

Tectonic Stress: Models and Magnitudes

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The combination of plate tectonic models of intraplate stress and observations of the directions of principal midplate stresses provides two types of constraints on the magnitude of deviatoric stress in the lithosphere. First, the fit of global tectonic stress models to observations can constrain stress magnitudes if the magnitude of one of the component driving forces can be independently estimated. Second, if in the vicinity of a calculable local source of stress the observations of stress orientations indicate comparable control by the local and regional stress field, then the magnitude of the regional field may be estimated. Global intraplate stress models have been calculated using a finite element technique for a wide variety of possible driving force combinations. The best fitting global stress models include ridge pushing forces as an essential element and have deviatoric stress magnitudes comparable to the horizontal compressive stress exerted by ridge elevation, estimated on independent grounds to be 200–300 bar. Regional stresses in the Indian plate are shown on the basis of midplate earthquake mechanisms to be larger than the ~100-bar additional compressive stress exerted by the isostatically compensated topography of the Ninetyeast Ridge. In the vicinity of Hawaii, however, plate bending stresses of perhaps 1-kbar or greater magnitude may dominate regional stress. An average level of several hundred bars for the magnitude of typical intraplate deviatoric stresses is consistent with these various constraints.

INTRODUCTION

Understanding the state of stress in the earth's lithosphere is one of the paramount problems in earth tectonics. The stress state is linked to causes—loading and unloading, heating and cooling, plate motions, and driving forces to consequences—creep deformation and seismic failure, and to rheology—the depth over which stress can be supported and the time dependence of material properties. None of the classes of links has been characterized in sufficiently quantitative detail to define the stress tensor in the lithosphere without ambiguity and without a long inference chain involving poorly tested assumptions. This paper deals with one cause of stress in the lithosphere: the system of forces that maintain plate motions. Specifically addressed are ways by which models of tectonic stress in the plates can be used to constrain the magnitude of regional deviatoric stress in the earth's lithosphere.

Global models of the intraplate deviatoric stress that arises from the driving and resistive forces controlling plate motion have been given by *Solomon et al.* [1975] and *Richardson et al.* [1976, 1979]. A principal objective of those studies has been to find those sets of forces that best match the body of intraplate stress observations. The observations held to be most reliable for such comparisons are the indications of principal stress directions inferred from the mechanisms of midplate earthquakes, from in situ stress measurements, and from the strikes of stress sensitive geological features. While a comparison of model predictions and observations on the basis of principal stress orientations is straightforward and serves as a useful test by which to reject possible force models, such an exercise does

not directly address the absolute magnitude of intraplate deviatoric stresses, since all deviatoric stresses in a model can be multiplied by an arbitrary constant without changing the relative magnitudes or the orientations of the principal stresses. We show in this paper, however, that under certain conditions the body of data on intraplate stress orientations does constrain the magnitude of tectonic stresses.

It might be argued that stress magnitudes can, in principle, be measured by direct in situ techniques in sufficient locations to characterize the stress field for length scales comparable to plate dimensions, thus obviating the need to apply indirect arguments to constrain tectonic stress magnitudes. This eventuality is doubtful for the near term because of the difficulty of extrapolating near-surface measurements to greater depths in the lithosphere, and because further advances in technology will be necessary to conduct routinely measurements of in situ stress over the large fraction of the earth's surface covered by oceans. On the basis of available hydrofracture data it may at least be concluded that deviatoric stress magnitudes are of the order of several hundred bars to depths of several kilometers in a number of continental regions [*Haimson*, 1977; *McGarr and Gay*, 1978].

Thus the question remains: given the large and growing body of data on the orientations of principal stresses within the plates, what information on the magnitudes of regional deviatoric stresses can be obtained from numerical models for tectonic plate stresses? We discuss in this paper two routes by which useful information on stress magnitudes can be derived: (1) For the driving force models that best fit the stress orientation data, if independent information on the magnitude of one or more of the forces in the system can be obtained, then the

magnitudes of the total predicted stress field are constrained to comparable precision. The best fitting force models that we have examined to date all involve a significant contribution from ridge forces, the pushing forces that arise because of the elevated topography of ridge axes with respect to abyssal seafloor. Since ridges exert forces equivalent to compressive plate stresses of 200–300-bar magnitude, this leads to the prediction that regional deviatoric stresses are of this magnitude. (2) If in the vicinity of a known local source of stress, the observations of stress orientations indicate comparable control by the local and regional stress field, then the magnitude of the regional field may be estimated. This line of argument holds special promise for oceanic intraplate regions where earthquakes have occurred in the vicinity of islands or large bathymetric features characterized by sufficiently good topographic and gravity data to model the associated local lithospheric stress.

It should be mentioned that when direct in situ measurements of stress magnitudes have high reliability, the magnitude data can be used alongside the stress orientation data as a more powerful set of constraints on both regional and local forces on the lithosphere.

STRESS MAGNITUDES AND GLOBAL PLATE MODELS

The comparison of predicted and observed directions of principal intraplate stresses can be a sensitive test of possible sources of stress. As noted above, if such a comparison indicates a significant contribution from a source of stress of known or estimable magnitude, then a strong constraint on the general magnitude of deviatoric stress in the lithosphere on regional scales is obtained. In this section, we summarize our recent work [Richardson *et al.*, 1979] on testing global models of intraplate stress predicted by plate tectonic driving forces against observed directions of principal stresses, with particular emphasis on possible inferences on the magnitude of deviatoric stresses.

