1983

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REVIEWS OF GEOPHYSICS AND SPACE PHYSICS, VOL. 21, NO. 6, PAGES 1503-1511, JULY 1983
U.S. NATIONAL REPORT TO INTERNATIONAL UNION OF GEODESY AND GEOPHYSICS 1979-1982

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Abstract. Recent estimates of the magnitude and orientation of lithospheric stresses are reviewed. Data come from a variety of sources including earthquake focal mechanisms, fault slip data, young volcanic dikes and feeders, in-situ stress measurements at depth, lithospheric flexure models, microstructure paleopiezometry, and consideration of constraints on maximum stress differences from laboratory-determined friction and flow laws.

Introduction

Studies related to understanding the magnitude and orientation of lithospheric stresses have been going on at an active pace during the past four years. In this brief report, I intend to highlight some of the recent work in this field, concentrating on investigations that have attempted to integrate geophysical observations and theory. Recent work on stress that is based solely on seismological observations (such as stress drop estimates), or laboratory studies, are not covered here [see other chapters of this report by D. Boore and S. Kirby]. An excellent compendium of recent work on the state of stress in the lithosphere can be found in a special issue of the Journal of Geophysical Research published in November 1980. The papers in this volume originated from a conference on the Magnitude of Deviatoric Stresses in the Earth's Crust and Uppermost Mantle convened by Thomas Hanks and C. Barry Raleigh in the summer of 1979 [Hanks and Raleigh, 1980]. Other notable recent publications that make repeated reference to the magnitude and orientation of lithospheric stresses are the compendiums Earthquake Prediction [edited by Simpson and Richards, 1981] and Mechanical Behavior of Crustal Rocks, The Handin Volume [edited by Carter et al., 1981] both published by the American Geophysical Union.

Paper number 3R0070.

Magnitude of Lithospheric Stresses

Numerous techniques and methods of analysis have been advanced in the past four years to estimate the magnitude of lithospheric stresses. Unfortunately, different analysis methods often yield different types of stress estimates. For example, modeling of lithospheric flexure usually yields estimates of maximum bending stresses and differential stresses averaged over the upper 30-40 km of the lithosphere. Stress estimates based on the frictional or rheological properties of rocks

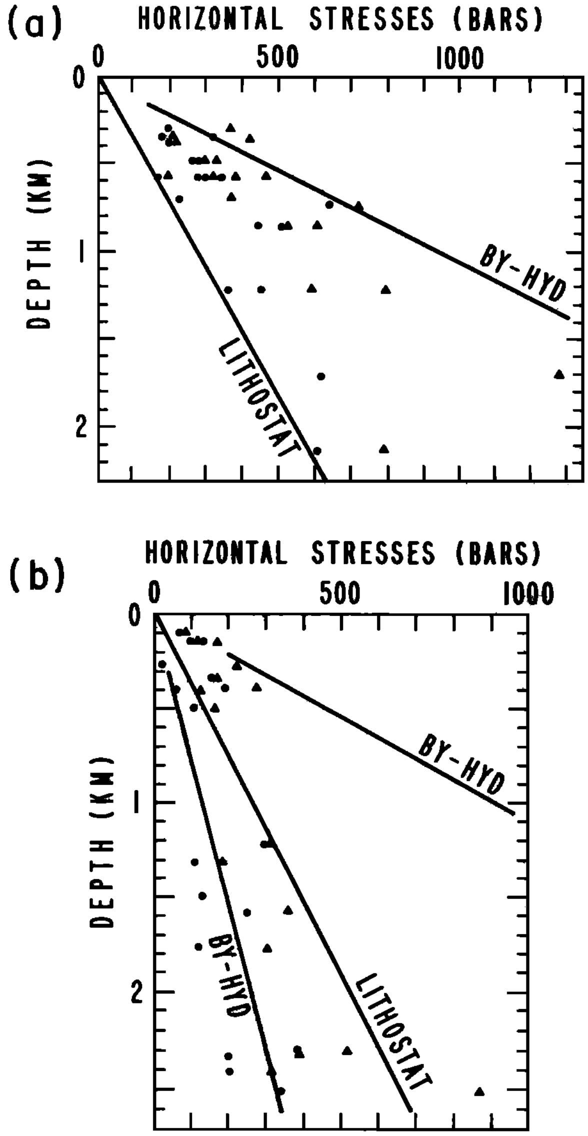

Fig. 1. Compilation of stress measurements from Canada (a) and South Africa (b) compared to the critical stress for frictional sliding based on Byerlee's law and hydrostatic pore pressure [after Brace and Kohlstedt, 1980; McGarr and Gay, 1978]. In both areas, the maximum horizontal stress at shallow depth is limited by frictional strength of reverse faults. In South Africa, normal faulting at depth prevents further decrease in the least horizontal stress. How do triangles and dots differ

studied in the laboratory, however, usually yield an upper-bound strength estimate (or maximum differential stress) at a particular pressure, temperature, and strain rate. At the end of this section, an attempt will be made to synthesize the results from the various studies cited below.

Stress in the Brittle Crust and Byerlee's Law

One of the most important findings over the past several years is that the magnitude of in-situ stress in the shallow crust seems to be limited by the frictional strength of faulted rock. For a wide variety of rock types Byerlee [1968] fit a simple relationship between laboratory measured frictional shear strength, and normal stress, σ_n. The simple relations

$$\tau = 0.85\ \sigma_n \qquad 30 < \sigma_n < 2000 \text{ bars}$$

$$\tau = 60 \pm 10 + 0.6\ \sigma_n \qquad \sigma_n > 2000 \text{ bars}$$

seem to be virtually independent of rock type (with the exception of some clays), displacement, and surface roughness. These relations have been referred to as Byerlee's law [Brace and Kohlstedt, 1980].

Assuming that there is at least one pre-existing fault plane that is well oriented with respect to the principal stresses, Brace and Kohlstedt [1980] show that in-situ stress data from southern Africa and Canada [compiled by McGarr and Gay, 1978] are limited by the frictional strength of faulted rock in the upper ~2 km of the crust (Fig. 1). Zoback [1982a] and Zoback and Hickman [1982] present several other examples, primarily in reverse-faulting environments, which support this contention by showing that seismically active areas have stress differences near the limiting value established by Byerlee's law. Byerlee's law also seems to hold for areas of incipient normal faulting [Hubbert and Willis, 1957; McGarr and Gay, 1978; Healy et al., 1982].

