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Parallel thrust and normal faulting in Peru and constraints on the state of stress

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We present evidence for recent normal faulting in the Cordillera Blanca of Peru along planes trending approximately N40°W, parallel to the chain. This type of faulting suggests that there is an important component of extension perpendicular to the chain and contrasts markedly with the underthrusting of the Nazca plate on the west side of Peru and with the folding and thrusting observed in the Sub-Andes, on the eastern flank of the chain. These contrasting styles of deformation and associated stress fields can be explained by buoyancy forces due to the high mountains and crustal roots. In so far as this explanation is correct, the difference in elevation between zones of normal and thrust faulting can be used to place an upper bound of 500 bars on the average stress difference in the crust.

1. Introduction

The close proximity of thrust and normal faulting implies locally different stress fields and should place constraints on the values of the stresses. Recently, there has been discussion of several regions in which thrust and normal faulting occur near to one another in various tectonic settings. Normal faulting in Tibet seems to occur on approximately north-south planes, and therefore with extension perpendicular to the direction of crustal shortening in the Himalaya to the south [1–4]. Because of the approximately perpendicular directions of shortening and extension, large changes in a regional stress field are not required. More problematic is the situation in the Aegaean and northern Greece, where normal faulting occurs in close proximity to the thrust faulting in western Greece and along the Aegaean arc [5–8]. There remains some controversy about the directions of extension in the Aegaean area, but it is clear that the distribution of normal faulting is more complicated than in Tibet, where there are fewer data. McKenzie [6] believes that much of the normal faulting occurs on planes parallel to the thrust faults and he appeals to processes occurring beneath the lithosphere to generate this stress distribution. Dewey and Sengör [9], Le Pichon and Angelier [10], Tapponnier [11] and others, however, consider the normal faulting to be more nearly perpendicular to the thrust faulting, and they appeal stress fields generated in the plates from forces applied to their margins and/or to buoyancy forces to explain the juxtaposition of faulting. Closely related normal and thrust faulting have also been reported for Italy [12], but the data there are still too fragmen-

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tary to place a strong constraint on the stress fields that operate in that region.

One of our purposes here is to discuss another example of such a juxtaposition of normal and thrust faulting, in Peru. We consider the thrust and normal faulting in Peru to be the best example of a region where such faulting occurs on planes with approximately the same strike. We then use this difference in fault type and differences in elevation to place a constraint on the average stress differences in the Andes and surrounding stable regions.

2. Thrust and normal faulting in Peru

Fault plane solutions of earthquakes clearly show eastward subduction of the Nazca plate beneath Peru [13]. This subduction seems to have occurred since the late Cretaceous and perhaps since the late Paleozoic [14–16]. In the Sub-Andes, on the eastern slope of the Andean chain, Pliocene folding and west-dipping thrust faulting attest to crustal shortening perpendicular to the chain [14,16–19]. Fault plane solutions of crustal earthquakes indicate continued thrusting (Fig. 1; [13,41]), and in most cases, the vergence of the folds and the directions of the overthrusting is to the east or northeast. This two-sided nature of the Andes, at least for the last 5 m.y., with faults and folds verging in opposite directions on the two sides, is characteristic of many intracontinental belts: both the Pyrenees and the High Atlas during the Mesozoic and Cenozoic [20,21], the Tien Shan at present [22], as well as for the Cordillera of western North America in the late Cretaceous and early Tertiary [23]. What is more interesting about Peru, however, is that there is also recent normal faulting in the high Andes on planes also approximately parallel to the chain.