Premises. That observations of principal stress directions in the plates can be used to constrain plate tectonic driving force models requires the adoption of three working premises: (1) that regionally consistent stress orientation fields exist for large fractions of the stable interiors of plates; (2) that such stress fields are steady over time periods less than that ($\sim 10^6$

yr) characterizing changes in plate motions; and (3) that a recognizable portion of these stress fields is dominated by contributions from plate tectonic forces.

The first premise has substantial observational support for most of the plates [Sykes and Sbar, 1974; Sbar and Sykes, 1973; Richardson *et al.*, 1979]; see Figure 1. The second premise depends on the question of whether within plate interiors the deformation and stress arising from past plate boundary slip superpose to produce steady motion and stress or whether individual stress 'waves' from large earthquakes are discernible [e.g., Anderson, 1975]. This issue may be resolved by ultraprecise geodetic measurements of short-term plate motions soon to be made [Neill *et al.*, 1979; Smith *et al.*, 1979; Bender *et al.*, 1979]. The third premise will be the most difficult to establish with certainty, but it is a reasonable working hypothesis for regions well removed from such other notable sources of stress as recent tectonic or thermal activity, recent topographic loading or unloading, and pronounced structural heterogeneities.

Possible driving forces. We consider several simply parameterized driving and resistive forces as potential elements of a plate tectonic force model: plate boundary forces at ridges, trenches, transform faults, and zones of continent-continent collision, and basal forces associated with viscous interaction between the lithosphere and the asthenosphere. While all of these forces contribute to lithospheric stress, it is important to recognize that potentially large stress contributions can also arise from lithospheric cooling [Turcotte and Oxburgh, 1973], latitudinal plate motion [Turcotte and Oxburgh, 1973], crustal thickness inhomogeneities [Artyushkov, 1973], lithospheric loading and unloading [Walcott, 1970; Watts and Cochran, 1974; Haxby and Turcotte, 1976] and past tectonic events [Swolfs *et al.*, 1974; Tullis, 1977]. In the interpretation of stress observations in terms of plate driving forces, care must be exercised to remove or to avoid where possible the effects of these additional sources of lithospheric stress.

The compressive stress produced in oceanic plates by the elevation of mid-ocean ridges is the easiest to quantify among the set of possible driving and resistive forces and is in the range 200–300 bar [Hales, 1969; Frank, 1972; McKenzie, 1972]. At subduction zones the negative buoyancy of sub-

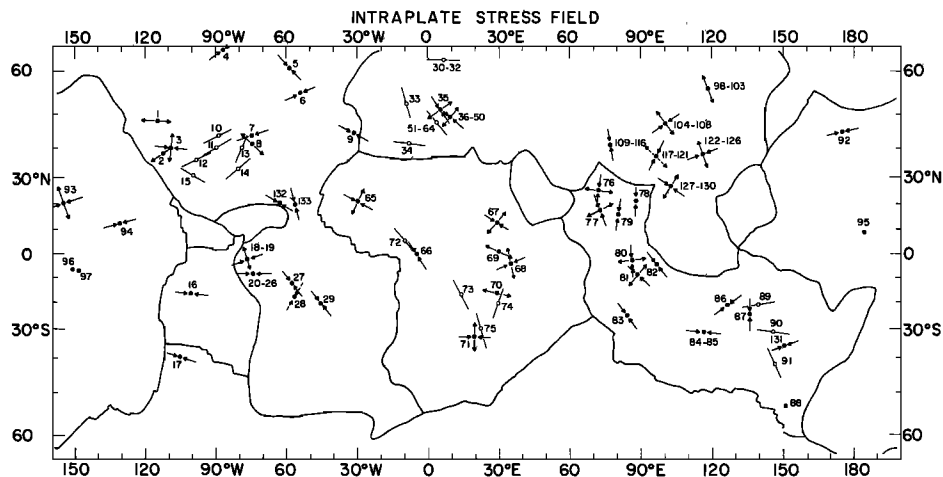


Fig. 1. A summary of intraplate stress orientation data [Richardson *et al.*, 1979]. Solid circles denote fault plane solutions; arrows denote P and T axes, where nearly horizontal. Solid circles without arrows denote thrust faults with poorly constrained P axes. Open circles represent in situ data; the line gives the direction of maximum horizontal compressive stress.

ducted lithosphere is capable of exerting an extensional force equivalent to several kilobars stress on the adjacent plates [McKenzie, 1969; Turcotte and Schubert, 1971], but the greater fraction of available pulling force is counterbalanced by forces resisting descent of the slab into the mantle [Smith and Toksöz, 1972; Forsyth and Uyeda, 1975; Richter, 1977]. The net pull by slabs on the surface plates is uncertain but is considerably smaller than that due to available negative buoyancy. At zones of continent-continent collision the net force on the adjacent plates may be resistive (net compression) because of the contribution from the excess topography of the mountain belt marking the collision zone; the contribution from topography involves shear stresses of 200–300 bar for the main boundary fault at the base of the Himalayas [Bird, 1978]. The resistive force at transform faults is uncertain [Brune et al., 1969; Brace and Byerlee, 1970] but is not likely to be a major contributor to the plate driving mechanism on the basis of the relatively small fraction of boundary taken up by transforms for most plates and the poor correlation of plate speeds with length of transform boundary [Forsyth and Uyeda, 1975; Aggarwal, 1978].

