The GSHAP Global Seismic Hazard Map

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INTRODUCTION

Minimization of the loss of life, property damage, and social and economic disruption due to earthquakes depends on reliable estimates of seismic hazard. National, state, and local governments, decision makers, engineers, planners, emergency response organizations, builders, universities, and the general public require seismic hazard estimates for land use planning, improved building design and construction (including adoption of building construction codes), emergency response preparedness plans, economic forecasts, housing and employment decisions, and many more types of risk mitigation. The Global Seismic Hazard Assessment Program (GSHAP) was designed to assist in global risk mitigation by providing a useful global seismic hazard framework and by serving as a resource for any national or regional agency for further detailed studies applicable to their needs. GSHAP was launched in 1992 by the International Lithosphere Program (ILP) with the support of the International Council of Scientific Unions (ICSU) and endorsed as a demonstration program in the framework of the United Nations International Decade for Natural Disaster Reduction (UN/IDNDR). GSHAP promoted a regionally coordinated, homogeneous approach to seismic hazard evaluation, including the production and distribution of the Global Seismic Hazard Map (GSH Map), a special issue of *Annali di Geofisica* (December 1999) describing the map and project, and a Web site (http://seismo.ethz.ch/GSHAP/) containing regional reports, GSHAP yearly reports, summaries, and maps of seismicity, source zones, and seismic hazard values.

STRATEGY

The GSHAP strategy was to establish a mosaic of regions under the coordination of regional centers (Figure 1). The goal in the first implementation Phase (1993-1995) was to establish for each region or test area a working group of national experts covering the different fields required for seismic hazard assessment, to produce common regional earthquake catalogs and databases, and to assess the regional seismic hazard. The second Phase (1995-1998) of GSHAP involved expansion of these regional efforts to assess the seismic hazard over whole continents and finally the globe. This strategy was maintained in many of the originally established ten regions, while elsewhere the activities focused directly on key test areas under the coordination of large working groups. The Mediterranean and the Middle East were covered by a mosaic of overlapping projects, while in parts of Africa, the Western Pacific rim, and North America the hazard map values were derived from published national seismic hazard maps. We included these national maps without smoothing discrepancies along any common borders, since these maps appear in some form in national or local building codes. In addition, GSHAP allied with existing hazard projects to avoid duplications and strengthen cooperation across borders in the Balkans and Near East. The methods and data used in the generation of each national or regional map used to produce the Global Seismic Hazard Map are documented in a special issue of *Annali di Geofisica* (December 1999) and on the Web site http://seismo.ethz.ch/GSHAP/, along with the names and contact information for the scientists responsible for the maps. The user is encouraged to contact the appropriate scientists and/or agencies for more detailed information.

METHOD

The global evaluation of seismic hazard requires the characterization of the earthquake cycle over recurrence times spanning from 10-10^3 years in active tectonic areas to 10^3-10^5 years in areas of slow crustal deformation. GSHAP implemented a multidisciplinary approach to seismic hazard assessment that combined the results from geological disciplines dealing with active faulting (neotectonics, paleoseismology, geomorphology, geodesy) with the historical and instrumental records of earthquakes. For the actual calculation of seismic hazard values, GSHAP selected the probabilistic seismic hazard assessment (PSHA) approach originally described by Cornell (1968), as applied by several different practitioners. The most widely used PSHA applications Software was *FRISK88M*®, developed by Robin McGuire of Risk Engineering, Inc. Under a special licensing agreement with GSHAP, *FRISK88M*® was distributed free of charge to working groups in the GSHAP centers and test regions for varying lengths of time adequate to allow hazard value calculations and verifications.

The basic elements of modern PSHA can be grouped into four main categories:

1. *Earthquake catalogs*: the compilation of a uniform catalog of seismicity for the historical (pre-1900), early instrumental (1900-1964), and instrumental periods (1964-today).

2. *Earthquake source characterization*: the creation of a master seismic source model to describe the spatial-temporal distribution of earthquakes, using evidence from earthquake catalogs, seismotectonics, paleoseismology, geomorphology, mapping of active faults, geodetic estimates of crustal deformation, remote sensing, and geodynamic models.

