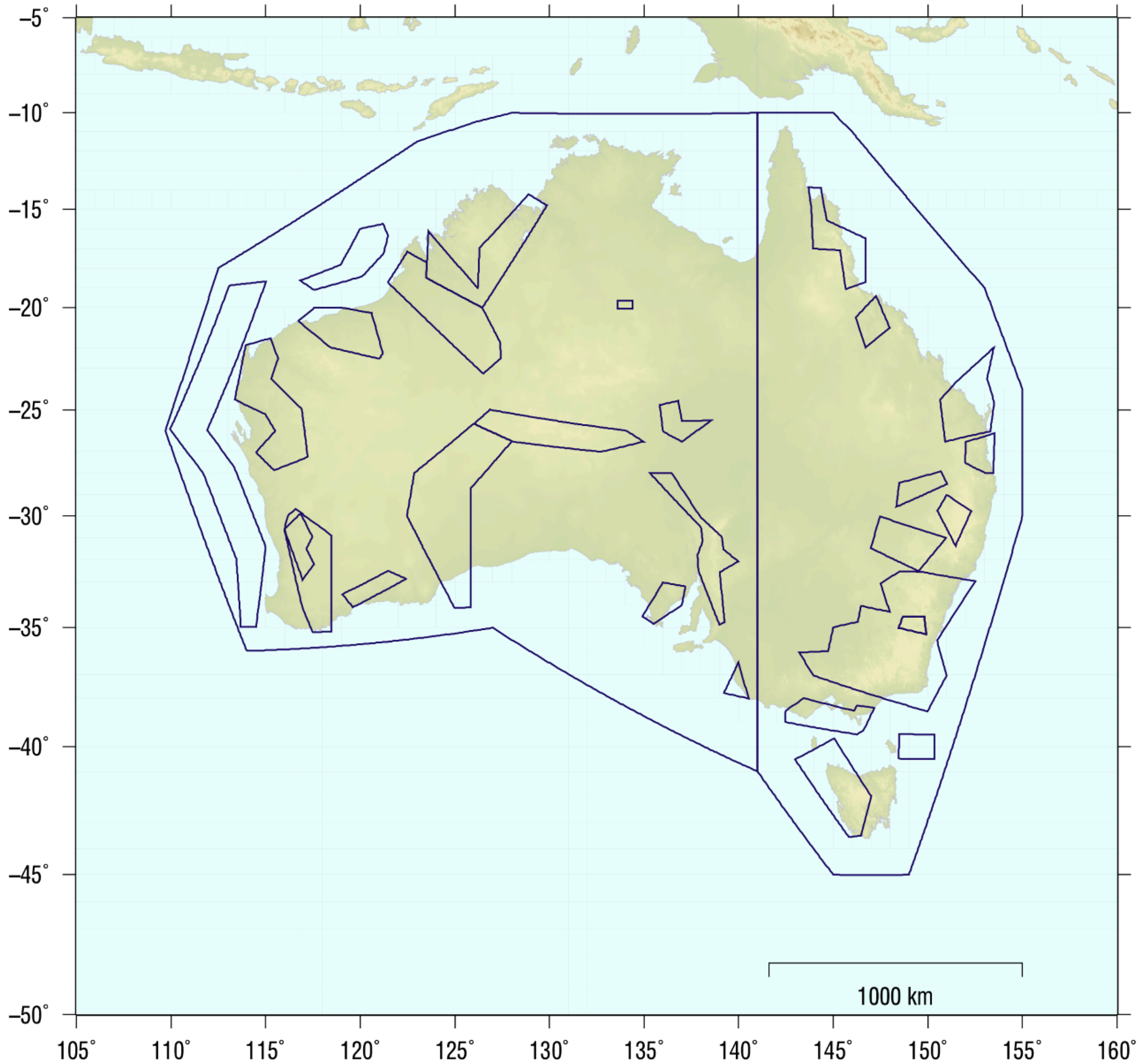

Figure A.2 Seismic sources contained in the Australia PSHA input model.

Seismicity temporal occurrence follows a Poisson process whereas the magnitude-frequency distribution (MFD) of earthquakes is defined by means of a Gutenberg-Richter distribution (GR).

In particular, the GR distribution is here specified in terms of the following parameters [Robinson et al., 2005; page 22]:

- Minimum (m_{min}) and maximum values (m_{max}) of magnitude.
- The λ_{mmin} value
- The b_{GR} value

The ground motion prediction equation adopted for hazard computation is the one of Atkinson and Boore [2006]. This hazard input model does not include a logic tree. Interestingly, in the Australia model site-effects are accounted through the definition of amplification factors for different soil categories and magnitude values.

Table A.3 Australia input model: summary table

Seismotectonic environments incorporated in the model	- Stable Continental Region (SCR)
Number of area sources contained in the model	30
Number of gridded seismicity sources contained in the model	None
Number of fault sources contained in the model	None
Logic tree/ epistemic uncertainty treatment	No
Ground motion prediction equations	- Atkinson and Boore [2006]
Model minimum magnitude (M_W)	4.5
PSHA code used	EQRM

A.4 Canada

The Geological Survey of Canada developed the model currently available to GEM1. This input model was used to create the fourth generation of seismic hazard maps for Canada.

Seismotectonic Settings

Canada largely sits on the North American craton. Active plate boundaries exist along the western coast where the Juan de Fuca microplate (JF) subducts under the North America plate (NA) and the Pacific plate moves against NA (Bird, 2003).

Input Model Description

The Canada model contains four distinct PSHA input sub-models used to describe distinct seismotectonic provinces recognized in the Canadian national territory. In the following we give a brief description of each sub-model:

1. Two sub-models based on two distinct sets of area sources, named “H” and “R”, respectively (see **Table A.4**), and one fault source (Queen Charlotte fault – Western Canada). These two sets of seismic sources are different schematizations of the seismicity distribution. The “H” model generally contains small size sources (usually

corresponding to areas where clusters of historical seismicity occurred), whereas the "R" generally contains seismic zones of regional dimension (representing large seismotectonic provinces).

2. One sub-model for stable Canada named "F". This model provides a "floor" value of hazard for the entire Canadian territory.
3. A deterministic model (named with the "C" acronym) for the Cascadia subduction zone based on a magnitude 8.2 earthquake [Adams and Halchuk, 2003; page 12].

Seismicity temporal occurrence is assumed to follow a Poisson process whereas the Magnitude-Frequency Distribution (MFD) of earthquakes is defined by means of a Gutenberg-Richter distribution (GR) estimated by maximum likelihood.