If Byerlee's law is nearly correct for most crustal materials, and pore pressures in the upper crust are approximately hydrostatic, it is straightforward to show that the approximate value of maximum shear stress in the crust increases with depth by about 200 bars/km in thrust-faulting environments, 80 bars/km in strike-slip faulting areas (if $_n$ is equal to the average horizontal stress), and 50 bars/km in areas of normal faulting [see Sibson 1974, 1980]. These gradients correspond to maximum differential stresses ($_D$ = 2) of 400, 160, and 100 bars/km, respectively. Laboratory studies suggest that such stress gradients would be applicable until thermally activated creep processes began to affect rock strength at depths of about 12 km in quartz-rich continental rocks, or 30 km in olivine-rich oceanic crust [Brace and Kohlstedt, 1980].

Shear Stress on the San Andreas Fault

A crucial question regarding the mechanical behavior of the San Andreas fault is the magnitude of mean shear stress on the fault within the seismogenic layer (0-15 km). Although this subject has been widely discussed and debated, the issue basically remains unresolved.

As heat flow near the fault is proportional to the mean stress times the displacement rate, the lack of any observable heat-flow anomaly near the fault has led a variety of workers to suggest that the mean shear stress on the fault was at most a few hundred bars [Brune et al., 1969; Lachenbruch and Sass, 1973, 1980; Turcotte et al., 1980]. On the basis of the lack of an observable heat-flow anomaly, and other evidence, Raleigh and Evernden [1981] concur with this low stress estimate. The heat-flow constraint would seem to place an upper bound for the long-term mean shear stress of only 100-200 bars, but such low stress estimates are clearly incompatible with Byerlee's law [Hanks, 1977] unless the fault is composed of very low-strength clay-gouge [Morrow et al., 1982] or frictional strength is reduced during faulting [Lachenbruch, 1980; Raleigh and Evernden, 1980].

Because high pore pressure could significantly lower frictional strength [Hubbert and Rubey, 1959], Lachenbruch [1980] extensively investigates the manner in which transiently high fluid pressure could be generated during faulting. Raleigh [1977] discusses a thermally induced dehydration mechanism that could raise fluid pressure (and lower frictional strength), and Sibson [1980] points out that either transient high pore pressure or frictional melting [Jeffreys, 1943; Anderson, 1951; McKenzie and Brune, 1972; Richards, 1976] could be important mechanisms for lowering frictional strength.

Some workers have cited evidence of shear heating near major faults that they interpret as an implication of high shear stress [Sheppard et al., 1975; Scholz et al., 1979; Scholz, 1980; Sibson, 1980]. In the schists adjacent to the Alpine fault in New Zealand, Scholz et al. [1979] attribute argon depletion and isograds that are subparallel to the fault as evidence of shear heating. Scholz [1980] cites 16 other cases in which there is apparent evidence of shear heating. Sibson [1975] suggests that pseudotachlyte, found near some exhumed reverse faults in crystalline host rocks, is evidence for frictional melting on fault planes, but Sibson [1980] argues that there appear to be both high- and low-stress faulting on the basis of rock deformation textures from exhumed fault zones.

O'Neill and Hanks [1980] challenge the use of conductive heat-flow measurements as a valid constraint on the frictional strength of the San Andreas fault, and point to geochemical data which suggest that there may be a considerable amount of convective heat flow away from the fault plane. However, Lachenbruch and Sass [1980] point out that there is no evidence for appreciable convective heat flow (such as thermal springs) near the fault.

Unfortunately, in-situ stress measurements made to date near the San Andreas do not yet constrain estimates of shear stress on the fault at depth. In a well approximately 1 km deep near the San Andreas in the western Mojave desert, Zoback et al. [1980] report an increase in shear stress (resolved onto a plane parallel to the fault) with depth at a rate of about 95 bars/km. This rate is consistent with that expected from Byerlee's law, and extrapolation of this gradient to greater depths rapidly leads to stresses that exceed the 100-200-bar value allowed by the heat-flow data [see also McGarr et al., 1982]. Although these stress measurements seem to support a high-stress fault, the stresses measured in the 1-km-deep well increase with depth in a step-like manner, and simple linear extrapolation of the data to greater depth may not be reasonable. McGarr et al. [1982] point out, however, that the stress measurements from the western Mojave do not indicate particularly low values compared to other areas of the world. As the maximum magnitude of in-situ stresses from these other areas seem constrained by the frictional strengths of faults (as discussed above), they claim that this is indirect evidence that there is high stress on the San Andreas. Nevertheless, until stress measurements near the fault are available from greater depths, this issue will probably not be resolved.

Flexure and Gravitational Models

Estimates of the average magnitude of differential stresses and maximum bending stresses can be gotten from theoretical models of lithospheric flexure in response to various types of loads [Walcott, 1970a,b; Hanks, 1971; Watts and Talwani, 1974; Caldwell et al., 1976; McAdoo et al., 1978] and the manner in which topography and gravity anomalies are compensated [Jeffreys, 1976; Artyushkov, 1973, 1974; McKenzie, 1969; McNutt, 1980; Lambeck, 1980]. Recent advances in these types of studies come from attempts to better constrain models by using more realistic rheological rock properties. That is, because of the importance of plastic deformation below depths of about 30 km, the use of lithospheric flexure models with only thick elastic plates can yield average regional differential stresses that exceed values based on laboratory rheological data [Kirby, 1977, 1980; Goetze and Evans, 1979] by as much as 5 kilobars.

In elastic-plastic models, the yield strength $_c$ is a function of both temperature T (or depth) and strain rate through an equation of the type

$$= A_{c} \exp(-Q/RT) \qquad (1)$$

where A and n are constants to be derived experimentally, Q is the activation energy, and R is the gas content [after Carter, 1976]. In the case of subducting slabs, Forsyth [1980] suggests that models using an elastic-plastic rheology [Liu and Kosloff, 1978; Chapple and Forsyth, 1977] are not only most compatible with laboratory rheological data, they also best explain the location and concentration of earthquake activity near the trench, the depth to which normal faulting persists, and the cumulative seismic moment of the normal faulting earthquakes. On the basis of his analysis with elastic-plastic rheological models, Forsyth concludes that models which require large regional stress differences are generally unsatisfactory.

