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D3.3 – Homogeneous determination of maximum magnitude

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Istituto Nazionale di Geofisica e Vulcanologia (INGV)

Carlo MELETTI, Vera D'AMICO, Francesco MARTINELLI

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Dissemination Level		
PU	Public	x
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

Summary

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1. Introduction

This deliverable represents the result of the activities performed by a working group at INGV. The main object of the Task 3.5 is defined in the Description of Work.

> *This task will produce a homogeneous assessment (possibly multiple models) of the distribution of the expected Maximum Magnitude for earthquakes expected in various tectonic provinces of Europe, to serve as input for the computation and validation of seismic hazard. This goal will be achieved by combining input from earthquake catalogues, regional strain rates, knowledge of active faults and seismogenic zones, as well as the definition of the seismic source zones.*

As stated above, the maximum magnitude (Mmax) has to be derived by the combination of several products of the Work Package 3. The deadline of the other deliverables is contemporary or subsequent to the scheduled release of the Mmax map; this means that at the moment it is not possible to provide a final map, but only to describe the preliminary work and the delineated approach for getting the final version of the deliverable.

In fact the determination of Mmax has to be based on an earthquake catalog and on a seismic source zones (SSZs) model. At the 18-months deadline (the deadline for Deliverable 3.3) the catalog is not yet released in a proper way for the aim of this task and the seismic source zones model is available in a preliminary release.

According to the temporal alignment of the deliverables, the SHARE Management Committee decided in the 4th teleconference meeting that an outline of the methods to be used in the PSHA including a review of state-of-the-art Mmax determination practices shall be presented including preliminary examples. This first version is presented here. With both, the final earthquake catalog and source zones models available (D3.1, D3.2 and D3.4), a final version will be released.

2. State of the art

It is not possible to summarize the huge number of studies and papers on probabilistic seismic hazard assessment (PSHA) all around the world in the last decades, where different approaches to the determination of maximum magnitude were defined and applied.

What we can remark from this large bibliography is that two main strategies were followed in the past: from one side, the maximum magnitude was determined by people in charge of the definition of the catalog and/or the seismic source zones model; on the other side, the maximum magnitude was determined by people in charge of the hazard computation (Figure 2.1).

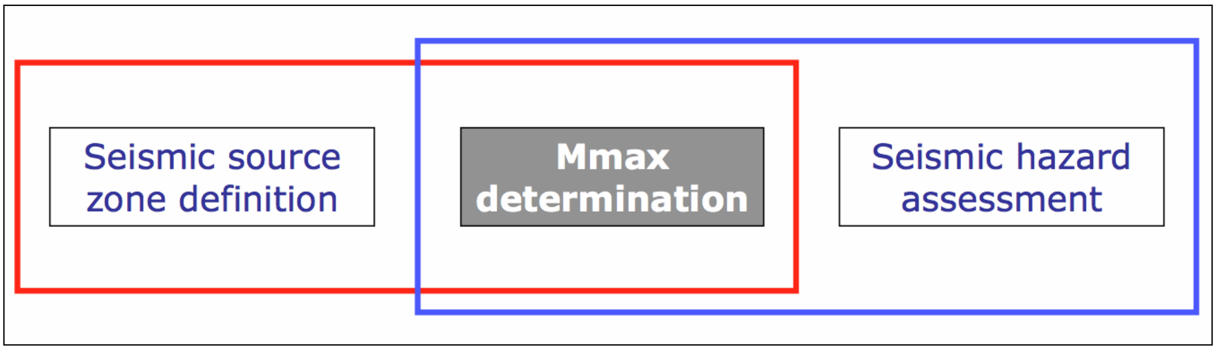

Figure 2.1. Schematic representation of the determination of Mmax: as attribute of the seismic source zones model or as derived for the hazard assessment.

In other words one can observe that in some cases Mmax is supplied as an attribute of the seismic source zones, independently of a possible application in PSHA; in the other cases Mmax is determined only for the hazard assessment by people that not necessarily have a full knowledge of information and data contained in the seismic source zones model and in the earthquake catalog. In very few cases, the Mmax determination is part of a complete roadmap from the catalog and the source zones modeling to the hazard assessment performed by a unique team; an example in this sense is represented by the seismic hazard model of Italy (Stucchi et al., 2010).

In order to describe recent applications on this issue, two cases from USA are considered as representative of a good level of state of the art in two different conditions: Central and Eastern US for Stable Continental Regions (SCRs) and Western US for high seismicity area. Finally, a short review of the studies performed in Europe and Mediterranean region is presented and briefly commented.

In our opinion these studies represent the best description of the state of the art for the determination of Mmax, although different levels of quality and reliability still remain.

2.1.The case of Central and Eastern US

Few weeks before the kickoff meeting of the SHARE project, on the website of the USGS a review of the approaches to the Mmax determination in Stable Continental Regions appeared (Wheeler, 2009). Each method is described together with considerations on related pros and cons.

[X, method was used by authors of the cited publication; XX, method was weighted more heavily than others by the authors; --, method was not used; *m*, magnitude, generally m_b in the first three columns, Ms or M_L in the fourth column, and moment magnitude in the last column; *m*-f, magnitude-frequency graph]

Method	Algermissen and Perkins (1976)	Perkins and others (1979)	Thenhaus (1983)	Algermissen and others (1982)	Frankel and others (1996, 2002), Petersen and others (2008)
1 Largest observed *m* (Mobs)	X	X	XX	X	X
2 Mobs plus increment	--	--	--	--	--
3 Seismicity rate	--	X	XX	X	--
4 *m*-f extrapolation of historical record	--	--	X	--	--
5 m_b saturates at m_b 7.5	--	--	--	--	--
6 Local geologic features	--	--	X	X	--
7 North American analogs	--	XX	--	--	--
8 Global analogs	--	--	--	--	XX

Figure 2.2. Methods used by the USGS to estimate Mmax for the National Seismic Hazard maps 1976-2008 (from Wheeler, 2009).

