Evidence for a strong San Andreas fault

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ABSTRACT

Stress measurements in deep boreholes have universally shown that stresses in the Earth's crust are in equilibrium with favorably oriented faults with friction coefficients in the range 0.6-0.7 and with nearly hydrostatic pore-pressure gradients. Because of the lack of any fault-adjacent heat-flow anomaly as predicted by a conductive model of frictional heating, the San Andreas fault has long been thought to be an exception: far weaker than this standard case. Borehole stress measurements near the San Andreas fault have failed to confirm this weak-fault hypothesis, being either inconclusive or in conflict with it. Directions of maximum horizontal stresses reported to be nearly fault normal in central California are now known not to be regional stresses but a result of active folding within folds that have been rotated 20°-30° clockwise from their original orientations. Everywhere in southern California it is observed that the maximum stress directions rotate to smaller angles (30°-60°) with the San Andreas, within 20 km of it. The sense of this rotation is opposite to that expected from the weak-fault hypothesis and indicates that the shear stress on the San Andreas is comparable in magnitude to all other horizontal stresses in the system. In the "big bend" section of the fault, this rotation is predicted from a transpressional plate-boundary model in which the San Andreas is loaded by a deep shear zone with a locking depth of 10 km. If the adjacent minor thrust faults are assumed to obey Byerlee friction, the crustal-average shear stress on the San Andreas must lie, in that region, in the range 100-160 MPa, regardless of the pore pressure in the fault. These stresses are many times greater than permitted by the weak-fault hypothesis. In the more trancurrent regions farther south, the San Andreas shear stress will be smaller than this estimate, but similar stress rotations observed there indicate that the San Andreas cannot be weak relative to minor faults in that region, either. These stress rotations can only be consistent with weak-fault hypothesis if it were assumed that all faults in California were equally weak, which is known to be untrue. The conclusion is that the heat-flow model is flawed, probably in its assumption that all heat transfer is governed by conduction.

INTRODUCTION

Stress measurements made in deep (>1 km) boreholes in a variety of tectonic settings have universally shown that stresses in the crust are in equilibrium with favorably oriented faults governed by friction coefficients in the range $0.6 < \mu < 0.7$ with nearly hydrostatic pore-pressure gradients (McGarr and Gay, 1978; Zoback and Healy, 1984, 1992; Brudy et al., 1997). This range of friction coefficients agrees with laboratory measurements for a wide variety of rock types (Byerlee, 1978). The dips angle of active dip-slip faults, when known incontrovertibly, also lie universally within the range expected from Andersonian mechanics, the same Byerlee friction values, and an acceptable range of pore-pressure gradients (Jackson, 1987; Sibson and Xie, 1998). Thus this Anderson-Byerlee stress state appears to be the standard state of the crust.

The San Andreas fault in California has long been thought to be far weaker than given by the Anderson-Byerlee state because of the lack of a heat-flow anomaly adjacent to the fault as predicted by a steady-state conductive model of frictional heating (Brune et al., 1969; Lachenbruch and Sass, 1980, 1992). The conclusion from this is that the crustal-average shear stress on the San Andreas cannot exceed 20 MPa, which is lower than expected by the Anderson-Byerlee state by a factor of 4 or 5.

Here this issue is reexamined by testing whether stress data in California are consistent with the weak-fault hypothesis for the San Andreas fault, as implied by the heat-flow model, or with the San Andreas fault's obeying Anderson-Byerlee mechanics.

TESTING THE WEAK FAULT HYPOTHESIS WITH STRESS MEASUREMENTS

The weak fault hypothesis makes two predictions: (1) the magnitude of shear stresses measured near the San Andreas will be low, and (2) because the San Andreas must be close to a principal plane the direction of σ_1, the maximum horizontal stress, will rotate to a nearly fault-normal orientation as it approaches the San Andreas. In the strong-fault hypothesis the predictions are the following: (1) the magnitude of the shear stresses will be high near the San Andreas, and (2) σ_1 will rotate as it approaches the San Andreas to a more acute orientation with it. Note that this sense of rotation is the opposite of that predicted by the low-strength hypothesis. In addition, the high strength hypothesis predicts that the angle Ψ between σ_1 and the San Andreas immediately adjacent the the fault must be ≤60°, the limiting case for $\mu = 0.6$ and the pore pressure $p = \sigma_3$.