The basic problem with attempting to estimate the magnitude of differential stresses solely from flexure and gravitational models is that there is a fundamental trade-off between stress magnitude and elastic plate thickness - the thicker the plate, the lower the stresses. In fact, McNutt and Menard [1982] demonstrate that it is possible to constrain lithospheric plate models with eqn. (1) and fit flexure data by adjusting the plate thickness and activation energy. In other words, their estimate of lithospheric stress is constrained as much by the laboratory-derived flow law than the flexure data. Similarly, from analysis of gravity anomalies and topography, Lambeck [1980] and Lambeck and Nakiboglu [1980] show that previous estimates of average differential stress as large as 5-10 kbar required to support crustal loads can be reduced to about 1 kbar by considering an elastic-plastic rheology.

Microstructure Paleopiezometry

Estimates of the maximum stress difference that a deformed rock has been subjected to can be made on the basis of recrystallized grain size, or subgrain size [Twiss, 1977, 1980; Mercier et al., 1977; Mercier, 1980] and dislocation density [Weathers et al., 1979]. Exhumed fault zone materials and peridotite xenoliths from the mantle have been used to estimate the maximum magnitude of paleostresses. Although an advantage of these methods is that they are relatively independent of temperature, an obvious disadvantage is that it is not known at what time during a rock's history a given microstructural texture developed. For example, Christie and Ord [1980] report that the quartz-bearing Coyote Mountain mylonite yields a maximum paleostress difference of 160-740 bars on the basis of grain size, but a maximum paleostress difference of 500-1300 bars on the basis of dislocation density. They attribute this difference to different deformation stages in the rocks' past. Presumably the grain size is the result of a low-stress annealing period, whereas the dislocation density results from a late-stage high-stress pulse.

Kohlstedt and Weathers [1980] summarize the results of microstructural analysis of rocks from various thrust and shear zones. These studies indicate maximum differential stresses of 1000-2000 bars for fault-zone materials exhumed from depths as great as 20-30 km. While recognizing problems such as that illustrated by Christie and Ord [1980], Kohlstedt and Weathers conclude that in most cases stress estimates made using different microstructural parameters agree well.

Mercier [1980] presents stress estimates from grain sizes in peridotite xenoliths. As these samples came from depths greater than 40 km, the results probably apply only to the lower crust and upper mantle, and indicate that differential stresses are in the 450-800 bars range.

Summary

The results of some of the studies discussed above are summarized in Table 1. In quartz-rich continental rock, a variety of evidence indicates that maximum differential stresses are in the 1-1.5 kbar range in the mid-crust (to depths of 10-20 km). Paleopiezometry indicates that maximum differential stresses decrease to about half that value at depths of 20-50 km. These results are generally consistent with average differential stresses in the upper 40 km of about 1-2 kbar yielded by studies of gravity and topography.

In oceanic areas, friction probably controls strength to a depth of about 30 kb. This yields a maximum strength of 3.0-6.0 kb. As average differential stresses in the upper 30-40 km indicated by topography and gravity modeling are only in the 1-1.5 kbar range, they are well within the limit of rock strength. More importantly, so are maximum bending stresses of about 5 kbar at 25 km depth yielded by flexure models with elastic-plastic rheologies.

Orientation of Horizontal Principal Stresses

There have been several attempts to compile data on the orientation of the in-situ stress field in the conterminous U.S. [Raleigh, 1974; Haimson, 1977; McGarr and Gay, 1978]. Due to the severe lack of data over very large areas, these studies were only marginally successful. Zoback and Zoback [1980] attempted to overcome the data shortage by synthesizing various types of-stress-field indicators (geologic, seismologic (focal plane), and in-situ stress measurements from depth). A rigid criterion was established for each type of data that was used. The different stress-field indicators gave results that were generally consistent with respect to each other as well as with the current tectonics within the various stress provinces (Figure 2).

The fact that stress measurements made at only a few hundred meters depth, or a few kilometers at most, yield horizontal stress orientations consistent with well-constrained focal-plane information from much deeper earthquakes indicates that the orientation and relative magnitude of horizontal principal stresses are generally consistent throughout much of the crust. Thus, tectonic forces seem to be reflected in the stress field at relatively shallow depths, and it seems reasonable to attempt to constrain tectonic models with both deep and relatively near-surface stress data. However, within a few tens of meters of the earth's surface the stress field often seems to be affected by topographic, or stress-relief, mechanisms [see Sbar et al., 1979]. In general, such measurements cannot be expected to yield reliable tectonic stress orientations, although in some cases they do appear to agree with other stress-field indicators [e.g., Froidevaux et al., 1980].

Stress Provinces

The concept of stress provinces, or areas in which the relative magnitude and orientation of the in-situ stresses are uniform, has been evolving over the past few years as reliable data have accumulated. In addition to the discussion by Zoback and Zoback [1980] of stress provinces in the conterminous U.S., Nakamura and Uyeda [1980] discuss stress provinces associated with subduction zones and volcanic arcs. They find that (1) the area immediately landward of the trench is characterized by thrusting (with the direction of maximum compression parallel to the direction of convergence), (2) the volcanic arc is characterized by strike-slip faulting (with the direction of maximum horizontal compression still parallel to the convergence direction), and (3) the back-arc area is

TABLE 1

DEPTH RANGE	MAXIMUM DIFFERENTIAL STRESS	REMARKS	REFERENCES
CONTINENTAL			
0-12 km	1.2 kb (extensional) 1.9 kb (shear) 2.5 kb (compressional)	Stress limited by frictional strength; hydrostatic pore pressure assumed	Brace and Kohlstedt [1980]; Sibson [1975, 1980]
4-10 km	0.5-2.0 kb	Paleopiezometry-Moine thrust	Twiss [1977]; Weathers et al. [1979]
7.5 km	0.3-1.5 kb	Paleopiezometry-Massif Central shear zone	Burg and Laurent (1978)
10-15 km	1.0 kb	Paleopiezometry-Shear zone in Colorado	Kohlstedt and Weathers [1980]
15-20 km	1.0-2.0 kb	Paleopiezometry-Shear zone in Wyoming	Weathers et al. [1979]
15-30 km	0.2-1.1 kb	Paleopiezometry-Shear zone in Greenland	Kohlstedt et al. [1979]
0-40 km	1.5-2.0 kb	Gravity and topography	McNutt [1980]; Lambeck [1980]
40-50 km	0.4-0.8 kb	Paleopiezometry-peridotite xeno-liths	Mercier [1980]
OCEANIC			
0-30 km	3.0 kb (extensional) 4.8 kb (shear) 6.0 kb (compressional)	Stress limited by frictional strength; hydrostatic pore pressure assumed	Brace and Kohlstedt [1980]; Sibson [1975, 1980]
0-40 km	5 kb	Outer Rise	McNutt and Menard [1982]
0-35 km	1 kb	Seamount Load	McNutt and Menard [1982]