The viscous traction at the base of the plates is less well characterized than plate boundary forces and is uncertain both in magnitude and in direction. The uncertainties are linked to questions of the radial scale for upper mantle convection, the planform for 'counterflow' to balance plate creation and destruction, and the existence of a smaller secondary scale of asthenospheric convection to transport heat [Richter and Parsons, 1975; McKenzie and Weiss, 1975; Harper, 1978; Chase, 1979; Hager and O'Connell, 1979]. Some simple forms for viscous drag are adopted as a basis for testing models, but the various potential complexities must be kept in mind.

Stress models. A variety of driving force models incorporating different relative amounts of boundary forces and basal tractions as described above have been tested against the observations of intraplate stress orientations. The lithosphere is modeled as a thin, spherical, elastic shell, and stresses are calculated from the imposed forces using the finite element analysis described by Richardson [1978]. The results of many models are given in Richardson et al. [1979], and only a summary of the results pertinent to the question of stress magnitudes will be given here.

A summary of stress orientation data for intraplate regions is given in Figure 1. Most of the data come from the mechanisms of intraplate earthquakes; the remainder are from in situ measurements (see Richardson et al. [1979] for the original sources of the data shown). In compiling such a data set, it is necessary to establish criteria for the selection of those data most appropriate for constraining the tectonic stress field. While such criteria are of necessity at least partly arbitrary, our approach has been to exclude only those data very near (~100 km distance or less) plate boundaries and those data likely reflecting unmodeled processes. Thus data from continental margins have been excluded on the basis of possible contributions from sediment loading or thermal contraction, effects not modeled, and data are not used from regions of complex tectonics not likely to be a response solely to plate scale forces (e.g., Alps, Appalachians, and North America west of the Rockies).

On the basis of a comparison with the observed stress orientations in Figure 1, the predicted stresses are in best agreement with the observations when pushing forces at ridges are included in the driving force model and when the net pulling

force due to subducted lithosphere is comparable in magnitude or is at most a few times larger than other forces acting on the plates. On the basis of intraplate stresses, therefore, resistive forces opposing the motion of the slab with respect to the mantle must nearly balance the negative buoyancy of the relatively cool, dense slab, in agreement with similar conclusions derived from other considerations [Smith and Toksöz, 1972; Forsyth and Uyeda, 1975; Richter, 1977]. The maximum ratio of net slab pull to net ridge push is not sensitive to a dependence of net slab pull on subduction rate or to the inclusion of other forces in the system. Forces resisting further convergence at continental collision zones along the Eurasian plate are important for intraplate stresses and improve the fit to the data in Europe, Asia, and the Indian plate. Resistive viscous drag forces acting on the base of the plate in a direction opposite to 'absolute' plate velocity improve the fit to the intraplate stress field for several plates (e.g., Nazca and South America). The intraplate stress field is relatively insensitive to an increased drag coefficient beneath old oceanic lithosphere in comparison to young oceanic or continental lithosphere. Increasing by a factor of 5 or 10 the drag coefficient beneath continental lithosphere relative to oceanic lithosphere changes the calculated stresses only slightly and has little effect on the overall fit to observed stresses as long as some resistive drag acts beneath oceanic plates.

Models in which drag forces drive (i.e., act parallel to absolute plate velocity) rather than resist plate motions are in poor agreement with the data. This poor agreement may depend on the oversimplified model of the adopted interaction between the plate and the asthenosphere. As noted above, the actual flow pattern in the mantle, including counterflow and possible multiple scales of convection, may be considerably more complicated than has been assumed in these models.

Two models that provide reasonably good fits to a large fraction of the intraplate stress orientation data are shown in Figures 2 and 3. In Figure 2 are shown the predicted intraplate stresses for a model with the following forces: (1) a symmetric pushing force at ridges equivalent to a compressive stress of 100 bar across a 100-km thick plate, (2) a symmetric pulling force at trenches of the same absolute magnitude, (3) a symmetric resistive force at continental collision zones of the same absolute magnitude, and (4) a drag stress $-Dv$, where v is absolute plate velocity in cm/yr and D is 0.1 bar/cm/yr beneath oceans and 0.6 bar/cm/yr beneath continents. Note that only the relative magnitudes of these forces are constrained by the stress orientation data; their absolute magnitudes are proportional to an unspecified multiplicative constant.

