Unified seismic hazard modelling throughout the Mediterranean region

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Abstract - The generation of a uniform seismic hazard modelling for the whole Mediterranean basin has been carried out under the coordination of activities of the IUGS-UNESCO IGCP-382 project "Seismotectonics and Seismic Hazard Assessment of the Mediterranean Basin" (SESAME) and the European Seismological Commission Working Group on Seismic Hazard Assessment. While the final approach for the Mediterranean region in the global hazard map of the "Global Seismic Hazard Assessment Program" was to assemble independent regional and national hazard maps, main efforts within recent SESAME activities have focused on the development of a unified seismic source model for the whole Mediterranean for homogeneous hazard computations. This unified source model is based on the compilation of existing data on seismogenic models for the region. The individual regional and national zonations have been joined, new seismic sources at border areas between different regions have been redesigned to avoid ambiguities coming from different approaches, and draft source zones have been established in areas where these were not yet availble. For the first time, a unified seismic source model for the whole of the Mediterranean region is presented and a suite of probabilistic hazard maps computed in a homogeneous fashion have been generated.

1. Introduction

Over the past eight years several international projects and programs have aimed at the establishment of improved global and regional seismic hazard assessment and a number of multinational programs were set up to produce earthquake catalogues, seismic source zonations

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and hazard assessment in Europe and the Mediterranean.

Within the framework of GSHAP (Global Seismic Hazard Assessment Program; 1992-1998), SESAME (Seismotectonics and Seismic Hazard Assessment of the Mediterranean Basin; 1996-2000), and the ESC/WG-SHA (European Seismological Commission Working Group on Seismic Hazard Assessment; 1996-2000), several programs, projects and test areas for multinational seismic hazard assessment have been active within the Mediterranean region.

The first regional seismic hazard map for the Mediterranean in terms of peak ground acceleration (PGA), as part of the GSHAP global map (Giardini, 1999), was compiled based on the integration of independent hazard results of a number of different test areas and regional and national programs (Grünthal et al., 1999b).

Recently, an attempt to integrate the GSHAP regional results in order to obtain a uniform seismic hazard modelling for the whole Mediterranean basin, following the seismotectonic probabilistic approach, has been carried out under the coordination of activities through both the SESAME project, and the ESC/WG-SHA.

Main efforts have focused on the development of a unified source model through the joining of the existing seismic source zones as derived for the individual regional and national hazard maps, the design of new sources in the border areas between different regions to avoid ambiguities coming from different approaches, and the establishment of draft source zones in areas where these were not yet available to avoid gaps in the geographical coverage.

For the first time, within the framework of SESAME, a unified seismogenic source model for the Mediterranean basin is presented together with a set of regional probabilistic hazard maps computed in a homogeneous fashion which express ground motion in different parameters for different soil types and different probabilities.

This paper summarizes the development and results of the generation of the first comprehensive model of hazard assessment for the whole Mediterranean.

2. Methodological approach in relation to the status on regional hazard assessment in the Mediterranean

The development of the unified seismic hazard model for the Mediterranean region has been based on the Seismotectonic Probabilistic Methodology. By following this approach (see e.g. McGuire, 1993; Muir-Wood, 1993), the region for which hazard is to be computed should be first subdivided into seismic source zones which are established according to tectonic, geophysical, geological and seismological data. A uniform seismic behaviour is assumed for each zone, the magnitude-frequency parameters and the maximum expected magnitude are determined on the basis of the seismic catalogue, and finally the expected ground motion is computed through an appropriate attenuation relationship.

Ideally, a comprehensive hazard model for the Mediterranean should have been worked out for this purpose through a homogeneous realization which should include, not only the homogeneous development of a seismogenic source model but also the corresponding seismic characterization parameters as derived from a unified seismic catalogue. This homogeneity in the procedure of hazard assessment for the whole Mediterranean basin is clearly out of reach at present. The completion of certain tasks involved in the homogeneous procedure would have needed more effort and time than those compatible with the development of the projects which hitherto have focused on regional hazard assessment in the Mediterranean. Since no general earthquake catalogue has been yet established for the region and since the quality and availability of the basic information for the establishment of a homogeneous seismogenic source model is still highly heterogeneous throughout the entire geographical domain, other approaches have to be implemented for regional hazard assessment. Main factors which pose strong limitations on the kind of effective approaches when dealing with large geographical regions are not only the heterogeneous quality and availability of the basic data, but also geographical gaps in this basic information.

A first attempt to overcome these difficulties to obtain a reference seismic hazard map for the Mediterranean was carried out within GSHAP (Grünthal et al., 1999b) through an approach that consisted in generating such a map by the use of independent regional hazard maps of PGA at a 10% probability of exceedance in 50 years. This GSHAP reference map for the Mediterranean block was built upon the integration of hazard results from GSHAP Central-Northern Europe region, a number of ad-hoc test areas (e.g., ADRIA (Adriatic region), CAUCAS (Caucasus), Ibero-Maghreb), independent projects (e.g., EC-Copernicus CIPA (Quantitative Seismic Zoning of the Circum Pannonian Basin), UNESCO RELEMR (Reducing Earthquake Losses in the Eastern Mediterranean Region), and also specific national maps (e.g., Greece, Turkey), some of which were partly introduced in areas of pronounced border discrepancies (e.g., Slovenia). Fig. 1 from Grünthal et al. (1999b) depicts the different seismogenic models produced by different projects in the Mediterranean region available at the time of the development of GSHAP.

As pointed out in Grünthal et al. (1999b), all of these independent hazard maps were produced following the same basic seismotectonic approach, but due to the differences in the delineation of the seismic source zones or the adoption of different attenuation laws, the harmonization of the hazards in the assemblage of the final GSHAP map for the Mediterranean required several iterations of smoothing and border matching between the different regional results. No attempt was made within GSHAP to harmonize the individual regional or national seismogenic models in the Mediterranean.