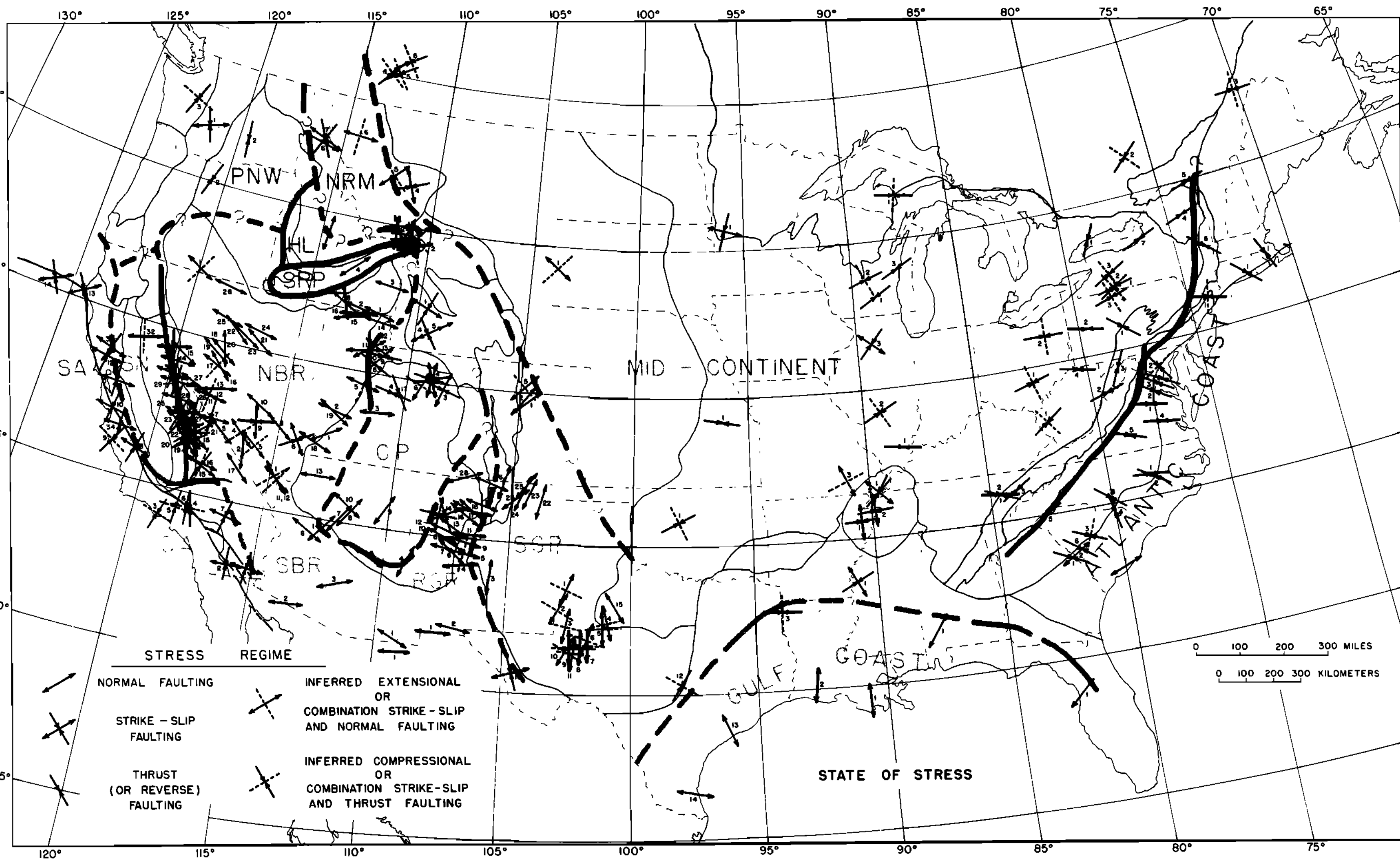

Fig. 2. Compilation of stress data in the conterminous U.S. [from Zoback and Zoback, 1980]. Heavy shaded lines define the boundaries of the stress provinces discussed in the text; heavy dashed lines mark the approximate boundaries. Stress provinces are abbreviated as follows: SA, San Andreas; SN, Sierra Nevada; PNW, Pacific Northwest; NRM, northern Rocky Mountains; HL, Hebgen Lake-Centennial Valley; SRP, Snake River Plain-Yellowstone; CP, Colorado Plateau; and SGP, southern Great Plains. The Basin and Range-Rio Grande Rift stress province includes the northern (NBR) and southern (SBR) Basin and Range and the Rio Grande Rift (RGR). Physiographic provinces are shown by light solid lines for reference. The number by each data point refers to a description of the point.

characterized by normal faulting (where the least horizontal compressive stress direction is parallel to the convergence direction). Elements of this pattern can also be seen in Japan, Alaska, the Hellenic arc, and central Europe [see also Mercier, 1981 and Angelier et al., 1982].

The fact that some stress provinces can be geographically small in tectonically active areas appears reasonable if local sources of stress like shallow magmatism, variations in crustal thickness [Artyushkov, 1973], and heat flow [McGarr, 1982] are considered. In the past, relatively small-scale stress provinces (those smaller than a few hundred kilometers) have generally been ignored in studies of global plate interaction aimed at resolving the forces responsible for plate motion [Richardson et al., 1976; Solomon et al., 1980].

Intraplate Stresses in the Conterminous U.S.

The origin of stresses in intraplate areas is of interest for a number of reasons. The uniform direction of the intraplate stress field in the central and eastern U.S. led Zoback and Zoback [1980] to suggest drag at the base of the lithospheric plate as a possible causative mechanism. Whether or not this hypothesis is correct will require further testing as more data become available and more sophisticated models are developed. However, one possible origin of intraplate stresses in the central and eastern U.S., asthenospheric counterflow [Chase, 1979; Hager and O'Connell, 1979], can apparently now be rejected; this mechanism predicts stress directions which are nearly at right angles to those observed in the region.