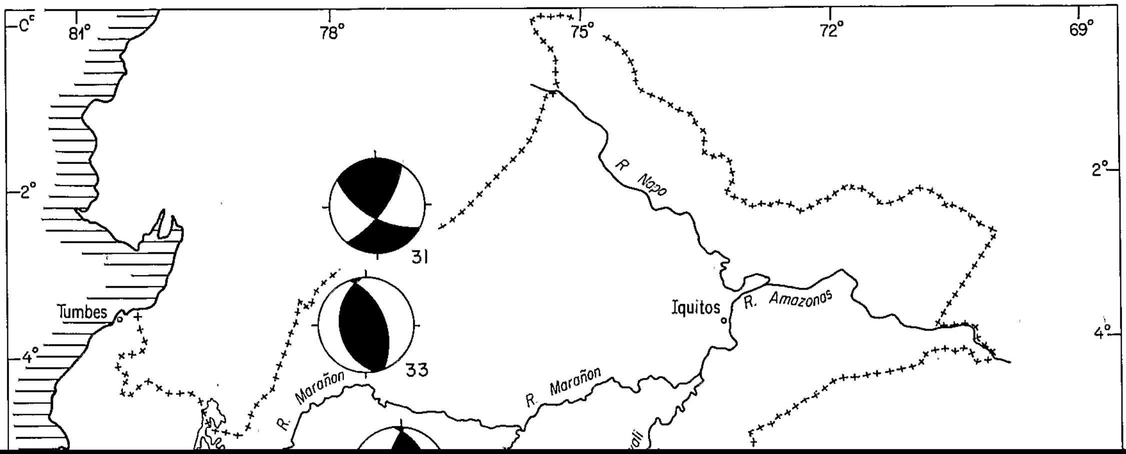
The clearest examples of recent normal faulting in the Andes seem to be the Cordillera Blanca (Figs. 2 and 3). The Cordillera Blanca extends for a distance of 180 km in a northwest direction in the central part of the Cordillera Occidental between 8°15′S and 10°S. Altitudes often exceed 5500 m and reach 6800 m on the peak Huascaran (Figs. 2 and 3). On the west the range is bounded by a depression along the Rio Santa that is about 5 km wide and, on the average, 2500 m high. The Cordillera Blanca consists of a plutonic complex 3–12 m.y. old [14,24,25].

Dalmayrac [26] thinks that the relief of the Cordillera Blanca is very recent because the marl and sandy deposits, of fluvial and lacustral origin, at the base of the massif and immediately beneath Quaternary moraines, do not contain any blocks suggesting the close proximity of high relief. These deposits are associated with ignimbritic tuffs, probably of Pliocene age. Thus, he inferred that there may have been 2000 m of uplift of the Cordillera Blanca during the Quaternary.

The boundary between the depression of the Rio Santa and the Cordillera Blanca corresponds to an important fault zone trending N40°W that seems to follow the entire length of the west flank of the Cordillera Blanca. The fault zone consists of normal faults with steep dips to the west or southwest. Slickensides generally have pitches between 70° and 90° indicating extension in approximately the direction N65°E. For 150 km, one finds a series of normal faults that displace Quaternary glacial deposits at the foot of the Cordillera Blanca 5–100 m (Fig. 2; [26]). Some faults seem older than others because they displace only older moraines, whereas those displacing younger moraines are not eroded much. Yonekura et al. [42] estimated the ages of moraines cut by the normal faults and concluded that rates of slip are about 2–3 mm/yr. They estimate that the total displacement is about 4000 m, so that indeed the displacement is Quaternary in age.

The en echelon arrangement of the faults (Figs. 2 and 3) suggests that they might be related to deep-seated strike-slip movement [27], but the movement on each individual fault seems to be primarily dip-slip. We infer that the strike-slip component is not large.