3. *Strong seismic ground motion*: the evaluation of ground shaking as a function of earthquake size and distance, taking into account propagation effects in different tectonic and structural environments and using direct measures of the damage caused by the earthquake (the seismic intensity) and instrumental values of ground motions.

4. *Computation of seismic hazard*: the computation of the probability of occurrence of ground shaking in a given time period to produce maps of seismic hazard and related uncertainties at appropriate scales.

The original goal of GSHAP was to assemble „an input seismicity database of (1) unprecedented uniformity in magnitude, (2) large time span from historical to modern times, and (3) true global scope" (Johnston and Halchuk, 1993). From the beginning, GSHAP researchers recognized that the characteristics of this global database would vary regionally, since the estimated size of a single, truly global seismicity catalog that included small and moderate earthquakes (magnitude ≥ 3.5) precluded any one center from assembling, verifying, and maintaining it for the global community. Instead, working groups at the regional centers assembled seismicity catalogs with clearly specified temporal and geographical boundaries, levels of completeness, and common magnitude scales (including the hierarchies and formulae used to convert between magnitude scales). These regional and/or national seismicity catalogs have been fully documented and made available through the GSHAP Web site, the cooperating institutions' Web sites, or the named national/regional contacts.

Earthquake source characterization involves the interpretation and translation of a wide variety of earthquake and deformation information into a master seismic source model. Given that the input data range from earthquake catalogs to remote sensing and geodynamic models, many interpretations and approaches are possible. Surprisingly, perhaps, only two different earthquake source characterization methods were used for GSHAP: the delineation of seismic source zones (fault or area) and the historic parametric method. Minor details of each method varied regionally or nationally.

The delineation of seismic source zones involves specifying the geographical coordinates of an area (polygonal) or fault (linear/planar) source (Cornell, 1968; McGuire, 1996). The hazard is assumed to be uniform within each polygon or along each fault segment and may be described using a few parameters: the minimum (damage threshold) and maximum magnitude earthquakes and the rate of seismicity, derived from the Gutenberg-Richter (GR) relationship

$$\log N = a - bM$$

where N is the number of earthquakes of magnitude M or greater per unit of time and a and b are constants.

The historic parametric method determines seismicity rates (again based on the GR equation) for each point of a grid through the spatial smoothing of historical seismicity (Veneziano *et al.*, 1984). Currently popular historic parametric applications supplement these seismicity rates with specific scenario earthquakes and background seismicity source zones (*e.g.*, Jacob *et al.*, 1994; Frankel, 1995).

The major difference between these two source characterization approaches is in the spatial distribution of hazard values. The source tone approach distributes the hazard throughout each area or fault zone. The spatially smoothed seismicity approach tends to concentrate the hazard nearer the sites of known earthquakes. The type of earthquake source characterization method used regionally or nationally in the creation of the GSH Map has been fully documented and made available through the reports published in the December 1999 issue of *Annali di Geofisica* and the GSHAP Web site.

Strong seismic ground-motion characterization involves determining both the site classification and the estimation of expected ground motion as a function of earthquake size, distance, and style of faulting. There are several site classification schemes, ranging from a description of the physical properties of near-surface material to very quantitative characterizations. In general, sites are classified as rock, soft rock/stiff soil, firm or deep soil, and soft soil, with a range of descriptions of each class and amplification factors to move between classes.

Estimates of expected ground motions are usually determined using equations, called attenuation relationships, that express ground motion as a function of magnitude, distance, and style of faulting. Ground-motion attenuation relationships may be determined empirically or theoretically. Different tectonic environments give rise to different ground-motion attenuation relationships. From the outset, GSHAP researchers recognized that obtaining regionally appropriate ground motion attenuation relationships for all regions of the world was a major challenge. Several of the GSHAP regional centers undertook thorough reviews of attenuation relationships and published their results (*e.g.*, *Seismological Research Letters* **68**, 1997), thus greatly increasing the availability of regionally appropriate attenuation relationships for use in the GSHAP. The site classification and attenuation relationships used regionally or nationally in the creation of the GSH Map have been fully documented and made available through the reports published in the December 1999 issue of *Annali di Geofisica* and the GSHAP Web site.