A better understanding of the consistency of the stress field within the central and eastern U.S. also helps constrain the causes and controls of the occurrence of intraplate seismicity. For example, Zoback and Zoback [1981] argue that because the stress field in intraplate seismic areas such as the New Madrid, Missouri area is consistent with the surrounding aseismic region, localized weak zones in the crust (such as repeatedly reactivated intracratonal rifts) may be controlling the locations of intraplate seismicity rather than areas of localized stress concentration [Kane, 1976; McKeown, 1978].

The delineation of stress provinces and determining how such areas correlate with physiography, crustal thickness, seismicity, and heat flow, is ultimately an interpretative problem. Sbar [1982], for example, presents an alternative interpretation to that shown in Figure 2 of stress provinces in the western U.S. The basic problems in comparing various interpretations of stress provinces are the extreme paucity of data in many critical areas and the accuracy of data needed for defining subprovinces. As more data become available, the stress provinces shown in Figure 2 will no doubt change. As they do, it will become more and more appropriate to constrain mechanisms of plate motion, crustal deformation, and intraplate volcanism and tectonism with stress data.

Measuring the Stress Field

The past four years have seen considerable progress in the development of methods to determine the magnitude and orientation of the crustal stress field. As mentioned above, comparison of various methods for determining the orientation of the principal stresses seems to yield consistent results. Moreover, the magnitudes of stresses determined with the hydraulic fracturing and overcoring techniques have recently been found to compare quite well in several control tests [Haimson, 1982]. In fact, it is just in the past few years that there have been sufficient stress measurements made with the hydraulic fracturing method (and by enough groups of investigators) to confirm the reliability of the method and data interpretation methods [see Zoback and Haimson, 1982].

Although there is considerable inherent uncertainty in determining the orientation of principal stresses from earthquake focal mechanisms [see McKenzie, 1969; Raleigh et al., 1972], recent progress has been made in analysis of such data. First, greater accuracy can be attained by considering focal mechanisms from earthquakes generated on multiple fault planes in a given area [Zoback and Zoback, 1980]. Second, in areas where body-wave data are sparse, surface-wave focal mechanisms [Hermann and Canas, 1978; Hermann, 1979] seem to work quite well. Finally, formal inversion of nodal plane and slip information from earthquakes on different fault planes in a given area [Ellsworth and Xa, 1980] is yielding information on both the orientation of the principal stresses, and the ratio of the differences of the principal stresses. This inversion method is based on methods for inverting fault slip data [see Angelier, 1979], which are yielding principal stress directions that are very similar to other stress-field indicators [Zoback, 1982b].

Finally, the use of stress-induced well-bore elongation [Cox, 1970; Babcock, 1978] seems to be an exciting new method for determining the orientation of the horizontal principal stresses because either oriented 4-arm caliper logs or borehole televiewer logs can be used. The results of using this method compare well with other stress data for various regions [Bell and Gough, 1979, 1982; Hickman et al., 1982]. As there are data now available which can be used to determine stress field orientations in numerous oil and gas wells, the use of well-bore elongation for determining the orientation of the in-situ stress field may have extremely far-reaching consequences.

References

Abou-Sayed, A.S., C.E. Brechtel, and R.J. Clifton, In situ stress determination by hydrofracturing: A fracture mechanics approach, J. Geophys. Res. 83, 2851-2862, 1978.

Anderson, E.M., The Dynamics of Faulting, 2nd ed., p. 176, Oliver and Boyd, Edinburgh, 1951.

Angelier, J., Determination of the mean principal directions of stresses for a given fault population, Tectonophysics 56, 17-26, 1979, N. Lyberis, X. Angelier, J. LePickon, E. Barrier, P. Huckon, The tectonic development of the Hellenic Arc and the sea of Crete: A synthesis, Tectonophysics 86, 159-196

Artyushkov, E.V., The stresses in the lithosphere caused by crustal thickness inhomogeneities, J. Geophys. Res. 78, 7675-7708, 1973.

Artyushkov, E.V., Can the earth's crust be in a state of isostasy , J. Geophys. Res. 79, 741-752, 1974.

Babcock, E.A., Measurement of subsurface fractures from dipmeter logs, Amer. Ass. Petrol. Geol. Bull. 62, 1111-1126, 1978.

Baumann, H., Regional stress field and rifting in western Europe, Tectonophysics 73, 105-111, 1981.

Bell, J.S., and D.I. Gough, Northeast-southwest compressive stress in Alberta: Evidence from oil wells, Earth Planet. Sci. Lett. 45, 475-482, 1979.

Bell, J.S. and D.I. Gough, The use of borehole breakouts in the study of crustal stress, in Proc. Workshop on Hydraulic Fracturing Stress Measurements, U.S. Nat. Comm. Rock Mech., Wash., D.C., in press, 1982.

Bergman, E.A., and S. C. Solomon, Oceanic intraplate earthquakes: Implications for local and regional intraplate stress, J. Geophys. Res. 85, 5389-5410, 1980.

Birdwell, R.J., and C. Potzick, Thermal regimes, mantle drapirs, and crustal stresses of continental rifts, Tectonophysics 73, 15-32, 1981.

Bodine, J.H., and A.B. Watts, On lithospheric flexure seaward of the Bonin and Mariana trenches, Earth Planet. Sci. Lett. 43, 132-148, 1979.

Bodine, J.H., M.S. Steckler, and A.B. Watts, Observations of flexure and the rheology of the oceanic lithosphere, J. Geophys. Res. 86, 3695-3707, 1981.

Bott, M.H.P., Stress based tectonic mechanisms at passive continental margins, Grant Inst. Geol., Edinburgh, GBR, Geodynamics Series 6, 147-153, 1982.

Bott, M.H.P., and N.J. Kusznir, Stress distributions associated with compensated plateau uplift structures with application to the continental splitting mechanism, Geophys. J. R. Astr. Soc. 56, 451-459, 1979.

Brace, W.F., and D.L. Kohlstedt, Limits on lithospheric stress imposed by laboratory experiments, J. Geophys. Res. 85, 6248-6252, 1980.

Brown, E.T., and E. Hock, Trends in relationships between measured in-situ stresses and depth, Int. J. Rock Mech. Mining Sci. Geomech., Abstr. 15, 211-215, 1978.

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.

Byerlee, J.D., Brittle-ductile transition in rocks, J. Geophys. Res. 73, 4741-4750, 1968.

Caldwell, J.G., and D.L. Turcotte, Dependence of the thickness of the elastic oceanic lithosphere on arcs, J. Geophys. Res. 84, 7572-7576, 1979.

