

# Mantle Earthquake Mechanisms and the Sinking of the Lithosphere

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Downgoing slabs of lithosphere may exert a pull on the portions of plate left at the surface.

THE concept of the lithosphere as a stress guide<sup>1-3</sup> suggests that information about the major driving forces in global tectonics can be obtained from knowledge of the state of stress within the lithosphere. Most shallow earthquakes seem to occur between plates of lithosphere and therefore yield information about the direction of motion of one plate with respect to the other rather than the stress within a plate. But analysis of focal mechanism solutions from the Tonga and Japanese regions<sup>2</sup> suggested that deep and intermediate depth earthquakes occur within downgoing slabs of lithosphere in response to stresses within the plates. A chief purpose of this article is to show that a comprehensive and worldwide survey (our unpublished results) of focal mechanism solutions supports this interpretation of deep and intermediate depth earthquakes. We can therefore determine the orientations of stress within the various downgoing slabs on a worldwide basis.

## Gravitational Forces on Downgoing Slabs

The main result of this survey is that the stress in those portions of the mantle seismic zones that have a relatively simple inclined planar configuration, that is, in those portions removed from remarkable contortions or changes in trend, is often oriented such that either the axis of maximum compressive stress or the axis of minimum compressive stress is approximately parallel to the dip of the inclined seismic zone. We find clear evidence for down-dip extensional stress within slabs at intermediate depths in at least six regions. These regions seem to be also characterized by prominent gaps in the seismicity at depths between about 300 and 500 km or by an absence of earthquakes deeper than about 300 km. On the other hand, down-dip compressional stress is predominant at depths greater than 300 km in all regions studied.

These results are summarized in Figs. 1 and 2, and a simple model that attempts to account for them is given in Fig. 3. In this model a heavy slab sinks into the asthenosphere, exerts a pull on the portion of the plate remaining on the surface, and eventually hits bottom in such a way that the support for the load of excess mass within the slab is transferred from above the load to

beneath the load. Although the two-dimensional model is certainly too simple to explain all the data, the general predominance of down-dip stress orientations and, especially, the widespread occurrence of down-dip extensional stress, lend encouragement to the ideas that gravitational body forces on the downgoing slabs are important forces in determining the stress within the lithosphere and may be important forces in driving the global system of plate movements.

## Axes of Stress

The data include, primarily, focal mechanism solutions of the double-couple type for deep and intermediate depth earthquakes that are large enough ( $M \geq 5.5$ ) to obtain reliable first-motion data from the World-Wide Standardized Seismograph Network (WWSSN). Although these data are restricted to earthquakes that occurred since 1962, reliable solutions for previous earthquakes are also used for certain regions. The data are discussed in more detail elsewhere (our unpublished results). In this article we focus attention primarily on the results for fourteen island arcs and arc-like structures for which the orientations of the inclined seismic zones are relatively simple and well defined. This selection is required because the basic analysis consists of comparing the orientation of the double-couple mechanism solutions with the local orientation of the inclined seismic zone.

Some of the excluded earthquakes occur in zones or portions of zones that are remarkably contorted or complex in structure, such as the northern end of the Tonga arc. The mechanism solutions in these and similarly complex regions reflect the complexities of structure and are reported on in detail elsewhere (ref. 3 and our unpublished results). Others that are excluded occur in regions where the data are insufficient clearly to define a planar zone, such as the Mediterranean and Himalayan regions. Nevertheless, about 60 per cent of the earthquake mechanism solutions are included, and the results apply to most of the major island-arc structures of the world.

The overall results are shown in Fig. 1 in which the stress axes and the poles of nodal planes of the most reliably determined double-couple solutions are plotted relative to the local orientations of the seismic zones. One

of the nodal planes of a mechanism solution is the fault plane of the equivalent shear dislocation, and the pole of the other nodal plane gives the direction of slip<sup>4,5</sup>; the seismic data do not, however, distinguish which is which. The compressional (P), tensional (T) and null (B) axes coincide with the axes of maximum, minimum and intermediate compressive stress in the medium only if the nodal planes define planes of maximum shear stress in the medium. This must be taken as an assumption of the analysis. If a Coulomb-Navier type of fracture process is operative for deep and intermediate depth earthquakes and the effective coefficient of internal friction is less than one<sup>2,6</sup>, the P, T and B axes will still be good approximations (within the uncertainties of the analyses) to the principal stress axes.

