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Utilizing *in-situ* stress data for seismic hazard assessment: the World Stress Map Project's contribution to GSHAP

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Abstract
Stress information compiled as part of the International Lithosphere Program's World Stress Map Project is invaluable in seismotectonic zoning particularly in midplate regions where the stress field often exhibits a high degree of regional uniformity. The data are also useful to delineate structure and tectonic features which might locally concentrate or perturb the regional stress field. Utilization of stress information in conjunction with geologic data and geophysical information (such as potential field data) can prove a powerful combination for a physical-based assessment of seismic hazard.

1. Introduction

A rational first approach to evaluating seismic hazard of a region is based on the historic and instrumental seismicity record. This approach is particularly well suited to plate boundary regions where major seismic source zones are well-delineated and strain rates are on the order of 10^{-14}-10^{-15} sec^{-1}, hence a 100-200 year historical record typically encompasses at least one «maximum-likely» magnitude event. Results from GPS (Global Positioning Satellite), geodetic strain, seismic moment release and paleoseismologic studies all suggest that short term deformation rates (a few years to 1000+ years) along the plate boundary zones are comparable to long term (millions of years) rates of relative plate motions determined from global plate tectonics inversions (*e.g.* NUVEL) (Gordon and Stein, 1992). By contrast, strain rates in intraplate regions are 2 or 3 orders of magnitude lower than those in the plate boundary regions. Even longer historical seismicity records in these areas may not cover a «maximum likely event», nor may specific seismic zones or faults be identified. More commonly, intraplate seismicity is characterized by a diffuse pattern of a few moderate to large events per century, and a few concentrated clusters of modern day seismicity.

Geologic and geophysical data indicate that the modern seismicity and short-term (Holocene or late Holocene) deformation rates may not be representative of averaged long term deformation (all of Tertiary) in active intraplate seismic zones. In perhaps the best-studied intraplate seismic zone in eastern North America (and perhaps the world), the New Madrid, MO seismic zone, site of 3 M=8+ earthquakes in 1811-1812, trenching studies across a zone of young uplift and compressional deformation indicate 3 m of vertical relief on a surface dated as 2000 years old (Russ, 1982). Seismic reflection profiling across the same feature revealed no more than about 15 m of relief on the base of the Paleocene strata (Zoback *et al.*, 1980). Similarly, paleoliquefaction studies in the Charleston, S.C. region have revealed 6 liquefaction «events» in that region (presumed roughly equivalent to the M=6.5-7.0 1887 Charleston earthquake) in the last 6000 years (Amick and Gelinas, 1991); despite this apparent high rate of seismicity, no surface faulting features have been identified at Charleston.

Thus, while historical and instrumental seismicity records may be sufficient to define earthquake hazard in plate boundary zones, seismic hazard assessment in intraplate regions may be much more problematic. To rationally evaluate hazard in such regions, consideration should be given to additional geophysical and tectonic information which can help explain the source of intraplate seismicity and possible mechanisms for localization of such deformation. Data on the contemporary *in-situ* stress field is critical in such regard.

The purpose of this paper is to demonstrate the usefulness of stress data in a rational, physical-based (as opposed to a strictly mathematical or statistical based) seismic hazard assessment. A global digital data base of tectonic stress orientation in the earth's crust has been compiled as a result of the World Stress Map (WSM) Project, a task group of the International Lithosphere Program (ILP) (Zoback, 1992). The WSM data compilation has demonstrated that broad regions of the interior of plates are often subjected to rather uniform regional stress field. Recognition and delineation of these «stress provinces» is invaluable for broad scale zoning of regions of similar tectonic style. In addition, as described below, the stress orientation data can also be used to evaluate the source of forces stressing the crust and driving intraplate deformation. Finally, the stress data can be used to identify and investigate local stress perturbations which may be acting to localize seismicity.

2. The world stress map data base

Underway since 1986, the WSM project has come a long way to meeting one of its initial goals of compiling available crustal stress data. In fact, as knowledge of the project and its objectives and methodology have spread, many workers have been stimulated to collect (or release) new stress data.