Caldwell, J.G., W. F. Haxby, D.E. Karig, and D.L. Turcotte, On the applicability of a universal elastic-trench profile, Earth Planet. Sci. Lett. 31, 239-246, 1976.

Carter, N.L., Steady state flow of rocks, Rev. Geophys. Space Phys. 14, 301-360, 1976.

Carter, N.L., M. Friedman, J. M. Logan, and D.W. Stearns, eds., Mechanical Behavior of Crustal Rocks, The Handin Volume, American Geophys. Union, Wash., D.C., 326 pp., 1981.

Chapple, N.M., and D.W. Forsyth, Earthquakes and bending of plates at trenches, J. Geophys. Res. 82, 2001-2004, 1977.

Chase, C.G., Asthenospheric counterflow: A kinematic model, Geophys. J. Roy. Astron. Soc. 56, 1-18, 1979.

Christie, J.M., and A. Ord, Flow stress from microstructures of mylonites: Example and current assessment, J. Geophys. Res. 85, 6253-6262, 1980.

Cox, J.W., The high resolution dipmeter reveals dip-related borehole and formation characteristics, paper presented at the 11th Annual Logging Symposium, Soc. Prof. Well Log Anal., Los Angeles, Calif., 1970.

Dahlen, F.R., Isostasy and the ambient state of stress in the oceanic lithosphere, J. Geophys. Res. 86, 7801-7807, 1981.

Davies, G.F., Mechanics of subducted lithosphere, J. Geophys. Res. 85, 6304-6318, 1980.

Denham, D., L.G. Alexander, and G. Worotnicki, The stress field near the sites of the Meckering [1968] and Calingiri [1970] earthquakes, western Australia, Tectonophysics 67, 283-317, 1980.

Ellsworth, W.F., and X. Zhonghuai, Determination of the stress tensor from focal mechanism data, EOS 61, 1117, 1980.

Engelder, T., and P. Geiser, On the use of regional joint sets as trajectories of paleostress fields during the development of the Appalachian Plateau, New York, J. Geophys. Res. 85, 6319-6341, 1980.

Forsyth, D.W., Comparison of mechanical models of oceanic lithosphere, J. Geophys. Res. 85, 6364-6368, 1980.

Froidevaux, C., C. Paquin, and M. Souriou, Tectonic stresses in France: In situ measurements with a flat jack, J. Geophys. Res. 85, 6342-6346, 1980.

Fujita, K., and N.H. Sleep, Membrane stresses near mid-ocean ridge-transform intersections, Tectonophysics 50, 207-221, 1978.

Goetze, C., and B. Evans, Stress and temperature in the bending lithosphere as constrained by experimental rock mechanics, Geophys. J. Roy. Astron. Soc. 59, 463-478, 1979.

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.

Haimson, B.C., Crustal stress in the Michigan Basin, J. Geophys. Res. 83, 5857-5863, 1978.

Haimson, B.C., A comparative study of deep hydrofracturing and overcoring stress measurements at six locations with particular interest to the Nevada Test Site, in Proc. Workshop on Hydraulic Fracturing Stress Measurements, U.S. Nat. Comm. Rock Mech., Wash., D.C., in press, 1982.

Haimson, B.C., and F. Rummel, Hydrofracturing stress measurements in the Iceland Research Drilling Project drill hole at Reydarfjordur, Iceland, J. Geophys. Res. 87, 6631-6649, 1982.

Hanks, T.C., Earthquake stress drops, ambient tectonic stresses, and stresses that drive plate motions, Pure Appl. Geophys. 115, 441-458, 1977.

Hanks, T.C., Deviatoric stresses and earthquake occurrence at the outer rise, J. Geophys. Res. 84, 2343-2347, 1979.

Hanks, T.C., The Kurile trench - Hokkaido rise system: Large shallow earthquakes and simple models of deformation, Geophys. J. Roy. Astron. Soc. , 23, 173-189, 1971.

Hanks, T.C., and C.B. Raleigh, The conference on magnitude of deviatoric stress in the earth's crust and uppermost mantle, J. Geophys. Res., 85, 6083-6085, 1980.

Healy, J.H., S.H. Hickman, M.D. Zoback, and W.L. Ellis, Deep borehole stress measurements at the Nevada Test Site, EOS, in press, 1982.

Henning, J., I. Horst-Baumann, and B. Hoffers, Stress pattern and strain release in the Alpine Foreland, Tectonophysics 71, 157-172, 1981.

Hermann, R.B., Surface wave focal mechanisms for eastern North American earthquakes with tectonic implications, J. Geophys. Res. 84, 3543-3552, 1979.

Hermann, R.B., and J.A. Canas, Focal mechanism studies in the New Madrid seismic zone, Bull. Seismol. Soc. Amer. 68, 1095-1102, 1978.

Hickman, S.H., J.H. Healy, M.D. Zoback, J.F. Svitek, J.E. Bretches, In situ stress, borehole elongation, and natural fracture distribution at depth in central New York State, EOS Trans-Amer Geophys Un. 63, 1118, 1982.

Hubbert, M.K., and D.G. Willis, Mechanics of hydraulic fracturing, AIME Trans. 210, 153-168, 1957.

Hubbert, M.K., and W.W. Ruby, Role of fluid pressure in mechanics of overthrust faulting, 1, Mechanics of fluid filled porous solids and its application to overthrust faulting, Geol. Soc. Am. Bull. 70, 115-166, 1959.

Illies, H., and G. Greiner, Holocene movements and state of stress in the Rhinegraben rift system, Tectonophysics 52, 349-359, 1979.

Jamison, D.B., and G.W.N. Cook, Note on measured values for the state of stress in the earth's crust, Jour. Geophys. Res. 85, 1833-1838, 1980.

Jeffreys, H., The Earth, Cambridge Univ. Press, New York, 1943.

Jeffreys, H., The Earth, Cambridge Univ. Press, New York, 1976.

Kane, M.F., Correlation of major eastern U.S. earthquake centers with mafic/ultramafic masses (abstract), EOS Trans. AGU 57, 963, 1976.

Kato, T., K. Shimazaki, and K. Yamashina, State of stress within a thin elastic wedge: A model of internal deformation of the continental plate at arc-arc junctions, Geophys. J. R. Astr. Soc. 60, 377-390, 1980.

Keith, M.L., Regional mid-ocean stress and a proposed focal mechanism of stress-discordant earthquakes, Geophys. J. R. Astr. Soc. 65, 627-644, 1981.