A further attempt for regional hazard assessment in the Mediterranean is that carried out within SESAME. The approach in SESAME has allowed a homogeneous hazard computation through the establishment of a unified seismogenic source model. The procedure and development of a unified hazard modelling for the Mediterranean is described in detail in the following sections.

3. Building up a unified seismogenic source model for the Mediterranean basin

The development of a unified seismogenic source model for the Mediterranean region has been carried out in two main steps.

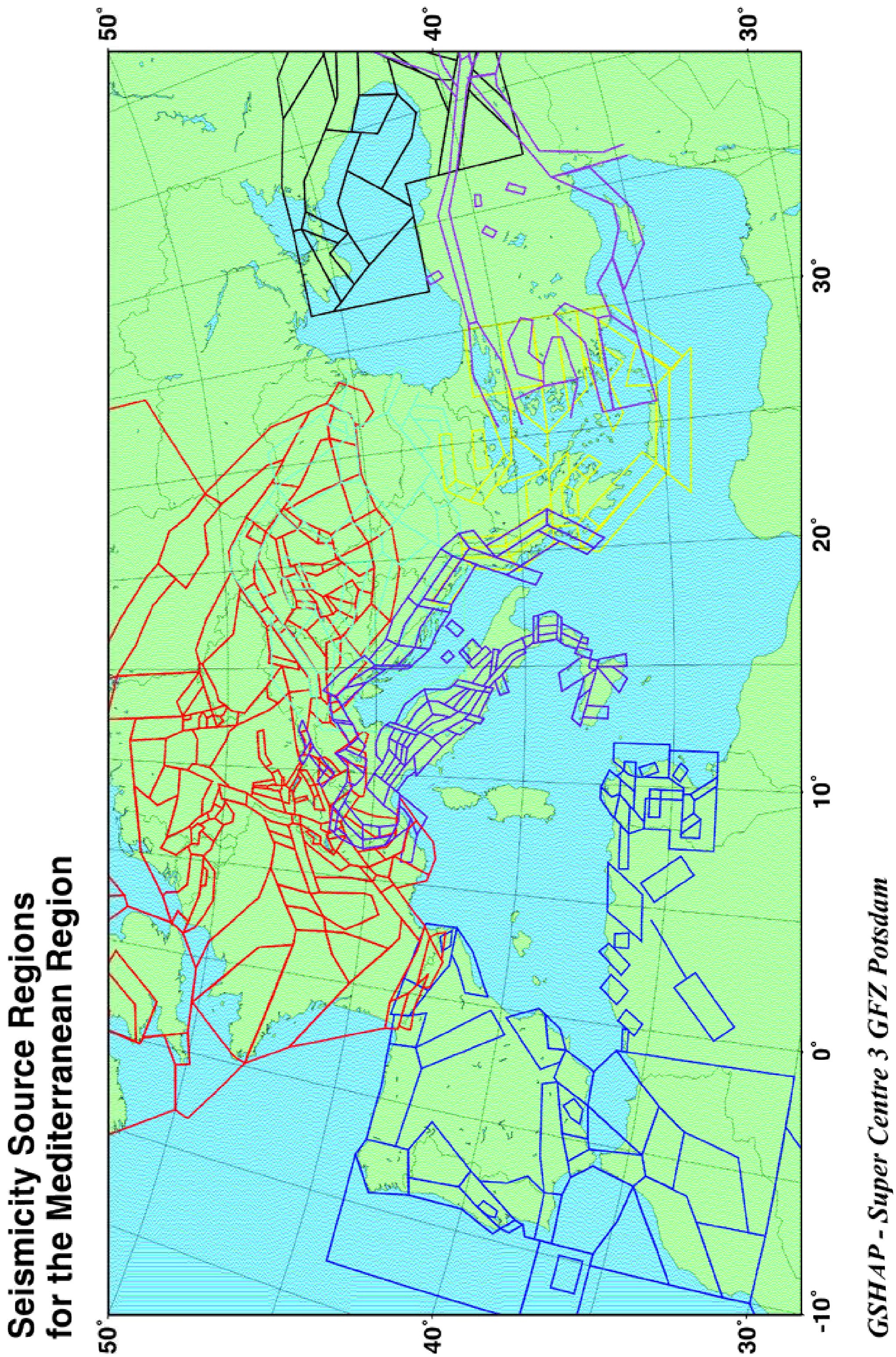

Fig. 1 - Seismogenic source models from test areas and projects in the Mediterranean compiled within GSHAP (from Grünthal et al., 1999b).

In the first step, models in the GSHAP database were compiled and complemented with existing models in the literature to avoid gaps in the geographical coverage. This compilation was based on regional data from ADRIA (Slejko et al., 1999), Bulgaria (van Eck and Stoyanov, 1996), Central-Northern Europe (Grünthal et al., 1999a), Eastern Mediterranean (Shapira and Shamir, 1994; El-Sayed and Wahlström, 1996), Greece (Papaioannou and Papazachos, 2000), Ibero-Maghreb (Jiménez et al., 1999), Libya (Grünthal et al., 1999b), North Balkan region (Musson, 1999), and Turkey (Erdik et al., 1999). Most of this compiled regional data stem from programs and test areas for multi-national seismic hazard assessment that have been coordinated in close relation to GSHAP, SESAME and the ESC/WG-SHA activities (e.g., ADRIA, Central Europe, North Balkan region, Ibero-Maghreb, Turkey and Libya), while others have been made available by independent studies or from published literature in some cases (e.g., Greece, Eastern Mediterranean (Israel and Egypt) and Bulgaria). The inclusion of these models was necessary to avoid either the lack of data on seismogenic sources, or gaps at border areas between the different regional models. Fig. 2 shows the distribution and overlapping of compiled seismogenic sources from the different regional and national models. For details on the different seismogenic source models and data we refer the reader to the original references which are summarized in Table 1.