The MFD is specified by the following parameters:

- Minimum magnitude of complete reporting
- Maximum values (m_{max}) of magnitude assigned using seismotectonic analogue regions.
- The λ_0 value (corresponding annual rate of occurrence for magnitudes 0 or larger)
- The b_{GR} value

The model contains different ground motion prediction equation accounting for distinct seismogenic and propagation properties. In the central and eastern sector of the nation, hazard is computed by means of the Atkinson and Boore [1995] GMPE. More complex is the setting of GMPEs in the western model where two GMPEs are used. The model accounts for epistemic uncertainties about seismicity occurrence parameters, however, for computational efficiency reasons, only a "trimmed-tree" was considered. Results coming from the four sub-models are combined using the "robust" method of Adams [1995; see also Halchuk and Adams, 2008; page 4]; this method simply consists on choosing at each grid node the highest value of ground motion (with a given probability of exceedance in a fixed time period) between the ones coming from the applicable input model models.

Table A.4 Canada input model: summary table.

Seismotectonic environments incorporated in the model	- Stable Continental Region - Subduction zones - Shallow active crust
Number of area sources	117 (distributed in four input models)
Gridded seismicity sources	None
Fault sources	2 (Queen Charlotte Fault in the two Western models)
Logic tree/ epistemic uncertainty treatment	Yes
Ground motion prediction equations (see also Halchuk and Adams, 2008; page 4)	Eastern and central Canada: - Atkinson and Boore [1995] – adjusted to firm ground
	Western Canada shallow sources: - Boore at al. [1993, 1994] – adjusted to have a period dependent anelastic attenuation when R > 100km
	Subcrustal extensional seismicity in western Canada (subducting slab in Puget Sound): - Youngs et al. [1997] – intraslab – adjusted to “firm-solid” and with an assumed depth of 50 km
	Cascadia earthquake scenario: - Youngs et al. [1997] – interface – with an assumed depth of 25 km (check the distance calculation method)
Model minimum magnitude (see also Halchuk and Adams, 2008; page 5)	4.75
R_{max} (maximum distance considered to calculate the hazard at a site)	Eastern part: 600 km
	Western part: 400 km
PSHA code used	GSCFrisk88 (a modified version of Frisk88)

A.5 Central America

The Central America model built-in the GEM1 repository was developed within the international cooperation project RESIS II (http://www.norsar.no/c-138-RESIS-II.aspx and Oterino and Torres, 2010).

Seismotectonic Settings

Central America is an area of complex interaction between several tectonic plates. The main tectonic process is the collision and subduction of the Cocos plate (CO) under the Caribbean (CA) plate. Panama is considered a microplate limited by the Nazca plate and an obscure subduction zone towards the Caribbean plate. The Motagua-Pologic fault zone in Guatemala divides the north America plate from the Caribbean plate. Central America tectonics is characterized by strong volcanic activity parallel to the subduction zone. The earthquake activity is concentrated in the subduction zone, within the volcanic chain and along the main fault zones.

Input Model Description

The model takes into account for the seismicity generated within distinct seismotectonic environments:

- Shallow active crust (i.e. the seismicity confined in the depth interval comprised between 0 and 25 km)
- Seismic sources connected to the subduction process and, particularly, sources associated with:
  - Interplate seismicity

– Intraplate seismicity

Seismicity temporal occurrence is assumed to follow a Poisson process whereas the Magnitude-Frequency Distribution (MFD) of earthquakes is defined in terms of a Gutenberg-Richter distribution (GR). The GR distribution is defined by means of the following parameters [Oterino and Torres, 2010]:

- Minimum (m_{min}) and maximum values (m_{max}) of magnitude.
- The λ_{mmin} value (corresponding to the annual rate for magnitudes comprised between m_{min} and m_{max})
- The b_{GR} value

The Central America input model deals with epistemic uncertainties related to the GMPE by considering more than one ground motion prediction equation.

Table A.5 Central America input model: summary table

Seismotectonic environments incorporated in the model	- Subduction zone - Shallow active crust
Number of area sources contained in the model	55
Number of gridded seismicity sources contained in the model	None
Number of fault sources contained in the model	None
Logic tree/ epistemic uncertainty treatment (see [4] and Oterino and Torres, 2010)	YES (on GMPE)
Ground motion prediction equations (see [4] and Oterino and Torres, 2010)	Shallow seismicity: - Climent et al. [2004] - Zhao et al. [2006]
	Subduction zones: - Youngs et al. [1997] - Zhao et al. [2006]
Model minimum magnitude (M_W – supposed - see [4] and Oterino and Torres [2010])	4.5
PSHA code used	CRISIS

A.6 Europe

The input PSHA model for Europe that resides in the GEM model repository relies on the model prepared by G. Grünthal and coworkers (GFZ, Potsdam). The input model represents an updated version of a basic model developed within SESAME project.

Seismotectonic Settings

Europe seismotectonics is fairly variable. Most of the continent facing on the Mediterranean Sea is involved in an extensive collision process currently active between the Africa and Eurasia. In this area, seismicity is present principally along the Italian Peninsula, the eastern coast of the Adriatic Sea and in Greece where earthquakes shallow sources and subduction sources are currently active. In the continental part of Europe seismicity is active especially along the Alps, beside the Rhein graben; the Vrancea Region (Romania) represents a particular case of intermediate depth seismicity.

Input Model Description

The Europe model consists of 435 single source zones and their associated seismicity parameters, as were reported by Grunthal et al. [2010]. Seismic sources are defined as area sources; seismicity temporal occurrence follows a Poisson process whereas the magnitude-frequency distribution (MFD) of earthquakes is specified by means of a Gutenberg-Richter distribution (GR). For each source the associated seismicity parameters are defined as:

- Minimum (m_{min}) and maximum values (m_{max}) of magnitude.
- The λ_{mmin} value (corresponding to the annual rate for magnitudes comprised between m_{min} and m_{max})
- b_{GR} value

Additionally, a focal depth parameter is reported for each source. A constant depth of 12km was assigned to shallow earthquake sources. Few sources within the Vrancea region and the Hellenic Arc region, for which the focal depth was fixed to 80 km. Among the defined seismic sources there are eleven sources that are not significant from the seismicity point of view. These sources are so called “empty” and they are seismic sources without any earthquake of magnitude greater than the threshold magnitude of the catalogue data.

The magnitude scale for this model is moment magnitude, and the minimum magnitude was fixed to 3.8 whereas the upper limit of the magnitude differ from source to source. A single ground motion predicting equation is used and there is not an explicit description of how the epistemic uncertainties are accounted in the final model. The region validity of the model extends between the 25N and 75N latitude and the 25W and 40E longitude.

Table A.6 Europe input model: summary table

Seismotectonic environments incorporated in the model	- Stable Continental Region (SCR – e.g. Northern Europe) - Shallow active crust (e.g. Central Italy) - Deep focus earthquakes (e.g. Vrancea Region) - Subduction (e.g. Greece)
Number of area sources	435 (used 424)
Number of gridded seismicity sources	None
Number of fault sources	None
Logic tree/ epistemic uncertainty treatment	No
Ground motion prediction equations	Akkar and Bommer [2010]
Model minimum magnitude (M_W)	3.8
PSHA code used	FRISK88M

A.7 India

The model of India at present built-in the GEM1 repository covers the peninsular part of the nation. Jaiswal and Sinha initially published the first version of this model in 2007; one year later, the same authors revised and extended the same model [Jaiswal and Sinha, 2008].