Fig. 1*d* shows clearly that neither of the possible fault planes is parallel to the seismic zone. This result supports the contention<sup>2,3</sup> that intermediate and deep earthquakes do not indicate slip along a major thrust fault defined by the inclined seismic zone. Figs. 1*a*, 1*b* and 1*c* show that, instead, the inferred stress axes of the double-couple solutions tend to be parallel or perpendicular to the planar geometry of the zones. This result suggests that the downgoing slabs act as stress guides. If the lithosphere can support stresses considerably larger than those in the asthenosphere, so that the shear stresses are relatively small along the upper or lower boundaries of the plate, then the principal axes of stress within a thin plate of lithosphere will be approximately parallel and perpendicular to the plate.

### Deviatoric Stresses

This interpretation is strongly supported by recent estimates<sup>7,8</sup> of the magnitude of the deviatoric stresses involved in deep and intermediate depth earthquakes. These stresses appear to be one to two orders of magnitude greater than the stresses estimated<sup>8,9</sup> for zones of shallow earthquakes where movements between plates of

lithosphere are apparently accommodated along zones of weakness. Also, Stacey<sup>10</sup> has pointed out that thermodynamic problems arise if stresses much greater than 10 bars are associated with the large strain rates in the mantle that are required by sea-floor spreading and continental drift. These problems may be circumvented if the earthquakes in the mantle indicate large stresses within lithospheric plates rather than the smaller stresses within the weaker asthenospheric material where most of the mechanical work is being done.

The predominance of simple down-dip stress orientations shown in Figs. 1*a* and 1*b* suggests that in those portions of the zones characterized by relatively simple planar geometry the stress may be a result chiefly of the forces directly involved in the downward motion of the plate. The presence of down-dip extensional stress suggests that the slabs may be pulled into the mantle as a result of a negative buoyancy of the slab as suggested by Elsasser<sup>1</sup>. At rates of descent of the order of 10 cm/yr, temperatures in the slab may be of the order of 1,000° C cooler than the adjacent mantle, and positive density anomalies of the order of 0.1 g/cc would result.

Hatherton<sup>11</sup> and Morgan and Smith<sup>12</sup> find support for such excess mass in analyses of gravity data. If this load were supported chiefly by tractions along the large areas beneath the surficial plates of lithosphere, then simple calculations show that the deviatoric stress within the downgoing plate would be extensional, of the order of several kilobars, and would decrease with depth (Fig. 3*a*). As the slab penetrates into stronger material beneath the asthenosphere the support for the load of excess mass is transferred from above to below the load, and the stress in the lithosphere would depend on the variation of excess mass within the slab and the variation of strength with depth. In general, one might imagine a stage in which part of the load is supported from below and part from above (Fig. 3*b*) such that the stress changes from extension at intermediate depths to compression at great depths,