From the example reported in Figure 2.2 one can observe that in the same project several approaches were used and combined in different ways. In order to understand the applicability of each method and the advantages and disadvantages of their adoption, the following table, again from the report by Wheeler (2009), results very useful.

Table 1. Summary of pros and cons of methods used to estimate Mmax (from Wheeler, 2009).

Method	Pros	Cons
1. Mmax = Mobs	The Mobs method is simple. It can be applied anywhere. It provides an unarguable lower bound for Mmax.	(1) Short historical records produce samples of seismicity that are too small to constrain Mmax. (2) Results of the Mobs method are inconsistent with paleoseismic findings, which show Mmax exceeding Mobs by as much as approximately 2.1- to 3.2-M units.
2. Mmax = Mobs + an increment	The increment method is simple. It can be applied anywhere.	(1) Short historical records produce samples of seismicity that are too small to constrain Mmax. (2) Results of the increment method are inconsistent with paleoseismic findings, which imply increments that range from approximately zero to 3.2.
3. Seismicity rates	A high moment-release rate may smooth and link faults faster, and allow larger rupture zones and slips than in less seismically active areas.	(1) The argument from fault smoothing and linking may apply to plate boundaries, but it is unclear whether it applies to stable continental regions (SCRs). (2) Even if the seismicity-rate method is valid in SCR, it does not appear to apply below Mmax of approximately 7.0. (3) Above Mmax 7.0, paleoseismic studies can

		provide support for Mmax estimates.
4. Extrapolation of the historical record by a magnitude-frequency graph	The extrapolation method calculates the M that would recur at whatever recurrence interval is specified, such as 1,000 years. The method is simple and it can be applied anywhere.	(1) The extrapolation method gives results that vary with the size of the study area and the specified recurrence interval. (2) Results of the method are inconsistent with paleoseismically determined recurrence intervals of large earthquakes.
5. Saturation value of mb	This is approximately 7.5 globally.	Moment magnitude does not saturate and is preferred for moderate and large earthquakes.
6. Local geologic features	An area with distinctive geology, faults, or geophysical anomalies might have distinctive fault properties that could control rupture-zone size, such as fault lengths, widths, strengths, or orientations.	(1) Short historical records of small source zones produce small samples of seismicity, which can be too sparse to clearly show long-term spatial associations between seismicity and geologic features. (2) Few CEUSAC earthquakes have been linked to specific faults or systems of faults. (3) The geologic controls on SCR rupture propagation are enigmatic.
7. North American tectonic analogs	(1) The arguments in favor of the method of North American tectonic analogs include those favoring the local-geology method. (2) Including all North American tectonic analogs of a CEUSAC source zone could capture larger earthquakes, providing a higher lower bound to Mmax.	(1) The arguments against the method of North American tectonic analogs are the same as those against the local-geology method. However, the arguments are weaker because the seismicity sample of the combined analog areas is larger. (2) The meaning of “analog” is unclear.
8. Global tectonic analogs	(1) The arguments in favor of the methods of local geologic features and of North American tectonic analogs apply here as well. (2) Including all global tectonic analogs of a CEUSAC source zone produces the largest possible sample of historical seismicity and makes capture of some true Mmax values more likely than with any smaller sample.	The meaning of “analog” is unclear.
9. Bayesian method	(1) The arguments in favor of the methods of global tectonic analogs apply here as well. (2) Including all global tectonic analogs of a CEUSAC source zone produces the largest possible sample of historical seismicity and makes capture of some true Mmax values more likely than with any smaller sample. (3) Separation of the analysis into specification of a prior distribution and a likelihood function can simplify explanation and justification.	(1) The meaning of “analog” is unclear. (2) The prior distribution is partly subjective, which can hinder its explanation and justification.
10. Arguments from physical principles	The arguments support the existence of an Mmax that could vary locally or regionally.	(1) Short historical records produce samples of seismicity that are too small to constrain Mmax. (2) The physics of rupture propagation in SCR crust may be poorly understood. (3) Few SCR areas have had earthquakes large enough to be recognized as Mmax. All three factors impede testing of physical theories.
11. Statistical methods	The methods do not require understanding of the physics or geologic controls on SCR rupture propagation.	(1) Short historical records produce small samples of seismicity. (2) Few SCR areas have had earthquakes large enough to be taken as Mmax. Both factors impede testing of statistical models.
12. Pattern recognition	The method does not require understanding of the physics or geologic controls on SCR rupture propagation.	Few SCR areas have had earthquakes large enough to be taken as Mmax. This impedes testing results of pattern recognition.
13. Q0	Q0 varies inversely with Mobs in China.	(1) Results of the Q0 method are inconsistent with paleoseismic findings. (2) Few SCR areas have had earthquakes large enough to be taken as Mmax.

It is important to remark how different approaches in the above table bring to different type of Mmax, as summarized in Figure 2.3.

	Global	Regional
Largest observed m (M_{obs})	X	
Local geologic features		X
M_{obs} plus increment	X	
Fixed value across the area	X	
Global analogs	X	
EPRI method (SCR)	X	

Figure 2.3. Characteristics of different Mmax, according to the adopted approach. Global and regional columns refer to the applicability of the method (generally speaking, geological data allow determination only in the areas where they are available). Dark and pale brown cells respectively refer to methods that give a sort of lower boundary of Mmax or a value greater than the observed one.

The first 3 methods reported in Figure 2.3 furnish a sort of lower boundary to Mmax (stricter in the first case); it means that the maximum magnitude cannot be lower than the value determined in such a way. The following 3 methods, on the contrary, provide a value greater than the largest observed magnitudes; this means that special care has to be adopted when handling these values in order to avoid unrealistically high values of Mmax.

All the above considerations show that the uncertainty on Mmax determination needs a careful management.