The predicted directions of principal stresses for this force model are in good agreement with the data for eastern North America, Europe, Asia near the Himalayas, and the Indian plate. The fit to the data is good in South America, especially far from the trench, and in western Africa and is acceptable in most of the Pacific plate. The orientation of the calculated maximum compressive stress in the Nazca plate for the model is only in moderate agreement with the orientation inferred from the single fault plane solution available. The fit to the data in the northern Pacific, eastern Asia, and east Africa is rather poor. The fit to the data in the northern Pacific and eastern Asia could be improved if subduction zone or drag forces were decreased along the western Pacific plate margin or if slab forces were concentrated on the subducted plate. No attempt, however, has been made to vary plate boundary

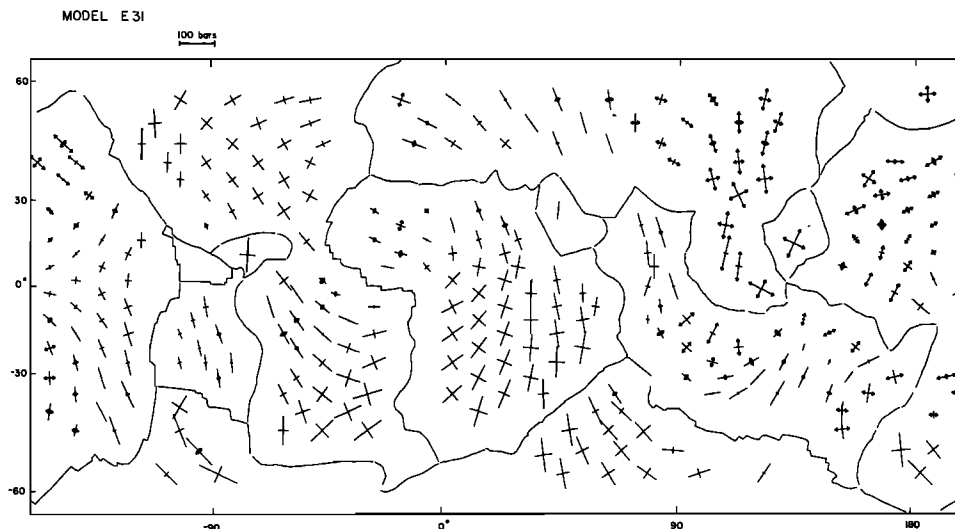


Fig. 2. Principal horizontal deviatoric stresses in the lithosphere for a model of plate driving forces (see text). Principal stress axes without arrows and with arrows pointing outward denote deviatoric compression and tension, respectively. Relative magnitude of principal stresses is indicated by the length of stress axes [from Richardson et al., 1979].

forces locally to match inferred stresses. If such an approach were adopted, most observed stresses could be matched, but the solution for the driving mechanism would be unjustifiably arbitrary and nonunique.

In Figure 3 are shown the intraplate stresses for a force model that takes the approach of Davies [1978] and Richardson [1978] based on the assumption that drag balances the net torque on each plate due to boundary forces. The resulting drag thus varies from plate to plate and need not bear a simple relationship to relative plate motions, in contrast to the drag derived from absolute plate motion models consistent with known relative velocities [Solomon and Sleep, 1974; Solomon et al., 1975; Minster et al., 1974]. The force model includes: (1) a symmetric force at ridges equivalent to a compressive stress of 100 bar across a 100-km-thick plate, (2) a symmetric resistive force at continental convergence zones of twice this magnitude, (3) a pulling force at trenches, on the subducted plate only, equivalent to an extensional stress of

100 bar across a 100-km-thick plate, and (4) a viscous drag on each plate, due to the rotation of the plate with respect to the underlying mantle (which may be moving), determined by balancing the total vector torque on the plate from boundary forces.

The predicted stress directions for this model (Figure 3) agree very well with the data for several areas. In the North American and Nazca plates the orientation of the maximum compressive stress is well matched by the model. The fit is almost as good in Europe and in Asia north of the Himalayas. In the Indian plate, compressive stresses trend NW-SE in continental India, in agreement with the data, but the fit is poorer in Australia. In South America the maximum compressive stress trends E-W, in only moderate agreement with the data. In the Pacific and the eastern part of the African plate the agreement with the data is poor. On the whole, this model provides a better fit to continental data than to oceanic data. Comparison of Figures 2 and 3 suggests that any force pulling

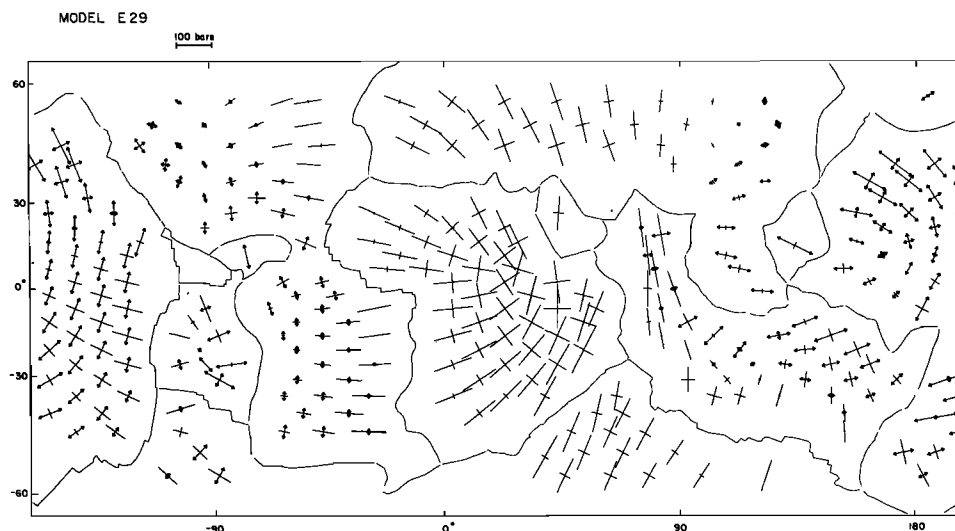


Fig. 3. Principal horizontal deviatoric stresses in the lithosphere for an alternative driving force model in which basal shear balances the torque due to boundary forces for each plate (see text) [from Richardson et al., 1979].

the overthrust plate toward the trench is probably lower in magnitude than the net pull on the subducted plate.