Table 1 - Regional seismogenic models in the Mediterranean on which SESAME compilation is based.

Basic data on regional seismogenic source models	
Region	**Reference**
ADRIA	Slejko et al. (1999)
Bulgaria	van Eck and Stoyanov (1996)
Central Europe	Grünthal et al. (1999a)
North Balkan region	Musson (1999)
Eastern Mediterranean (Israel, Egypt)	Shapira and Shamir (1994) El Sayed and Wahlström (1996)
Greece	Papaioannou and Papazachos (2000)
Ibero-Maghreb	Jiménez et al. (1999)
Libya	Grünthal et al. (1999b)
Turkey	Erdik et al. (1999)

In the second step, the existing zones, as derived in the individual regions, were joined; the original background sources, established in the individual models to account for seismicity in neighbouring regions, were eliminated; and new zones at overlapping border areas were redesigned to harmonise geometries were differences existed. These areas mostly correspond to the Pyrenees, the Alps, the Carpathians, Northern Greece and the Aegean, among others. In the Mediterranean, a new regional model for the Eastern Mediterranean region has been developed in cooperation with the GII (Geophysical Institute of Israel), while the GSHAP source model for Turkey (Erdik et al., 1999) has been updated. Fig. 3, where new geometries of sources are

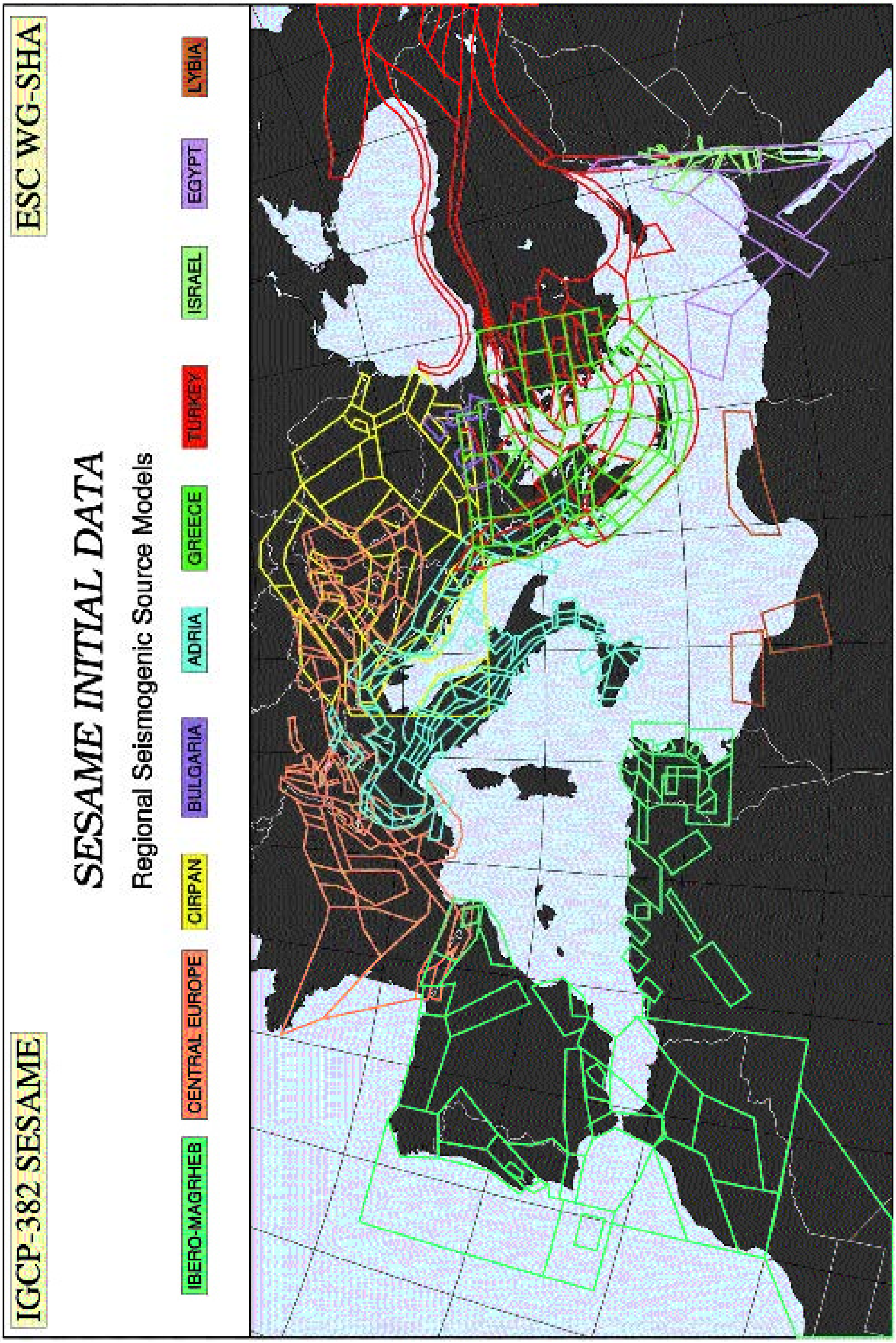

Fig. 2 - Distribution and overlapping of seismogenic sources from the different regional and national models throughout the Mediterranean region in the SESAME compilation.

filled in, highlights new sources and those border areas between the individual models for which redesigning of sources was carried out.

Finally, seismic parameters for redesigned sources were assigned, based on the new geometry and existing regional catalogues by following the same computational procedure as in the individual original computations.

Fig. 4 shows the final unified seismogenic source model for the Mediterranean region, which consists of a total of 346 sources, 338 shallow and 8 intermediate-depth (see Table 2 for details in relation with the original source data and the sources included in the final unified model). Each source is characterized by the corresponding seismicity parameters in terms of minimum and maximum magnitude, and earthquake occurrence rates with an associated sub-catalogue which stems from the corresponding regional catalogues.