In the 2008 update of National seismic hazard map of United States (Petersen et al., 2008) a set of magnitudes with the relevant weights was defined for each seismic source zone by adopting a global analogs approach.

2.2.The case of Western US

In Petersen et al. (2008) open-file report, the documentation for the National seismic hazard map of United States is rich, so that it is possible to follow the adopted procedure. For the present work it is interesting to observe how this issue was solved for those areas with high seismicity and well-documented faults.

In general, Mmax for the faults was determined by using empirical equations (Ellsworth, 2003; Hanks and Bakun, 2002) where the magnitude is function of the fault area; for seismic source zones or for gridded seismicity approach to PSHA fixed values were adopted: for shallow seismicity areas, Mmax was fixed to 7.0, for deep seismicity areas, Mmax was fixed to 7.2 and so on.

In our opinion (no further explanations are available in Petersen et al., 2008) the choice of fixed Mmax values for the SSZs depends on the consideration that the knowledge on seismicity is well constrained by the evidences in the catalog; in other words, the earthquake catalog can be considered complete for the highest magnitudes.

If we look to Europe, this can be the case of some regions characterized by high seismicity and in-depth research on earthquake geology, such as Italy or Greece.

2.3. A short review in Europe

In the early stages of the activity of this task, a list of the main papers dealing with the Mmax determination in Europe was compiled. As it is possible to note in Table 2, there is a large heterogeneity in the subject of these papers and this is also observable in the proposed approach for the determination of Mmax. This depends on many aspects, such as the level of seismicity in the region, the knowledge on active faults, the completeness of the catalogs, and also the know-how of the researchers involved in these projects, so that one can prefer the most familiar method.

Of course, this is not a complete review of all the papers published on this issue; due to the extended bibliography, surely some papers are missing. In any case, the sample is significant for the identification of some general tendency.

Table 2. Main papers on Mmax determination in Europe and adopted approaches.

Region	Reference	Adopted approach
Albania	Aliaj et al., 2004	Largest observed magnitude + tectonic considerations + global considerations
Algeria	Hamdache, 1998	Kijko and Sellevoll (1989, 1992) approach
	Pelaez Montilla et al., 2003	Pisarenko et al. (1996) procedure
Bulgaria	Simeonova et al., 2006	Maximum credible earthquake (in terms of macroseismic intensity)
Catalonia	Secanell et al., 2004	Map in terms of macroseismic intensity: Imax, Imax + 1, Imax + 2
Central, N, NW Europe	Gruenthal and GSHAP WG 1999	Statistical approach, checked with global analogs comparisons
Circum Pannonian and Balkan region	Musson, 2000	Largest observed magnitudes + a small cautionary margin
Cyprus	Tagnan and Tanircan, 2010	Largest observed magnitude + 0.3
Croatia	Markusic and Herak, 1999	Kijko and Sellevoll (1989, 1992) approach
Eastern Mediterranean	Jenny et al., 2004	From seismic and geodetic data
France	EPAS-AFPS WG, 1998	Max credible earthquake (from seismotectonic considerations) or largest observed magnitude + 0.5
	Marin et al., 2004	Largest observed magnitude + paleoseismological considerations on active faults.
Greece	Papaioannou and Papazachos, 2000	Largest observed magnitude

Italy	Meletti et al., 2008	From seismological and geological catalogue, plus cautionary increment
	Jenny et al., 2006	From seismic and geodetic data
Portugal	Villanova and Fonseca, 2007	Largest observed magnitude; maximum observed magnitude + 0.5
Pyrenees	Secanell et al., 2008	Largest observed magnitude + 0.5 or +1.0
Romania	Radulian et al., 2000	N.A.
Slovenia	Zivcic et al., 2000	Largest observed magnitude applied to deterministic method
Switzerland (PEGASOS project)	Wiemer et al., 2009	EPRI approach (Johnston et al., 1994)
	Schmid and Slejko, 2009	EPRI approach (Johnston et al., 1994); Kijko and Graham (1998)
	Burkhard and Gruenthal, 2009	EPRI approach (Johnston et al., 1994)
	Musson et al., 2009	Set of fixed values; statistical approach (from MLE or from synthetic catalog)
Turkey	Kayabali and Akin, 2003	From geological information applied to deterministic method
	Kalkan et al., 2009	From geological information

From Table 2 it is also evident that no method exists for Mmax determination which is adoptable with the same level of reliability across whole Europe. In the following figures (from Figure 2.4 to Figure 2.7) the application of the methods in different countries is shown (grouped in 4 large categories of approaches).

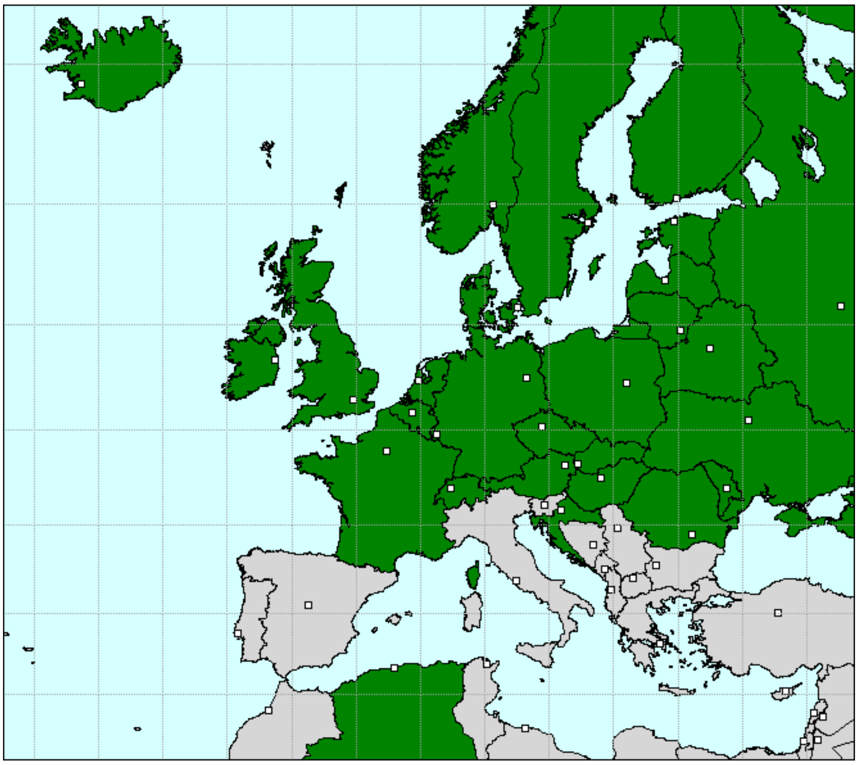

Figure 2.4. Countries where a statistical approach for Mmax determination was adopted.

