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Seismic hazard assessment for Central, North and Northwest Europe: GSHAP Region 3

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Abstract
The activities of the Regional Centre 3 of the Global Seismic Hazard Assessment Program (GSHAP) covering Europe north of 46°N and west of 32°E are summarized starting with the establishment of the GSHAP Centre at the GFZ Potsdam in 1993 and leading finally in the calculation and creation of the GSHAP seismic hazard map in terms of horizontal Peak Ground Acceleration (PGA). Moreover, the activities of separate working groups which contribute with their results for certain parts of the study area to the final product of the Regional Centre are described. Details are given on the development of the homogeneous seismicity working file, the delineation of seismic source zones, the data preprocessing as well as on the chosen PGA-attenuation relations.

Key words *seismic hazard assessment – Europe – earthquakes – seismicity – UN/IDNDR*

1. Introduction

The Global Seismic Hazard Assessment Program (GSHAP; Giardini and Basham, 1993) aims at promoting regionally coordinated and homogeneous seismic hazard evaluations and to produce regionally harmonized seismic hazard maps. This paper presents the seismic hazard assessment for Central, North and Northwest Europe.

A basic element of GSHAP is the regional organization of this global project. Ten GSHAP Regions were etablished. The GSHAP Region 3, with the Regional Centre at the GeoForschungs-Zentrum Potsdam, covers Central, North and Northwest Europe (fig. 1). It is defined as the area north of 46°N and west of 32°E (Grünthal

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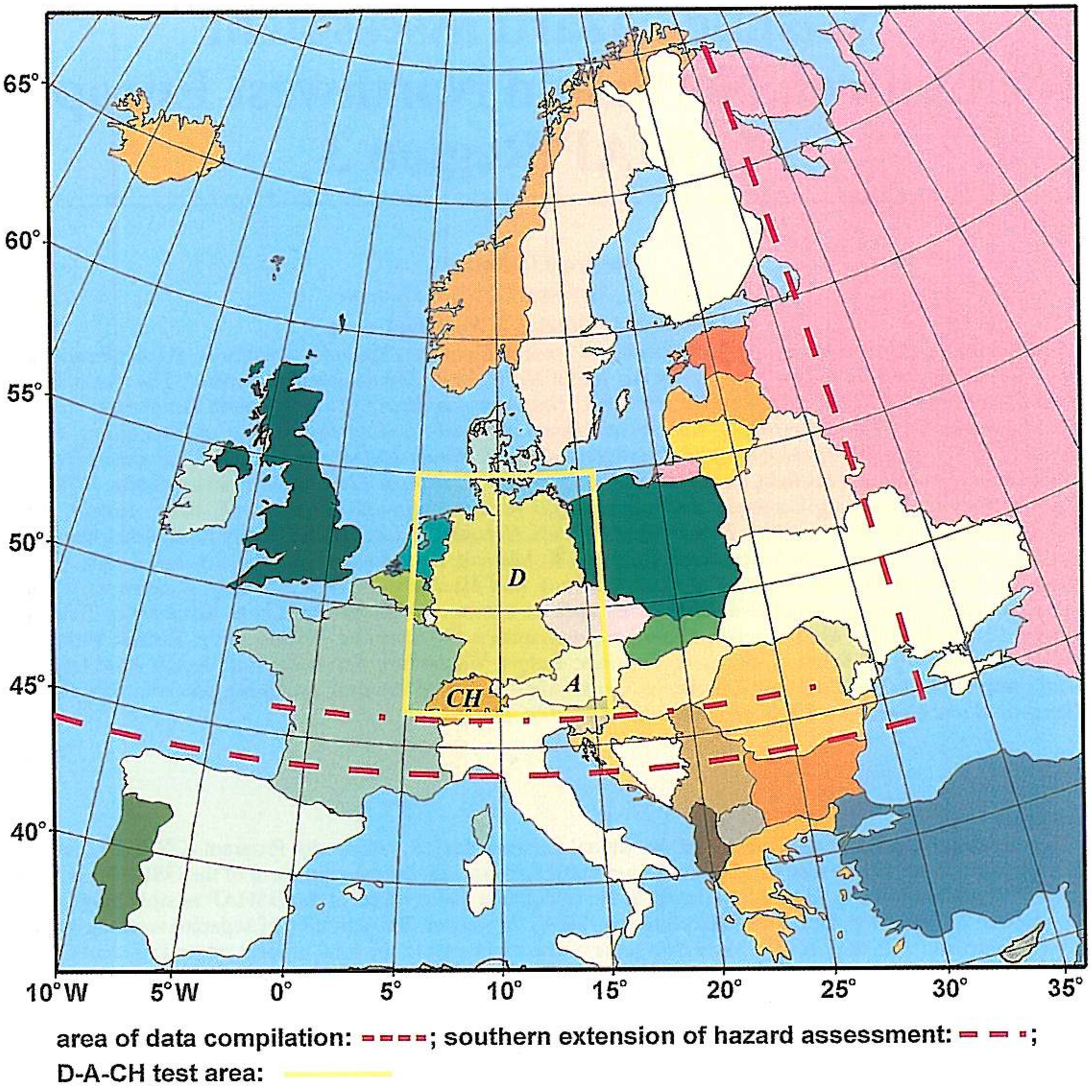