The final element of seismic hazard assessment is the actual calculation of expected ground-motion values. Once sources are characterized and attenuation functions are selected, the potential ground motions from each possible source are calculated for every point on a grid. The ground-motion values from each earthquake have the same probability of occurrence as the earthquake that produces them. This calculation of site-specific ground-motion values is performed for every possible source that can affect that site. All of these calculations are turned into an annual frequency of occurrence, and exceedance, of various levels of the ground-motion parameter of interest. The final hazard values are determined by summing over the time period of interest. Details of the software packages used to calculate hazard values for the GSH Map may be found in various publications (Frankel, 1995; McGuire, 1996; Tanner and Shepherd, 1997).

RESULTS AND DISCUSSION

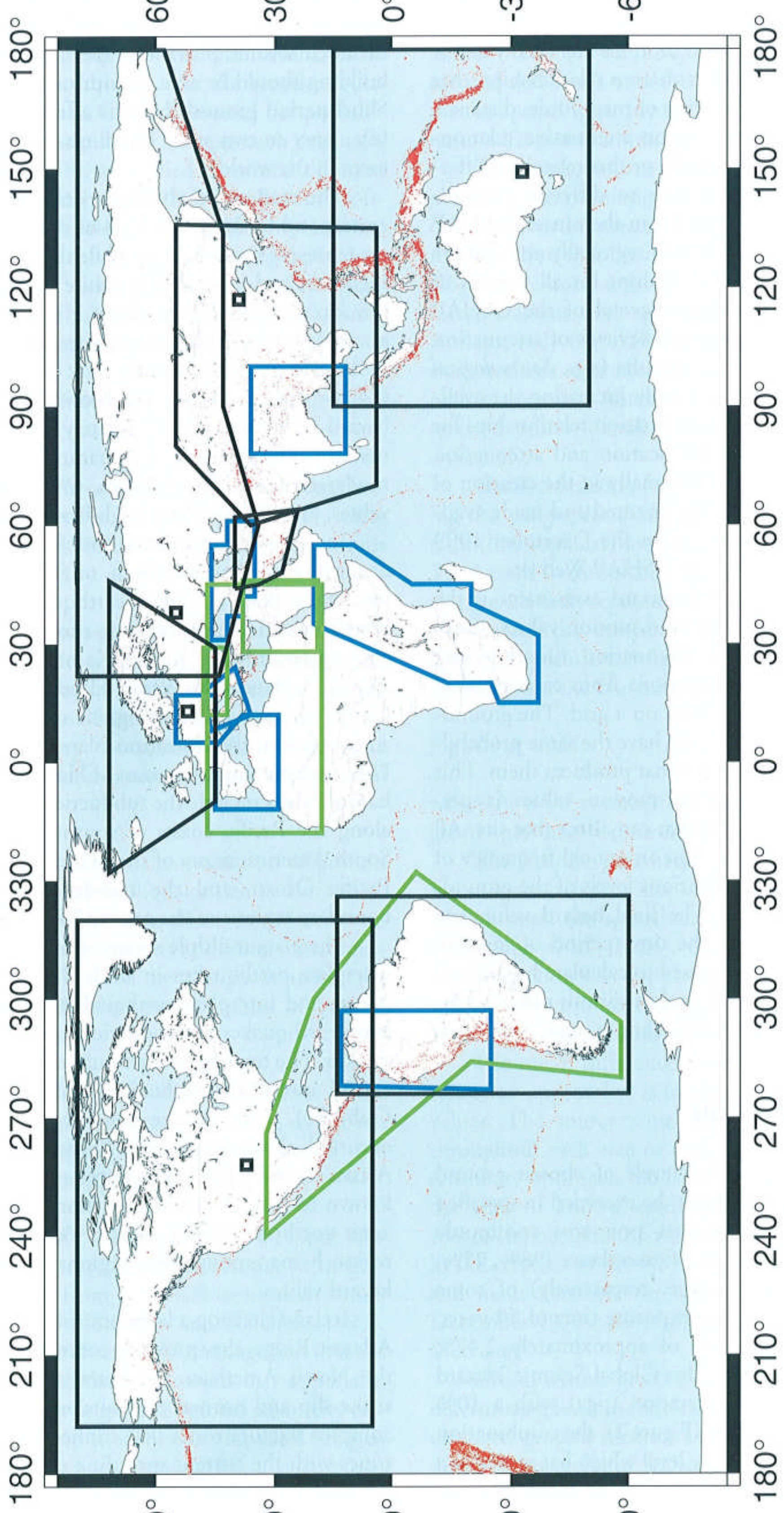
Seismic hazard maps depict the levels of chosen ground motions that likely will, or will not, be exceeded in specified exposure times. Hazard assessment programs commonly specify a 2%, 5%, or 10% chance of exceedance (98%, 95%, or 90% chance of non-exceedance, respectively) of some ground-motion parameter for an exposure time of 50 years, corresponding to return periods of approximately 2,475, 975, or 475 years, respectively. This Global Seismic Hazard Map depicts peak ground acceleration (pga) with a 10% chance of exceedance in 50 years (Figure 2), the combination of ground motion and probability level which has served as a fundamental input to building codes for decades. The site classification is rock everywhere except Canada and the United States, which assume rock/firm soil site classifications. pga, a short-period ground-motion parameter that is proportional to force, was the most commonly mapped ground motion parameter because building codes that included seismic provisions specified the horizontal force a building should be able to withstand during an earthquake. Short-period ground motions affect short-period structures (*e.g.*, one- to two-story buildings, the largest class of structures in the world).