Although these faults appear to be the clearest examples of active normal faulting, there seem to be others in the Andes. The faulting associated with the 1946 Ancash earthquake indicated primarily normal faulting on a plane parallel to the chain [28–31]. Megard [16] cites examples of normal faulting farther south, and Lavenu [32], Lavenu and Soulas [33], Mercier [8], and Suarez et al. [41]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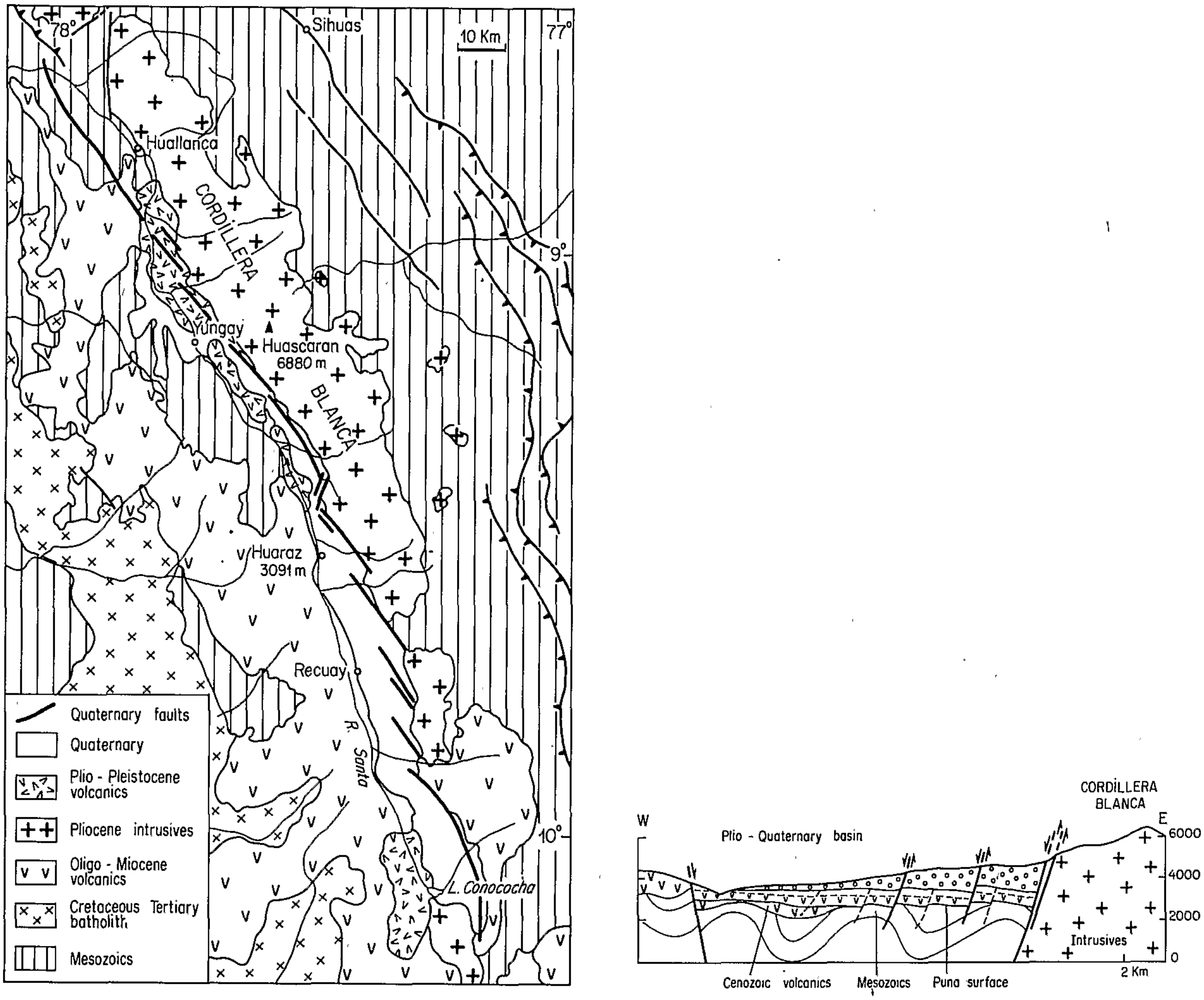


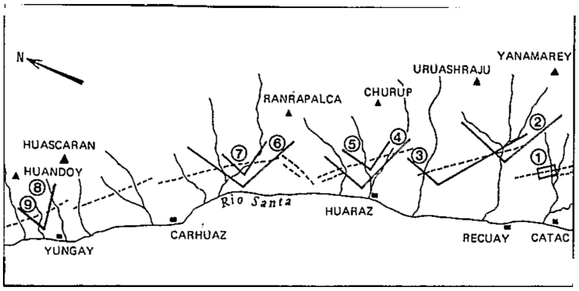
Fig. 2. Geologic map (a) of and cross-section (b) through the Cordillera Blanca of Peru.

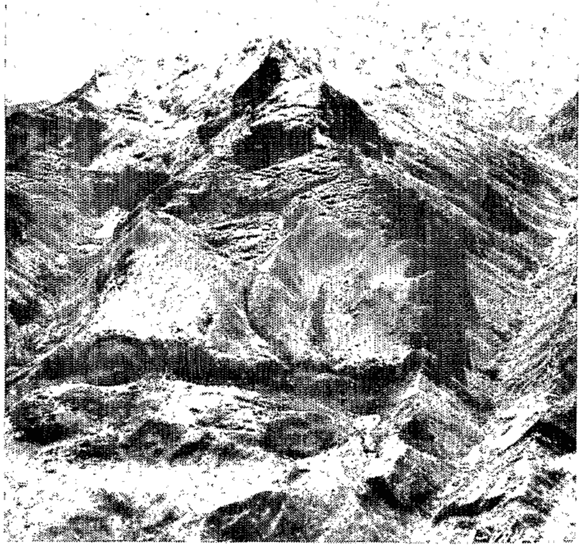
report normal faulting in the Altiplano of Bolivia and Southern Peru. In all cases, the normal faulting seems to occur where the altitudes are high.