Borehole Stress Measurements

The Cajon Pass Scientific Borehole was drilled expressly for the purpose of answering the question now being debated. Stress measurements in this borehole, located about 4 km from the San Andreas fault in southern California, were made to a depth of 3.5 km and showed a typical Anderson-Byerlee stress profile (Zoback and Healy, 1992). However, the orientation of the shear stresses was left-lateral, probably reflecting the stresses driving the Cleghorn fault, a minor but active left-lateral strike-slip fault which is locally subparallel to the San Andreas and 1 km from the borehole. This finding led Zoback and Healy to conclude that the the strength of the San Andreas must be very low, but Scholz and Saucier (1993) showed that at the particular location of the borehole, the stresses are insensitive to assumptions regarding the strength of the San Andreas. Thus the Cajon Pass stress measurements did not provide any information regarding the strength of the San Andreas. They only confirmed the expectation, from the worldwide findings, that minor faults in California, even those quite close to the San Andreas, obey Anderson-Byerlee mechanics.

The only other relevant stress measurements are from a series of boreholes at various distances from the San Andreas in the Mojave block northwest of Cajon Pass (McGarr et al., 1982). Those measurements, to a depth of 0.85 km, show stresses increasing linearly with depth at a rate consistent with a friction coefficient of $\mu = 0.45$ or higher. This stress gradient is thus consistent with a gouge-filled fault (Morrow et al., 1992) but if extrapolated would predict a crustal-average shear stress of 56 MPa, several times larger than allowed by the heat flow argument. Hickman et al. (1988) and Stock and Healy (1988), citing conflicting stress orientations between most boreholes in the Mojave and one measurement at the Black Butte borehole and those at Cajon Pass, argued that stress orientations in the Mojave were too variable to allow the extrapolation of McGarr et al. (1982). Because the Cajon Pass stress orientations have subsequently been shown to be a local effect (Scholz and Saucier, 1993), they should not be compared with the other Mojave measurements, which considerably weakens this latter argument.

Thus the magnitude of stresses obtained from borehole measurements are either inconclusive regarding San Andreas strength (Cajon Pass) or indicate a high-strength San Andreas (Mojave), or are also inconclusive there.

Stress Orientations

The oft-cited result that σ_1 is nearly normal to the San Andreas is from Mount and Suppe (1987; also cited in Zoback et al., 1987). They pointed out that near the San Andreas in central California, a series of active anticlines have fold axes that are nearly parallel to the San Andreas. Breakouts in boreholes within these folds indicate σ_1 directions normal to the fold axes and hence about 85° from the San Andreas. Earthquakes occur on blind thrusts within these folds with slip vectors normal to the fold axes (Ekstrom et al., 1992). Mount and Suppe assumed that these folds were formed in their present orientations and thus that the fold axes, breakouts, and earthquake mechanisms were indicators of the regional σ_1 direction, implying that $\psi = 85°$, which would indicate that not only is the San Andreas very weak, but that it also must possess a very low friction coefficient, $\mu \leq 0.1$ (Lachenbruch and Sass, 1992). This is the stress evidence that most conclusively supports the weak-fault hypothesis.

Miller (1998) has now shown that the Mount and Suppe (1987) assumption is incorrect. From paleomagnetic and other data he showed that since these folds first formed, they have rotated, by distributed shear, 25°-30° in a clockwise direction. They thus were initiated in a wrench tectonics configuration consistent with the Anderson-Byerlee framework. The folds, as structures, are weaker than the surrounding rock and they continue to be active even after rotating away from their optimum orientation in the stress field that initiated them. The stresses within the folds, i.e., compression normal to the fold axes, as indicated by the thrust earthquakes and breakouts, are thus likely to be stresses induced by the folding itself, and not indicators of the regional stress direction. This conclusion is confirmed by stress directions from inversions of earthquake focal mechanisms in the same area (Hardebeck and Hauksson, 1999). Hardebeck and Hauksson found that only within the folds is σ_1 near fault normal: farther from the fault than the folds, $\psi \approx 60°$; and closer in, $\psi \approx 50°$.