Discussion. From the standpoint of deviatoric stress magnitudes, the most important general conclusion from the modeling of plate tectonic stresses and the comparison with intraplate stress orientation data is that ridge pushing forces are an important element of the set of driving forces for the models that provide the best fit to observations. The stresses that arise from ridge topography are 200–300 bar compression, as noted above. We are thus led to the conclusion that regional deviatoric stresses in plate interiors are of this same general magnitude, or 200–300 bar to within a factor of perhaps 2–3.

This conclusion should be tempered, however, by several general observations on the results of the plate tectonic stress models. The models represented in Figures 2 and 3, though providing good matches to the data for a number of regions with well characterized stresses, do not fit all of the data. Thus either there are simple models not tested that provide a better fit to the global data set than those shown, or the stress observations are influenced by processes not included in the simple models. Even if a model were obtained that fit all reliable observations to within their estimated errors, it is likely on the basis of models tested to date that this model would not be unique. Thus statements based on elements of best fitting force models must be understood in recognition of this non-uniqueness.

STRESS MAGNITUDES AND LOCAL VERSUS REGIONAL STRESSES

An alternative approach to constrain the magnitude of regional deviatoric stresses in the lithosphere from stress orientation data and plate tectonic models is to find situations in which observed stress orientations are sensitive in approximately equal measure to a local stress field that may be readily quantified and to a regional stress field whose magnitude is to be determined. Such an approach holds high promise for constraining the magnitudes of plate tectonic stresses in oceanic lithosphere.

Consider the effect of a volcanic load on oceanic lithosphere. Such a load leads to lithospheric flexure and to potentially large local bending stresses. For a very large load, such as Hawaii, the local stresses may be in excess of 1 kbar [Walcott, 1970; Watts and Cochran, 1974] and may dominate the regional stress. That bending stresses may dominate regional stresses for Hawaii is supported by the report by Rogers and Endo [1977] that greatest compressive stress axes from composite fault plane solutions for many mantle earthquakes beneath and near the island of Hawaii are radial with respect to the island.

For loads appropriately smaller in magnitude than Hawaii, the local stresses should be comparable in magnitude to the regional stresses. Thus the mechanisms of earthquakes in the vicinity of such loads might be expected to indicate P and T axes which differ somewhat from regional trends but which are not predictable simply from stress models for the local load only. For earthquakes near very small loads or distant from any pronounced topographic relief, the mechanisms should reflect the regional stress field.

As an illustration of this approach, consider the region near the Ninetyeast Ridge in the central Indian Ocean. The Ninetyeast Ridge is a pronounced linear feature some 5000 km long and rising 1500–2000 m above the surrounding seafloor [e.g., Bowin, 1973]. The ridge is isostatically compensated ex-

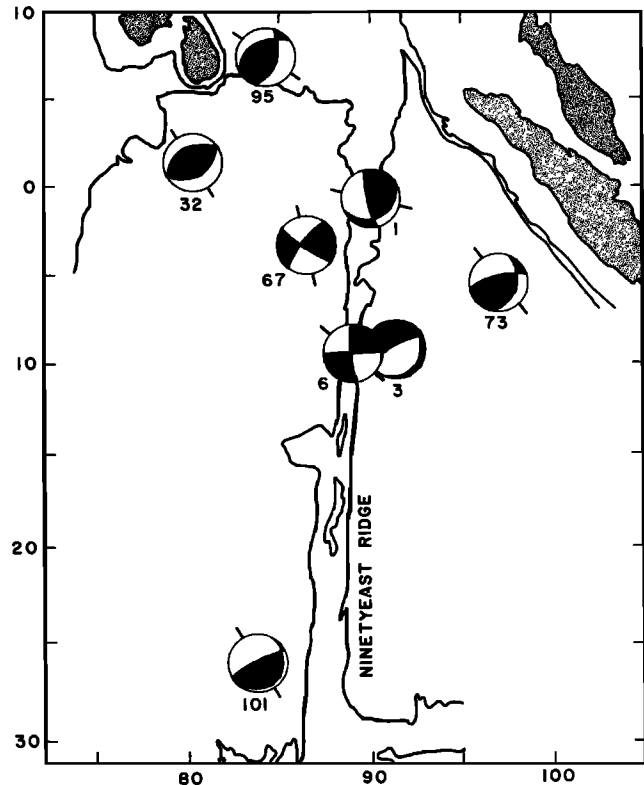


Fig. 4. Summary of focal mechanisms for earthquakes in the Ninetyeast ridge region of the Indian plate. Fault plane solutions are shown as equal area projections; compressional quadrants are shaded. Lines through each solution denote the orientation of the P axis. Data are from Sykes [1970], Fitch [1972], Sykes and Sbar [1974], Stein and Okal [1978], and Bergman and Solomon [1980].

cept at short wavelengths [Bowin, 1973; Detrick and Watts, 1979]. Several large earthquakes have occurred in the Indian plate in the general vicinity during this century [Sykes, 1970; Stein and Okal, 1978].