Table 2 - Original data on seismic sources and SESAME unified seismogenic source model. In parentheses is the number of redesigned sources.

SESAME Unified Seismogenic Source Model				
Region	**Original sources**		**SESAME sources**	
	Shallow	**Intermediate**	**Shallow**	**Intermediate**
ADRIA	101	0	85 (3)	0
Bulgaria	7	0	5 (1)	0
Central Europe	98	0	91 (8)	0
North Balkan	49	1	19 (7)	1
Eastern Mediterranean: Israel	17	0	7 (7)	0
Eastern Mediterranean: Egypt	10	0	4 (2)	0
Greece	67	7	43 (21)	7
Ibero-Maghreb	67	0	62 (9)	0
Libya	3	0	3	0
Turkey	37	0	19 (7)	0
Totals	**456**	**8**	**338**	**8**

4. Ground motion attenuation relationships

Existing regional hazard projects in the Mediterranean have considered different ground motion attenuation relationships for hazard computation (e.g., Ambraseys and Bommer, 1991; Ambraseys et al., 1996; Sabetta and Pugliese, 1996; Spudich et al., 1996). The criteria for the choices of an appropriate attenuation relationship are based on the assumption of its general or regional adequacy. Also a common practice for large regional hazard assessment is to consider several relationships and a weighting scheme through which final ground motion values are computed (see e.g., Grünthal et al., 1999a ; Erdik et al., 1999).

For SESAME computations the Ambraseys et al. (1996) relationships in terms of PGA and absolute spectral acceleration (SA) were considered to be adequate for the regional hazard assessment since they were obtained on the basis of a wide European strong motion data set

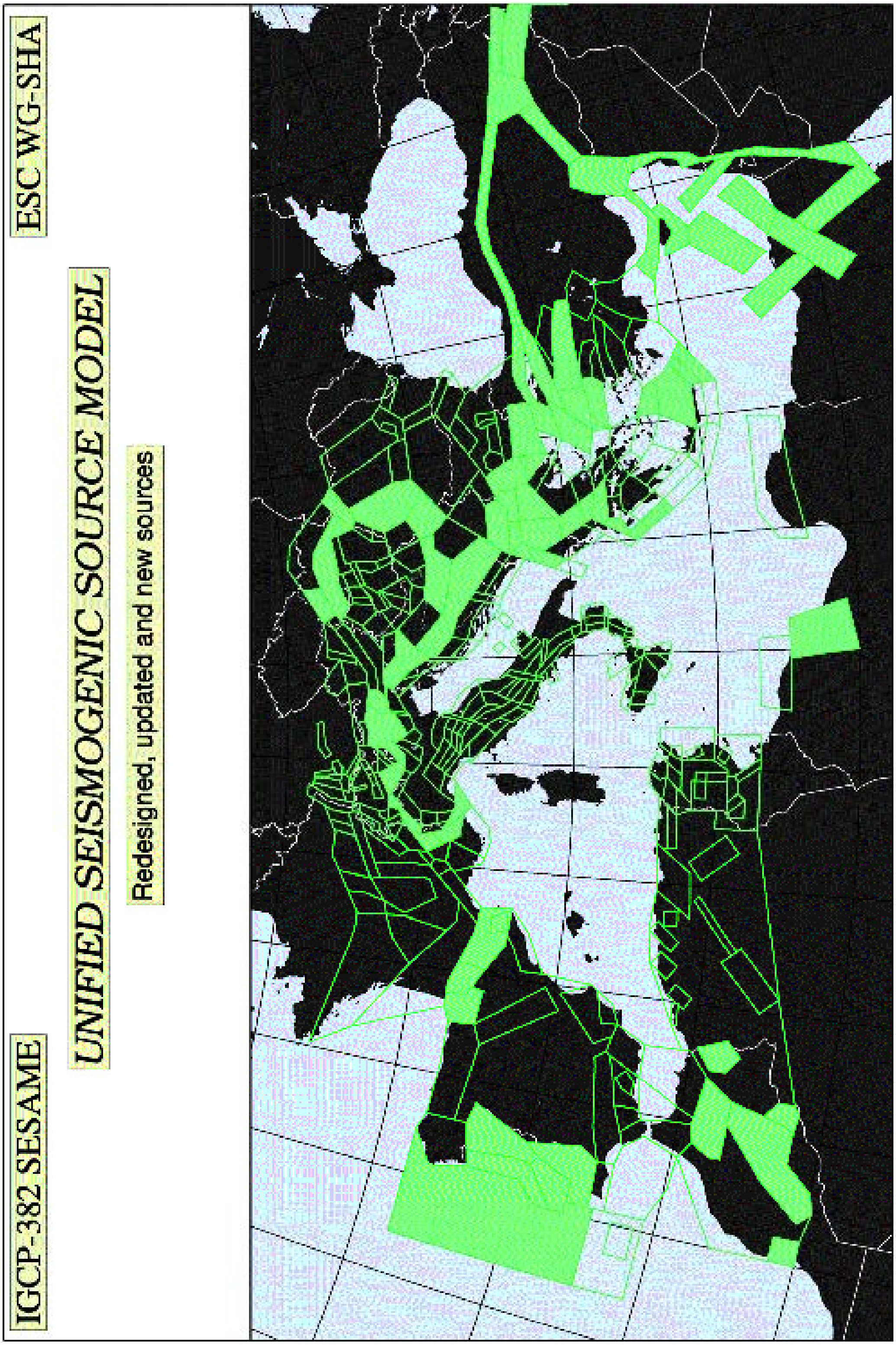

Fig. 3 - Filled in sources highlight new source geometries in the SESAME unified source model for the Mediterranean.