Fig. 1. Definition of the areal extent of the GSHAP Region 3 and the 29 countries, or parts of them, belonging to this region.

et al., 1995a). What complicated the work is the fact that 29 different countries, or parts of them, belong to the study area. The sometimes conflicting interests of the responsibilities of these countries with their specifics had to be considered. Moreover, there exists a large number of national seismicity data files of quite different style, quality and availability, which often show considerable overlap with neighbouring territories.

Several previous probabilistic seismic hazard assessments have been made in the study area of GSHAP Region 3, mostly on a national level (*cf.* selected contributions in McGuire, 1993). One of the first European approaches was made for Switzerland by Sägesser and Mayer-Rosa (1978). Other published national seismic hazard maps include, in selection, Germany (Ahorner and Rosenhauer, 1986, 1993; Grünthal, 1989, 1991; Grünthal and Bosse, 1996), The Netherlands (de Crook, 1993, 1996), France (Bottard and Ferrieux, 1992; Bottard and Gariel, 1995; Dominique *et al.*, 1998), Austria (Lenhardt, 1995) and the Czech Republic (Schenk *et al.*, 1997a). Almost all of these studies, with applications in the civil engineering practice, were carried out for the intensity as shaking parameter.

Although GSHAP is aiming at producing regionally coordinated, harmonized seismic hazard maps to overcome border problems which were obvious in previous approaches, this project does not intend to replace national and local studies. Instead, the results from several such studies have been included in the now published GSHAP map. The contribution of GSHAP Region 3 so far has been to increase of the awereness of seismic hazard, to provide homogeneous techniques to promote future more detailed studies and to avoid possible resulting border problems.

The GSHAP activities in Europe coincide with those devoted to the preparation of seismic zoning for the National Application Documents (NAD) of the Eurocode 8. Although the Global Seismic Hazard Program was not coordinated with the Eurocode 8 activities, the now existing regional GSHAP seismic hazard maps support the process of harmonizing the engineering seismological basis of different NAD's.

To simplify the coordination of the activities in the GSHAP Region 3, four overlapping substudy areas were established during the first workshop at the Potsdam Centre in July 1993:

1) The D-A-CH study area, covering Germany (D), Austria (A) and Switzerland (CH). This served as a test area to derive suitable procedures for the different steps of data preprocessing, which should be uniformly applicable to the whole GSHAP Region 3.

2) Fennoscandia.

3) Northwestern Europe, *i.e.*, the area west of the D-A-CH countries.

4) Eastern Central Europe, including the Baltic Republics and the area east of the D-A-CH countries.

The progress of activities of the GSHAP Region 3 Centre is documented in reports given at the ESC General Assembly in Athens 1994 (Grünthal *et al.*, 1995a), IUGG meeting in Boulder, 1995 (Grünthal *et al.*, 1995b), ESC General Assembly in Reykjavik, 1996 (Grünthal *et al.*, 1996), IASPEI meeting in Thessaloniki, 1997 (Grünthal, 1997) and ESC General Assembly in Tel Aviv, 1998 (Grünthal and Giardini, 1998). Peak ground acceleration hazard maps for the whole GSHAP Region 3 were presented for the first time at the 1997 meeting and the harmonized results for Europe, the Middle East and continental Africa at the 1998 meeting.

At a late stage of the project it has been agreed within the GSHAP Region 3 Working Group to present, in the final seismic hazard map, the results obtained by different sub-groups (*cf.* the respective reports of this volume), *e.g.*, for Fennoscandia by the Nordic group (Bungum and Lindholm, 1997; Lindholm *et al.*, 1997) and for Slovakia, Poland and the Czech Republic by Schenk *et al.* (1997b). For Iceland it has been agreed to show an updated version of the national seismic hazard map (BSTR, FRV og Rb, 1995).