The orientation of principal stresses in the Indian plate may be estimated from the fault plane solutions of intraplate earthquakes. Figure 4 shows the P axis orientations for all large earthquakes with known focal mechanisms in the Indian plate near the Ninetyeast Ridge. There is a strongly regionally consistent NW-SE trend to the direction of inferred greatest compressive stress.

Two aspects of this general consistency are noteworthy: (1) The P axes for strike slip events on and near the Ninetyeast Ridge trend in general agreement with those for thrust events in the plate off the ridge. Thus while a zone of weakness associated with the ridge may control the type of faulting [Stein and Okal, 1978], the inferred direction of maximum horizontal stress for Ninetyeast Ridge events is still reliable. The data in Figure 4 are entirely consistent with a generally uniform stress field across the portion of the Indian plate shown, with strike slip rather than thrust motion being the preferred fault type within weak zones in the lithosphere. (2) The P axes for thrust events off the Ninetyeast Ridge are not orthogonal to the strike of the ridge. Thus stresses associated with ridge topography do not dominate the local stress field.

This second conclusion can be quantified to produce a constraint on the magnitude of the regional stress field. Adopting Bowin's [1973] model for the isostatic compensation of the Ninetyeast Ridge, the compressive force that the ridge exerts

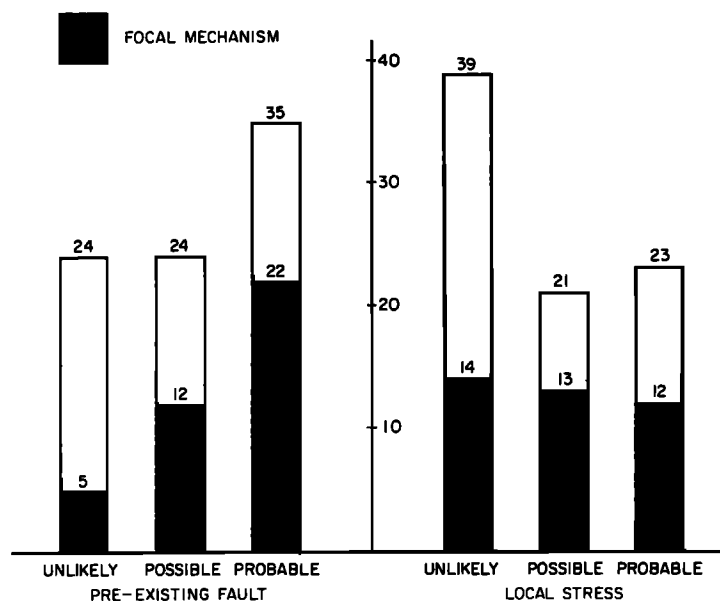


Fig. 5. Histograms of the number of oceanic intraplate earthquake epicentral regions in the catalog of *Bergman and Solomon* [1980] sorted by likelihood of association with either preexisting zones of weakness (left), such as fracture zones or volcanic seamount chains, or with topographic relief (right) that may provide a significant local source of stress.

per unit length on the lithosphere beneath the adjacent abyssal plain may be estimated from equations (47–49) in *Artyushkov* [1973]:

$$\Sigma = \int (\sigma_{xx} - \sigma_{zz}) dz = - (0.14\zeta + 0.067\zeta^2) \times 10^9 \text{ bar cm} + \Sigma_{\text{ridge}} \quad (1)$$

where σ_{xx} and σ_{zz} are horizontal and vertical normal stress components (\sim principal stresses), ζ is the height of the ridge (in kilometers) with respect to the abyssal plain, Σ_{ridge} is the value of Σ beneath the ridge, the integral is taken over the depth range of horizontal density variations, and the minus sign denotes a compressive force. Note that (1) includes the effects of topography and isostatic compensation only; the effects of viscous forces at the base of the plate and of thermal stress due to any differential cooling between the ridge and surrounding seafloor, for instance, are not included. For $\zeta = 1.5\text{--}2$ km [Bowin, 1973], (1) gives $\Sigma - \Sigma_{\text{ridge}} = - (0.35 \text{ to } 0.54) \times 10^9$ bar cm, or the equivalent of 70–110 bars additional horizontal deviatoric stress over a 50-km-thick plate. For comparison, *Artyushkov* [1973] gives -1.2×10^9 bar cm and 240 bar compression for the force/length and stress associated with spreading ridges.

Thus the regional deviatoric stresses in the Indian plate (excluding the contribution from the Ninetyeast Ridge) must be larger than ~ 100 bar in magnitude in order to account for the pattern of stress orientations in Figure 4. This result provides only a lower bound on the magnitude of regional deviatoric stresses in one plate, but the result is at least consistent with the inference made above that regional stresses are similar in magnitude to the stresses produced by ridge forces, which are 3 ± 1 times as large as the force exerted by Ninetyeast Ridge topography.

