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Lithosphere dynamics and continental deformation

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The unifying theme in this section is the remarkable weakness of major faults. I will consider the diverse new evidence for weakness, and the evidence for high pore pressure localized in faults as a fundamental cause. With this background one can better understand why faults remain active even after large rotations with respect to stress: I will look at large Neogene (≤23.7 million year old) rotations about horizontal axes in the Basin and Range province, and about vertical axes along the Pacific margin. Recent developments will be summarized from studies of Neogene tectonics (neotectonics) in California, Alaska, and the Mississippi embayment, in the context of a weak North American stress field that results mainly from topographic forces. To close, I will present new geophysical studies relevant to the continuing controversy over whether the basic structure of the North American mantle lithosphere was altered by an early Tertiary episode of flat subduction.

Weakness of Major Faults

Both laboratory and *in-situ* studies of crustal rocks far from faults have typically shown them to have high coefficients of friction (0.65-0.85, dimensionless). *Zoback et al.* [1993] find such behavior to 6 km depth in the KTB borehole in Germany. However, there is something different about major faults.

In the last Report, *Hickman* [1991] summarized the evidence for a weak San Andreas fault: the lack of a heat-flow anomaly, and of proven hydrothermal circulation to remove the heat by advection. The lack of any heat-flow anomaly in the new Cajon Pass scientific borehole next to the San Andreas fault limits the vertical integral of shear traction to 10^{11} N/m [*Lachenbruch and Sass,* 1992].

In many places, a nearly perpendicular/parallel relationship between principal stress axes and the fault plane limits the possible shear tractions to low values. In-situ stress measurements in the Cajon Pass hole show that crustal blocks have high friction internally, but that the most-compressive horizontal principal stress direction (σ_1) is perpendicular to the San Andreas, precluding any dextral shear on that fault today [*Zoback and Healy*, 1992]. Next to the southern San Andreas fault, Pliocene-Quaternary folds are forming with axes parallel to the fault, and extension along these axes [*Burgmann,* 1991]. On the part of the San Andreas fault that slipped in the Loma Prieta earthquake, stress directions from aftershocks imply no measurable shear traction remaining after slip on the main fault [*Zoback and Beroza*, 1993]. On the San Francisco peninsula, for 35 km north of the Loma Prieta rupture, fault plane solutions also show σ_1 almost perpendicular to the San Andreas fault [*Olson and Zoback*, 1992]. *Mount and Suppe* [1992] collected borehole-elongation data and showed that in both California and Sumatra, the most compressive (σ_1) direction is 70-90° from major strike-slip faults, requiring them to be very low-friction surfaces. In the Sumatran arc the minimum angle between slip vectors and the trench is 65-75°, implying that the dextral fault along the arc is no stronger than the water-lubricated subduction shear zone [*McCaffrey,* 1992].

In one of the most exciting developments of the last four years, *Hauksson* [1994] showed that the regional stress field in the area of the Landers earthquake permanently rotated 7-20° in that event, with the local rotation approximately proportional to the local fault slip (and stress drop). This proves that the seismic stress drop was a large fraction of the initial shear stress, and therefore that the fault was weak even at the start of slip. This method of quantitative shear stress estimation is unique in the large volume of crust that it samples; unfortunately, it can only be applied where a large earthquake falls within a well-established seismic network.

A nonlinear thin-plate finite-element model of California and its faults [*Bird and Kong,* 1994] was optimized with respect to geologic, geodetic, and stress data, with the result that friction on major faults is only 0.12-0.17. *Bird* [1992b] found typical fault friction in Alaska to be at least this low, with the same method.

A hint that fault weakness may persist for very long times is given by the reactivation of Cretaceous thrust faults in Wyoming-Utah as Quaternary normal faults [*West,* 1993].

Pore Water at High Pressure

Scholz et al. [1993] reviewed the literature on new faults, and concluded that they are self-similar, implying that the strain-weakening that created the fault is followed by further slip-weakening. However, since major slip-weakening is not seen in the laboratory, local anomalous pore pressure is a more popular explanation for fault weakness. Such pressures would have to approach lithostatic pressure, which is the weight/area of the rock overburden.