In the easterly parts of the GSHAP Region 3, the seismic hazard data for Western Russia, Estonia, Latvia, Lithuania, Belorussia, Ukraine and Moldavia were adopted from the GSHAP Centre 7, covering Northern and Central Asia (Ulomov, 1997). In the adjacent areas to the south, for Italy the seismic hazard data were directly incorporated from the Adria region (Slejko *et al.*, 1999), for Slovenia a national map was provided by Zabukovec (1998) and for Romania the data were part of a special project covering large parts of the Balkans (*cf.* Musson, 1999). The seismic hazard assessments carried out at the GSHAP Regional Centre in Potsdam were, in agreement with the national partners, extended to cover also Southern France down to the Pyrenees, although this area is located south of the GSHAP Region 3.

2. Seismic activity and seismicity working-file

The seismic activity in the GSHAP Region 3 is in general rather low (fig. 2). The highest seismic activity is associated with active tectonic processes in the Alps, on Iceland and locally at intermediate depths in the Vrançea area (Romania). The strongest earthquakes reach magnitudes $M_w = 6.2$-6.5 in the upper crust in the Alps (*e.g.*, Basel 1356 and Friuli 1976) and exceed relatively frequently $M_w = 7$ in the Vrançea area (*e.g.*, 1940, 1977 and 1986). These areas of high seismicity underline the importance of seismic hazard assessments in the GSHAP Region 3 even in the global context. Other concentrations

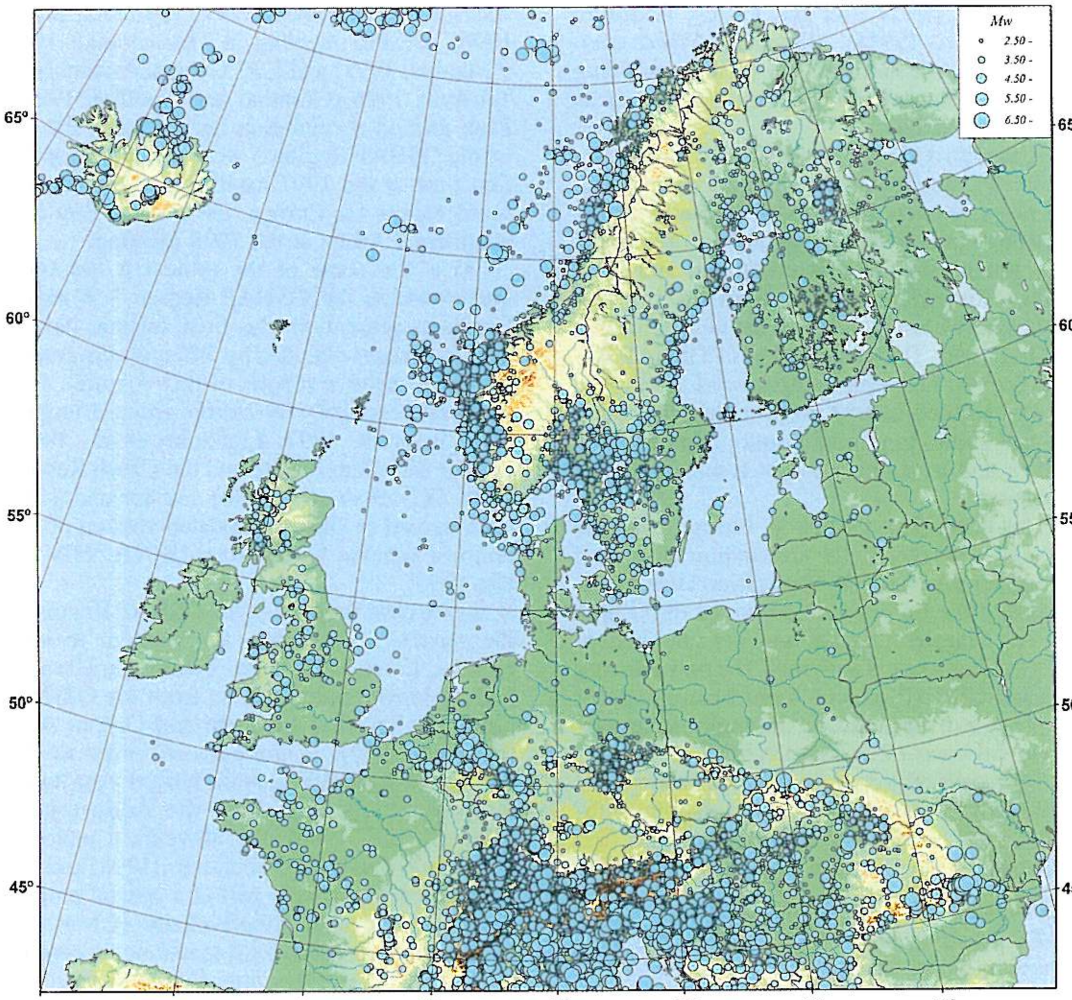

Fig. 2. Epicentre map for the GSHAP Region 3 according to the seismicity working-file for this area. Moment magnitudes, M_w, are used. The data sources used for creating the working-file are mentioned in the text.