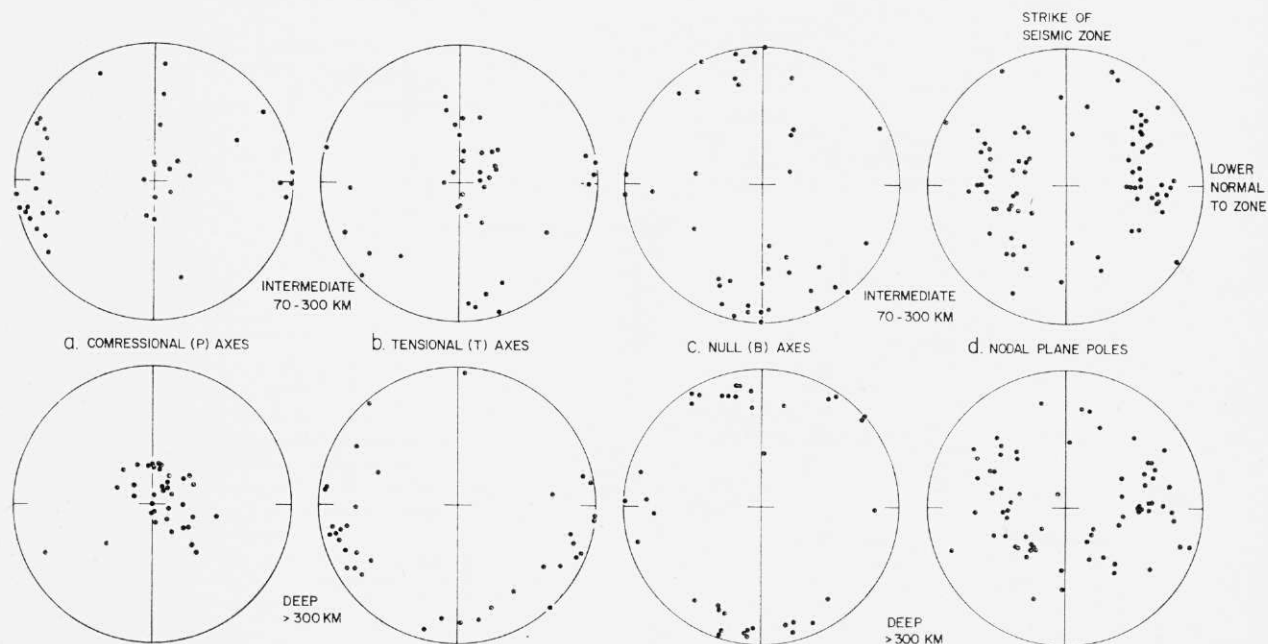


Fig. 1. Equal-area projections of the axes of compression (P), axes of tension (T), null axes (B) and the poles of the nodal planes of the most reliably determined double-couple mechanism solutions of deep and intermediate depth earthquakes. The centre of each plot is in a direction parallel to the dip of the inclined seismic zone; the strike of the zone and the direction normal to the zone (on the lower side) are as shown in Fig. 1*d*. The regions and number of earthquake mechanisms included in this plot are as follows: Tonga<sup>3,4,22</sup> (15° S–26° S), 14; Kermadec<sup>3,21</sup> (26° S–36° S), 1; North Island, New Zealand<sup>23,24</sup> (36° S–41° S), 1; New Hebrides<sup>19</sup> (10° S–22° S), 9; Sunda (unpublished results of B. I. and P. M. and of T. Fitch and P. M.) (100° E–127° E), 9; Marianas<sup>25</sup> (12° N–24° N), 2; Izu-Bonin<sup>25–28</sup> (24° N–35° N), 8; Philippines<sup>19</sup> (3° N–12° N), 3; Ryukyu<sup>25</sup> (24° N–33° N), 2; northern Honshu<sup>26–29</sup> (35° N–43° N), 4; Kuriles<sup>21</sup> (43° N–52° N), 8; Aleutians<sup>19</sup> (145° W–170° E), 1; Middle America<sup>30</sup> (14° W–105° W), 5; Chile<sup>19</sup> (15° S–30° S), 8. The data on focal mechanisms and the structures of the seismic zones are described in more detail in the references indicated here.