Kilty, K.T., Stress fields of the San Andreas and Queen Charlotte transport faults, Tectonophysics 77, 203-212, 1981.

Kirby, S.H., State of stress in the lithosphere: Inference from the flow laws of olivine, Pure Appl. Geophys. 115, 245-258, 1977.

Kirby, S.H., Tectonic stresses in the lithosphere: Constraints provided by the experimental deformation of rocks, J. Geophys. Res. 85, 6353-6363, 1980.

Kohlstedt, D.L., R.F. Cooper, M.S. Weathers, and J.M. Bird, Paleostress analysis of deformation-induced microstructures: Moine thrust zone and Ihertoq shear zone, in U.S. Geo. Survey Open-File Report 79-1239, pp. 394-425, 1979.

Kohlstedt, D.L., and M.S. Weathers, Deformation-induced microstructures, paleopiezometers, and differential stresses in deeply eroded fault zones, J. Geophys. Res. 85, 6269-6285, 1980.

Lachenbruch, A.H., Frictional heating, fluid pressure, and the resistance to fault motion, J. Geophys. Res. 85, 6097-6112, 1980.

Lachenbruch, A.H., and J.H. Sass, Thermo-mechanical aspects of the San Andreas fault system, in Proc. of the Conference on Tectonic Problems of the San Andreas Fault System, pp. 192-205, Stanford Univ. Press, Palo Alto, Calif., 1973.

Lachenbruch, A.H., and J.H. Sass, Heat flow and energetics of the San Andreas fault zone, J. Geophys. Res. 85, 6185-6222, 1980.

Lago, B., and A. Cazenave, State of stress in the oceanic lithosphere in response to loading, Geophys. J. R. Astr. Soc. 64, 785-799, 1981.

Lambeck, K., Estimates of stress differences in the crust from isostatic considerations, J. Geophys. Res. 85, 6397-6402, 1980.

Lambeck, K., and S.M. Nakiboglu, Seamount loading and stress in the ocean lithosphere, J. Geophys. Res. 85, 6403-6418, 1980.

Liu, H.P., and D. Kosloff, Elastic-plastic bending of the lithosphere incorporating rock deformation data, with application to the Hawaiian Archipelego, Tectonophysics 50, 249-274, 1978.

Liu, H.S., Convection generated stress field and intra-plate volcanism, Tectonophysics 65, 225-244, 1980.

McAdoo, D.C., J.G. Caldwell, and D.L. Turcotte, On the elastic perfectly plastic bending of the lithosphere under generalized loading with application to the Kurile trench, Geophys. J. Roy. Astron. Soc. 54, 11-26, 1978.

McGarr, A., Some constraints on levels of shear stress in the crust from observations and theory, J. Geophys. Res. 85, 6231-6238, 1980.

McGarr, A., Analysis of states of stress between provinces of constant stress, J. Geophys. Res., in press, 1982.

McGarr, A., and N.C. Gay, State of stress in the earth's crust, Ann. Rev. Earth Planet. Sci. 6, 405-436, 1978.

McGarr, A., M.D. Zoback, and T.C. Hanks, Implications of an elastic analysis of in-situ stress measurements near the San Andreas fault, J. Geophys. Res. 87, 7797-7806, 1982.

McKenzie, D.P., The relationship between fault plane solutions for earthquakes and the directions of the principal stresses, Bull. Seismol. Soc. Amer. 59, 591-601, 1969.

McKenzie, D.P., and J.N. Brune, Melting on fault planes during large earthquakes, Geophys. J. Roy. Astron. Soc. 29, 65-78, 1972.

McKeown, F.H., Hypothesis: Many earthquakes in the central and southeastern United States are causally related to mafic intrusive bodies, J. Res. U.S. Geol. Surv. 6, 41-50, 1978.

McNutt, M., Implications of regional gravity for state of stress in the earth's crust and upper mantle, J. Geophys. Res. 85, 6377-6396, 1980.

McNutt, M., M.K. and H.W. Menard, Constraints on yield strength in the oceanic lithospheric derived from observations of flexure, Geophys. J.R. Astron. Soc., in press, 1982.

Mendiguren, J.A., and F.M. Richter, On the origin of compressional intraplate stresses in South America, Phys. Earth Planet. Interiors 16, 318-326, 1978.

Mercier, J.-C.C., D.A. Anderson, and N.L. Carter, Stress in the lithosphere: Inferences from steady-state flow of rocks, Pure Appl. Geophys. 115, 199-226, 1977.

Mercier, J.-C.C., Magnitude of the continental lithospheric stresses inferredfrom rheomorphic petrology, J. Geophys. Res. 85, 6293-6303, 1980.

Mercier, J.C., Extensional-congressional techtonics associated with the Segean Arc:

Comparison with the Anelean Cordillera of south Peru - north Bolivia, Phil. Trans. Roy. Soc. Land. A 300, 337-355, 1981.

Morrow, C.A., L.Q. Shi, and J.D. Byerlee, Strain hardening and strength of clay-rich fault gouges, J. Geophys. Res. 87, 6771-6780, 1982.

Nakamura, K., and S. Uyeda, Stress gradient in arc-back arc regions and plate subduction, J. Geophys. Res. 85, 6403-6418, 1980.

O'Neill, J.R., and T.C. Hanks, Geochemical evidence for water-rock interaction along the San Andreas and Garlock faults, J. Geophys. Res. 85, 6286-6292, 1980.

Raleigh, C.B., Crustal stress and global tectonics, in Advances in Rock Mechanics, Proc. 3rd Congr. Int'l. Soc. Rock Mech., 1A, pp. 593-597, 1974.

Raleigh, C.B., Frictional heating, dehydration, and earthquake stress drops, in Experimental Studies of Rock Friction with Application to Earthquake Prediction, pp. 291-304, U.S. Geological Survey, Menlo Park, Calif., 1977.

Raleigh, C.B., and J. Evernden, Case for low deviatoric stress in the lithosphere, in Mechanical Behavior of Crustal Rocks, The Handin Volume, Geophysical Mono. 24, Amer. Geophys. Union, Wash., D.C., 1981.

Raleigh, C.B., J.H. Healy, and J.D. Bredehoeft, Faulting and crustal stress at Rangely, Colorado, in Flow and Fracture of Rocks, Geophys. Monogr. Ser., vol. 16, edited by H.C. Heard, et al., pp. 275-284, AGU, Washington, D.C. 1972.