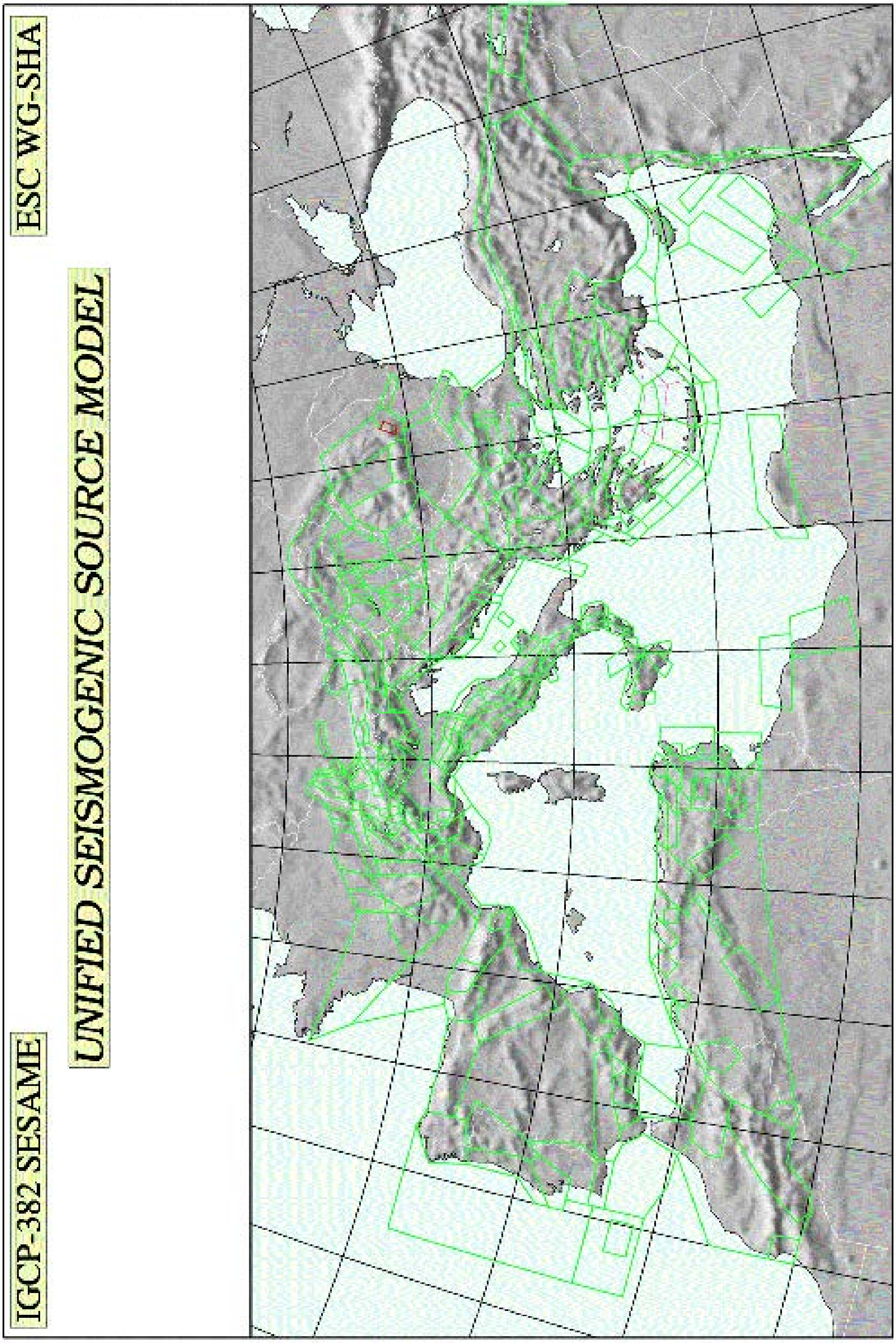

Fig. 4 - Unified seismogenic source model for the whole Mediterranean region.

with magnitudes between 4.0 and 7.9 and four categories of soil condition (rock, stiff, soft and very soft soil).

While Ambraseys et al. (1996) equations were assumed to be adequate for all crustal sources in the SESAME unified model, specific attenuation relationships have to be considered for the eight sources of intermediate-depth seismic activity in the Mediterranean region. Intermediate earthquakes originating in Vrancea (Romania) are known to present markedly directional characteristics in ground motion attenuation (see e.g. Musson, 1999) which have to be accounted for in hazard computations for this region. Vrancea's specific attenuation was considered through the relationships derived from Musson (1999). For intermediate-depth seismic activity sources in the Hellenic Arc, the specific attenuation relationships in Papaioannou and Papazachos (2000) were used.

5. Hazard computation technical procedure

Hazard computations were performed through SEISRISK III (Bender and Perkins, 1987). Tests have shown that computation of hazard through the most widely used codes SEISRISK III, EQRISK (McGuire, 1976) or FRISK88M (Risk Engineering Inc., 1996) give almost identical results (Grünthal et al.,1999a).

The fact that some of the seismogenic source data (those of ADRIA, Turkey and Ibero-Maghreb) were made available already in SEISRISK III input format eased the decision on the election of the computation code. The rest of regional source zonings (all of them areal sources) were mounted in SEISRISK III compatible input. Due to complicated geometries of some of the sources, which might cause severe numerical instabilities, some seismogenic sources were split into several technical sources for computation.

The input for SEISRISK III code requires the attenuation relationship in tabular form (ground motion versus magnitude and distance) and the description of each source including the geometry, the uncertainty in earthquake location and the occurrence rates (number of earthquake occurrences at given magnitude intervals normalized to a given number of years). These seismicity rates are not restricted to fit an exponential distribution. SEISRISK III also allows for earthquake location uncertainty by considering locations normally distributed with standard deviation σ. Ground motion variability is incorporated in the computations assuming a lognormal distribution of the ground-motion parameter with standard deviation σ_a.