This whole area of central California is typified by strain partitioning, in which the fault-normal component of plate motion is taken up by thrusting, uplift, and folding in close proximity to the San Andreas, which accommodates the transverse component (Page et al., 1998). In such a region, stress directions are likely to be spacially quite variable. For example, Oppenheimer et al. (1988) showed that active thrusting occurs within 5 km of the strike-slip Calaveras fault in the southern San Francisco Bay area. Inverting focal-mechanism data from both sources, as well as from other nearby strike-slip faults of other orientations, Oppenheimer et al. concluded that ψ was in the range 63° - 80°. This spread is too wide to be diagnostic for the purposes of this paper, but it does point out the possibility that the stress directions may vary within their sampling area, which would violate the underlying premise of their inversion. In the next example, such rapid variations of stress direction will be demonstrated.

Hardebeck and Hauksson (1999) systematically inverted focal-mechanism data over much of southern California. They found variable σ_1 directions that commonly fluctuate over short distances. They had one systematic finding: everywhere within 20 km of the San Andreas or one of its major strands, σ_1 was observed to rotate to a smaller angle with the fault. Just adjacent to the fault, ψ was always in the range 30°-60°. The example in Figure 1 is their Fort Tejon profile, which crosses the fault from southwest to northeast in the “big bend” section of the San Andreas. In the southwestern part of this profile, $\psi \approx 90°$ and is associated with thrust faulting south such as the 1971 San Fernando and 1994 Northridge earthquakes. However, within 20 km of the San Andreas, the σ_1 direction rotates towards the fault, with $\psi \approx 40°$ in its immediate vicinity.

This stress rotation is exactly as predicted by the strong -fault hypothesis and just the opposite of what would be expected from the weak-fault hypothesis. For σ_1 to rotate toward the fault in this manner means that the shear stress on the San Andreas must be of a magnitude comparable to all other horizontal stresses in the system.

ESTIMATE OF THE SHEAR STRESS ON THE SAN ANDREAS FAULT

Hardebeck and Hauksson (1999) made an attempt to interpret their data in accord with the weak-fault hypothesis. Rice (1992) proposed a weak fault model in which the fault contains a narrow Coulomb plastic core that is very impermeable, hence can support pore pressures significantly exceeding lithostatic and thus be weak while preventing hydrofracture in the adjacent rock. Within such a Coulomb plastic core, stress will be rotated, owing to its rheology, to 45° to the fault strike (cf., Byerlee and Savage, 1992) . Hardebeck and Hauksson proposed that this is the mechanism of the stress rotation that they observed, which requires that the weak fault core be 30 km wide!

The observed cataclasite fault core, however, has a width of the order of 10-100 m (Chester et al., 1993). This model also repudiated by the Cajon Pass stress measurements, which showed that the crust is strong just 4 km from the San Andreas (Zoback and Healy, 1992). Furthermore, the Rice model cannot apply to a wide weak zone. As was explicitly stated by Rice (1992), the weak zone must be very narrow with respect to any deforming region. This requirement exists because it is only in that case that the weak zone can still be prescribed to deform only in the right-lateral-fault-parallel sense. As will be shown later, in a case such as shown in Figure 1, where there is thrust faulting in the adjacent crust, there must be very large normal stresses applied to the fault. If the fault contained a 30km-wide weak core, it would simply collapse by thrusting.

There must be very high pressures within the weak fault core to balance those high imposed normal stresses. To maintain this pressure (and prevent the fault core from being extruded), it must be in equilibrium with opposed vertical shear stresses (J. R. Rice, 1999, written commun.). These shears can only be small if the weak zone is narrow. Rice's (1999) estimate of their magnitude indicates that for a "weak" zone 10 km wide, there must be a vertical shears with a magnitude 0f 150 MPa -- which contradicts the notion of the core being weak.