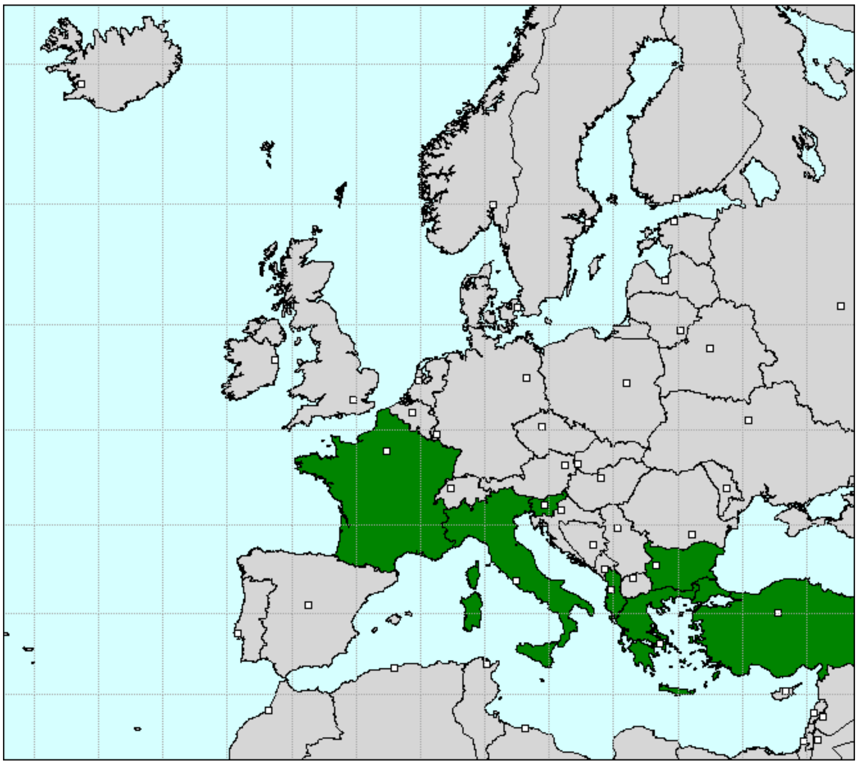

Figure 2.5. Countries where data on earthquake catalogs and geologic observations were used in the approach for Mmax determination.

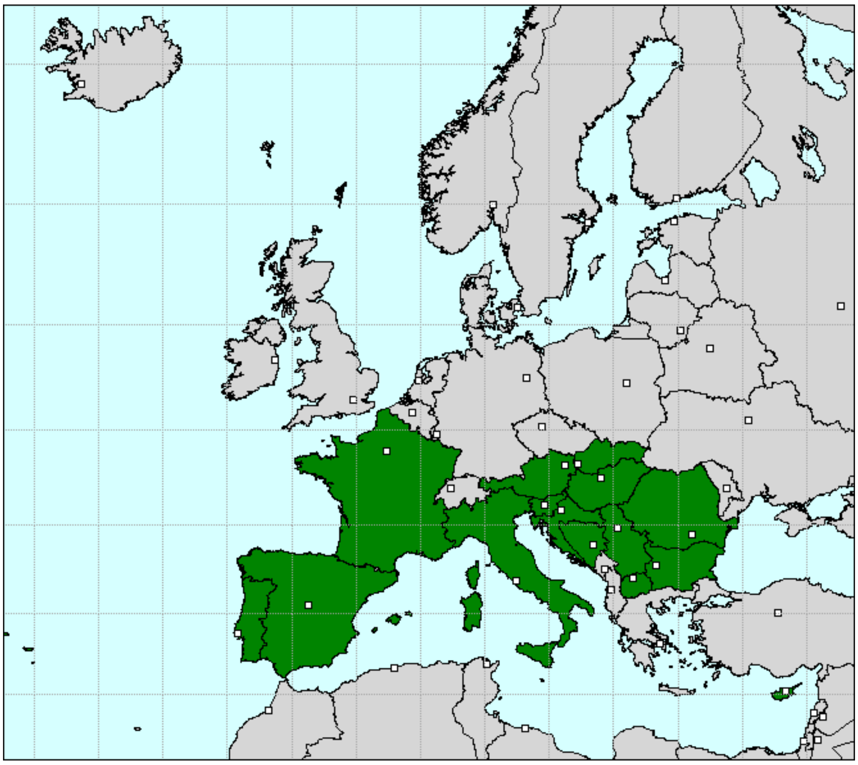

Figure 2.6. Countries where data on earthquake catalogs in combination with a safety coefficient were used in the approach for Mmax determination.