The compilation effort has relied primarily on a network of regional compilers (table I). Coordination of the European data compilation effort has been the responsibility of Birgit Müller, Geophysikalisches Institute, Karlsruhe University, Germany. Coordination of data from the rest of the world was the responsibility of the project leader, Mary Lou Zoback, U. S. Geological Survey, Menlo Park, CA, U.S.A. The stress data were obtained from a variety of geologic and geophysical stress indicators using a common quality evaluation criteria. The objective was to compile data on the «contemporary» stress field (considered as extending from the present back through Quaternary time-or to the youngest deformational phase in areas of multiple Quaternary deformation events). In stable intraplate regions we have extended the time window back to post-Miocene time.

The goals, methodology, stress indicators, evaluation criteria of the WSM project have been described in several recent summary articles and are not repeated here (Zoback *et al.*, 1989; Zoback, 1992). The data are compiled in a common digital format, and the entire data base is available on floppy diskettes through World Data Center A at the National Geophysical Data Center in Boulder, CO. Currently over 5500 «reliable» (orientations to within ±25°) horizontal stress orientations are available throughout the world. The inferred maximum horizontal stress orientations are shown by oriented lines in fig. 1 where the line length is proportional to data quality. Unfortunately, these data are not uniformly distributed, however all continental intraplate areas (except Antarctica) are at least representatively sampled and there are scattered data in the oceanic areas.

Even at a page-size scale the regional uniformity of stress orientation in many midplate or intraplate regions is obvious, as indicated by the S_{Hmax} (maximum horizontal stress) trends shown in fig. 1: ENE in eastern North America, generally E-W in South America, NNW in Western Europe, NNE in India, and a quasi-radial pattern (centered on the Himalayan collision zone) in China. Even in regions more poorly sampled some regional patterns can be discerned, *e.g.* about E-W S_{Hmax} orientation in Western Africa extending east to the east African rift. Australia is the only

Table I. World Stress Map Project participants.

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South America

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Australia

- David Denham, BMR, Canberra, Australia

China

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- Robert Klein, BP Research, Great Britain
- Birgit Müller, Univ. Karlsruhe, Germany
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Oceanic Intraplate

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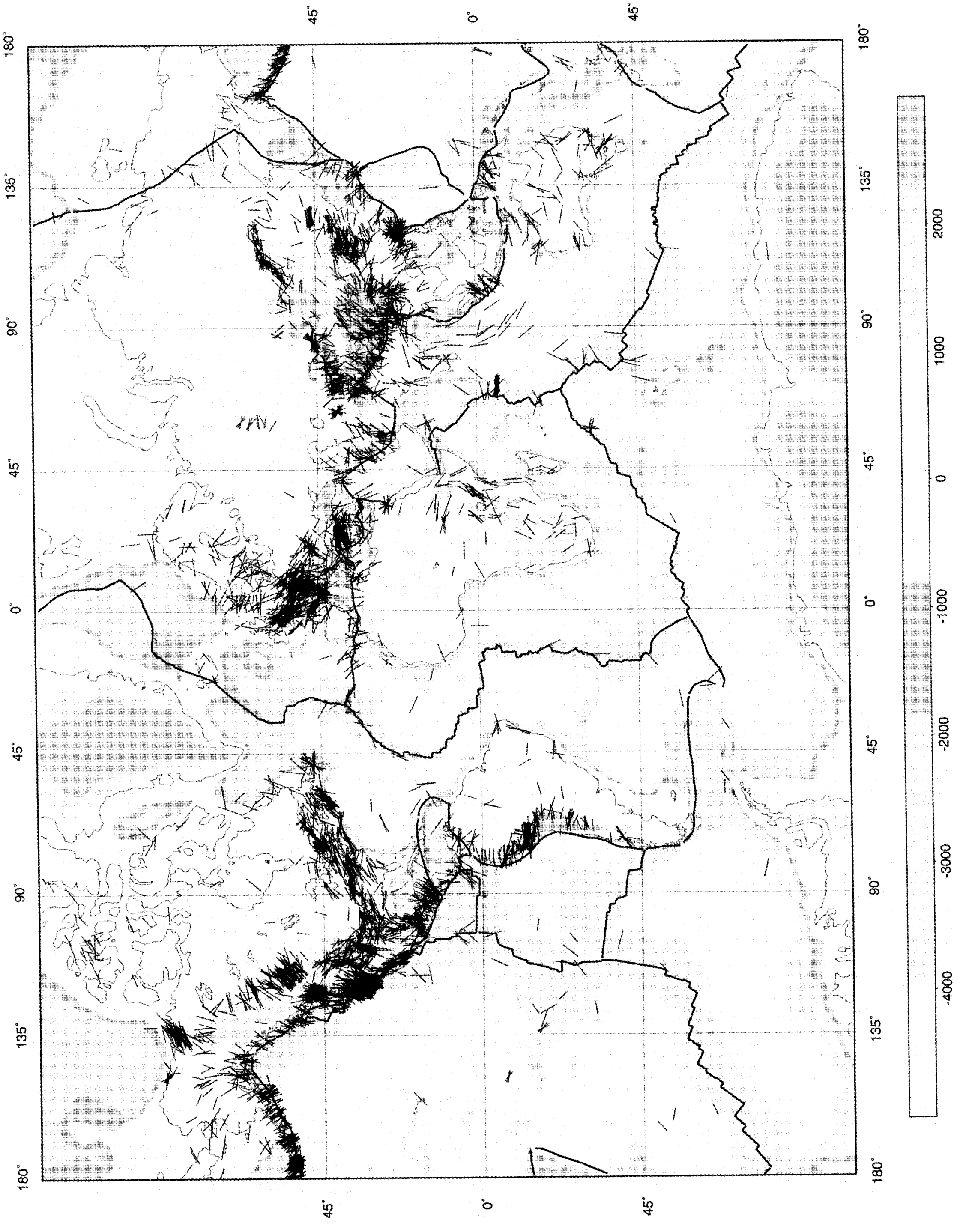