of earthquake foci are connected with the ongoing tectonics of Tertiary and Quaternary graben structures, *e.g.*, the upper Rhine graben with its northwest extension towards the lower Rhine embayment (*e.g.*, Düren, 1756 and Roermond, 1992, both M_W = 5.4), and the transpressive neotectonics of the Pannonian basin and its surrounding orogeny. Local sources of seismic activity occur around the stable block of the Bohemian massif.

The scattered seismic activity in Western France and Great Britain is not well understood and is yet hard to relate to known neotectonic elements (Musson, 1997). The seismic activity of Fennoscandia, with concentration mainly in some coastal regions of Norway and Sweden, has been interpreted partly as a result of deglaciation, partly may have tectonic origin, *i.e.*, push from the Mid Atlantic ridge (*e.g.*, see Wahlström, 1993). In the northwestern part of the GSHAP Region 3, the Mid-Atlantic ridge zone crossing Iceland creates a narrow belt of relatively high seismic activity. On the contrary, nearly aseismic areas are represented by Ireland, the North German basin and the East European platform, *i.e.*, the area northeast of the mountainous parts surrounding the Pannonian basin and the Bohemian massif.

In the absence of a homogenized earthquake catalogue for the GSHAP Region 3, based on uniformely treated original data, a seismicity working-file was compiled from available but in several cases confidential sources. The geographical borders of this working-file are extended by at least 2 degrees compared to the defined area subject to the seismic hazard calculations. The creation of this working-file was to some extent carried out as a joint venture between the GSHAP Regional Centre 3 and the CEC project, Basic European Earthquake Catalogue and Database for the evaluation of longterm seismicity and seismic hazard (BEECD) (Stucchi, 1998). The working-file, based on the current and most complete versions of national catalogues, is produced by cautiously merging all input catalogues into a single file without eliminating individual entries. When different catalogues have different interpretations of an event, the highest priority was generally given to the catalogue of the country where the event occurred.

The seismicity working-file was created on the basis of, in most cases, current versions of national earthquake catalogues: Austria (Lenhardt, 1996), Belgium (Verbeiren *et al.*, 1994), the Czech Republic (Schenková, 1993), Croatia (Čivčić, 1994), Denmark (Gregersen, 1995), Fennoscandia (Ahjos and Uski, 1994; earthquakes in Northern Europe, 1997), France (Lambert *et al.*, 1996), Germany (Leydecker, 1986; Grünthal, 1988), Iceland (Halldorsson, 1997), Hungary (Zsíros *et al.*, 1994), Italy (Camassi and Stucchi, 1997), The Netherlands (Houtgast, 1993, 1995), Poland (Guterch, 1995), Slovakia (Labák, 1998), Slovenia (Čivčić, 1993; Ribarić, 1982), (former) Soviet Union (Kondorskaya and Shebalin, 1977; Nikonov, 1992; Nikonov and Sildvee, 1991; Boborikin *et al.*, 1993), Switzerland (Mayer-Rosa and Baer, 1993; Rüttener, 1995), United Kingdom (Musson, 1994). For the Mid Atlantic ridge zone the ISC seismicity data file (1996) was used. Some of the national catalogues represent new, improved but confidential data and were made available exlusively for the Regional Centre 3 for the purpose of GSHAP for the purpose of GSHAP.

As the first step, the seismicity data for the GSHAP Region 3 were homogenized with respect to the epicentral or maximum intensity. The reason is that within the long earthquake history in the study area, up to one millennium, the vast majority of the events with essential importance for hazard assessment is primarily known only by intensity.

In the following steps, a homogeneous moment magnitude, M_W, based working-file for the whole study area was developed. Reliable data on isoseismal areas, A, are available for a minority of the felt earthquakes. Based on carefully selected data of A and the seismic moment, M_0, a set of empirical relations was established, *e.g.*, the following for intensity III:

$$\log(M_0) = 25.87 - 2.92 \log(A_{III}) + 0.45 \log(A_{III})^2$$

$$R^2 = 0.943. \tag{2.1}$$

This regression is valid for $\log(M_0) = 21.3\text{-}26$ (M_0 in dyne·cm). Equation (2.1) is similar to a relation by Johnston (1994) for $\log(M_0) =$ $= 22.5\text{-}26$.