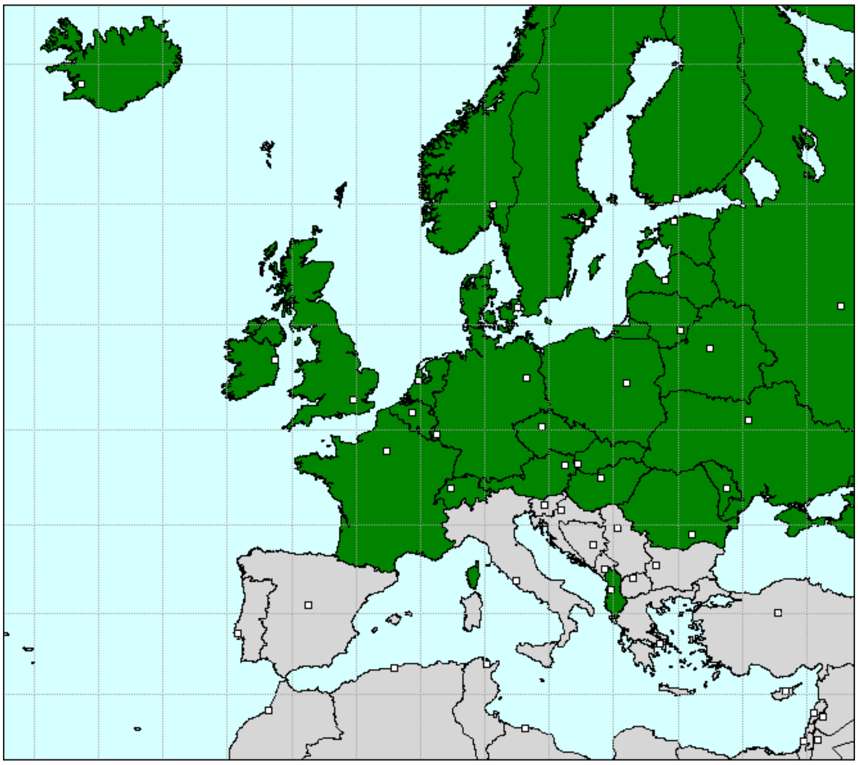

Figure 2.7. Countries where the global analogs approach for Mmax determination was adopted.

With respect to the last figure (Figure 2.7), the large number of countries in Northern and Central Europe where the global analogs approach was adopted corresponds to the countries where this method was applied in a sort of validation of other methods, namely the EPRI approach (Johnston et al., 1994).

3. Maximum magnitude on the seismic source zones

As discussed in Section 2, we cannot conclude that a single, reliable approach to the determination of Mmax is identified in the large bibliography available on this issue.

On the other hand, considering the crucial role of Mmax on PSHA, especially for long return periods evaluation, the choice of the approach (or approaches) to be adopted has to be based on sound considerations and, possibly, large consensus.

The general approach followed in this Task was to give priority to the data everywhere they are available and reliable, rather than to models. In such a way, we acknowledge people that spent a lot of their time in the retrieval of information.

As stated in the Introduction, at the moment we cannot release a final map of the maximum magnitude in Europe, due to the lack of complementary data. It is only possible to produce some preliminary map, while the final deliverable will be available when the source zones model, the reference earthquake catalog, the related completeness time-intervals will be released to the project users.

3.1.Regions with low and moderate seismicity

A preliminary elaboration was possible by using the available data, in order to understand the criticality of both the data and the procedure for Mmax determination.

With regard to the seismic source zones model, a first release of the compilation of existing regional and national source zones (Deliverable 3.1) was released by GFZ colleagues in June 2010 to the partners of Work Package 3. This is not the final version because some modifications are still possible, but the general frame is delineated in the available document.

At the moment the most used and available earthquake catalog that covers Northern and Central Europe is the CENEC catalog by Grünthal et al. (2009), spanning from A.D. 1000 to 2004, for the portion of Europe north to 44° parallel.

By simply overlaying the earthquake catalog and the source zones model and by taking into account in each SSZ the magnitude of the maximum observed earthquake, one obtain the map of Figure 3.1.

The patchwork that appears does not surprise: we are considering a very wide area, covering a large number of different conditions from a geodynamic point of view. A more careful look to the map lets us discover that there are some SSZs without color ($M < 3.5$) and too many zones with largest observed magnitude not larger the 4.5.