Fig. 1. World stress map, maximum horizontal stress orientations plotted on a base of average topography. Line length proportional to quality.

major continental region which seems to lack broad scale consistent regional patterns, however, the vast largely stable interior portions of the former Soviet Union are unsampled. Zoback (1992) summarized the stress modeling efforts of a number of workers which indicate that the orientation of the intraplate stress field is largely the result of compressional plate-driving boundary forces (primarily ridge push and continental collision) acting on the plate boundary.

Furthermore, an overall uniformity of the stress field with depth in the brittle crust is implied by the generally excellent agreement between stress orientations inferred for all depth ranges (earthquake focal mechanism (typically depths of 5-20 km), surface geologic data, and shallow (1-2 km) stress measurements, and well-bore breakout data from intermediate depths (1-5 km). The breakout data (generally obtained from petroleum exploration wells) comprise roughly 1/3 of the data set and have been extremely valuable in linking shallow and deep stress orientations and also provide information on stresses in relatively aseismic intraplate regions.

The identification of large scale stress provinces characterized by uniform (both laterally and with depth) stress orientations and stress regime (relative magnitudes) suggests that active seismic deformation, particularly in intraplate regions, occurs in response to a relatively uniform stress field whose origin, as described above, is far-field and tied to slowly changing plate-driving forces. In fact, evaluation of the best constrained focal mechanisms for eastern North American midplate earthquakes indicated that the observed slip in 92% of the post-1970 $m>4.0$ earthquakes was geometrically compatible with the broad scale relatively uniform (±15°) regional stress field as defined by independent stress data. Thus, the stress data provide a rationale for seismotectonic zoning (in terms of constraining potentially active structures) even in regions of relatively low seismicity; one example of which is described below.

2.1. *Seismotectonic zoning in areas of low seismicity: Western Africa*

Most seismicity and deformation in the African continent is concentrated on the zone of rifting extending through much of Eastern Africa. However, low level background seismicity persists throughout the continent, including Western Africa. Suleiman *et al.* (1992) recently described 7 earthquakes of magnitude 5.8 to 6.8 which have occurred in westernmost Africa since 1930. As noted in Zoback *et al.* (1989), the plate tectonic setting of Africa, surrounded by mid-ocean ridges and a continental collision to the north, suggests that the interior of the plate should be subjected to a compressional stress field. A zone of NNW compression has been identified from earthquake focal mechanisms and geologic evidence along the northernmost boundary of the African plate consistent with the convergence of Africa and Eurasia. Now, new stress data in Central and Western Africa shown in fig. 2 suggest the existence of a midplate compressive (strike-slip) stress regime with an S_{Hmax} orientation of approximately E-W outside of the east African rift area of high topography and asthenospheric upwelling (Zoback, 1992). These data include focal mechanisms determined from waveform modeling of large magnitude earthquakes occurring in West Africa between 1939-1983 (Suleiman *et al.*, 1992) as well as some recent CMT solutions including a $m=7.0$ earthquake in the Southern Sudan. As shown in fig. 2 all these data indicate a relatively consistent pattern of strike-slip deformation with a roughly E-W P-axes orientation. A similar approximately E-W S_{Hmax} orientation is also observed in breakout data from 11 wells covering a region over 1000 km wide in the Sudan (Bosworth *et al.*, 1992). The approximate western boundary between this midplate compressional regime and the east African rift extensional zone is indicated by the dashed line in fig. 2.