For most of the events empirical relations based on epicentral intensity, I_0, and focal depth, h, had to be applied to get M_W or M_0. Attempts to create a relation for a direct conversion failed due to very large scatter. To minimize the bias in the conversion of I_0 and h into M_W it was necessary to use an intermediate conversion into the local magnitude, M_L, and to treat different national catalogues separately. In such a way empirical relations between M_L, I_0 and h were created for the different national catalogues. In the next step, a conversion relation was developed from carefully selected, independently determined M_0 and M_L data from the GSHAP Region 3:

$$\log(M_0) = 18.6 + 0.2\,M_L + 0.13\,M_L^2. \qquad (2.2)$$

Using the M_W definition of Hanks and Kanamori (1979), this relation was used to determine M_W from the M_L values of the different national catalogues. The details of establishing this complex of empirical conversions in creating a homogeneous M_W based seismicity working-file will be the subject of a special study.

3. Seismic source zones

The seismic source zones required for the approach need to be constructed according to seismotectonic findings and reflecting the distribution of seismicity. Whenever available, the source zones produced for national purposes were adopted if in accordance with these conditions. In detail, the zonations were prepared by Th. de Crook for The Netherlands, S. Gregersen for Denmark, G. Grünthal, G. Schneider and L. Ahorner for Germany (see also Grünthal and Bosse, 1996), P. Labák for Slovakia, W. Lenhardt for Austria, C. Lindholm for Norway, P. Mäntyniemi for Finland, R. Musson for United Kingdom and Ireland, R. Wahlström for Sweden and T. Zsíros for Hungary. For Switzerland the source zones after Sägesser and Mayer-Rosa (1978) were preferred. For France the seismic source zones were supplied by the AFPS according to the results of an EPAS-AFPS Working Group (*cf.* Autran *et al.*, 1998). The seismic source zones for Italy and the Northern Adriatic Sea by Scandone *et al.* (1992) were adopted with slight modifications. In general, the provided source regions needed only minor modifications where areas from different zonations overlap, to create a homogeneous set for the whole Region 3 (fig. 3). No seismic source zones were provided from Iceland, since all data on seismic hazard assessment were directly adopted for the GSHAP project.

It has to be stressed that the delineations shown in fig. 3 represent the superficial projections of the most shallow source zones. In several areas with a distinct layering of seismicity or with pronounced deeper events, a detailed delineation of source zones was extended into depth. Furthermore for technical reasons several regions with a complicated shape where split into different subregions with unique β and area specific ν. In total 285 «technical» seismic source zones have been used for the computation. They represent 196 seismic source zones.

It would be beyond the scope of this contribution to describe all the tectonic background for the constructed source zones in detail. The most prominent features are the sequence of zones delineating the upper Rhein area, the middle Rhine area and the lower Rhine embayment, the Mur-Mürz zone in Eastern Austria, the belt of seismic zones surrounding the Pannonian basin and the Bohemian massif, the North Sea graben and its northern prolongation as the Viking graben, and the Tornquist-Teisseyre zone forming the boundary between the East European platform and the Baltic shield.

4. Data preprocessing

Below, several steps of the preparation of the seismicity data for the calculations and the derivation of further input parameters are briefly described.

4.1. *Elimination of foreshocks and aftershocks*

The seismicity data file was made Poissonian by tagging the main shocks and applying simultaneously a distance-window and two