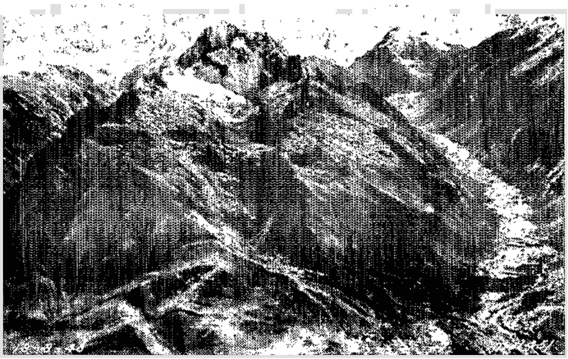
It is important to note, however, that in some other areas where the altitudes are high, recent or active reverse faulting and horizontal shortening have occurred. The surface faulting observed at 4500 m elevation associated with the 1969 Pariahuanca earthquake shows a component of reverse faulting [34]. Moreover, folding of Quaternary sediments near Huancayo (3300 m) indicates northeast-southwest crustal shortening [16,35].

3. Constraints on stress differences in the earth

The existence of mountains requires differential stresses in the crust to maintain the elevations and associated crustal roots. With some simple assumptions, which we think are reasonable, the amount of relief can be used to place limits on the stress differences. The existence of mountains and crustal roots, or any kind of lateral density variation, alone does not allow a unique solution for the stress distribution. In the absence of assumptions about the rheological properties (a constitutive relation), one may add or subtract an arbi-







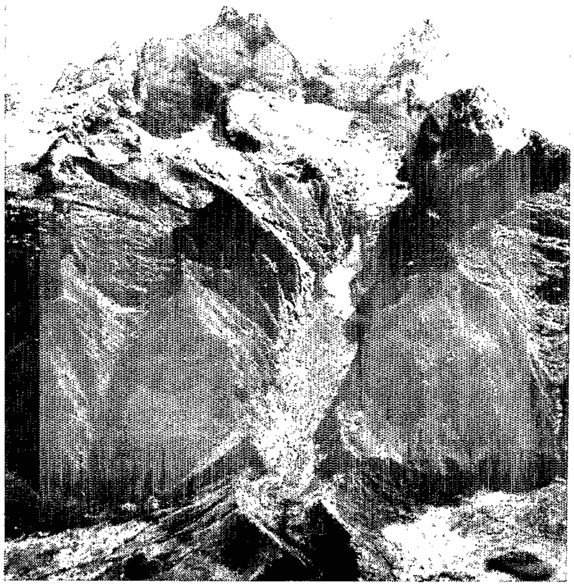


Fig. 3. Map (a) and oblique aerial photos (b, c, and d) of normal faults (from Dalmayrac [26]). Photos are of region 7 on map (b), of region overlapping southwest edge of region 4 and 5 on map (c), and of region 8 (d).

trary horizontal compressive stress to the medium without violating the equations of equilibrium or the boundary conditions at the surface. The reason why the juxtaposition of thrust and normal faulting in Peru is important is that it can be used as an argument to constrain the value of this arbitrary horizontal compression.

In two dimensions the equations of equilibrium are:

$$\frac{\partial \tau_{zz}}{\partial z} + \frac{\partial \tau_{xz}}{\partial x} = \rho g \qquad (1)$$

and:

$$\frac{\partial \tau_{xz}}{\partial z} + \frac{\partial \tau_{xx}}{\partial x} = 0 \qquad (2)$$

where the geometry is shown in Fig. 4, ρ is the density and can depend on both x and z, g is gravitational acceleration, and τ_{zz}, τ_{xx}, and τ_{xz} are the vertical normal, horizontal normal, and vertical (or horizontal) shear stresses. The boundary