Seismotectonic Settings

India is for a large part a stable craton. The most tectonically active area is placed in the North where collision between the India plate (IN) and the Euroasiatic one (EU) is effective. Seismicity concentrates at the foothill of the Himalayan chain, in the Hindukush and Andaman regions [Jaiswal and Sinha, 2008]. A sporadic seismic activity is active in the cratonic part of the nation, with rare earthquakes sometimes of destructive intensity (e.g. 1993 Latur earthquake).

Input Model Description

The approach adopted to calculate seismic hazard [Jaiswal and Sinha, 2008] follows the smoothed seismicity approach proposed by Frankel [1995] and extensively tested in several versions of the USA – NSHMP.

Seismicity temporal occurrence is assumed to follow a Poisson process whereas the Magnitude-Frequency Distribution (MFD) of earthquakes is described by using a Gutenberg-Richter distribution (GR). Although the PSHA approach adopted is based on a smoothing kernel the authors defined also a seismotectonic zonation containing nine zones. These zones are used to fix regional values of the b_{GR} and of m_{max}.

The ground motion prediction equations contained in this model are GMPEs commonly used in the eastern portion of the United States of America (see **Table A.7**) to compute PSHA. Epistemic uncertainties due to ground-motion models are accounted by considering some alternative GMPEs.

Table A.7 Peninsular India input model: summary table.

Seismotectonic environments incorporated in the model	- Stable continental region (SCR)
Areal sources	None
Gridded seismicity sources	Yes (9 macro-areas used to fix regional values of m_{max} and b_{GR})
Fault sources	None
Logic tree/ epistemic uncertainty treatment	Yes (on GMPEs)
GMPEs	Stable continental region: - Frankel et al. [1996] - Toro et al. [1997] - Atkinson and Boore [2006] - Silva et al. [2002]
Minimum magnitude (M_W) of the model	The value of the m_{min} is variable within the different macro-areas.
PSHA code	USGS-NSHMP suite of codes (hazgridXnga4 particularly)

A.8 Iran

The information related to the PSHA model for Iran was retained from the GSHAP data repository (http://www.seismo.ethz.ch/gshap/iran/). The available information is limited to seismicity parameters associated to each seismic source. The geographically boundaries of the model are spanning the area between 25-40N and 44-63E.

More detailed information can be found in the report by Takavoli and Ashtiany [1999].

Seismotectonic Settings

Current tectonics processes in Iran are driven by the convergence between Arabia and Eurasia. Active faults spread over the whole country and particularly along the Zagros region in south-west Iran where high seismicity rates are observed; a second area of high seismicity rates is in the Dasht-e-lut (Central-East Iran).

Input Model Description

The model was prepared in the framework of the GSHAP project; it contains 20 area sources. Since source geometry parameters were not available in the GSHAP data repository, the source geometries here adopted were reconstructed from Figure 2 of Takavoli and Ashtiany [1999]. Seismicity temporal occurrence is assumed to follow a Poisson process whereas the Magnitude-Frequency Distribution (MFD) of earthquakes is described by using a Gutenberg-Richter distribution (GR).

For each source, the following parameters characterizing the GR distribution were reported:

- Minimum magnitude (m_{min});
- Observed maximum values of magnitude;
- Estimated maximum values (m_{max}) of magnitude;
- The λ_{mmin} value (corresponding to the annual rate for magnitudes comprised between m_{min} and m_{max})
- b_{GR} value;
- Number of events observed and completeness period for each source zone.

Table A.8 Iran input model: summary table.

Seismotectonic environments incorporated in the model	- Shallow active crust
Areal sources	20
Gridded seismicity sources	None
Fault sources	None
Logic tree/ epistemic uncertainty treatment	No
GMPEs	- Campbell [1990] - Campbell and Bozorgnia [1993]
Minimum magnitude (M_W) of the model	4.5
PSHA code	SEISRISKIII

A.9 Japan

[Description was revised by K. Shimazaki, ERI, Japan]

The Japan model available in the GEM1 repository is the one downloadable from J-SHIS (Japan Seismic Hazard Information Station - for additional information you can refer to the following website: http://www.j-shis.bosai.go.jp/). Japan seismic hazard maps are revised annually because they're time-dependent. A major revision of the hazard models was made in 2009. In this new revised version site conditions are accounted on grid of 250x250m instead of earlier 1km by 1km and near-source ground motion uncertainty for shallow crustal earthquakes is raised on the basis of accumulated data. The version of this model included in the GEM1 repository was kindly provided by P. Somerville.

Seismotectonic Settings

Japan current tectonics is driven by the subduction of the Pacific and the Philippine Sea plates below the Amur and Okhotsk ones. Seismicity is occurring mostly in the area bordered to the east by the Japan trench and the Nankai trough and the Ryukyu trench and, to the west, by the occidental coasts of the main islands, where, in part, premature subduction of the Amur plate beneath the Okhotsk plate is taking place and by offshore rifting region in the back-arc in the southern part.

Input Model Description

The Japan PSHA input model consists of a set of fault sources and a set of area sources, The fault source can be divided in two main typologies: rectangular shallow crustal fault and subduction sources. Three sets of area sources exist: shallow crustal, interplate, and intraslab sources. There exist two more local models: Tokachi and Tokyo ones.

In particular, the model in our repository contains 563 rectangular fault surfaces and twelve large subduction faults. The Japan model describes the seismicity occurrence model mostly using either a Poisson or a Brownian-Time-Passage model. A combination of time-predictable model and BPT is used for limited cases. Usually, activity rates for a specified magnitude value are provided.

Table A.9 Japan model: summary table

Seismotectonic environments incorporated in the model	- Active shallow tectonics region - Subduction region
Areal sources	None
Gridded seismicity sources	None
Fault sources	563 + 12
Logic tree/ epistemic uncertainty treatment	None
GMPEs	n.d.
Minimum magnitude (M_W) of the model	n.d.
PSHA code	Proprietary code (non publicly available)

A.10 Mexico

The Mexico model was provided by Mario Ordaz (UNAM – Universidad Nacional Autonoma de Mexico).

Seismotectonic Settings

The western coast of Mexico is currently an area of complex interaction between several continental and oceanic plates. In the north part of Mexico (Baja California area) the Pacific plate is subducting under the North America (NA) plate. More to the south, the small Rivera plate and the Cocos plate subduct under the NA plate. Seismicity concentrates in the Baja California area and along the trench located offshore of the south-western coast of the nation.