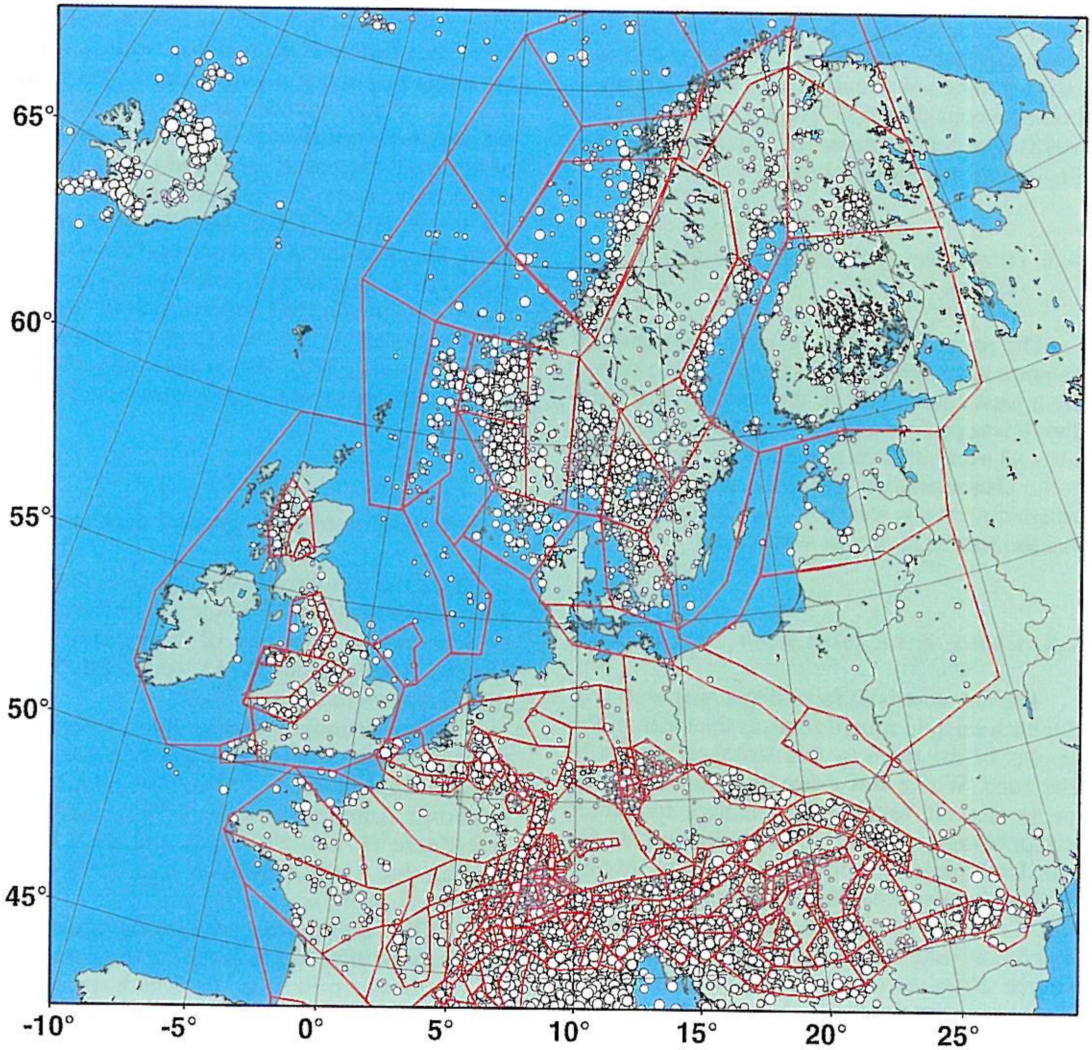

Fig. 3. Seismic source zones for the GSHAP Region 3 defined from seismicity distribution and seismotectonic criteria.

time-windows for eliminating foreshocks and aftershocks. The window parameters, derived from earthquake sequences in Central Europe (Grünthal, 1985), are dependent on the main shock magnitudes and are similar to those derived for California by Gardener and Knopoff (1974).

4.2. *Data completeness with time*

The data completeness was studied for 12 gross regions defined according to geographical and cultural-historical aspects which obviously influenced the data compilation. The completeness with time has been analyzed with different methods, the simplest based on a graphical test assuming that a constant gradient for the cumulative number of events *versus* time denotes a homogeneous detection level (*cf.* Grünthal *et al.*, 1998). The completeness test was performed for M_L in half magnitude classes.

4.3. *Parameters of the magnitude-frequency relation*

The parameters of the magnitude-frequency relation were determined for each source region by a least squares fit. In the case of poor data, the fit was performed for a larger area enclosing also adjacent source regions with similar tectonic characteristics. From the obtained β, the seismicity rate, v, was then calculated separately for the source region in such cases.

4.4. *Characteristic focal depth*

The characteristic focal depth was assessed, for each seismic source zone, as the mean of the dephts of the three to five strongest events in the zone. Where this procedure was not applicable, default values representative for larger surroundings were used. The characteristic focal depth varies in the range 4-22 km, except for the Vrançea area (Romania) and Fennoscandia. Several source zones required special consideration and different depth horizons, *i.e.*, source zones at different depths, were introduced, *e.g.*, in the Vrançea area with its intermediate depth earthquakes and the Hainaut zone in Belgium characterized by both shallow and deeper crustal events. For Fennoscandia, different weights were assigned to different focal depths.

4.5. *Upper bound earthquake magnitudes*

The assigned upper bound magnitude for each source zone was chosen to be well above the largest historically observed magnitude in that zone. The assignments were made from various criteria such as earthquake catalogue data, seismotectonics and paleoseismological data. They follow in general the conclusions for intraplate seismicity in Coppersmith (1994) that in areas of non-extended continental crust the maximum observed magnitudes are in the range of 6.3 ± 0.5 (M_S mean value and standard deviation) and in areas of extended continental crust 6.4 ± 0.8. Higher values have to be expected along the interplate Alpine belt and the Vrançea area, where magnitude 7.7 earthquakes are generated by a downward sinking slab of oceanic crust representing the final stage of subduction (Wenzel *et al.*, 1999). The smallest upper bound magnitudes are set at 6 in accordance with Frankel (1996).