To ensure that the computation through the procedure established gave fully compatible results with the original regional hazards, individual tests were performed for all regions to detect possible misfits and therefore identify the causative reasons. This way the resulting differences in the hazard results through the SESAME unified procedure should arise solely in relation to the harmonization of the basic input data (e.g, source geometries at border areas, attenuation relationship) or specific to the computations for a large geographical region (e.g. larger grid spacing).

Hazard computations were carried out for the area stretching from 10º W-40º E and 30º N-50º N at a grid interval of 0.2 degrees. The number of computation nodes is around 25,000.

Due to technical limitations in the number of points to be computed at a time, and also to avoid distortion originating from the coordinate system transformations, the whole region was split into 12 sub-regions for which hazard was computed independently. Through this computation scheme the maximum distance error introduced is less than 0.6 percent.

A severe limitation in the computational procedure was to handle the non-isotropic attenuation for the intermediate-depth earthquakes of Vrancea's seismogenic source. This specific directional attenuation was handled independently by applying the procedure and code used for the regional hazard mapping of the North Balkan region (Musson, 1999).

6. Regional hazard maps

Main results of SESAME have been the generation of a suite of regional probabilistic hazard maps computed in a homogeneous fashion. For the first time regional probabilistic seismic hazard assessment throughout the Mediterranean has been performed on the basis of a unified seismogenic source model which consists of 346 sources, 8 of which correspond to intermediate-depth seismic activity, adopting Ambraseys et al. (1996) attenuation relationships for crustal sources and specific ground motion attenuation for intermediate sources (Musson, 1999; Papaioannou and Papazachos, 2000). For the first time the procedure has made it possible to obtain homogeneously computed regional hazard maps for the Mediterranean in terms of different ground motion parameters (PGA, 0.3 s and 1.0 s SA), different soil conditions (rock, stiff soil) and different probability levels (1%, 10% and 65% of exceedance in 50 years).

Figs. 5 to 7 show final maps depicting PGA, 0.3s SA and 1.0s SA at a 10% probability of exceedance in 50 years for stiff soil conditions, respectively (the maps are updated to include last results from the unified model of the European Mediterranean region available at the time of printing). The maps in Figs. 6 and 7 were produced using only shallow sources.

These maps reproduce the main seismic hazard trends in the Mediterranean region and show that regional hazard maps for the Mediterranean can be generated through a homogeneous computation procedure, based on the established approach.

7. Some conclusions, discussion and outlook

For the first time, within the framework of SESAME, a unified seismic source model throughout the Mediterranean region is presented and a suite of regional probabilistic hazard maps, computed in a homogeneous fashion, have been generated.

Through the procedure established within SESAME, this unified hazard modelling for the Mediterranean will allow a homogeneous hazard computation but still many aspects in its realization will remain unavoidably heterogeneous. Since no homogeneous seismicity and seismotectonic data is yet available for the entire domain of the Mediterranean, regional hazard assessment has to be built upon heterogeneous existing models and data, among which the most up-to-date are not always readily accessible. Improvements to harmonize models and data