Input Model Description

The model takes into account for the seismicity generated within distinct seismotectonic environments:

- Shallow active crust
- Seismic sources connected to the subduction process and, particularly, sources associated with:
  - Interplate seismicity
  - Intraplate seismicity

Seismicity temporal occurrence is assumed to follow a Poisson process whereas the Magnitude-Frequency Distribution (MFD) of earthquakes is defined in terms of a Gutenberg-Richter distribution (GR) for some sources or a Characteristic-Earthquake (CE) model for other sources (large subduction earthquakes).

The GR distribution is defined by means of the following parameters:

- Minimum (m_{min}) and maximum values (m_{max}) of magnitude, and other parameters related to the uncertainty in the maximum magnitude.
- The λ_{mmin} value (corresponding to the annual rate for magnitudes comprised between m_{min} and m_{max})
- The b_{GR} value, including a measure of the uncertainty in this parameter.

The CE distribution is defined by means of the following parameters:

- Minimum (m_{min}) and maximum values (m_{max}) of magnitude.

- The λ_{mmin} value (corresponding to the annual rate for magnitudes comprised between m_{min} and m_{max})
- Two parameters defining the shape of the MFD between m_{min} and m_{max}.

The Mexico input model does consider epistemic uncertainties related to maximum magnitude and b-value in the GR magnitude-frequency distribution.

Table A.10 Mexico input model: summary table.

Seismotectonic environments incorporated in the model	- Subduction zone - Shallow active crust
Number of area sources contained in the model	43
Number of gridded seismicity sources contained in the model	None
Number of fault sources contained in the model	None
Logic tree/ epistemic uncertainty treatment	Considers epistemic uncertainties related to maximum magnitude and b_{GR}-value in GR MFD, as well as epistemic uncertainties in the depth of some of the area sources.
Ground motion prediction equations	GMPEs: - Abrahamson and Silva [1997] - Garcia et al. [2005] - Ordaz et al. [1989]
Model minimum magnitude	4.5
PSHA code used	CRISIS

A.11 New Zealand

Mark Stirling, GNS Science, provided the available New Zealand model [see Stirling et al., 2002].

Seismotectonic Settings

New Zealand is situated on the eastern border of the Australian plate in an area where the oceanic crust subduces to accommodate oceanic consumption. Two are the main subduction areas, the Hikurangi and Fiordland subductions zone, situated east of the Northern Island and at the northwestern tip of the Southern Island, respectively. In the back-arc an oceanic rifting process is currently active. Of relevance for hazard also the oblique slip faults related to the Alpine fault lineament.

Input Model Description

The New Zealand input model [see also the paper of Stirling et al., 2002] contains grid and fault sources. For this reason, it's conceptually comparable to the PSHA input models prepared by the USGS during the latest fifteen years.

The New Zealand model includes an extensive number of faults (328) comprising both shallow and subduction (interface) seismogenic structures; each source is characterized in terms of geometry, characteristic magnitude and corresponding recurrence interval. The gridded seismicity file contains a list of cells organized on a regular grid with a given spacing; each node is described in terms of geometry (i.e. the geographic coordinates plus the depth of the cell centre) b_{GR}, and cut-off magnitude. To account for the depth distribution of seismicity the gridded seismicity is divided into five layers placed at depths of 1, 30, 50, 70 and 90 km [see Stirling et al, 2002 page 1885]. Note that gridded seismicity is used to account for intra-slab seismicity related to the subduction processes active in the area.

Three are the tectonic environments considered:

- Active shallow tectonics;
- Volcanic;
- Subduction (interface and intra-slab)

The New Zealand input model does not consider explicitly epistemic uncertainties.

Table A.11 New Zealand input model: summary table.

Seismotectonic environments incorporated in the model	- Shallow active crust - Subduction - Volcanic (Taupo zone)
Number of area sources contained in the model	None
Number of gridded seismicity sources contained in the model	One (the calculation of this grid is completed by following the method of Frankel; see Stirling et. al., 2002). 37 seismotectonic areas were used to fix the maximum value of magnitude
Number of fault sources contained in the model	328 (taken from the received PSHA input file)
Logic tree/ epistemic uncertainty treatment	Yes. For example, in the Hikurangi subduction zone they implemented several alternative models.
Ground motion prediction equations	- McVerry [2000]
Model minimum magnitude (M_W)	5.25
PSHA code used	SeisHaz code (M. Stirling)

A.12 Northern Eurasia [GSHAP]

Ulomov and coworkers implemented, in the framework of the GSHAP project, the Northern Eurasia model currently adopted in GEM1. In their original work, Ulomov et al. [1999] computed hazard - via a probabilistic approach – using a method called Earthquake Adequate Source technology [EAST; Ulomov, 1997]

Seismotectonic Settings

The Northern Eurasia region is a vast area considered relatively stable from a tectonic point of view. This PSHA Input model comprehends vast stable platforms such as the Russian platform, the West-Siberian one and the Siberian one. Main orogenic areas with relevant seismic activity included in the model are: the Iran-Caucasus-Anatolia, Central Asia, Altay-Sayany-Baikal [Ulomov et al., 1999]. In the model is also included the subduction area located along the Kurili arc and Kamchatka peninsula.

Input Model Description

The Eurasia PSHA model developed in the framework of the GSHAP projects contains several peculiar and interesting aspects. The seismicity occurrence model is based on two source zonation typologies named: Source Zone Model and Seismic Effect Model.

Table A.12 Eurasia input model: summary table.

Seismotectonic environments incorporated in the model	- Stable Continental Region (SCR) - Shallow active crust
Number of area sources contained in the model	457
Number of gridded seismicity sources contained in the model	None
Number of fault sources contained in the model	1066
Logic tree/ epistemic uncertainty treatment	None
Ground motion prediction equations	- Aptikaev and Shebalin [1988] - (it's an intensity based GMPE- values of Intensity are than converted to PGA using an empirical relationship)
Model minimum magnitude (M_W)	Mw (see ASCII file header and Ulomov et al., 1999; page 1035)
PSHA code used	Proprietary code (authors: Gusev, Pavlov and Shumilina)