5. Attenuation of peak ground acceleration

Since the tectonic conditions vary considerably within the GSHAP Region 3, different sets of attenuation relations of horizontal Peak Ground Acceleration (PGA) were used. Three main areas were distinguished:

1) The Fennoscandian shield, where the GSHAP group of the Nordic countries assigned equal weight to each of five PGA-attenuation relations: Ambraseys *et al.* (1996), Atkinson and Boore (1997), NORSAR and Risk Engineering, Inc. (1991), Spudich *et al.* (1997) and Toro *et al.* (1997).

2) The Vrançea area, with strong intermediate depth earthquakes influencing large parts of the Northeastern Balkans, for which special attenuation relations were derived (Lungu *et al.*, 1999).

3) The remaining part of the GSHAP Region 3, covering quite different tectonic units, where equal weight was assigned to each of the PGA-attenuation relations by Ambraseys *et al.* (1996), Sabetta and Pugliese (1996) and Spudich *et al.* (1997). While Spudich *et al.* (1997) is focused on normal-faulting events, which are dominating in large parts of this sub-area, *e.g.*, in the lower Rhine embayment, the other two relations were derived from entirely European strong motion data. The three relations show good agreement over the whole magnitude range.

6. Seismic hazard calculation and the resulting seismic hazard map

One of the main goals of GSHAP was to produce a homogeneous seismic hazard map for horizontal peak ground acceleration representative for stiff site conditions, for the probability level of an occurrence or exceedance of 10% within 50 years. Different computer programs were used in the calculations. Test calculations have shown that the code SEISRISK III (Bender and Perkins, 1987) as well as the classical