A number of other oceanic intraplate earthquakes large enough so that their focal mechanisms are known have occurred in close proximity to prominent bathymetric features. *Bergman and Solomon* [1980] have compiled a comprehensive catalog of 159 oceanic intraplate earthquakes, and for a

representative subset of 83 epicentral regions, they have assessed the degree of association of these earthquakes with large bathymetric features and with zones of expected lithospheric weakness (e.g., fracture zones). A histogram of the results (Figure 5) shows that the epicenters of at least 12 oceanic intraplate earthquakes with known focal mechanisms, and at least 11 additional earthquake localities with one or more $m_b \geq 4.7$ events since 1964 are situated near features of pronounced seafloor topography. Several of these features involve lithospheric loads that should lead to bending stresses larger than the stresses indicated above for the Ninetyeast Ridge. Thus it may be possible by a combination of detailed stress models and careful source mechanisms to bound regional deviatoric stress magnitudes from both above and below using this approach.

Two potential difficulties with this approach should, however, be noted: (1) Many oceanic intraplate earthquakes occur in or near such obvious zones of weakness as fracture zones and volcanic areas. Over 70% of the oceanic earthquake epicentral regions in the listing of *Bergman and Solomon* [1980] are located in such areas (Figure 5). Stress directions inferred from earthquake mechanisms for such events should be used only with caution in the absence of corroborative information from events removed from the weak zone (e.g., Figure 4). (2) Bending stresses associated with lithospheric flexure, for given rheology and thermal structure, are extremely sensitive to depth. Thus for an observation of stress orientation from an earthquake mechanism to be a useful constraint on stress amplitude, the focal depth must be known with high precision, probably to within a few kilometers.

CONCLUSIONS

The global data on directions of principal stresses in plate interiors can serve as a test of possible plate tectonic force models. Such tests conducted to date favor force models in which ridge pushing forces play a significant role. For such models, the general magnitude of regional deviatoric stresses

is comparable to the 200–300-bar compressive stress exerted by spreading ridges.

An alternative approach to estimating magnitudes of regional deviatoric stresses from stress orientations is to look for regions of local stress either demonstrably smaller than or larger than the regional stresses. The regional stresses in oceanic intraplate regions are larger than the ~100-bar compression exerted by the Ninetyeast Ridge and less than the bending stresses (≥ 1 kbar) beneath Hawaii.