Saline hot springs in the California Coast Ranges expell ancient fluids from Cretaceous shales (or deeper sources) and imply some degree of anomalous pore pressure [*Unruh et al.,* 1992]. Fluid inclusions in the exhumed footwall of the Dixie Valley fault in Nevada record essentially lithostatic pore pressure at (305°C, 1.57×10^6 Pa) [*Parry et al.*, 1991]. Internal structures of the San Gabriel and Punchbowl faults, exhumed from 2-

5 km, show up to 50% deformed hydrothermal vein material in the central ultracataclasite zones, which are only 1-10 m thick [*Chester et al.,* 1993]. The presence of veins becomes significant if one accepts that these faults probably slipped at low shear stresses; with small shear stresses, pore pressure that is equal to the least-compressive principal stress (to open a crack) cannot be very much less than lithostatic.

The source of high pore pressures is less clear. *Byerlee* [1993] proposed that interseismic compaction of fault gouges creates these high pressures, and that some earthquake precursors are due to fluid flow when barriers are breached between separate reservoirs. *Rice* [1992] presented a different model, in which water from the mantle or lower crust rises preferentially along faults, creating haloes of high pore pressure, due to pressure-dependent permeability. (The self-sealing of unidirectional hydrothermal systems due to silica precipitation may also be important.)

If high pore pressure is localized only along faults, it should cause local rotation of the principal stress axes, and of secondary shear surfaces; in fact, this is observed along the San Andreas fault [*Byerlee,* 1992].

Extension in the Basin and Range Province

The argument about the kinematic history of detachment faults in metamorphic core complexes has become quite heated. One school believes that these faults form and slip at high (65°) dip angles, but that the footwall bends to near-horizontal dip as it nears the surface. *Buck* [1993] extended this bending-footwall model for normal fault rotation and showed why low-angle detachment faults should only be found in regions of anomalous heat flow. The classic example of the active normal fault along the front of the Black Mountains in Death Valley has been shown to be segmented in dip, from a maximum of 60°W in the subsurface to a minimum of 17°W where the footwall is exposed to the east [*Miller,* 1991].

However, striking evidence has also been presented for the view that at least some detachments slip while in a near-horizontal orientation. *Dokka* [1993] used a new technique of paleodepth determination to show that the Newberry Mountains detachment in California had an initial dip of only 20 to 27°. The Rawhide detachment fault in Arizona was active at a low dip [*Scott and Lister,* 1992], as shown by a marker tuff and truncated normal faults (in a section that cannot be balanced) in the upper plate. In southeast Arizona, a Miocene detachment with a dip of 20° down to 6 km also projects updip to within 100 m of Quaternary scarps [*Johnson and Loy,* 1992], which seems to show that the fault remains active at this dip.

If well-developed faults of large slip are intrinsically weak, however, these two views may not be incompatible. Detachments faults could form at high dips (while still strong), rotate to low dips by footwall bending, and continue to slip due to an aquired weakness. Some compensating deformation of the hanging wall would be required; in fact, almost all hanging walls seen in the Basin and Range province are extensively fractured and faulted.

An important new idea which has arisen in the last four years is that the lower crust of the Basin and Range province should behave as a viscous fluid, flowing in to fill the voids that extreme extension would otherwise form. Simple two-dimensional calculations [*Bird,* 1991] show that in this province the high heat-flow should cause Moho topography to be destroyed in 1-20 million years (Ma) by lateral extrusion of the lower crust. In fact, observed variations of crustal thickness at the edge of the Basin/Range province are much less than they would be in balanced cross-sections, implying either lateral extrusion or massive intrusion; *McCarthy and Parsons* [1994] use seismic data to limit the amount of intrusion.