The map colors chosen to delineate the hazard roughly correspond to the actual level of the hazard. The cooler colors represent lower hazard, while the warmer colors represent higher hazard. Specifically, white and green correspond to low hazard (0%-8% g, where g equals the acceleration of gravity); yellow and orange correspond to moderate hazard (8%-24% g); pink and dark pink correspond to high hazard (24%-40% g); and red and brown correspond to very high hazard (> 40% g). Approximately 70% of the Earth's continental landmasses have low hazard (pga) values, 22% have moderate hazard (pga) values, 6% have high hazard (pga) values, and 2% have very high hazard (pga) values.

In general, the largest seismic hazard values in the world occur in areas that have been, or are likely to be, the sites of the largest plate boundary earthquakes. The areas with the largest hazard values are along the subduction plate-boundary regions of the Kuriles-Kamchatka-Aleutians-southern Alaska, Iceland, the Pamir-Hindu Kush-Karakorum and China/Myanmar border regions of the India-Asia collision zone, Taiwan, the transform plate boundary of the western U.S., and the southeast coast of Hawaii. Areas with very high hazard values include the subduction plate-boundary regions along the Pacific coasts of southern Mexico, Central and South America, many of the island nations of the southwest Pacific Ocean, and the transform fault and subduction boundary regions of the eastern Mediterranean.

There are multiple seismic sources in subduction zones: intraplate earthquakes in both the under- and overriding plates, and interplate earthquakes. Furthermore, the interplate earthquakes in subduction zones are very large earthquakes. The ten largest earthquakes of the twentieth century are all interplate subduction (collision) zone earthquakes (Table 1). Five of the ten largest known earthquakes occurred along the Kuriles-Kamchatka-Aleutians-southern Alaska arc since 1952. The number of very large earthquakes known to have occurred in a short time results in the Eurasian-northern Pacific-North American plate-boundary region being among those regions with the highest seismic hazard values.

Iceland sits atop a large hot spot and is split by the Mid-Atlantic Ridge, the spreading center plate boundary between



▲ **Figure 1.** GSHAP regions and regional centers are outlined in black, multinational test areas are outlined in blue, and cooperatin projects are outlined in green.