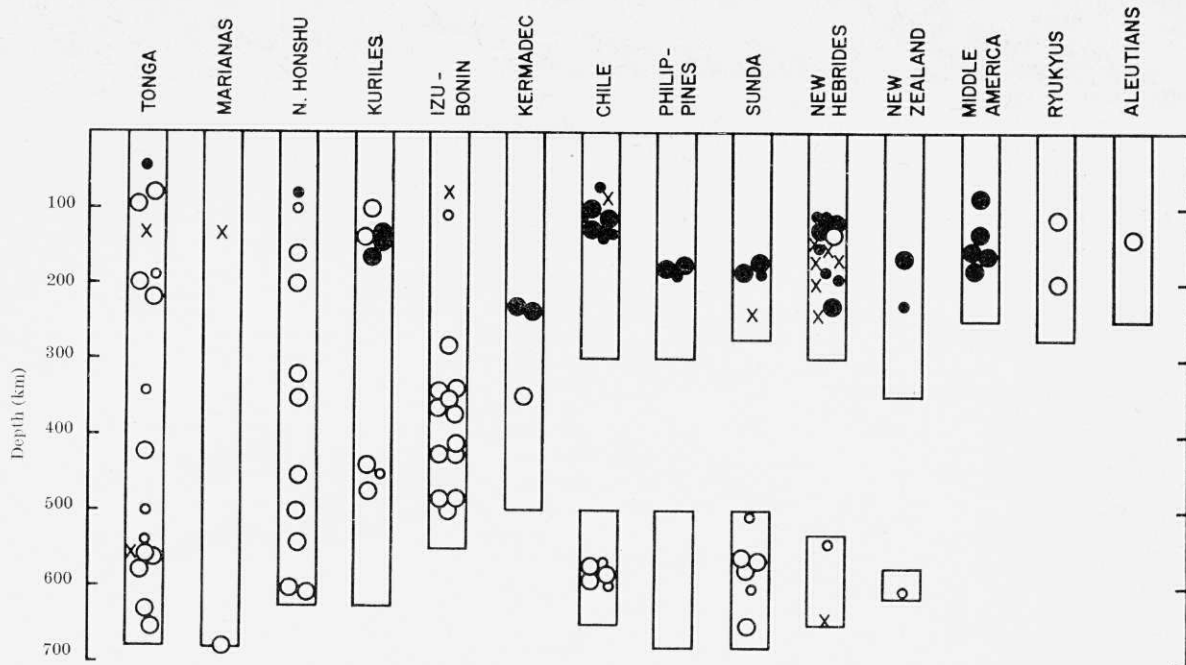


Fig. 2. Down-dip stress type plotted as a function of depth for fourteen regions (see caption for Fig. 1 for locations of regions and sources of data). A filled circle represents an orientation such that the axis of tension  $T$  is within 20–30 degrees of the local dip of the zone, that is, down-dip extension; an unfilled circle represents an orientation such that the axis of compression  $P$  is within 20–30 degrees of the local dip of the zone, that is, down-dip compression; and the Xs represent orientations that satisfy neither of the preceding. Smaller symbols represent less reliable determinations. The enclosed rectangular areas approximately indicate the distribution of earthquakes as a function of depth by showing the maximum depths and the presence of gaps for the various zones. In addition to the references listed in the caption to Fig. 1, data from Barazangi and Dorman<sup>19</sup> and Gutenberg and Richter<sup>18</sup> were used for each of the fourteen regions. The zones are grouped (from left to right) according to whether the zone is continuous to depths of 500–700 km, discontinuous with a gap between intermediate depth and deep earthquakes, or continuous but reaching depths less than 300–400 km.

with zero deviatoric stress somewhere between. When the load is fully supported from below, the stress becomes compressional throughout. Fig. 3*d* shows an alternative development where, as a result of the extensional stress and a possible stoppage in the movements, a piece of lithosphere breaks off, sinks independently, hits bottom and thereby comes under compression. In Figs. 3*b* and 3*d* gaps in the distribution of earthquakes as a function of depth might occur between extensional type mechanisms at intermediate depths and compressional type mechanisms at great depths. Where the seismic zone is continuous, that is, where earthquakes occur throughout the range of depths to 600–700 km, the slab would be under compression throughout.

### Seismicity and Depth

The model shown in Fig. 3 thus predicts a correlation between the respective depth variations of focal mechanism and seismicity. Fig. 2 shows that this correlation is partially supported by the data. The regions where down-dip extensional stress predominates, such as Middle America, the New Hebrides and Chile, are characterized by notable gaps in seismicity as a function of depth or, in the case of Middle America, an absence of deep earthquakes. On the other hand, in regions such as Tonga, Izu-Bonin and northern Honshu the zones are apparently continuous and exhibit down-dip compressional stress at intermediate depths as well as great depths. Thus Tonga, Izu-Bonin and northern Honshu would be represented by Fig. 3*c*; Middle America would be represented by Fig. 3*a*; and Kermadec, Chile, North Island of New Zealand, New Hebrides, Sunda and Philippines would be represented by Fig. 3*b* or 3*d*.

Anderson<sup>13</sup> and others have proposed a phase change at depths near 350–400 km where the density increases by 9–10 per cent. If  $dT/dP$  for the phase boundary is positive (as proposed by Anderson), and the change occurs with

sufficient rapidity, the transition to greater density in the lithospheric plate might occur above the level of the transition in the adjacent mantle. This added load applied near 300–400 km depth might help to explain the prevalence of compression everywhere below 300 km as well as the prevalence of minima or terminations (Fig. 3) in the various distributions of seismicity as a function of depth.