This mechanism for the stress rotation may thus be confidently rejected. Here I adopt a more conventional model. For the profile shown in Figure 1, the San Andreas is highly oblique to the plate motion direction. A simple model for such a transpressional plate boundary is shown in Figure 2. The fault-normal component of plate motion, V_n induces a fault normal compression σ_{xx} that must be continuous across the plate margin and in equilibrium with thrust faulting in adjacent regions. The shear stress τ_{xy}, however, will be localized within several locking depths *H* by slip on a deep ductile shear zone beneath the San Andreas (Turcotte and Spence, 1974). There is clear evidence from geodetic (Gilbert et al., 1994) and seismic reflection observations (Henstock et al., 1997; Parson, 1998) that such a shear zone extends through the lower crust beneath the San Andreas. This localization of τ_{xy} can account for the observed stress rotations, but only if the magnitude of τ_{xy} is comparable to σ_{xx}. Independently of this model, it is possible to obtain, from a simple Mohr circle construction, an expression for $\tau_{xy}{}^0$, the shear stress on the fault,

$$\tau_{xy}^0 = (\sigma_{xx} - \sigma_3{}^{ss}) \cot \Psi^0 \qquad (1a)$$

and

$$\tau_{xy}^0 = \mu_{ss}(\sigma_{xx} - p^{ss}), \qquad (1b)$$

where Ψ^0 is the value of Ψ adjacent to the fault, and p^{ss}, μ_{ss}, and $\sigma_3{}^{ss}$ are the pore pressure, friction coefficient, and least compressive stress for the San Andreas. Notice that the expression for $\tau_{xy}{}^0$ (equation 1a) is independent of pore pressure. The normal stress σ_{xx} is in equilibrium with favorably oriented thrust faults in the adjacent crust so it is given by

$$\frac{(\sigma_{xx} - p^t)}{(\sigma_3^t - p^t)} = \left[(\mu_t^2 + 1)^{1/2} + \mu_t\right]^2, \qquad (2)$$

where the t notation now refers to the appropriate parameters for the thrust regime (Jaeger and Cook, 1969, p.89). For these minor thrust faults we assume that Anderson-Byerlee mechanics apply, i.e., $\mu_t = 0.6$, $\sigma_3^t = \rho gh$, and p is hydrostatic, $0.4\rho gh$. These parameters yield a crustal-averaged value for σ_{xx} of 284 MPa (assuming a 10 km seismogenic zone).

The range of μ and crustal-average τ_{xy}^0 obtained by substituting this value of σ_{xx} into equations 1a and 1b, for the range of observed Ψ^0, is shown in Figure 3. For this calculation, it was assumed that $\sigma_3^{ss} = \sigma_2^{ss} = \rho gh$, which minimizes τ_{xy}^0. The range of shear stresses obtained is from 100 to 160 MPa, many times too high to be compatible with the heat-flow model and precisely that predicted by Anderson-Byerlee mechanics. For the Fort Tejon profile, $\Psi^0 = 40°$, so the upper limit applies. Assumptions regarding pore pressure, $p = \lambda\rho gh$, affect only estimates of μ, not τ_{xy}^0. Using these estimates of τ_{xy}^0 and σ_{xx} in the Turcotte and Spence model with a locking depth of 10 km predicts the rotation of midcrustal Ψ shown in Figure 4 (open circles), where it is compared with the data from the Fort Tejon profile (filled squares).

South of the "big bend" the San Andreas fault system becomes more purely transcurrent and consists of several sub-parallel strands. There the stress profiles no longer resemble the one shown in Figure 1, nor does the model shown in Figure 2 apply. Nonetheless, in that region the stress data of Hardebeck and Hauksson (1999) show local minima of Ψ near each major strand. Equations 1a and 1b still apply to those cases, but equation 2 overestimates σ_{xx} because there are no active thrust faults in the adjacent crust. Thus in those areas τ_{xy}^0 will be lower than the estimate for the Fort Tejon profile but the stress rotations indicate that it is still of a comparable magnitude to all other horizontal stresses in that region, hence the San Andreas cannot be weak relative to the minor faults in that area.

DISCUSSION

It will be noticed that the above stress rotation problem is indexed by the assumed strength of the thrust faults in the adjacent crust. One could make τ_{xy}^0 compatible with the heat-flow model only if one assumes that these faults are also very weak. Because this stress rotation is observed everywhere in southern California, this approach is tantamount to assuming that all faults in southern California are weak. But such an assumption violates the basic ground rule from borehole stress measurements worldwide that shows that faults generally obey Anderson-Byerlee mechanics; the assumption also specifically is in conflict with the Cajon Pass stress measurements, that showed that a minor fault quite close to the San Andreas is strong.