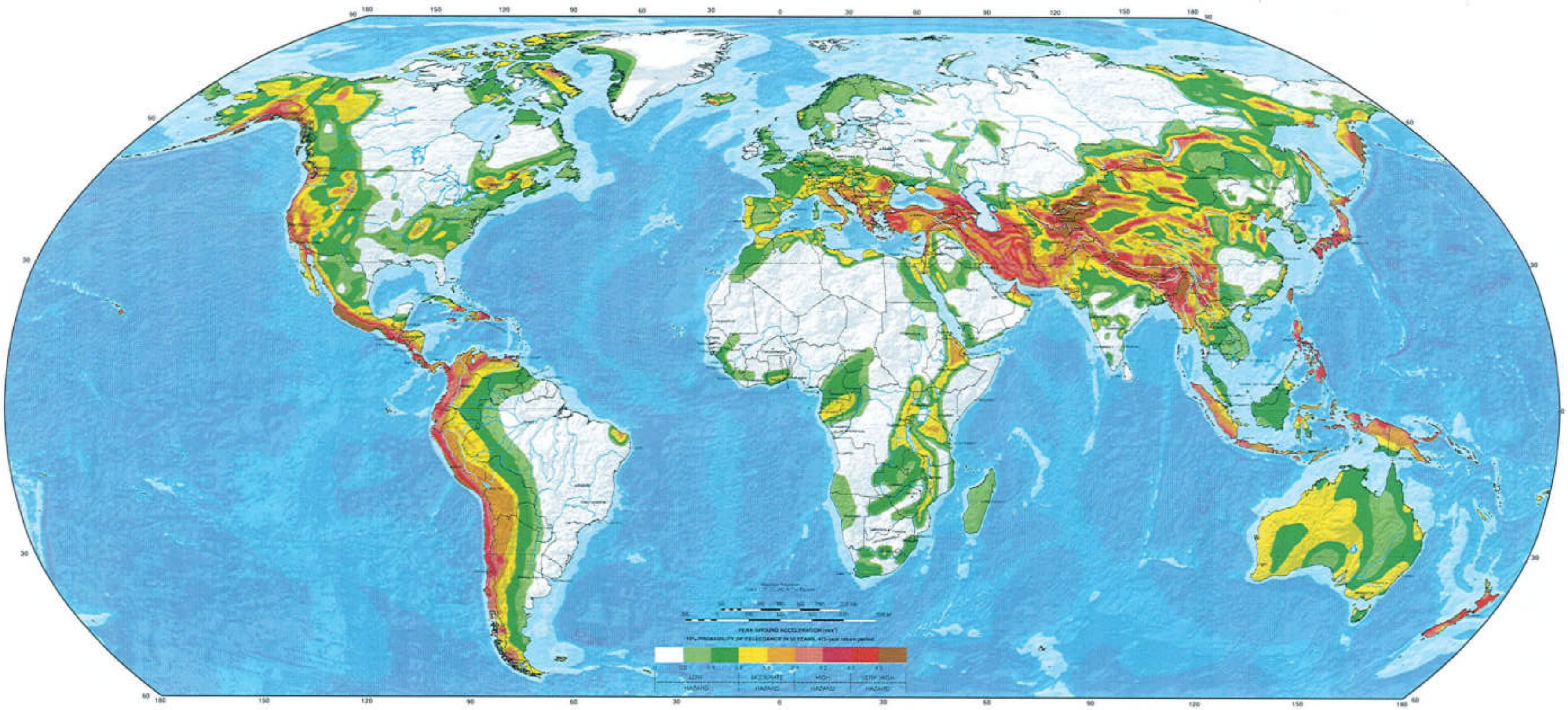


Figure 2. The Global Seismic Hazard Map. Peak ground acceleration (pga) with a 10% chance of exceedance in 50 years is depicted in m/s^2. The site classification is rock everywhere except Canada and the United States, which assume rock/firm soil site classifications. White and green correspond to low seismicity hazard (0%-8%g), yellow and orange correspond to moderate seismic hazard (8%-24%g), pink and dark pink correspond to high seismicity hazard (24%-40%g), and red and brown correspond to very high seismic hazard (greater than 40%g).