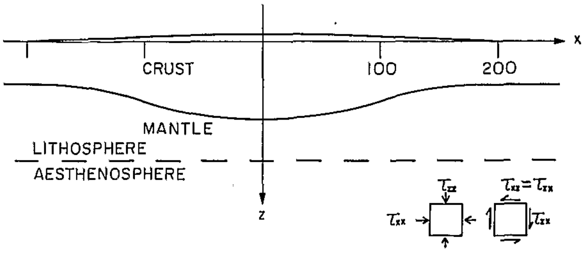


Fig. 4. Simple cross-section of mountainous region to define coordinates.

conditions at the top surface are that the normal and shear stresses vanish. If the gradients in the relief are not large, this corresponds with $\tau_{zz} \approx \tau_{xz} \approx 0$. We may also assume that $\tau_{xz} \approx 0$ at the bottom of the lithosphere, because the aesthenosphere is presumably too weak to support substantial shear stress. Before proceeding, notice that if we add to the horizontal stress (τ_{xx}) an additional compressive stress that depends only on z, we will violate neither equations (1) or (2) nor the boundary conditions. This is the additional compressive stress mentioned in the preceding paragraph.

It is customary to assume that $\tau_{xz} = 0$ at all depths [36–40]. Because it is zero at the surface and essentially zero at the bottom of the plate, it is not likely to be large within the plate. Clearly, if $\tau_{xz} = 0$, then:

$$\tau_{zz}^{(x,z)} = \int_{\text{surface}}^{z} \rho(x,z) g \, \mathrm{d}z$$

equal to the lithostatic pressure. Notice also that the horizontal stress (τ_{xx}) is independent of x, and that both the horizontal (τ_{xx}) and the vertical (τ_{zz}) compressive stresses are principal stresses. Even if τ_{xz} were not zero everywhere, the mean value of τ_{xx} in the layer would be independent of x (see Appendix 1).

Because of the load of the mountains in some areas, the values of the vertical stress (τ_{zz}) as a function of depth will be different for different horizontal positions (x) with the same depth. Fig. 5 shows profiles of the vertical stress beneath the mountains ($x = 0$) and beneath the neighboring plains (large x). (The scale is distorted to emphasize the form of the stress differences.) Because

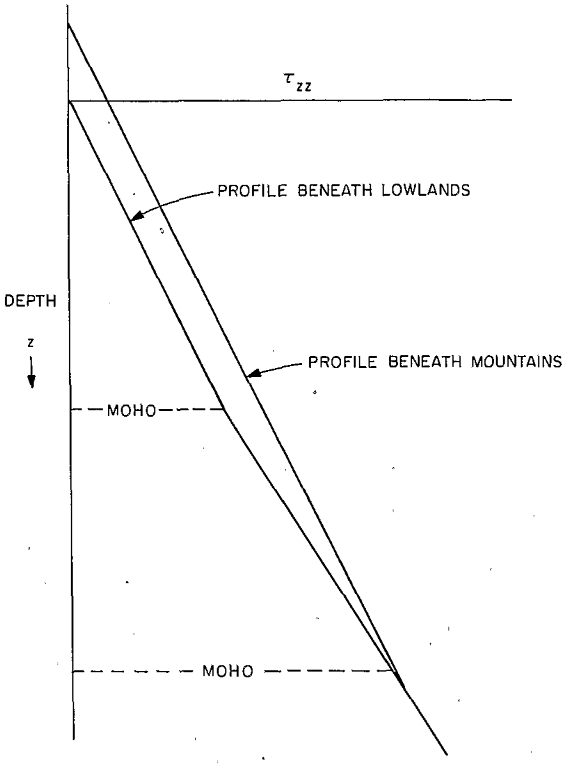


Fig. 5. Plots of τ_{zz} with depth for regions of high and low altitudes. Note the difference is such that τ_{zz} is larger at any depth beneath the mountains than beneath the lowlands.

the earth is probably nearly in hydrostatic equilibrium, the horizontal and vertical stresses are probably not very different. Because the vertically averaged value of the horizontal stress is independent of x (see Appendix 1) but that for the vertical stress (τ_{zz}) varies with x, there will exist differences between horizontal and vertical stresses. For instance, if the horizontal and vertical stresses were equal beneath the mountains ($\tau_{xx}(0, z) = \tau_{zz}(0, z)$), then the horizontal stress would exceed the vertical at all depths where elevations were lower and the difference would reach a maximum in the neighboring lowlands. We would expect thrust faulting in these regions. If instead, the horizontal and vertical stresses were equal in the lowlands, then within the mountains, the vertical stress would exceed the horizontal stress at all depths and we would expect normal faults there. Notice, however, that the boundary conditions at the surface allow the values of horizontal stress to be either greater than or less than those of the vertical stress, everywhere. In these cases, we would expect thrust or normal faulting everywhere.