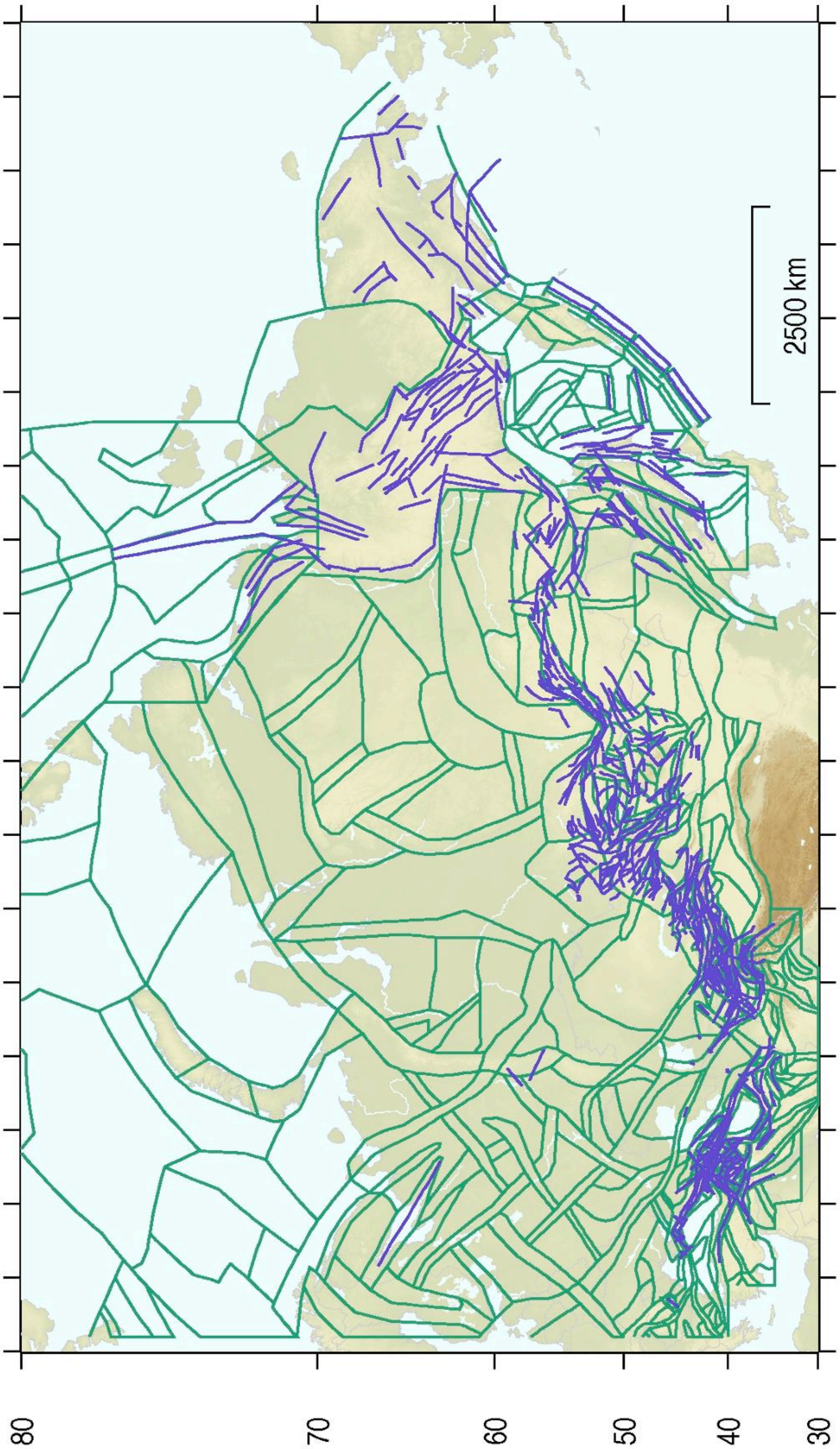

Figure A.3 Area sources and fault sources contained in the Northern Eurasia model

A.13 South America [USGS]

The model for South America is a preliminary model recently developed by the USGS National Seismic Hazard Mapping Group in conjunction with the Centro Regional de Sismologia para América del Sur (CERESIS) [Petersen et al., 2010].

Seismotectonic Settings

The western coast of the South American continent is the area where active tectonic concentrates; the process is driven by the subduction of the Nazca (NZ), and Antartica (AN) plates below the North Andes (ND), South America (SA), and Altiplano (AP) plates. Two important orogens are also present alongside the western coast: the Peru, and the Puna- Sierra Pampeanas ones [Bird, 2003].

Seismicity concentrates on the subduction structures, in the two orogens, and along the continental convergent boundaries situated in the back-arc areas [Bird, 2003]. Historically South America was subject to strong earthquakes of very high magnitudes (e.g. the 1960 Chile earthquake M=9.5).

Input Model Description

This model, as habitually done by the USGS National Seismic Hazard Mapping team, contains three source typologies: shallow faults, subduction zones and gridded seismicity (also called background seismicity).

In particular, two background seismicity models account for distributed seismicity occurring within the craton and inside the region undergoing active tectonics (the seismogenic thickness is assumed to be 15km).

The model implementation follows the NSHMP PSHA software (see 0).

Distinct suites of GMPES are used to take account of particular source mechanisms and propagation paths. The model-summary table (see **Table A.13**) synthesizes the ground motion prediction equations adopted for the seismotectonic classes considered.

Table A.13 South America model: summary table

Seismotectonic environments incorporated in the model	- Subduction zone - Stable continental region - Shallow active crust
Number of area sources contained in the model	None
Number of gridded seismicity sources contained in the model	91622 grid points
Number of fault sources contained in the model	226 crustal faults + 15 subduction faults
Logic tree/ epistemic uncertainty treatment	Yes
Ground motion prediction equations	Subduction zone: - Youngs et al. [1997] - Atkinson and Boore [2003] - Zhao et al. [2006]
	Crustal faults: - Boore and Atkinson [2008] - Chiou and Youngs [2008] - Campbell and Bozorgnia [2008]
	Stable continental region - Toro et al. [1997] - Frankel et al. [1996] - Atkinson and Boore [2006] – 140 bar stress drop - Atkinson and Boore [2006] – 200 bar stress drop - Campbell [2003] - Tavakoli and Pezeshk [2005] - Silva et al. [2002]
Model minimum magnitude (M_W)	5.0
PSHA code used	USGS-NSHMP suite of codes