The general uniformity of the ~E-W S_{Hmax} orientations from both the focal mechanism and breakout data throughout Western and Central Africa as well as the consistency of this orientation with an inferred ridge push direction in this region can be used to define a seismotectonic province for hazard evaluation. Not only is the approximate orientation and source of the causative stress defined, the overall stress re-

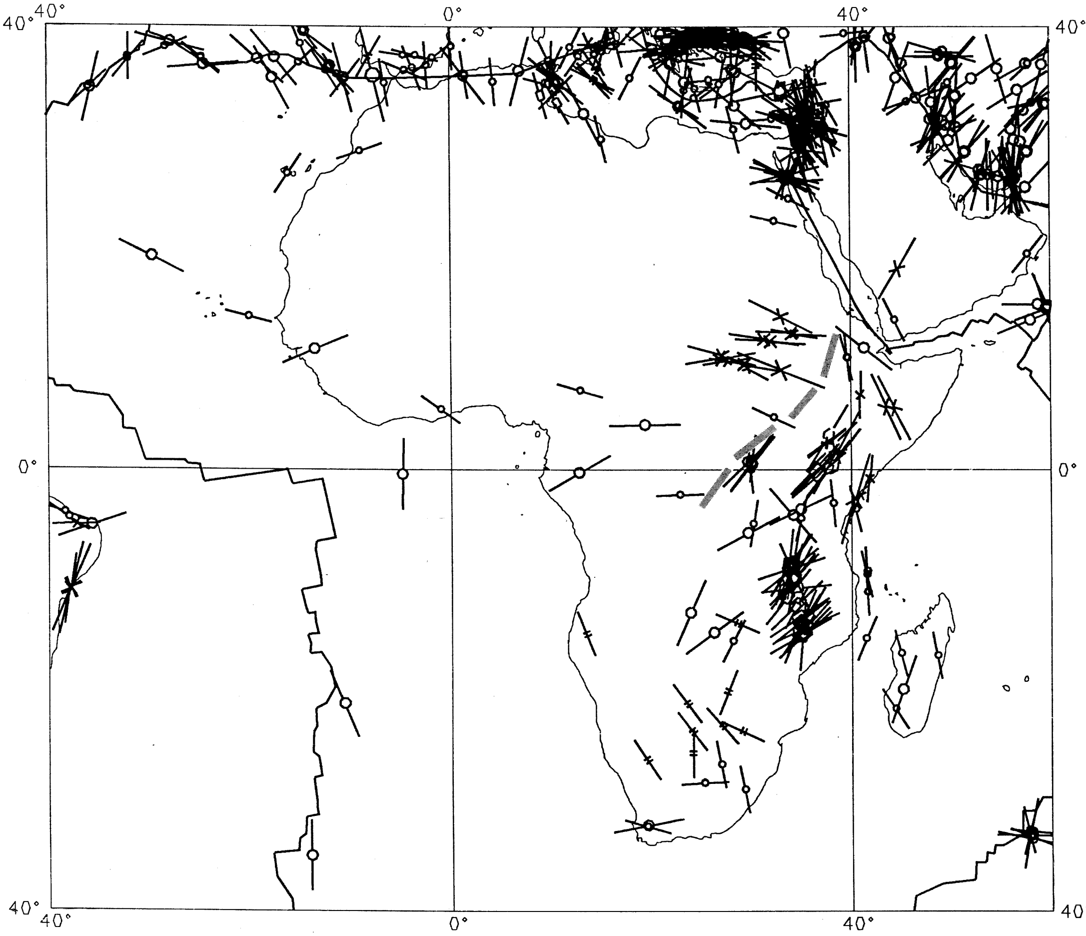

Fig. 2. Maximum horizontal stress orientations in Africa. Heavy dashed line indicates the eastern limit of the midplate compressional province (see text).

gime (strike-slip) is also defined. Applying simple frictional faulting theory and laboratory studies of frictional faulting (Raleigh *et al.*, 1972) we can even predict that the faults most likely to be reactivated would have very steep dips and trend between about 20-50° north. Thus the stress data permit zoning of a broad region within a continent with very little additional geologic or geophysical information.