TABLE 1 Earthquakes of Large M (modified from Kanamori,1988)		
Event	**Year**	**M**
Chile	1960	9.5
Alaska	1964	9.2
Aleutian	1957	9.1
Kamchatka	1952	9.0
Ecuador	1906	8.8
Aleutian	1965	8.7
Assam	1950	8.6
Kurile Islands	1963	8.5
Chile	1922	8.5
Banda Sea	1938	8.5

the North American and Eurasian Plates. Large, shallow strike-slip and normal earthquakes in Iceland occur within complex fracture zones that connect the older, displaced rift zones with the current spreading centers (Einarsson, 1991). There are also earthquake swarms associated with the volcanoes. The highest hazard values in Iceland are in the Tjörnes fracture zone at the northern tip of the island, where several large damaging earthquakes have occurred (1872, 1934, and 1963).

The collision of India with Asia is the region of greatest continental tectonic deformation in the world (Molnar and Deng, 1984; Molnar and Lyon-Caen, 1989; Gupta, 1993). Almost 15% of the great (**M** ≥ 8.0) earthquakes documented in the twentieth century have occurred here, including the seventh largest known earthquake, the 1950 Assam **M** = 8.5 earthquake. The entire collision zone is subject to high seismic hazard values, and large areas within the collision zone are subject to some of the highest hazard values depicted. The eastern India/Asia collision zone has accommodated 38 ± 12 mm/yr of relative plate motion during the last 85 years through intraplate earthquakes and strain release (Holt *et al.*, 1991). Broadly distributed shallow-depth crustal deformation in the China/Myanmar border region of the collision zone is accommodated by large strike-slip and normal faulting earthquakes (Holt *et al.*, 1991). Similarly, the Pamir-Hindu Kush-Karakorum region of the collision zone accommodates much of the 40-55 mm/yr decrease in distance between Novosibirsk and Delhi (Roecker, written communication, 2000). Again, the strain is broadly distributed but concentrates at the fronts of mountain ranges and Plateaus, resulting in frequent, large, shallow and intermediate-depth earthquakes. The high hazard values throughout the collision zone region are attributed to the combination of underlying large to great interplate earthquakes and frequent, shallow, often large, crustal earthquakes.

The seismic hazard values for Taiwan are all in the highest hazard range. Taiwan is the result of the collision between the northern end of an island arc on the Philippine Plate and the Eurasian continental shelf (Roecker *et al.*, 1987). South of Taiwan, the Philippine Plate is overthrusting the Eurasian Plate; east of Taiwan, the Eurasian Plate is overthrusting the Philippine Plate. The landmass of Taiwan is a product of both plates. The Taiwan Telemetered Seismographic Network (TTSN) records between 4,000-5,000 earthquakes yearly, representing all types of faulting and at depths from the near surface to the plate interfaces (Roecker *et al.*, 1987). One of the great (**M** = 8.0) earthquakes of the twentieth century occurred on Taiwan in 1920. The complicated tectonics and high seismicity rate result in high seismic hazard values throughout Taiwan.

Although the energy release in large subduction zone earthquakes is much greater than the energy release in transform fault (strike-slip) earthquakes, the highest hazard values calculated in the western hemisphere are in southern California (U.S.), along the San Andreas Fault System, the southeast coast of Hawaii, and southeast Alaska (even when reduced to match the site classification of other countries). Large subduction zone earthquakes are deep (many tens to hundreds of kilometers), and the subduction zones along coasts of the Americas are tens to hundreds of kilometers offshore. Thus, energy released in large subduction zone earthquakes in the western hemisphere has begun to attenuate before it reaches onshore population centers. The high hazard values in southeastern Alaska are due to both large interplate subduction zone earthquakes and large shallow intraplate earthquakes. Earthquakes along the San Andreas Fault (and transform faults in general) are shallow (< 20 km) and often involve surface rupture. The San Andreas Fault is an shore for much of its length, and it passes through southern California. Energy released in a large southern San Andreas Fault earthquake passes through population centers immediately, producing a higher shaking hazard. Although Hawaii is not near a plate boundary, it overlies a hot Spot, where whole-plate (rather than intraplate) tectonic processes dominate. The collapse of the southeast flank of Kilauea produces large, shallow earthquakes that often involve surface rupture. Hence, the shaking hazard here is comparable to that in southern California.