Richards, P.G., Dynamic motions near an earthquake fault: A three-dimensional solution, Bull. Seismol. Soc. Amer. 66, 1-32, 1976.

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. Soloman, 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, 981-1020, 1979.

Rispoli, R., Stress fields about strike-slip faults inferred from stylolites and tension gashes, Tectonophysics 75, T29-T36, 1981.

Roquemore, G., Structure, tectonics, and stress field of the Coso Range, Inyo County, California, J. Geophys. Res. 85, 2434-2440, 1980.

Sbar, M.L., Delineation and interpretation of seismotectonic domains in western North America, J. Geophys. Res. 87, 3919-3928, 1982.

Sbar, M.L., T. Engelder, R. Plumb, and S. Marshak, Stress pattern near the San Andreas fault, Palmdale, California, from near-surface in-situ measurements, J. Geophys. Res. 84, 156-164, 1979.

Scheidegger, A.E., The geotectonic stress field and crustal movements, Tectonophysics 71, 217-226, 1981.

Scholz, C.H., Shear heating and the state of stress on faults, J. Geophys. Res. 85, 6174-6184, 1980.

Scholz, C.H., J. Beavan, and T.C. Hanks, Frictional metamorphism, argon depletion, and tectonic stress on the Alpine fault, New Zealand, J. Geophys. Res. 84, 6770-6782, 1979.

Schubert, G., D.A. Yuen, C. Froidevaux, L. Flertant, and M. Souriau, Mantle circulation with partial shallow return flow: Effects on stresses in oceanic plates and topography of the sea floor, J. Geophys. Res. 83, 745-758, 1978.

Sheppard, D.S., C.J. Adams, and G.W. Bird, Age of metamorphism and uplift in the Alpine schist belt, New Zealand, Geol. Soc. Amer. Bull. 86 1147-1153, 1975.

Sibson, R.H., Frictional constraints on thrust, wrench, and normal faults, Nature 249, 542-544, 1974.

Sibson, R.H., Generation of pseudotachylite by ancient seismic faulting, Geophys. J. R. Astron. Soc. 43, 775-794, 1975.

Sibson, R.H., Power dissipation and stress levels on faults in the upper crust, J. Geophys. Res. 85, 6239-6247, 1980.

Simpson, D.W., and P.G. Richards, eds., Earthquake Prediction, An International Review, American Geophys. Union, Wash., D.C., 680 pp., 1981.

Solomon, S.C., R.M. Richardson, and E.A. Bergman, Tectonic stress: Models and magnitudes, J. Geophys. Res. 85, 6086-6092, 1980.

Tullis, T.E., The use of mechanical twinning in minerals as a measure of shear stress magnitudes, J. Geophys. Res. 85, 6263-6268, 1980.

Turcotte, D.L., R.J. Willemann, W.F. Haxby, and J. Norberry, Role of membrane stresses in the support of planetary topography, J. Geophys. Res. 86, 3951-3959, 1981.

Turcotte, D.L., D.H. Tag, and R.F. Cooper, A steady state model for the distribution of stress and temperature on the San Andreas fault, J. Geophys. Res. 85, 6223-6230, 1980.

Twiss, R.J., Theory and applicability of recrystallized grain size paleopiezometer, Pure Appl. Geophysics 11, 227-244, 1977.

Twiss, R.J., Static theory of size variations with stress for subgrains and dynamically recrystallized grains, in U.S.G.S. Open-file Report 80-625, pp. 665-683, 1980.

Walcott, R.I., Flextural rigidity, thickness, and viscosity of the lithosphere, J. Geophys. Res. 75, 3941-3954, 1970a.

Walcott, R.I., Flexture of the lithosphere at Hawaii, Tectonophysics 9, 435-446, 1970b.

Watts, A.B., J.H. Bodine, and M.S. Steckler, Observations of flexure and the state of stress in the oceanic lithosphere, J. Geophys. Res. 85, 6369-6376. 1980.

Watts, A.B., and M. Talwani, Gravity anomalies seaward of deep-sea trenches and their tectonic implications, Geophys. J. Roy. Astron. Soc. 36, 57-90, 1974.

Weathers, M.S., J.M. Bird, R.F. Cooper, and D.L. Kohlstedt, Differential stresses determined from deformation-induced microstructures of the Moine thrust zone, J. Geophys. Res. 84, 7495-7509, 1979.

Yang, J.-P., and Y. P. Aggarwal, Seismotectonics of the northeastern United States and adjacent Canada, J. Geophys. Res. 86, 4981-4998, 1981.

Yuen, D.A., L. Flestart, G. Schubert, and C. Froidevaux, Shear deformation zones along major faults and subducting slabs, Geophys. J. R. Astr. Soc. 54, 93-119, 1978.

Zoback, M.D., In-situ studies in highly fractured granitic rock, Proc. Eng. Foundation Conference, Santa Barbara, Calif., in press, 1982a.

Zoback, M.D., and B.C. Haimson, Status of the hydraulic fracturing of the hydraulic fracturing method for in-situ stress measurements, in Proc. 23rd Symposium on Rock Mechanics, Soc. Mining Engr. of A.I.M.E., New York, pp. 143-156, 1982.

Zoback, M.D., and S. Hickman, In-situ study of the physical mechanisms controlling induced seismicity at Monticello Reservoir, S. Carolina, J. Geophys. Res. 87, 6959-6974, 1982.

Zoback, M.D., H. Tsukahara, and S. Hickman, Stress measurement at depth in in the vicinity of the San Adreas fault. Implicatious for the magnitude of sheer stress at depth, J. Geophys. Res. 85, 6157-6173, 180.

Zoback, M.D., and M.L. Zoback, State of stress and intraplate earthquakes in the United States, Science 213, 96-104, 1981.

Zoback, M.L., and M.D. Zoback, Faulting patterns in north-central Nevada and strength of the crust, J. Geophys. Res. 85, 275-284, 1980.

Zoback, M.L., and M.D. Zoback, State of stress in the conterminous United States, J. Geophys. Res. 85, 6113-6156, 1980.

Zoback, M.L., Structure and Cenozoic tectonism along the Wasatch fault zone, Utah, Tectonics and Stratigraphy of the Eastern Great Basin, Geol. Soc. Amer., Boulder, Colo., in press, 1982b.

(Received October 15, 1982;
accepted January 13, 1983.)