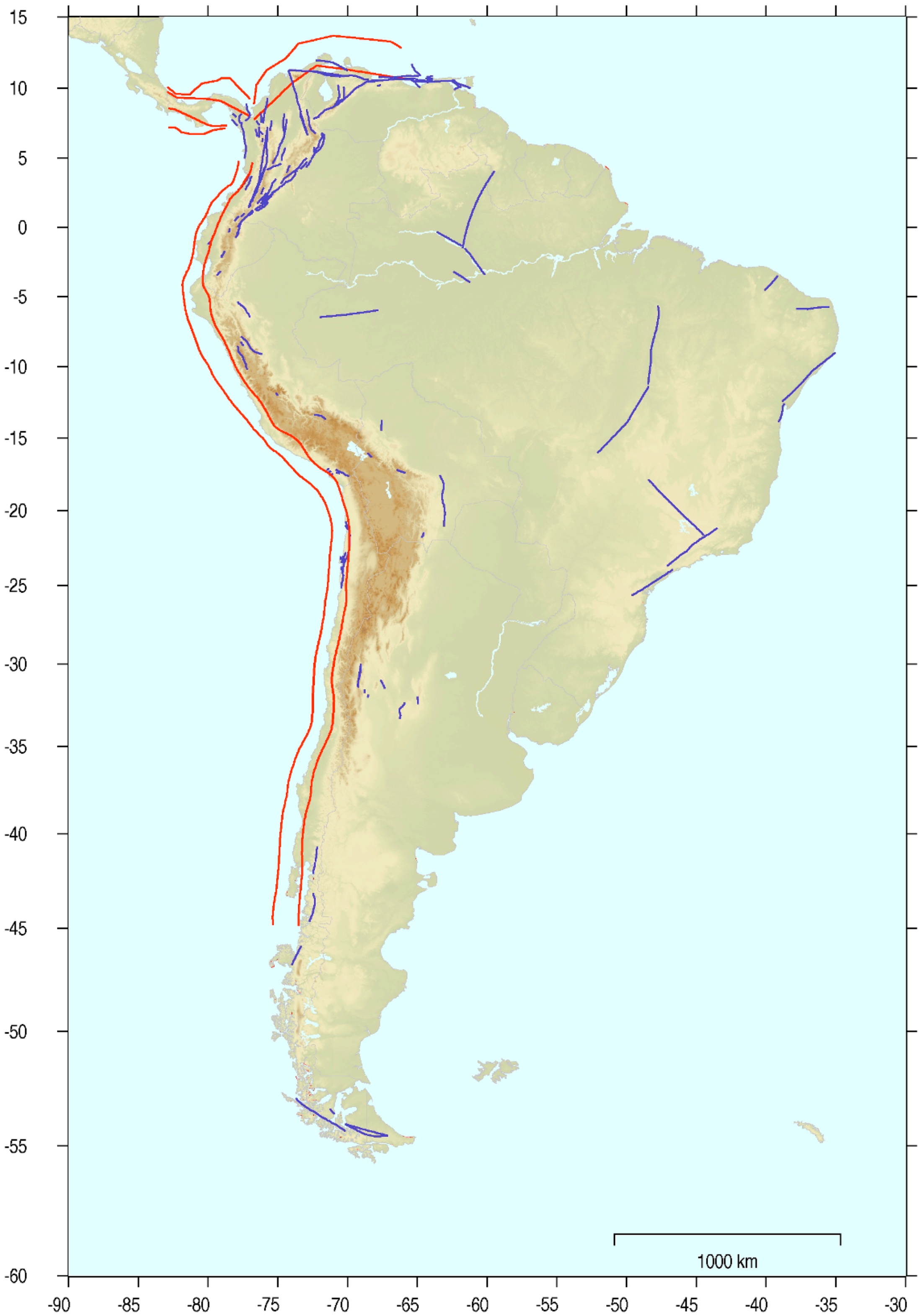

Figure A.4 Geometries and geographic distribution of area sources and fault sources contained in the USGS South America model. Lines in purple are shallow fault sources, while the red lineaments delimitate the subduction planes considered in the model.

A.14 South East Asia [USGS]

The South East Asia model includes:

- The Indonesia model prepared by the USGS National seismic hazard mapping team [see Petersen et al. 2004; Petersen et al. 2007; Irsyam et al., 2009] in collaboration with Indonesian researchers from a few institutions.
- The Thailand model prepared by the USGS national seismic hazard map team.

Seismotectonic Settings

Indonesia is one of the areas with the strongest seismic potential in the World. Seismotectonics is dominated by the subduction of the Australia plate (AU) under the Burma (BU) and Sunda (SU) ones along the Sumatra-Java arc and by the oblique subduction of the India and Australia plates under Eurasia (Burma-Andaman-Sunda system of Bird, 2003). The seismogenic potential of the area is relevant; surprisingly, the area of the Sunda Sea is lacking of seismic activity.

Input Model Description

The approaches and the tools adopted to calculate seismic hazard are the ones commonly adopted by the USGS-NSHMP team (see 0). Distinct suites of GMPES are used to better account for particular source mechanisms and propagation paths. The model-summary table below synthesizes the ground motion prediction equations adopted for distinct seismotectonic classes.

Table A.14 South East Asia input model: summary table

Seismotectonic environments incorporated in the model	- Subduction zone - Shallow active crust
Number of area sources contained in the model	None
Number of gridded seismicity sources contained in the model	287643 grid points
Number of fault sources contained in the model	69 crustal faults + 4 subduction sources
Logic tree/ epistemic uncertainty treatment	Yes
Ground motion prediction equations	Subduction: - Youngs et al. [1997] - Atkinson and Boore [2003] - Zhao et al. [2006]
	High Q (Gridded seismicity) - Frankel et al. [1996] - Toro et al. [1997] - Atkinson and Boore [2006] - Silva et al. [2002] - Campbell [2003] - Tavakoli and Pezeshk [2005]
	Low Q (Gridded seismicity): - Frankel et al. [1996] - Campbell and Bozorgnia [2008] - Chiou and Youngs [2008]
	Shallow sources (Faults): - Boore and Atkinson [2008] - Campbell and Bozorgnia [2008] - Chiou and Youngs [2008]
Model minimum magnitude (M_W)	5.0
Rmax	200
PSHA code used	USGS-NSHMP suite of codes