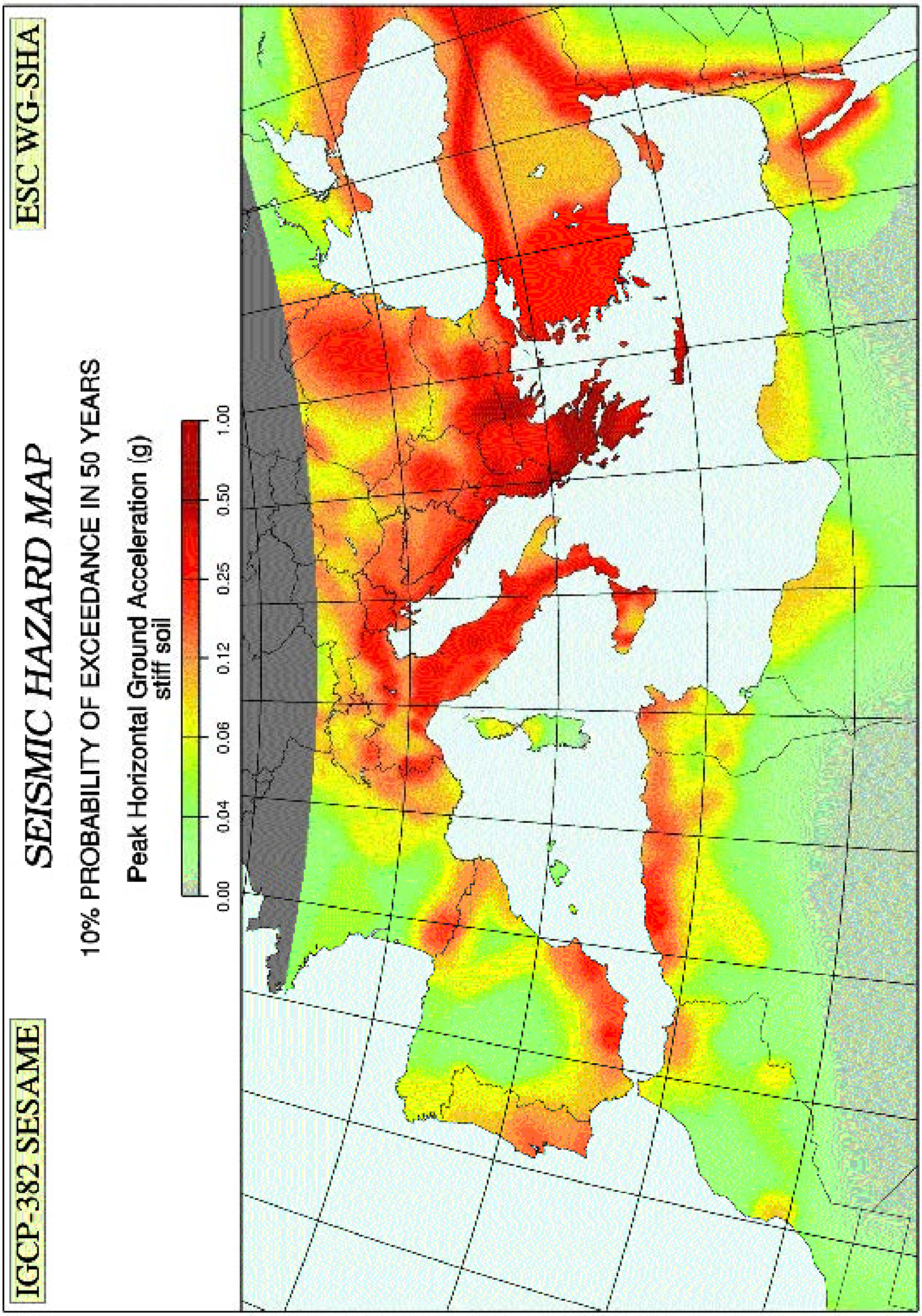

Fig. 5 - Seismic hazard map of the Mediterranean region depicting PGA on stiff soil in g units for a 10% probability of exceedance in 50 years.

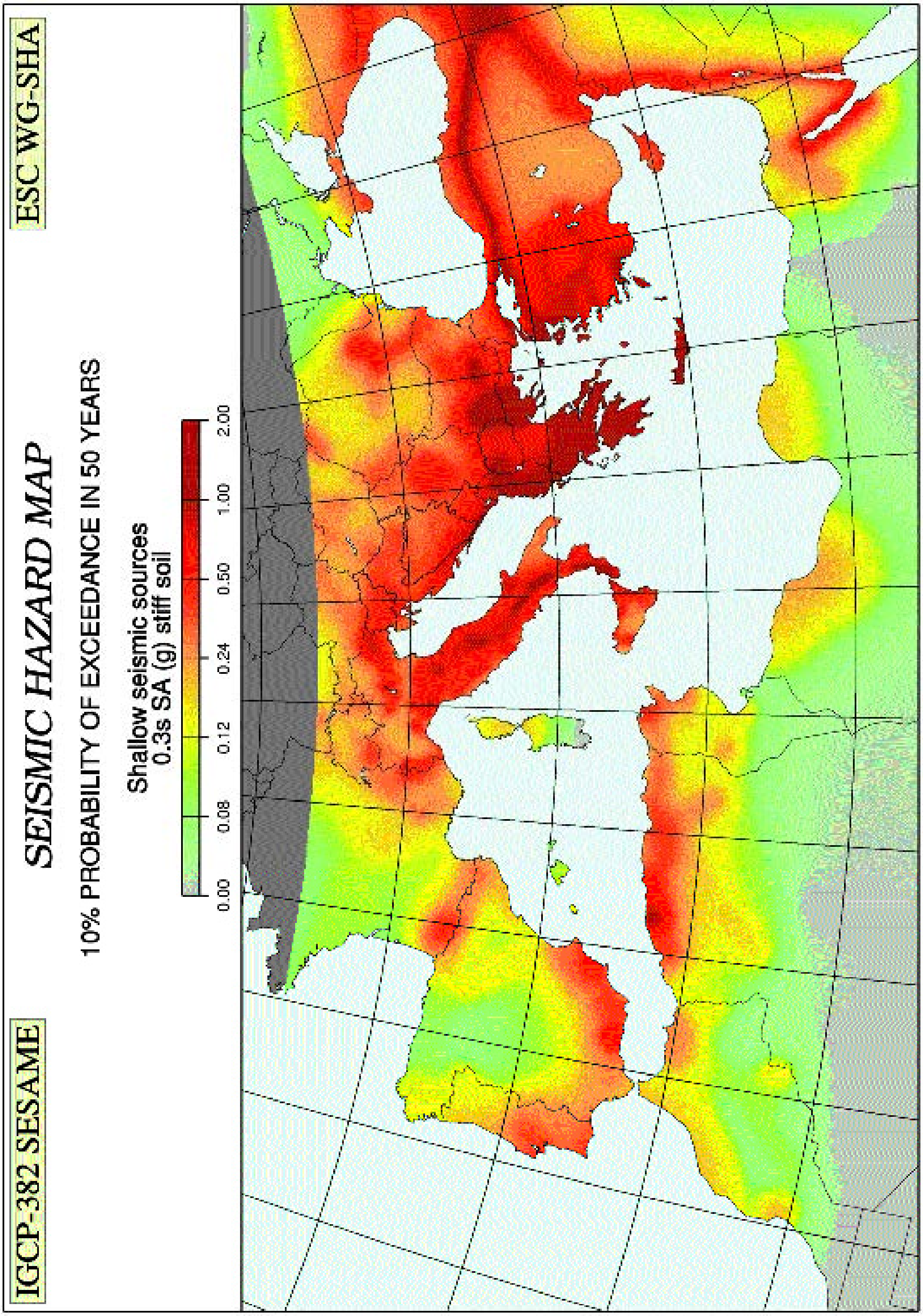

Fig. 6 - Seismic hazard map of the Mediterranean region depicting 0.3 s SA on stiff soil in g units for a 10% probability of exceedance in 50 years.