The spatial and temporal relationships between the different core complexes (the integration of regional velocity fields) and their ultimate cause remain problems for the future. One place where there is clarity is in a benchmark study of the patterns of faulting around the moving Yellowstone plume, by *Pierce and Morgan* [1992]; because much of this deformation was clearly distinct from earlier distributed Basin/Range extension, it may serve as a model for the interpretation of structure along other, more ancient plume tracks.

Block Rotations Along the Pacific Margin

A problem presented in the last report was the explanation of anomalous paleomagnetic declinations (mostly deflected clockwise, some over 90°) in the Transverse Ranges of California. In a major revision of his previous model for Miocene rotations in California, *Luyendyk* [1991] now proposes that locally extreme extension occurred between rotating blocks, adding the degrees of freedom to make rotation possible. *Nicholson et al.* [1994] reconstructed the probable cause of this transtensional rotation event: the subducting Monterey plate froze onto the Pacific plate 20 Ma ago, suddenly changing the direction of shear tractions on the base of the margin of North America from northeastward to northwestward.

In Oregon today, the remarkable discovery of seafloor fracture zones cutting upward through the forearc wedge on the North America plate [*Goldfinger et al.*, 1992] suggest that the subduction zone is locked, and that clockwise rotation must be occurring in a dextral transpressive setting.

In the future, the interpretation of paleomagnetic data will be much more open to all earth scientists, thanks to the creation of a searchable database [*Harbert,* 1993].

Stress Field of North America

The publication of the World Stress Map has focussed thinking on the big picture; *Zoback* [1992] showed that to first order the world stress field is the result of ridge-push and continental collision resistance, with little evidence for strong basal tractions. *Richardson and Reding* [1992] used thin-plate elastic models to show that both shear and super-lithostatic normal tractions on the San Andreas and Caribbean transforms are only 5 to 10×10^6 Pa, and that this value can be explained primarily by ridge-push effects. A collection of surface-wave moment tensors from 51 western U.S. events confirms the σ_1 directions of the World Stress Map, and shows a convergence of tensional axes (σ_3) on the Mendocino triple junction [*Patton and Zandt*, 1991].

As efforts are gradually applied to study paleostress, attention should be paid to the exhaustive study of *Bergerat et al.* [1992], who used joints and faults to infer a 9-stage stress history for the Colorado Plateau since the Jurassic. Another source of data can be calcite twinning in limestones, which *Craddock et al.* [1993] used to map the Paleozoic strain (and paleostress) field in the eastern U.S.

California Neotectonics

Furlong [1993] presented an elegant synthesis of how the northward migration of the Mendocino triple junction removed the Gorda plate from under North America, creating a "mantle San Andreas transform" which was to the northeast of the surficial margin; with time, surficial fault activity jumped inboard, as from the San Andreas to the Hayward-Calaveras fault system in the San Francisco Bay area. The complicating effects of a slightly convergent Pacific plate velocity since 7 Ma are being recognized; in particular, seismic studies show probable oceanic crust of the Pacific(?) plate underthrust along the California margin from Morro Bay north to San Francisco [*Page and Brocher,* 1993].

The maturity of California neotectonic studies is shown by the fact that *Bird and Kong* [1994] were able to predict fault slip rates and geodesy to within 3 mm/year in a finite-element model; such models may serve as supplements to hard data in seismic hazard estimation.

In the area of hazard studies, it is being realized that few new (Pliocene-Quaternary) thrust faults in the Transverse Ranges actually break the surface; instead, anticlines involving Holocene sediments should be assumed to overlie seismically dangerous blind thrusts. *Shaw and Suppe* [1994] used reflection sections and balanced-section methods to infer three active thrusts under the Santa Barbara Channel, with slip rates that add up to 3 mm/year (or half the geodetically-determined rate of shortening). A Wilshire fault with a slip rate of 1.5-3.2 mm/year has also been proposed as the explanation for the Quaternary Wilshire arch under Los Angeles and Hollywood [*Hummon et al.*, 1994].