Certain other areas not included in the present analysis because of uncertainties in the configuration of the subcrustal zone may offer further support for the models of Fig. 3. Intermediate depth earthquakes in the Hindu Kush, for example, are characterized by  $T$  axes that dip gently northward<sup>14,15</sup>. If this zone of intermediate depth earthquakes is a remnant of a larger slab underthrust

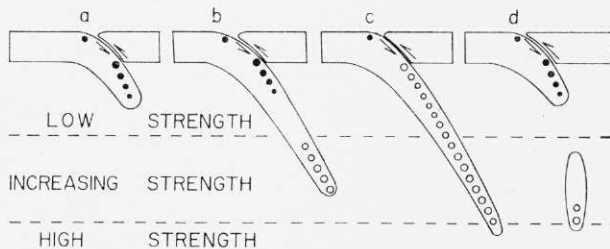


Fig. 3. A cartoon showing possible distributions of stresses in slabs of lithosphere that sink into the asthenosphere (*a*) and hit bottom (*b*) and *c*. *d* represents the case where a piece of lithosphere has broken off. The symbols are the same as in Fig. 2; the filled circles represent down-dip extension and the unfilled circles represent down-dip compression. The size of the circles qualitatively indicates the amount of activity at the respective depths. In *b* and *d* gaps in the seismicity would be expected. Also shown is the underthrusting and the extensional stresses near the upper surface of the slabs due to the bending of the slab beneath the trenches. These features are inferred from the mechanisms of shallow earthquakes<sup>2</sup>. The lower boundary where the slabs hit bottom might correspond to the transition region or discontinuity near 650–700 km<sup>13,31</sup>.

beneath the Himalayas, then the focal mechanism orientations might be indicative of down-dip extensional stress. The deep earthquakes beneath western Brazil are located nearly vertically beneath intermediate depth earthquakes and are apparently associated with the island arc-like features of the Peru trench. The deep mechanisms are characterized by nearly vertical P axes (refs. 16 and 17 and our unpublished results). Although the structure of the seismic zone is not well defined, the locations of earthquakes<sup>18,19</sup> suggest that the deep zone also dips very steeply beneath western Brazil.

### Limitations of the Two-dimensional Model

Further comparisons of Figs. 2 and 3 show that the correlation breaks down in certain regions. In particular, the down-dip compressional stresses in the Aleutians and Ryukyus, the presence of both compressional and extensional stresses at intermediate depths in the Kuriles and New Hebrides, and the solutions denoted by "X" are not explained by the two-dimensional models of Fig. 3. These discrepancies, as well as the complex mechanisms and structures excluded in the analyses of Figs. 1 and 2, indicate the unsurprising result that the two-dimensional model of Fig. 3 does not explain all the data. Certainly, contortions and disruptions of the lithospheric plates would be expected to affect the stresses, although a search for such effects does not yield any simple relationship between the mechanism orientations and the contortions of the zones.

Nevertheless, one interesting association can be pointed out. The down-dip compressional stresses present in the Aleutians, the New Hebrides and the Ryukyu are (Fig. 2) are located where the curvature of the arc is appreciable. In each case the T axis, instead of the B axis, is nearly parallel to the strike of the seismic zone; this orientation of the extensional stress might result from the type of deformation of the slab suggested by Stauder<sup>20</sup>. In the less arcuate portion of the New Hebrides the T axes are predominantly parallel to the dip of the seismic zone and the B axes are parallel to the strike. Many of the mechanisms represented by Xs in Fig. 2 may reflect other unresolved contortions of the downgoing slab or other sources of stress such as thermal gradients within the plates or local density variations.

Nevertheless, the consistent pattern shown in Fig. 2 for zones that are relatively uncontorted offers support for the interpretation that gravitational body forces are a major source of stress in the lithosphere. If we make this interpretation, then the results require that in many regions the slabs are sinking and are exerting a downwards pull. The results also require the complications of Fig. 3 in which the sinking slabs are supported from above or below, or both. Thus if we use the results to extract information on the forces that drive the global plate move-

ments, we can infer two important effects: (1) the downgoing slabs can exert a pull on the surface portions of the plates, and (2) as the downgoing slabs "hit bottom" beneath the lithosphere the downward pull on a surface plate is significantly decreased. These interpretations suggest that the pull of the descending slabs may be an important contribution to the driving forces of global tectonics. Moreover, hiatuses or changes in the rates and direction of sea-floor spreading and continental drift might result when the descending slabs reach depths of 500-700 km.

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