3. Stress perturbations

Identification of the broad scale regional stress patterns permits definition of local stress perturbations (recognized through stress rotations) due to local geologic or tectonic structure. Sonder (1990) and Zoback (1992) demonstrate how these local stress rotations can be used to constrain the relative magnitude of the regional horizontal stress differences and the local stress. Using available geologic and geophysical data, the local stress effect of the structures can be modeled and hence can be used to obtain valuable stress magnitude constraints at earthquake focal depths and help explain causes of localized seismicity.

3.1. *Example of stress perturbation: Amazonas rift*

One dramatic example of a local stress perturbation is the roughly 90° rotation of S_{Hmax} orientations in Central Brazil in the vicinity of the Amazonas rift, a Paleozoic E-W trending failed rift whose rift basin controls the course of the modern Amazon river. Available stress data indicate that the interior of the South American plate is subjected to approximately E-W compression, consistent with ridge push forces acting along its eastern margin and possibly a component of compression related to E-W convergence along its western margin (*e.g.* Stefanick and Jurdy, 1992). Two moderate sized earthquakes (1964 m=5.0, 1984 m=5.0) have occurred on the northern margin of the Amazonas rift (Assumpcao, 1992). Both events had focal mechanisms which showed dominantly reverse slip on E-W trending nodal planes, clearly incompatible with regional E-W compression. The local ~N-S compression inferred from these 2 earthquakes is verified by analysis of breakouts nearby in petroleum wells at moderate depths in the Amazonas basin (2.0-2.5 km, Birgit Müller, Karlsruhe Univ., written comm., 1992).

A pronounced long wavelength Bouguer gravity high over the rift (100 mgals) has been interpreted together with seismic reflection data as indicating the presence of a dense mass in the lower crust ($\Delta\rho=0.15$ g/cm^3), a so called «rift pillow» (Nunn and Aires, 1988). The rift pillow is believed to represent intrusion of mantle material into the crust during rifting. This mass acts as a load on the lithosphere and is presently being supported by the strength of the surrounding crust. Modeling of the stress effect of this rift pillow due to lateral density contrasts indicates that the rift pillow is capable of generating 80-100 MPa of rift-normal compression. If this local N-S compression is greater than the regional horizontal stress differences then a local horizontal stress rotation of approximately 90° will occur, as observed.

Thus, once again the stress data define a basis for seismotectonic zoning in a region in which there is very little additional geologic and geophysical data. Interestingly, this rift pillow stress effect may be a relatively common and significant feature of many ancient rift zones now frozen in midplate settings. Analyses of occurrence of intraplate seismicity invariably show a correlation with «continental rifts» or crustal zones with a history of extensional tectonics (Johnston, 1989). This rift pillow stress effect thus may be a factor influencing both the style and likelihood of intraplate seismicity (Richardson and Zoback, 1990; Grana and Richardson, 1991; Zoback and Richardson, 1992). The impact of this effect depends on the orientation of the rift relative to the regional S_{Hmax} direction and stress regime, as well as the relative magnitude of the local density contrast associated with the rift pillow. It is possible that significant local rift-normal compressive stresses may effectively neutralize regional horizontal stress differences in some cases and hence inhibits intraplate seismicity (Zoback and Richardson, 1992).

4. Conclusions

Stress information compiled as part of the World Stress Map Project of the International Lithosphere Program can be invaluable in a rational, physical-based approach to seismic hazard assessment. In most midplate regions the stress field has been shown to exhibit a high degree of regional uniformity hence the stress data can be used to extend seismotectonic zoning in regions of very low present-day seismicity, such as Western Africa. The stress data have also defined stress perturbations which can be linked to local geologic structures or lateral variations in physical properties in the crust. One example of such a local effect is a ~90° rotation of S_{Hmax} in the vicinity of the Amazonas rift. This rotation is believed to be due to local rift-normal compressive stresses related to the support of a dense lower crust «rift pillow» beneath the rift. Similar effects may be associated with other intraplate ancient rift zones and may help explain the common association of intraplate seismicity with these ancient rifts (Johnston, 1989). Utilization of regional or local stress information in conjunction with local structural information inferred from geologic data and geophysical information (such as potential field data) can thus prove a powerful combination for a physical-based assessment of seismic hazard.

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