The juxtaposition of thrust and normal faulting in Peru is important because the normal faulting in regions of high altitude implies that the vertical stress is maximum there, but the thrust faulting on the flanks of the mountains suggests that the horizontal stress is maximum there. Thus, since the average value of the horizontal stress in the plate is constant, the difference between the horizontal and vertical stresses is everywhere less than the difference between the vertical stress in the mountains ($x \sim 0$) and in the lowlands (large x). The average differential stress, averaged over depth, between τ_{xx} and τ_{zz} is everywhere less than:

$$\overline{\Delta\tau_{zz}} = \frac{1}{h}\int_{\text{surface}}^{h} \left[\tau_{zz}(0,z) - \tau_{zz}(\infty,z)\right] \mathrm{d}z \qquad (3)$$

The value of the integral is simply the area between the two curves in Fig. 5. For mountains 4 km high and with a density of 2.7 g/cm^3, $\overline{\Delta\tau_{zz}} \approx$ 400–450 bars, depending upon whether isostatic compensation takes place solely by crustal thickening or also by the existence of lighter mantle material beneath the mountains than the plains. Therefore, the average difference between the horizontal and vertical stresses is less than 400–450 bars, and in so far as they are principal stresses, the maximum shear stress averaged through the crust is less than 200–225 bars.

Some words of caution in using these bounds are necessary. First, these bounds are for vertically averaged stresses. Both stress differences and maximum shear stresses could be larger at some depths than others and in some regions than in others. In particular the shear stresses on faults at shallow depths could be greater than these averages. Moreover, the assumption that τ_{xz} is zero is probably reasonable where the altitude and thickness of the crustal root are constant, but in the transition region between them, τ_{xz} may not be as close to zero as in the neighboring regions. Somewhere in this transition zone, $\tau_{xx} = \tau_{zz}$ so that there τ_{xz} would be the maximum shear stress. We presume that it is small, so that its average is less than 200 bars. Because the faulting of interest here, normal faulting in the high regions and thrust faulting in the foothills, does not occur in the transition region, the bounds on the average stresses are probably reasonable for the areas where faulting does occur.

It is also important to note that these are static arguments and do not depend on or constrain the dynamic processes that formed the mountains. We do not think that there has been extensive normal faulting and stretching of the crust in the Andes. The normal faulting merely indicates an orientation of the least compressive stress. Similarly the thrust faulting and folding indicate the orientation of the maximum compressive stress. The thrust faulting, however, is a consequence of convergence of South America and the Nazca plate and involves much greater displacements on the west, and probably on the east also, than the displacements on the normal faults. Thus the thrust faulting is not a consequence of the extension in the high Andes but instead contributes to the elevation that in turn creates a situation in which the gravitational body force is balanced by a stress system that causes normal faulting.

4. Conclusions

Whereas the Nazca plate underthrusts the western margin of the Andes and the Brazilian shield underthrusts the eastern margin, in the high Andes, there is clear evidence of recent normal faulting on planes approximately parallel to the chain. Thus, at low altitudes one has crustal shortening, and roughly horizontal compression perpendicular to the chain is present. At high altitudes in some regions, however, there is crustal extension, and the least compressive stress is perpendicular to the chain. These different stress distributions can be explained by buoyancy forces arising from the gravitational body force acting on the high mountains and the associated crustal root. The average stress difference in the crust due to the buoyancy forces is less than 500 bars, corresponding to a maximum average shear stress of less than 250 bars.

Similar arguments have been given for Tibet [2,3,40]. There, however, because the thrust and normal faulting seem to occur on planes with nearly perpendicular strikes, the constraint on the stress differences requires an additional assump- [illegible]

weight of the overburden and τ_{xx} is constant.

Furthermore, notice that in so far as the functions are well behaved, we can integrate equation [illegible]

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