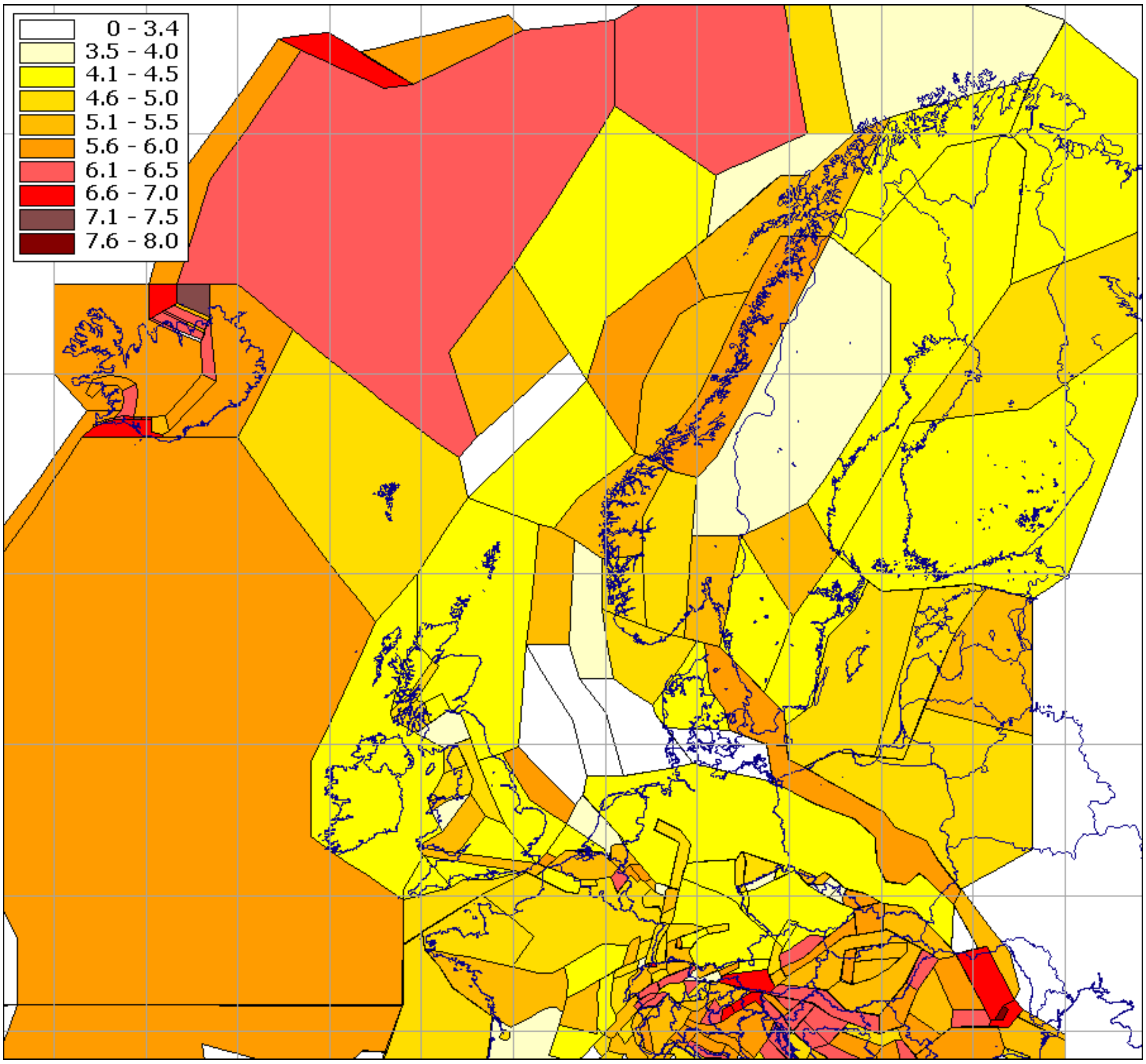

Figure 3.1. Largest observed magnitude in SSZs by adopting the CENEC catalog (Grünthal et al., 2009).

In order to better understand which data produce the pattern in Figure 3.1, a different map was elaborated. In Figure 3.2 each seismic source zone is represented with a color corresponding to the number of earthquakes that fall inside the zone. In many SSZs the number of events reported in the CENEC catalog (Grünthal et al., 2009) is less or equal to 10; this observation is more amazing if we consider that we took into account the whole catalog, without any consideration on the completeness time-intervals that certainly reduce the number of earthquakes.

The concluding remark is that the available data at the moment do not allow the determination of a reliable value of Mmax in each seismic source zone based on the largest observed magnitude. On the contrary, the adoption of a statistical approach to the Mmax determination probably allows to be more confident on the obtained estimate. However if in order to perform a statistically sound evaluation of the expected maximum magnitude in many case it will be necessary to group the SSZs in macroregions, so to have a significant data sample, as strongly recommended by Johnston et al. (1994). Paragraph 3.3 briefly describes the approach we intend to follow in low seismicity areas.