I conclude that the San Andreas fault obeys Anderson-Byerlee mechanics. Does this conflict with the heat-flow observations? It does not, in fact. A broad heat-flow anomaly, some 80 km wide, is centered on the San Andreas (Lachenbruch and Sass, 1980). The amount of heat in this anomaly is sufficient to account for the heat generated by the San Andreas sliding with a shear stress of 100 MPa (Hanks, 1977). Evidence relating this heat flow anomaly to shear heating is the fact that it decreases smoothly to zero at the end of the fault at

Cape Mendicino, just in the way expected from a shear-heating model (Ricard et al., 1983), although alternatives for this have been proposed (Lachenbruch and Sass, 1980).

The conflict, then, is with the model that has been used to interpret the heat-flow data, which assumes that all heat transfer is by conduction. Could this assumption be incorrect? In the most famous case of an expected lateral heat-flow anomaly that did not exist -- the one predicted adjacent to mid-ocean ridges -- the explanation was heat loss through convection of water through the oceanic crust (Anderson et al., 1977). Could this also be the explanation for the missing San Andreas fault anomaly? O'Neill and Hanks (1980) cited geochemical evidence for abundant water circulation adjacent to the San Andreas. Williams and Narasimhan (1989) showed that for a typical topographic profile of the San Andreas gravity-induced flow could sweep away the fault-generated heat-flow anomaly. Lachenbruch and Sass (1992) argued that permeabilities measured in the Cajon Pass borehole and cores are too small for this process to occur. Permeability, however, is well known tohave a strongly positive scale dependence (Brace, 1984; Neuman, 1994). This is particularly likely in a highly fractured medium such as that near the San Andreas, where larger fractures will be encountered at larger scales. It is thus likely that the crustal-scale permeability will be much larger than that measured at the borehole or core scale, which will favor advective flow.

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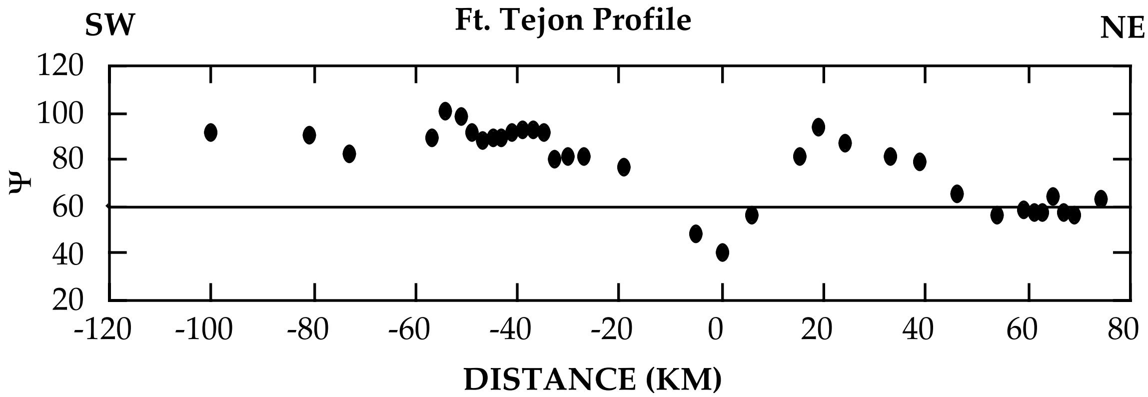

Figure 1. The angle Ψ between the maximum horizontal stress and the San Andreas fault on a profile running from southwest to northeast across western part of the "big bend" section of the San Andreas fault. Data from Hardebeck and Hauksson (1999), with permission.