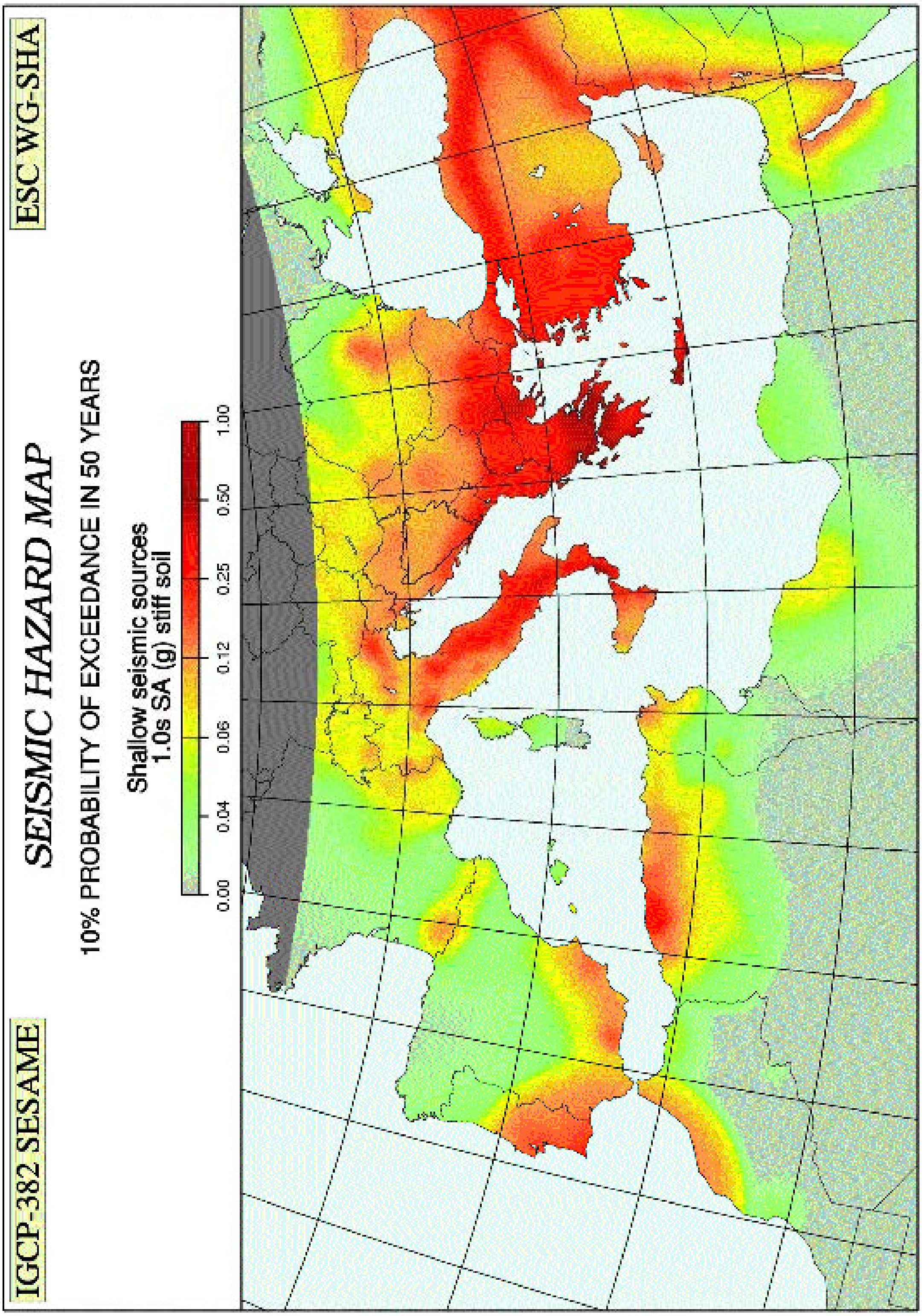

Fig. 7 - Seismic hazard map of the Mediterranean region depicting 1.0 s SA on stiff soil in g units for a 10% probability of exceedance in 50 years.

can be achieved through close regional cooperation and efforts in a reasonable period of time, but these cannot go beyond the limits posed by the differences in background knowledge and quality of the basic data. These differences remain unsolved and are reflected unavoidably in the final regional hazard maps.

The basic assumption in the seismotectonic probabilistic approach of an equal probability of occurrence of an earthquake at every point in the source is reflected in the seismic zonation of the hazard maps. Thus, areas of concentrated enhancements of the hazard or those with a wider distributed hazard in the regional maps will, in general, bear on the different hazard modelling criteria (e.g., level of detail in the delineation of sources) and the specific purposes for which the individual regional or national models were established.

Nevertheless, this unified hazard model for the whole Mediterranean will contribute to the establishment of a regional seismic hazard framework for the region in terms of PGA and SA from which seismologists, geologists and earthquake engineers can profit as a general guideline and reference for national and international initiatives.

The compiled databases (i.e., source zones, attenuation, seismic activity parameters) and the homogeneous hazard computation scheme constitute a unique tool through which relevant information for future regional research studies can be provided.

The SESAME results can be used for re-evaluation of hazard according to different criteria for sub-regions or for the whole Mediterranean region, for comparative regional studies dealing with both methodological and assessment issues, as an aid to modelling seismicity in neighboring regions for national hazard maps, as well as in educational projects, among other applications.

Finally, for the first time, our results on unified hazard assessment for the Mediterranean region together with Central-Northern Europe results in GSHAP allow the generation of a comprehensive model of seismic hazard assesment for the whole European-Mediterranean region which is being published under the auspices of the European Seismological Commission.

Acknowledgments. This study is based on data and efforts of many years of work of many individuals and institutions which were active in different projects related to hazard in the Mediterranean whose contributions have made it possible. We acknowledge all of them, and specially all those groups and individuals active within the framework of GSHAP and the ESC/WG-SHA. IUGS-UNESCO IGCP-382 SESAME project has partially supported some of the activities during the different stages in the development of the work. Preliminary results were presented at the 27th General Assembly of the European Seismological Commission. Figures in this paper were prepared using GMT software (Wessel and Smith, 1998).

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