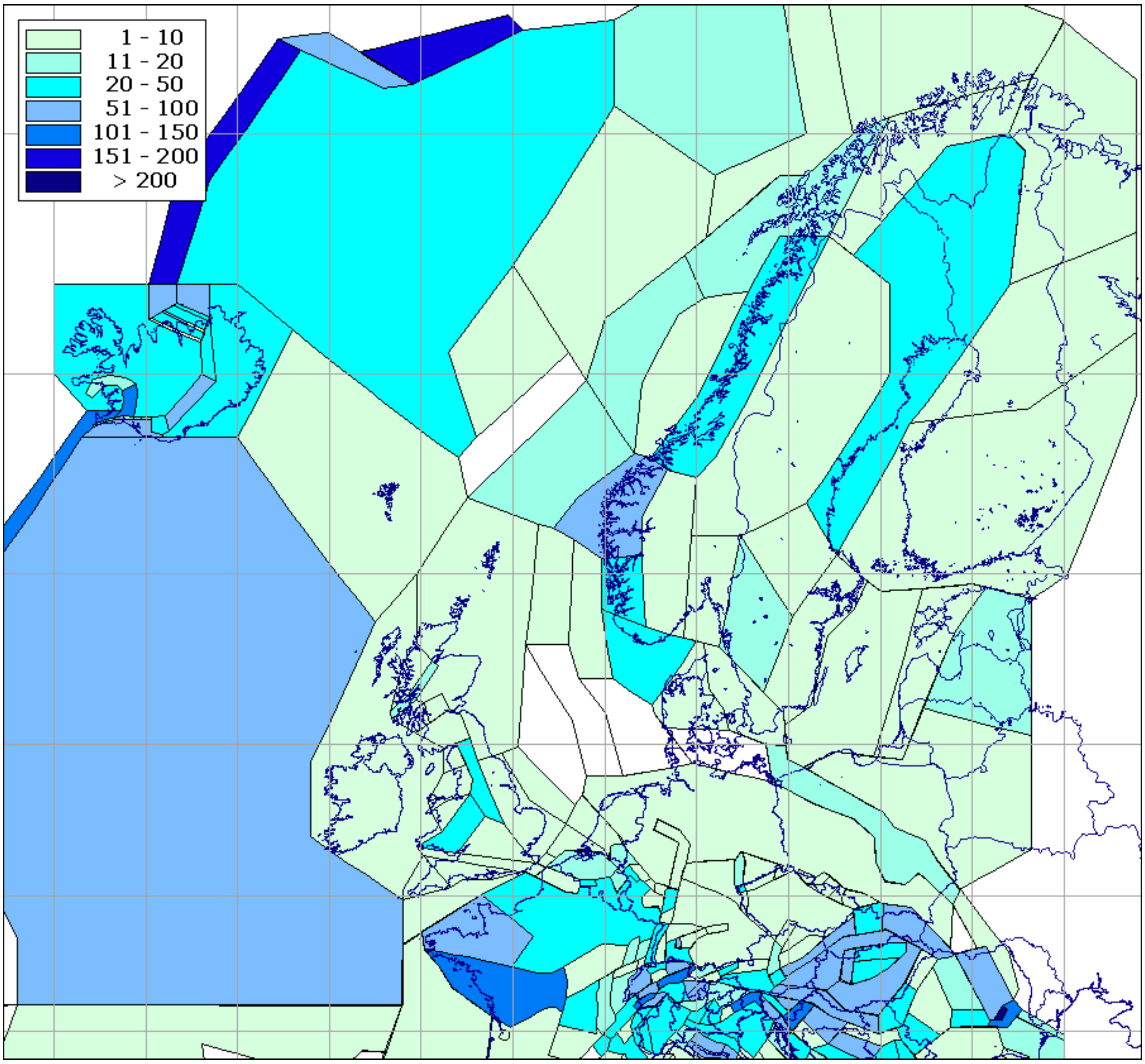

Figure 3.2. Number of earthquakes in each SSZ by adopting CENEC catalog (Grünthal et al., 2009).

3.2.Regions with high seismicity

When we consider a region with high seismicity, such us Central-Eastern Mediterranean countries, one can expect that the knowledge on the historical earthquakes and the seismic sources is more detailed and robust.

The area analyzed with the same approach of the previous paragraph is Italy. The SSZs model is the same preliminary model released by Task 3.4; for Italy the model adopts the ZS9 seismic source zones model (Meletti et al., 2008). The earthquake catalog that covers the area is the CPTI04 catalog (CPTI Working Group, 2004), spanning from A.D. 1000 to 2002.

Again, an operation of topological overlay was performed. Figure 3.3 shows the largest observed magnitude inside each SSZ, still without any consideration on the completeness time-intervals. In the case of Mmax, in fact, one can consider that if the largest magnitude occurred outside the complete period, that magnitude was observed anyway and thus it has to be taken into account.

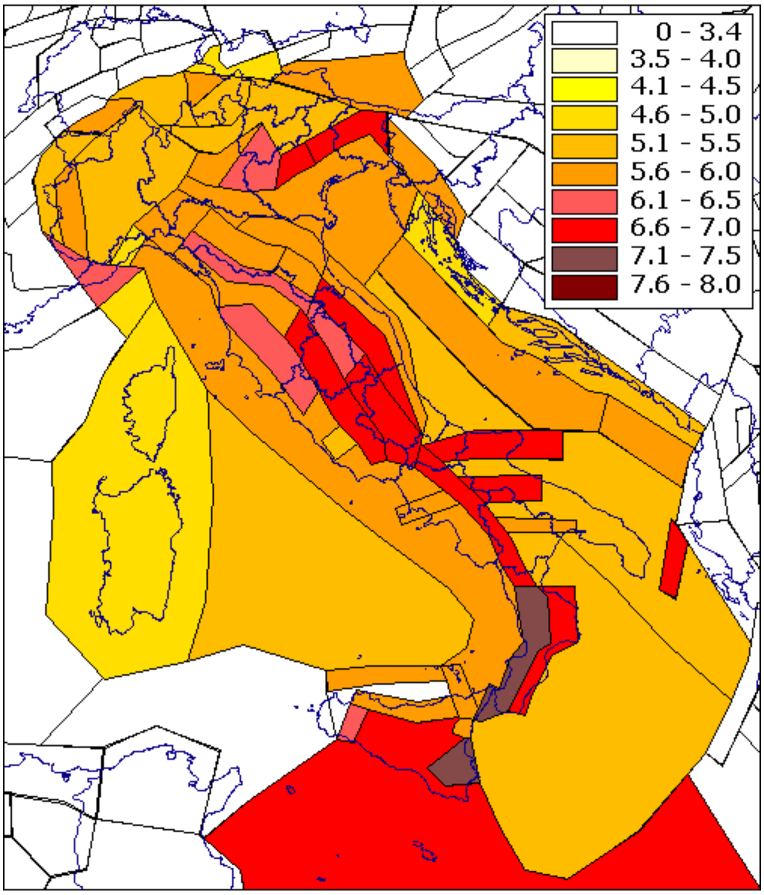

Figure 3.3. Largest observed magnitude in SSZs of Italy and surrounding areas by adopting CPTI04 catalog (CPTI Working Group, 2004).

In this application too, the number of earthquakes per SSZ was evaluated and it is shown in Figure 3.4. It is possible to observe that only in few zones, i.e. those that actually have lower seismicity, the number of events is small; in the remaining ones it can be considered significantly representative of the actual seismicity. The picture emerging from the present elaborations is consistent with other information, such as that reported by the "European database of active faults and seismogenic sources” (Task 3.2 of this project), and thus it can be considered reliable for the Mmax determination.