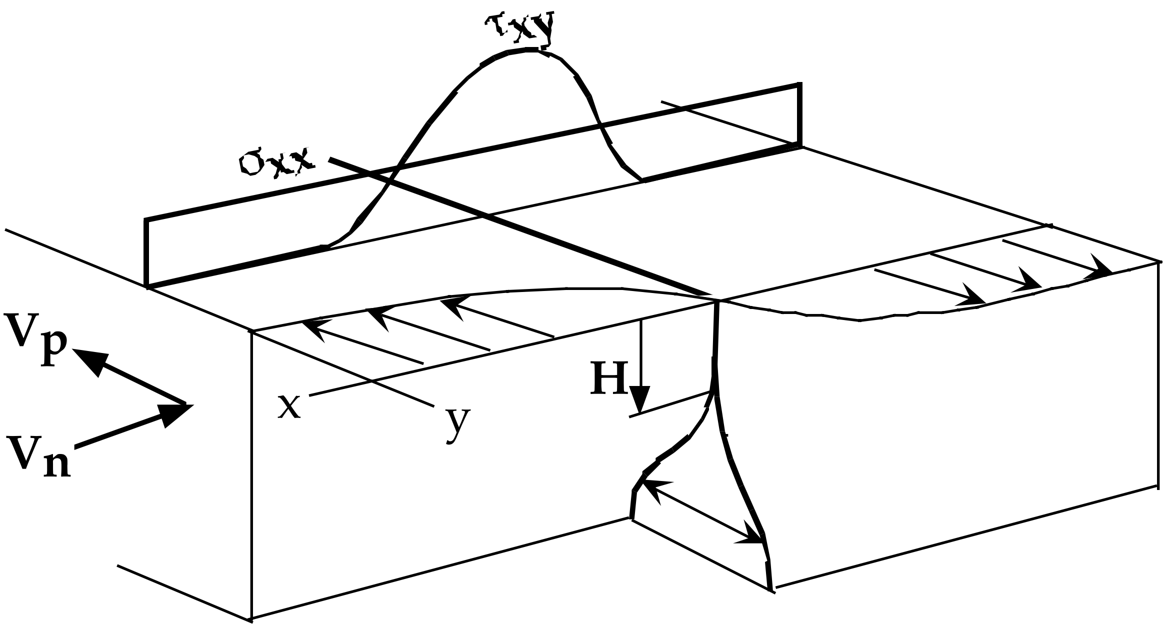

Figure 2 Model of transpressive loading of strike-slip fault with a ductile shear zone beneath a locking depth *H*. *V*p and *V*n are the plate velocities parallel and normal to the fault strike.