Alaskan Neotectonics

A compilation of 621 stress indicators in Alaska shows a fan pattern of σ_1 directions radiating from the syntaxis in the St. Elias range [*Estabrook and Jacob,* 1991]. In a uniform elastic material, such a stress pattern would suggest a stress singularity, or at least high values. However, a nonlinear thin-plate finite-element model with faults [*Bird*, 1992b] shows that the stress magnitudes are low, and that the pattern is due to the juxtaposition of transpression on the Fairweather fault with terrane collision of the Yakutat block. Thus, Alaska is no exception to the general weakness of major faults. The same model also predicted rapid westward transport of the west Aleutian forearc, which is consistent with the evidence of seismic slip vectors [*McCaffrey,* 1992].

Neotectonics of the New Madrid Seismic Zone

Li and Schweig [1993] questioned the view that the Mississippi embayment and New Madrid seismic zone represents simple reactivations of the Precambrian Reelfoot rift. After observed S-waves that were converted from P-waves to improve their velocity model, *Chiu et al.* [1993] relocated events and found a simple California-type pattern with thrusting in a left step of a dextral strike-slip system. The important questions remaining concern the overall rate of deformation, and how *(if)* these faults connect to plate boundaries at each end. *Liu et al.* [1992] reoccupied triangulation stations with GPS and found rapid strain accumulation (0.08 μrad/a) with a N67°E shortening direction (in agreement with stress data) and a relative velocity of 5-7 mm/year across the network. Such a rate would obviously imply significant seismic hazard along strike from the 1811-1812 aftershock zone, so confirmation of the result by homogeneous geodetic methods should be a high priority. If it is confirmed, we may have a unique opportunity to study new faults in a relatively simple midcontinental setting.

Huge Displacements of the Mantle Lithosphere?

Bird [1992a; 1994] modeled the simultaneous formation of the Rocky Mountains and the Basin/Range province by a single flat subduction event, which he suggested had sheared away and displaced the entire *tectonic* mantle lithosphere of the western U.S.. According to this model, the only *tectonic* mantle lithosphere (defined as cold and strong) remaining in the western U.S. should be a ≈40-km layer which has formed by cooling since mid-Tertiary times.

Geochemical objections have been raised to this model [e.g., *Livaccari and Perry,* 1993; 1994], especially that *geochemical* lithosphere (defined by certain element and isotope concentrations) is still present. But several recent studies have recently shown that the *seismic* lithosphere (defined by high velocity and low attenuation) has roughly the predicted structure. Humphreys and *Dueker* [1994] performed a regional tomographic inversion which confirmed that upper-mantle seismic velocities are systematically slower in the western U.S. than in the east, with the differences confined to the uppermost 300 km. In a profile from Utah to Kansas, P→S conversions at the Moho show that the crust thickens eastward from the Colorado Plateau to the Great Plains, so that the high topography of the former must be compensated in the mantle [*Sheehan et al.*, 1992]. An inversion of teleseismic data [*Halderman and Davis,* 1991] shows mantle lithosphere is 80 km thicker on the east side of the Rio Grande rift than on the west. This compares well with analysis of gravity data by *Cordell et al.* [1991] which shows mantle lithosphere thicknesses of 200 km to the East, but only 50-125 km to the west. Also, *Beghoul et al.* [1993] used teleseismic travel times to show that mantle lithosphere is typically 20-50 km under the Basin/Range and Colorado Plateau, but 150-190 km under the Great Plains. A tomographic image of uppermost-mantle (P_n) velocity in the western U.S. [*Hearn et al.*, 1991] shows that within the low-velocity region, local seismic velocity is lowest in areas of Neogene extension, and along the Yellowstone plume track.

Teleseismic shear wave splitting and polarization provide an exciting new tool to determine the stretching direction of the upper mantle fabric. At 3 sites in the west-central U.S., these directions are east/northeast-west/southwest [*Silver and Chan,* 1991]. If these fabrics are in the lithosphere, they are inconsistent with Bird's model; but if they are in the asthenosphere below, they are entirely consistent with past shallow-angle subduction. Improved depth resolution should be a priority.

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