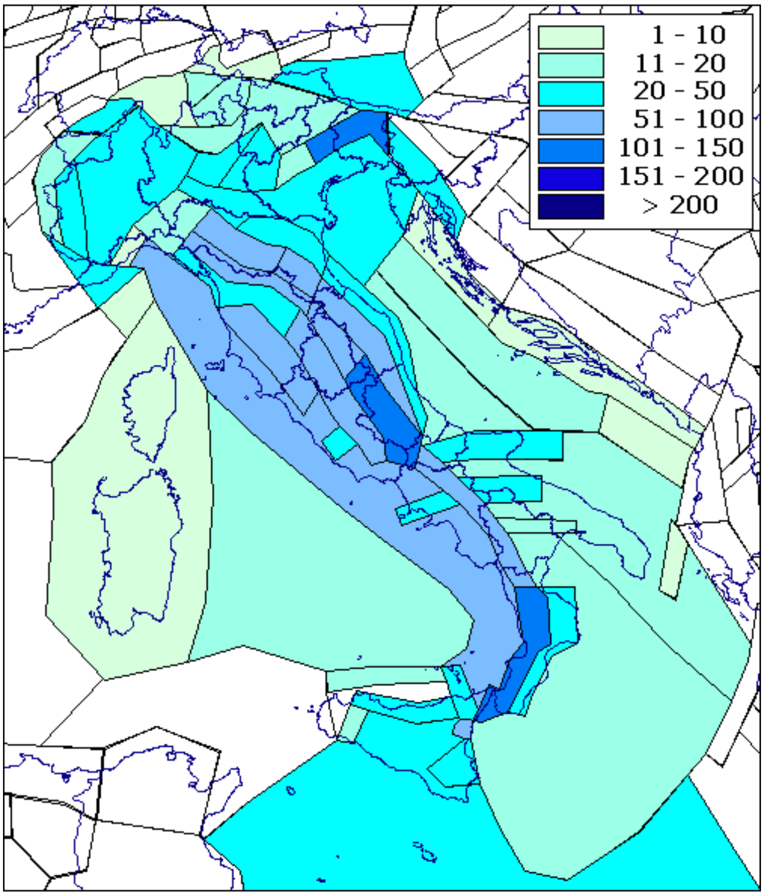

Figure 3.4. Number of earthquakes per SSZs in Italy and surrounding areas by adopting the CPTI04 catalog (CPTI Working Group, 2004).

3.3.Statistical approaches

One of the most common statistical procedures adopted to estimate Mmax in low-seismicity areas, like SCRs, is the so-called EPRI approach (Johnston et al., 1994). It has been applied in several PSH studies worldwide and, in Europe, in the framework of the PEGASOS project for Switzerland (Burkhard and Grünthal, 2009; Schmid and Slejko, 2009; Wiemer et al., 2009).

This approach provides a probability distribution of Mmax taking into account the large relevant uncertainty. It is based on information coming from the analysis of a global data set of seismicity in SCRs (Johnston et al., 1994), updated with local data available for the seismic source of interest (i.e. magnitude values of the earthquakes occurred inside the source zone) in the frame of Bayesian statistics. The basic concept is to compensate the small seismicity sample of the study area by considering observations from tectonically analogous regions worldwide.

In particular, the procedure requires defining a “prior” probability distribution for Mmax, which is derived from the statistical analysis of the global data set, and then combining the prior distribution with a source zone specific likelihood function to obtain a posterior distribution for Mmax to be used in PSHA.

Two prior worldwide normal distributions were derived by Johnston et al. (1994): one for extended and another for non-extended continental crust, which are characterized by different mean and standard error values (i.e. mean Mmax=6.4 vs 6.3, standard deviation=0.84 vs 0.5, respectively).

The likelihood function for the study area is computed from the reported magnitudes for earthquakes occurred inside the zone, assuming an exponential frequency-magnitude distribution. This function, describing the relative likelihood of different values of Mmax given the local seismicity sample, is zero for magnitudes lower than the largest observed magnitude in the area, is peaked about the latter, and then decays with a shape depending on the number of data available for the zone and the b-value of the frequency-magnitude distribution.

The posterior Mmax probability distribution is then derived by multiplying the prior distribution by the source-specific likelihood function. In case of very small seismicity samples, the shape of the posterior distribution is largely controlled by the selected prior one, except for truncation below the largest observed magnitude inside the zone. The obtained probability distribution is finally discretized at suitable intervals (e.g., 0.5 magnitude units) to derive a discrete distribution for Mmax to input into PSHA, e.g., by assigning to various magnitude values the relevant probability (weight).

Since the posterior distribution is generally characterized by a long upper tail, truncation at an upper magnitude bound is often performed to exclude unrealistically high Mmax values from the following hazard computation. A number of alternative techniques for truncation have been proposed, such as probability cut-off at a selected threshold probability level (e.g., 0.05) or geological truncation values estimated from the maximum possible size of faults within the study area (see, e.g., Burkhard and Grünthal, 2009).

Another statistical approach to assess Mmax is the one proposed by Kijko and Graham (1998), which is based on recorded seismicity and applies the theory of the extremes, avoiding any specific frequency-magnitude distribution. With respect to the EPRI approach, less recent PSH studies have applied this procedure (e.g., Schmid and Slejko, 2009). In fact, it is judged to be a robust technique only in case of a complete earthquake catalog spanning at least one seismic cycle, but to present significant limitations in low/moderate-seismicity areas like SCRs (see e.g., Wheeler, 2009; Wiemer et al., 2009).

4. Conclusions

As stated above, this is the first preliminary version of Deliverable 3.3. Missing or unstable versions of all the input data that contribute to the definition of Mmax, in the frame of the Work Package 3, do not allowed the completion of the activities of this Task in the due time.

Thus, this document reports the initial phases of the performed activities, mainly devoted to the definition of the state of the art in Europe and in USA, and to explore some criticality in the procedures for the Mmax determination.

Two main approaches were identified for the possible application in the next phase of the SHARE project.

The first method, to be adopted in areas with low seismicity, is a statistical approach, namely the EPRI approach (Johnston et al., 1994). This method requires not only a seismic source zones model, but, as mentioned in paragraph 3.1, a kind of superzones that group SSZs in order to have significant data sample for a robust statistical analysis. The superzones have to be defined within the Work Package 3 team, following the minutes of the meeting in Potsdam in October 12-14 2010, and they will also be used for the definition of seismicity rates and catalog completeness time-intervals. The final format for this output will be a discretization of the magnitude distribution in 5 values with the relevant weights that will be introduced in the logic tree for the hazard assessment.

The second method for the definition of Mmax will be adopted in those regions characterized by high seismicity and in-depth knowledge on the historical seismicity and on seismogenic sources. In those areas the maximum magnitude will be determined mainly by the largest observed magnitude in the catalog and by the expected maximum magnitude on the faults. A safety coefficient (fixed or proportional to the magnitude) could be adopted. The format of this output will be one Mmax value for each seismic source zone together with the corresponding uncertainty.

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