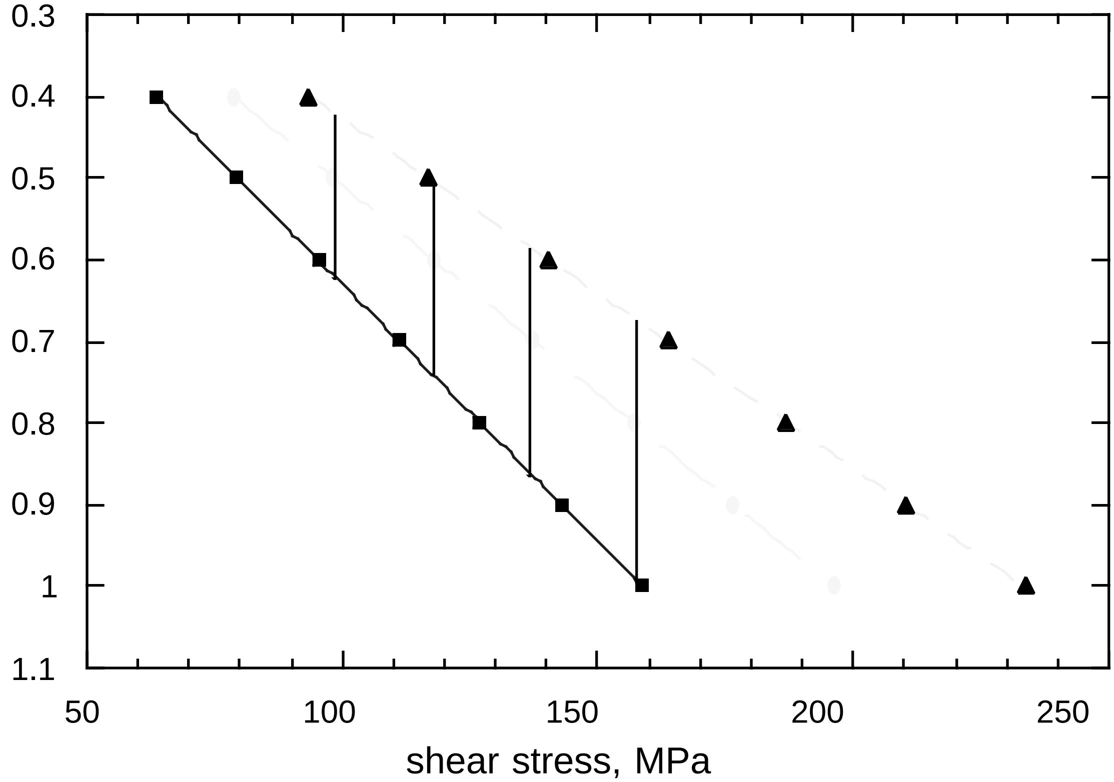

Figure 3. Shear stress and friction µ on San Andreas fault for the range of observed values of and pore pressure p = gh.

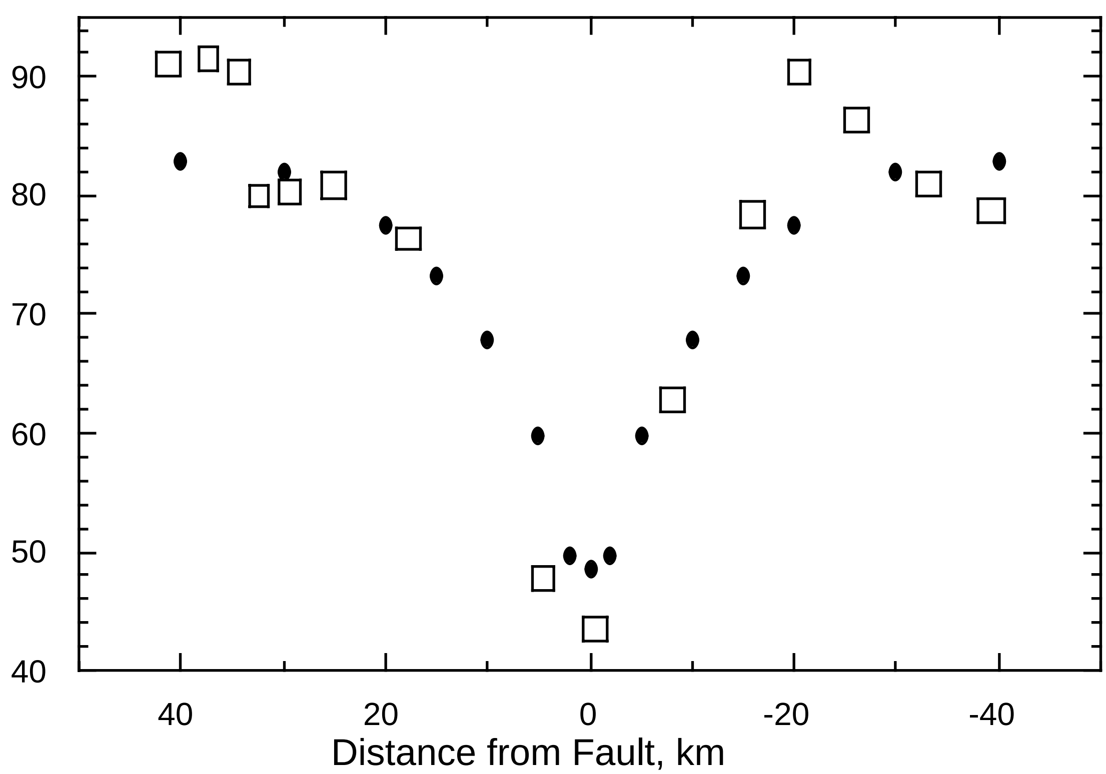

Figure 4. Mid-crustal values of obtained by using Turcotte and Spence (1974) model and stress values obtained in present calculations (open circles) compared with data of Figure 1 (filled squares).