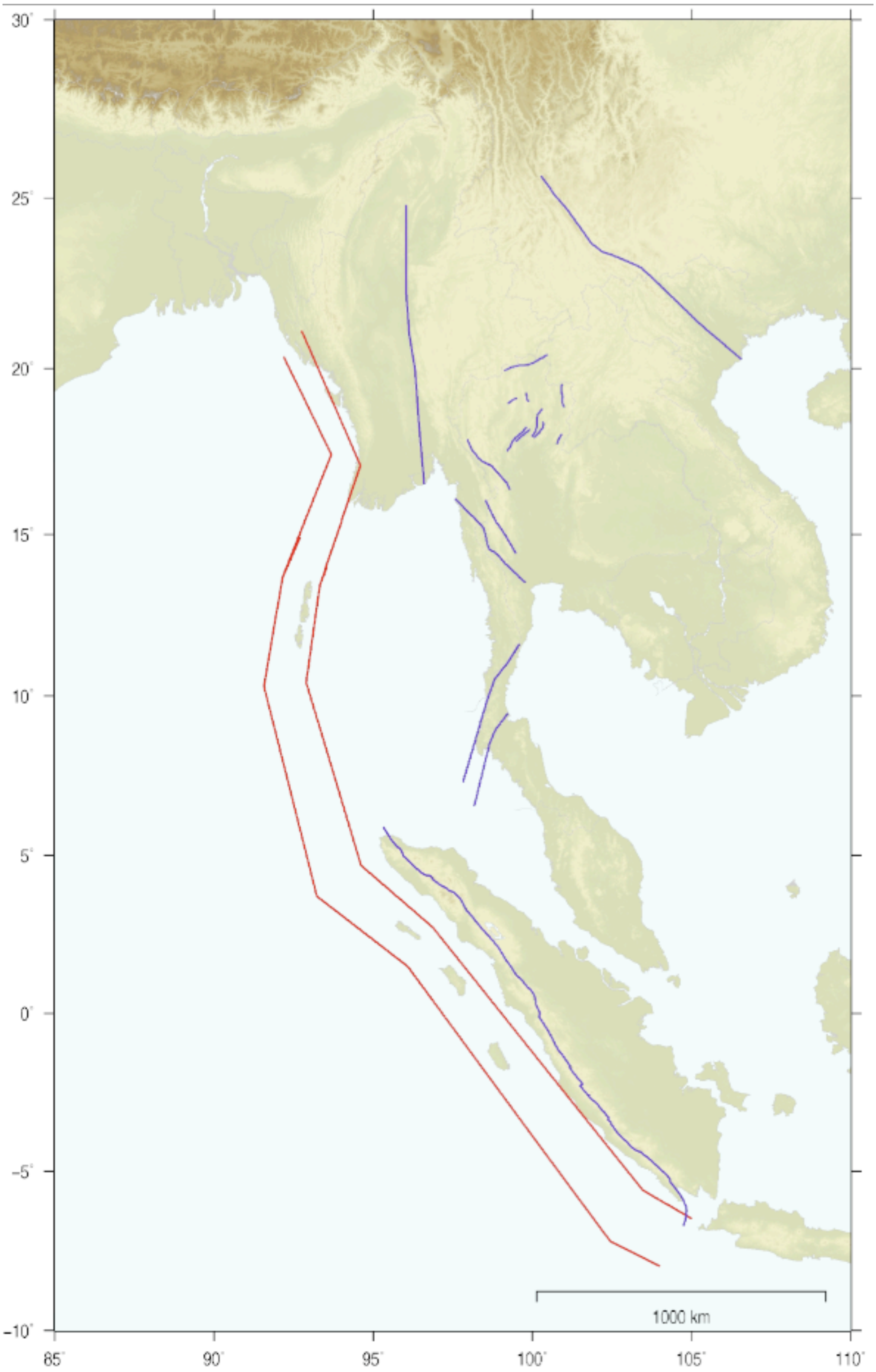

Figure A.5 - Geometries and geographic distribution of shallow and subduction sources contained in the USGS South East Asia model. Lines in purple are shallow fault sources, while the red lineaments delimitate the subduction planes considered in the model.

A.15 South East Asia [GSHAP]

The PSHA model for the South East Asia region included in the GEM1 repository was created within the GSHAP project (http://www.seismo.ethz.ch/gshap/eastasia). The model is the result of an extended collaboration between several regional centres, including SSB Beijing, JIPE Moscow, AGSO Canberra, USGS and research institutes of almost all the Eastern Asian countries. A complete description of the input model of Eastern Asia is contained in the report of Zhang et al. [1999]. The area covered by this model comprises China, Mongolia, Pakistan and India.

Seismotectonic Settings

The area included in this model is an area of complex interaction between tectonic plates where continental collision processes dominates the seismogenic activity. On the eastern flank – near Taiwan – earthquakes generated by the subduction processes contribute significantly to the observed seismicity. Shallow seismicity covers the entire area with local maxima along the northern edge of the Himalayan Chain, the border between China and Kazakhstan.

Input Model Description

The input model for South East Asia contains two types of area sources defined as: simple and background seismic sources. In particular, the model contains 26 background sources - delineated using regional patterns of geological information and regional seismicity - and 425 simple area sources.

Seismicity temporal occurrence is assumed to follow a Poisson process whereas the Magnitude-Frequency Distribution (MFD) of earthquakes is defined in terms of a Gutenberg-Richter distribution (GR). The following parameters were reported for each seismic source:

- Minimum (m_{min}) and maximum values (m_{max}) of magnitude.
- Earthquake occurrence rate
- b_{GR} value

Table 2-15 summarizes the available information for the South East Asia model.

A single ground motion predicting equation proposed by Huo and Yuxian [1992] was used for the hazard computation of the whole South East Asia region. Extensive work was conducted in order to homogenize the earthquake magnitude scale for the entire region by converting four different magnitude scales into moment magnitude scale. The lower magnitude associated to each single seismic source was ranging from 5 to 5.5, whereas the maximum magnitude was varying from source to source. The PSHA input model does takes into account epistemic uncertainties.

Table A.15 Eastern Asia input model: summary table

Seismotectonic environments incorporated in the model	- Subduction zone - Shallow active crust - Stable continental
Number of area sources contained in the model	425
Number of gridded seismicity sources contained in the model	0
Number of fault sources contained in the model	0
Logic tree/ epistemic uncertainty treatment	Yes
GMPE	Huo and Hu [1992]
Model minimum magnitude (M_W)	5 and 5.5
PSHA code used	FRISK88M

A.16 Turkey

Middle East is one of the first areas where, in spring 2009, GEM started a regional initiative. The Earthquake Model for the Middle East (EMME) is a hazard and risk project that involves about fifteen countries of the area. Further information about this project is available on its web site http://www.emme-gem.org/. The PSHA model currently available for this area covers Turkey; this model largely relies on the work performed during the latest years at the Kandili Observatory and Earthquake Research Institute (KOERI), Istanbul, Turkey [see Demircioglu et al., 2007].

Seismotectonic Settings

The Middle East tectonics is dominated by the northward migration of Africa and the interaction between the Euroasiatic (EU), Anatolian (AT), Arabian (AR), and African (AF) plates.

Seismicity is located along the North Anatolian fault (right lateral strike slip fault) and its conjugate, the East Anatolian fault (the two faults join at the Karliova triple junction) as well as along the western part of Turkey where a continental rift process is currently active. East of the Karliova triple junction point, where the predominant tectonic process is continental shortening, the seismicity appears more diffuse albeit with events of lower energy.

Input Model Description

The Turkey PSHA input model includes area sources as well as faults. The magnitude-frequency distribution used to describe seismicity occurrence is the classical Gutenberg-Richter relationship. For each source, the following parameters are provided [Demircioglu et al., 2007, page 7]:

- Minimum (m_{min}) and maximum values (m_{max}) of magnitude;
- The a_{GR} value;
- The b_{GR} value.

The ground motion prediction equations used are three GMPE commonly adopted within seismotectonic environments characterized by shallow active faults. Epistemic uncertainties are considered with regard of the ground motion prediction equation. The final hazard maps corresponds to the arithmetic mean of the results obtained using the GMPEs listed in Table below.

Table A.16 – Turkey input model: summary table

Seismotectonic environments incorporated in the model	Shallow active crust
Number of area sources contained in the model	36
Number of gridded seismicity sources contained in the model	None
Number of fault sources contained in the model	30
Logic tree/ epistemic uncertainty treatment	Yes. The procedure adopted to combine the result is not explicitly stated in the paper of Demircioglu et al., 2007
Ground motion prediction equations (Demircioglu et al., 2007; page 8)	Crustal faults: - Boore et al. [1997] – PGA and S_a - Sadigh et al. [1997] – PGA and S_a - Campbell et al. [2003] – Only PGA
Model minimum magnitude (M_W)	n.d.
R_{max}	n.d.
PSHA code used	Seisrisk III (modified version)

A.17 Conterminous USA

The latest (2008) seismic hazard model for the conterminous United States is made available by the USGS-National Seismic Hazard Mapping Project (NSHMP) group through their website (http://earthquake.usgs.gov/research/hazmaps/). It consists of a suite of distinct PSHA input models covering entirely and homogenously all the 48 states.