The high hazard values along the Pacific coasts of southern Mexico and Central and South America coincide with the subduction of the oceanic Cocos and Nazca Plates beneath the Caribbean and South American Plates. The largest earthquake ever recorded (**M** = 9.5) occurred along the coast of Chile in 1960. Although the high hazard values along the coasts of southern Mexico and Central and South America are not quite as large as those in the subduction zones discussed previously, the attenuation of ground motion appears to be slower, especially in South America. These differences are due to the type and distribution of seismic sources. Large inter- and intraplate earthquakes in the Americas' oceanic-continent subduction zones extend deep beneath the continents. There are more large, deep intraplate earthquakes beneath South America than beneath any other continent. Youngs *et al.* (1997) developed ground-motion attenuation relationships using data collected from oceanic-continental subduction zones all over the world. They illustrated that peak ground motions from subduction-zone earthquakes attenuate more slowly than those from shallow crustal earthquakes in tectonically active regions. They also found that intraplate earthquakes within the subducting oceanic plates produce larger peak ground motions than interface earthquakes for the same magnitude and distance. Thus, while the hypocenters of many of the large inter- and intraplate earthquakes in these subduction zones are far enough away (either deep, offshore, or both) to dampen the peak ground motion values at the continental surface, these earthquakes produce shaking over long distances inland from the coast.

The tectonic regime of the Mediterranean region is extremely complicated. The African and Arabian Plates are converging with the Eurasian Plate. The largest hazard values in the Mediterranean region coincide with the transform fault plate boundaries between the Anatolian microplate and Eurasia and Arabia. The North Anatolian fault zone has been the most active continental transform fault plate boundary in the world during the twentieth century. Between 1939 and 1999, eleven $\mathbf{M} \geq 6.7$ earthquakes have occurred along this System, including the devastating $\mathbf{M} = 7.4$ Kocaeli, Turkey, earthquake on 17 August 1999.

High to very high hazard values are a source of concern anywhere they occur, but even moderate hazard values combined with dense populations and old infrastructure or non-code construction practices can result in very high risk. For example, the hazard values in Italy are mostly in the moderate to high range. However, earthquakes in Italy have caused on average 100,000 casualties per century for the last four centuries. The hazard values in the Caucasus and Iran are mostly in the high, rather than very high, range. Yet several moderate to large earthquakes in the last decades of the twentieth century (1988 Armenia $M = 6.8$, 1990 Iran $\mathbf{M} = 7.7$, 1991 Georgia $\mathbf{M} = 7.0$, and 1997 Iran $\mathbf{M} = 6.0$ and $\mathbf{M} = 7.3$) resulted in over 100,000 deaths and great economic disruption and losses.

The Global Seismic Hazard Assessment Program was designed to promote a regionally coordinated, homogeneous approach to seismic hazard evaluation and to provide the first quantitative global seismic hazard map. The GSHAP map and Web site, which contains regional reports, data links, and contacts, will assist in global risk mitigation through improved national and regional assessments of seismic hazard to be used by decision makers, engineers, planners, etc. for land use planning and improved building design and construction. The data and methods used to create the GSH Map may be used by national or regional agencies for further detailed studier applicable to their needs, especially more detailed seismic hazard maps.

Copies of the Global Seismic Hazard Map may be obtained from:

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ETH Hoenggerberg
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USGS Information Services
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Copies of the *Annali di Geofisica* volume containing all of the published GSHAP reports may be obtained from

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