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REFERENCES

- Aggarwal, Y. P., Scaling laws for global plate motions: Consequences for the driving mechanism, interplate stresses and mantle viscosity (abstract), *Eos Trans. AGU*, 59, 1202, 1978.
- Anderson, D. L., Accelerated plate tectonics, *Science*, 187, 1077–1079, 1975.
- Artyushkov, E. V., Stresses in the lithosphere caused by crustal thickness inhomogeneities, *J. Geophys. Res.*, 78, 7675–7708, 1973.
- Bender, P. L., J. E. Faller, J. Levine, S. Moody, M. R. Pearlman, and E. C. Silverberg, Possible high-mobility LAGEOS ranging station, *Tectonophysics*, 52, 69–73, 1979.
- Bergman, E. A., and S. C. Solomon, Oceanic intraplate earthquakes: Implications for local and regional intraplate stress, *J. Geophys. Res.*, 85, 5389–5410, 1980.
- Bird, P., Initiation of intracontinental subduction in the Himalaya, *J. Geophys. Res.*, 83, 4975–4987, 1978.
- Bowin, C., Origin of the Ninety East ridge from studies near the equator, *J. Geophys. Res.*, 78, 6029–6043, 1973.
- Brace, W. F., and J. D. Byerlee, California earthquakes: Why only shallow focus?, *Science*, 168, 1573–1575, 1970.
- Brune, J. N., T. L. Henyey, and R. F. Roy, Heat flow, stress, and rate of slip along the San Andreas fault, California, *J. Geophys. Res.*, 74, 3821–3827, 1969.
- Chase, C. G., Asthenospheric counterflow: A kinematic model, *Geophys. J. Roy. Astron. Soc.*, 56, 1–18, 1979.
- Davies, G. F., The roles of boundary friction, basal shear stress and deep mantle convection in plate tectonics, *Geophys. Res. Lett.*, 5, 161–164, 1978.
- Detrick, R. S., and A. B. Watts, An analysis of isostasy in the world's oceans, 3, Aseismic ridges, *J. Geophys. Res.*, 84, 3637–3653, 1979.
- Fitch, T. J., Plate convergence, transcurrent faults, and internal deformation adjacent to southeast Asia and the western Pacific, *J. Geophys. Res.*, 77, 4432–4460, 1972.
- Forsyth, D. W., and S. Uyeda, On the relative importance of driving forces of plate motion, *Geophys. J. Roy. Astron. Soc.*, 43, 163–200, 1975.
- Frank, F. C., Plate tectonics, the analogy with glacier flow and isostasy, in *Flow and Fracture of Rocks*, *Geophys. Monogr. Ser.*, vol. 16, edited by H. C. Heard et al., pp. 285–292, AGU, Washington, D. C., 1972.
- Hager, B. H., and R. J. O'Connell, Kinematic models of large-scale flow in the earth's mantle, *J. Geophys. Res.*, 84, 1031–1048, 1979.
- Haimson, B. C., Crustal stress in the continental United States as derived from hydrofracturing tests, in *The Earth's Crust*, *Geophys. Monogr. Ser.*, vol. 20, edited by J. C. Heacock, pp. 576–592, AGU, Washington, D. C., 1977.
- Hales, A. L., Gravitational sliding and continental drift, *Earth Planet. Sci. Lett.*, 6, 31–34, 1969.
- Harper, J. F., Asthenosphere flow and plate motions, *Geophys. J. Roy. Astron. Soc.*, 55, 87–110, 1978.
- Haxby, W. F., and D. L. Turcotte, Stresses induced by the addition or removal of overburden and associated thermal effects, *Geology*, 4, 181–184, 1976.
- McGarr, A., and N. C. Gay, State of stress in the earth's crust, *Ann. Rev. Earth Planet. Sci.*, 6, 405–436, 1978.
- McKenzie, D. P., Speculations on the consequences and causes of plate motions, *Geophys. J. Roy. Astron. Soc.*, 18, 1–32, 1969.
- McKenzie, D. P., Plate tectonics, in *The Nature of the Solid Earth*, edited by E. C. Robertson, pp. 323–360, McGraw-Hill, New York, 1972.
- McKenzie, D. P., and N. O. Weiss, Speculations on the thermal and tectonic history of the earth, *Geophys. J. Roy. Astron. Soc.*, 42, 131–174, 1975.
- Minster, J. B., T. H. Jordan, P. Molnar, and E. Haines, Numerical modeling of instantaneous plate tectonics, *Geophys. J. Roy. Astron. Soc.*, 36, 541–576, 1974.
- Neill, A. E., K. M. Ong, P. F. MacDoran, G. M. Resch, D. D. Morabito, E. S. Claffin, and J. F. Dracup, Comparison of a radio interferometric differential baseline measurement with conventional geodesy, *Tectonophysics*, 52, 49–58, 1979.
- Richardson, R. M., Finite element modeling of stress in the Nazca plate: Driving forces and plate boundary earthquakes, *Tectonophysics*, 50, 223–248, 1978.
- Richardson, R. M., S. C. Solomon, and N. H. Sleep, Intraplate stress as an indicator of plate tectonic driving forces, *J. Geophys. Res.*, 81, 1847–1856, 1976.
- Richardson, R. M., S. C. Solomon, and N. H. Sleep, Tectonic stress in the plates, *Rev. Geophys. Space Phys.*, 17, 981–1019, 1979.
- Richter, F. M., On the driving mechanism of plate tectonics, *Tectonophysics*, 38, 61–88, 1977.
- Richter, F. M., and B. Parsons, On the interaction of two scales of convection in the mantle, *J. Geophys. Res.*, 80, 2529–2541, 1975.
- Rogers, D. B., and E. T. Endo, Focal mechanisms for upper mantle earthquakes and flexure of the lithosphere near Hawaii (abstract), *Eos Trans. AGU*, 58, 1231, 1977.
- Sbar, M. L., and L. R. Sykes, Contemporary compressive stress and seismicity in eastern North America: An example of intraplate tectonics, *Geol. Soc. Amer. Bull.*, 84, 1861–1882, 1973.
- Smith, A. T., and M. N. Toksöz, Stress distribution beneath island arcs, *Geophys. J. Roy. Astron. Soc.*, 29, 289–318, 1972.
- Smith, D. E., R. Kolenkiewicz, P. J. Dunn and M. H. Torrence, The measurement of fault motion by satellite laser ranging, *Tectonophysics*, 52, 59–67, 1979.
- Solomon, S. C., and N. H. Sleep, Some simple physical models for absolute plate motions, *J. Geophys. Res.*, 79, 2557–2567, 1974.
- Solomon, S. C., N. H. Sleep, and R. M. Richardson, On the forces driving plate tectonics: Inferences from absolute plate velocities and intraplate stress, *Geophys. J. Roy. Astron. Soc.*, 42, 769–801, 1975.
- Stein, S., and E. A. Okal, Seismicity and tectonics of the Ninetyeast ridge area: Evidence for internal deformation of the Indian plate, *J. Geophys. Res.*, 83, 2233–2245, 1978.
- Sykes, L. R., Seismicity of the Indian Ocean and a possible nascent island arc between Ceylon and Australia, *J. Geophys. Res.*, 75, 5041–5055, 1970.
- Sykes, L. R., and M. L. Sbar, Focal mechanism solutions of intraplate earthquakes and stresses in the lithosphere, in *Geodynamics of Iceland and the North Atlantic Area*, edited by L. Kristjansson, pp. 207–224, D. Reidel, Hingham, Mass., 1974.
- Swolfs, H. S., Jr., J. Handin, and H. R. Pratt, Field measurements of residual strain in granitic rock masses, in *Advances in Rock Mechanics, Proceedings of the 3rd Congress, International Society for Rock Mechanics*, vol. 2A, pp. 563–568, National Academy of Sciences, Washington, D. C., 1974.
- Tullis, T. E., Reflections on measurement of residual stress in rock, *Pure Appl. Geophys.*, 115, 57–68, 1977.
- Turcotte, D. L., and E. R. Oxburgh, Mid-plate tectonics, *Nature*, 244, 337–339, 1973.
- Turcotte, D. L., and G. Schubert, Structure of the olivine-spinel phase boundary in the descending lithosphere, *J. Geophys. Res.*, 76, 7980–7987, 1971.
- Walcott, R. I., Flexure of the lithosphere at Hawaii, *Tectonophysics*, 9, 435–446, 1970.
- Watts, A. B., and J. R. Cochran, Gravity anomalies and flexure of the lithosphere along the Hawaiian-Emperor seamount chain, *Geophys. J. Roy. Astron. Soc.*, 38, 119–141, 1974.

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