Seismotectonic Settings

The tectonics of the conterminous U.S. is driven by the interaction between the North America plate and the Pacific and Cocos plates. The Central and Eastern part is a stable continental region where seismicity concentrates on ancient tectonic structures. The Western part undergoes an intense tectonic activity with associated seismicity. Particularly, seismicity is affected by the presence of a continental transform fault (St. Andreas) and the Gorda-California-Nevada orogen [Bird, 2003]. Subduction processes are currently active in the Cascadia region.

Input Model Description

In the NSHMP U.S. model a major separation is done between to tectonic domains: the Central-Eastern United States (CEUS) and Western United States (WUS). The former includes the northern and central Rocky Mountains and the Colorado Plateau and extends to the east coast. In this large area finite faults are identified in the New Madrid zone (Missouri and adjacent states), Charleston (South Carolina), Meers (Oklahoma), and Cheraw (Colorado). In the latter domain, finite faults are identified in the Intermountain West region (Arizona, Colorado, Idaho, Montana, Nevada, New Mexico, Texas, Utah, Wyoming), Pacific North West region (Oregon, Washington), and California.

In the NSHMP (2008) model almost all sources are assumed to generate seismicity following a time-independent (Poissonian) recurrence models whilst Gutenberg-Richter (GR) Gaussian (named “Characteristic”, CHAR) are the two magnitude-frequency distribution distributions considered. The only exception is for the New Madrid Fault Model where a temporal cluster model is adopted instead.

Input Model Implementation

Fault sources are modelled as 3D surfaces with finite ruptures floating both in the strike and dip directions. Faults obeying a GR recurrence model are described in terms of minimum and maximum magnitude, incremental a value (10^a is the rate of events in a interval of length dM containing 0 in its interior), and b_{GR} value. CHAR faults are characterized in terms of mean magnitude, mean rate, and standard deviation plus a truncation level.

Gridded seismicity sources are derived by smoothing the observed earthquake recurrence rates across a grid of points. At each grid point, finite faults are generated (by using a magnitude-area scaling relationship) with a random strike or with a given strike (if supplied).

Uniform background zones account for earthquakes potentially spread uniformly across tectonic or geologic regions with constant geologic or strain characteristics. Uniform background zones are treated as gridded seismicity sources from the calculation viewpoint. The MFD in case of grid sources corresponds to a Gutenberg-Richter and it’s defined in almost the same way of GR distributions are specified for faults. The only difference is in the incremental a value where 10^a is considered as the rate of events for a magnitude bin centred on M=0 with a width of 0.1 units.

Uncertainties on GR maximum magnitude and CHAR mean magnitude are taken into account by using a logic tree approach (assuming conservation of total moment rate or total cumulative rate).

Ground motion is modelled by means of several ground motion prediction equations organized in a logic tree structure (reported in tables 9-22 and 9-23).

Table A.17 USA – Central and Eastern United States model: summary table

Seismotectonic environments incorporated in the model	- Stable continental region
Number of gridded seismicity sources contained in the model	1621904
Number of fault sources contained in the model	13 (without the New Madrid cluster model)
Logic tree/ epistemic uncertainty treatment	Yes
Ground motion prediction equations	Stable continental region: - Youngs et al. [1997] - Atkinson and Boore [2003] - Zhao et al. [2006]
Model minimum magnitude (M_W)	5
Rmax	200
PSHA code used	USGS-NSHMP suite of codes

Table A.18 USA – Western United States model: summary table

Seismotectonic environments incorporated in the model	- Subduction zone - Shallow active crust
Number of gridded seismicity sources contained in the model	183617 grid points
Number of fault sources contained in the model	2953 crustal faults + 20 subduction faults
Logic tree/ epistemic uncertainty treatment	Yes
Ground motion prediction equations	Subduction: - Youngs et al. [1997] - Atkinson and Boore [2003] - Zhao et al. [2006]
	High Q (Gridded seismicity) - Frankel et al. [1996] - Toro et al. [1997] - Atkinson and Boore [2006] - Silva et al. [2002]) - Campbell [2003] - Tavakoli and Pezeshk [2005]
	Low Q (Gridded seismicity): - Frankel et al. [1996] - Campbell and Bozorgnia [2008] - Chiou and Youngs [2008]
	Shallow sources (Faults): - Boore and Atkinson [2008] - Campbell and Bozorgnia [2008] - Chiou and Youngs [2008]
Model minimum magnitude (M_W)	5
Rmax	200
PSHA code used	USGS-NSHMP suite of codes

A.18 Global smoothed seismicity

(Text prepared by J. Zechar)

The global smoothed seismicity forecast was constructed using the Simple Smoothed Seismicity (TripleS) model of Zechar and Jordan (in review). This model has only one free parameter and is based on very few assumptions; therefore it may be considered as a model of least information. TripleS applies an isotropic Gaussian smoothing to the locations of past earthquakes to forecast the density of future seismicity. TripleS is characterized by one parameter: the smoothing distance, σ, which is equivalent to the standard deviation of a one-dimensional Gaussian distribution. Because there is little evidence that complex prediction algorithms substantially outperform very crude smoothed seismicity models, we used this simple model and a retrospective forecast experiment to optimize the smoothing distance with respect to the area skill score [Zechar and Jordan, 2008].

In the retrospective experiment, we smoothed the locations of earthquakes that occurred during the period 1900–1989 (inclusive) to forecast the locations of earthquakes during the period 1990–2007 (inclusive). We used an earthquake catalog that contained earthquakes with magnitude at least 7.0 during the period 1900–1972 inclusive and earthquakes with magnitude at least 4.7 in more recent years—these data came from the Pacheco-Sykes and USGS PDE catalogs, respectively. In choosing these data sources, we sought a compromise between a longer historical record and a more complete modern record. These data were smoothed with different smoothing distances, and we calculated the area skill score average misfit statistic for each distance [Zechar and Jordan, 2010]. The values are reported in the table below.

Smoothing distance, σ (km)	Area skill score average misfit, ξ
5	0.0448
10	0.0442
20	0.0334
25	0.0276
30	0.0210
50	0.0161
75	0.0496
100	0.0848
200	0.1869

The smoothing distance which obtains the smallest area skill score average misfit is considered optimal, and therefore a smoothing distance of σ = 50 km was used for the global smoothed seismicity forecast.

For this forecast, we smoothed all events in the catalogue from 1900–2009, inclusive. This yielded a spatial distribution, and in every cell we assumed a Gutenberg-Richter magnitude distribution. Moreover, we assumed that the overall rate of earthquakes should match the historical average, so the forecast values in each bin were scaled accordingly.