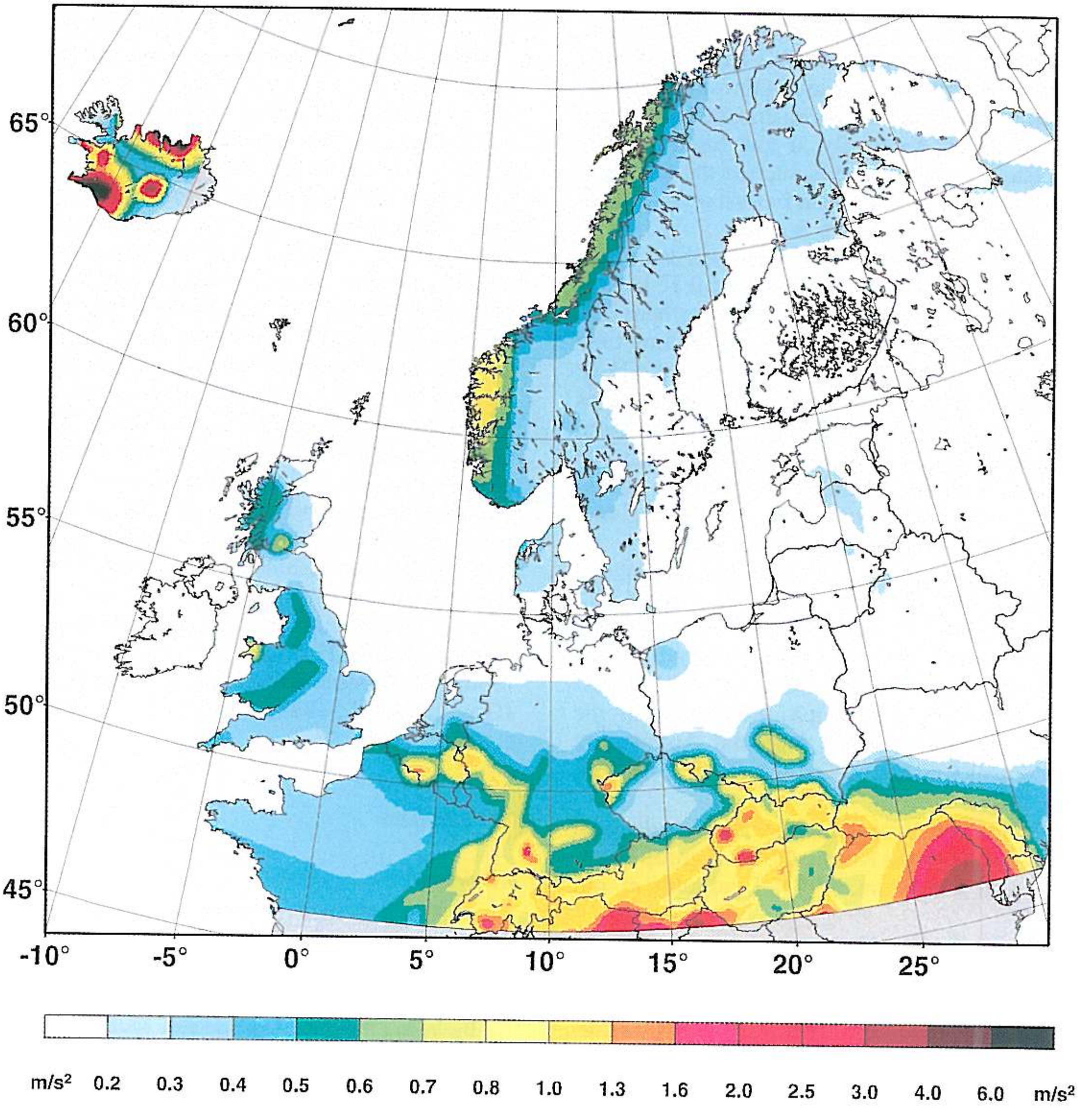

Fig. 4. Horizontal peak ground acceleration seismic hazard map representing stiff site conditions for an exceedance or occurrence rate of 10% within 50 years.

EQRISK (McGuire, 1976) give almost identical results. Since rather complicated geometrical shapes of seismic source zones had to be handled, numerical problems occurred in the application of SEISRISK III. Therefore, preference was given to the EQRISK code. Additionally, the code FRISK88M (Risk Engineering, Inc., 1996) was made available for the GSHAP Regional Centre for a limited time. Mean hazard values obtained from FRISK88M and EQRISK, respectively, are very similar. FRISK88M has a logic tree structure facilitating the calculation of fractile hazard values. Mean and median hazard values differ, especially at low hazard levels. For shorter return periods, such as the one specified by GSHAP, the mean hazard often falls in the range of the 60-70% fractiles.

The hazard calculations were performed for a grid of points with a spacing of 0.1° in latitude, 0.1° in longitude except in Northern Europe with 0.5° in latitude and 1.0° in longitude for a total of 59217 points. The final GSHAP Region 3 seismic hazard map is presented as fig. 4. It does not include only the results from the above described approach carried out at the GSHAP Centre in Potsdam, since it was agreed or desired to incorporate also several regional results into the final map. These are:

1) For Iceland the national map calculated for a slightly different hazard level of $2 \cdot 10^{-3}$ p.a. The map was compiled for a working group on the new building code nominated by the Icelandic Standardization Council (P. Halldorsson, 1997). It is an improved version of the maps prepared for the National Application Document for the Eurocode 8 (BSTR, FRV og Rb, 1995).

2) For Fennoscandia the almost identical local results of the Nordic GSHAP group (Bungum and Lindholm, 1997; Lindholm *et al.*, 1997).

3) For the East European platform, covering the most easterly part of the GSHAP Region 3, the results from the GSHAP Regional Centre 7 in Moscow (Ulomov, 1999). This region is almost aseismic, except for minor activity in Moldavia, Southwest Ukraine and the most northwesterly part of Russia. The original intensity data were transformed to PGA data using an empirical relation.

4) For Romania the results of Musson (1999). They show slightly increased PGA values compared to those derived at the Potsdam GSHAP Centre.

5) For the Czech Republic, Poland and Slovakia the calculations by Schenk *et al.* (1997b), upon request.

6) For the small parts of Italy (in the northeast) and Slovenia (in the north) which belong to the GSHAP Region 3 study area, the results of Slejko *et al.* (1998) and Zabukovec (1998), respectively.

For Ukraine, Moldavia and Romania minor adjustments were performed in the border regions. The highest seismic hazard shown in fig. 4 is found in Romania, with the Vrançea area, and Iceland, at the active plate boundary. Areas characterized by moderate seismic hazard (PGA-values greater than 1.6 m/s^2 for the given hazard level) are Northeastern Italy (Friuli), the Wallis in Southern Switzerland, a part of the Swabian Alb (Hohenzollerngraben) in Southwestern Germany and local areas in Western and Southwestern Slovakia. A moderate to low seismic hazard level is represented in most parts of the Alps, the Mur-Mürz zone in Austria, the circum-Pannonian belt, parts of Hungary, Southwestern Germany, the German-Belgian border region of the lower Rhine embayment and coastal regions of Norway.

The continuation of the seismic hazard map south of GSHAP Region 3 is presented in a report for Europe, Africa and the Middle East (Grünthal *et al.*, 1999).

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