Evolution of Stresses in Rock Masses, as Related to Compressive Strengths and Plate Tectonics

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SUMMARY. Measurements of vertical and horizontal compressive stresses in rock masses show a global tendency for a linear increase with depth, with the horizontal stresses being a function of, and greater than, the vertical stresses due to gravity This relationship can be explained if the horizontal stresses are equivalent to the long-term strengths of the rock masses, which are functions of the vertical confining pressure. The horizontal forces which load the rock masses until the stresses are in equilibrium with the strengths are those which drive the movements of the earth's crustal plates in the process known as plate tectonics. It is shown that measured stress magnitudes and directions are consistent with this explanation for their evolution.

1 SUMMARIES OF RESULTS OF WORLD-WIDE STRESS MEASUREMENT

The first publications summarizing results of measurements of in-situ stress, drawing trends from them, and recognizing that the existence of continent-wide or even global patterns could be recognized, are to the credit of Nils Hast (Refs. 1, 2, 3). In his contribution to the International Symposium on the Determination of Stresses In Rock Masses in Lisbon in May 1969 Barry Voight (Ref. 4) discussed the recent recognition of continental drift and plate tectonics, and speculated that these phenomena could be related to the global stress patterns described by Hast. He concluded that direct causal relationships could not yet be drawn, as the amount of data on in-situ stress measurements were insufficient to as yet conclusively prove the nature of the stress patterns, and the mechanisms driving the continental drift were still very speculative, but he speculated that the same mechanism could be responsible for horizontal compressive stresses and the movements of the lithospheric plates.

Shortly thereafter Hast (Ref. 5) published another paper, expanding on his earlier ones, and demonstrating the even wider geographical applicability of the stress pattern that he had deduced – a linear increase of average horizontal compressive stress with depth below the surface of the earth's crust ($\sigma_x+\sigma_y$ = 19.5MPa + 0.1MPa/m depth). He demonstrated that high horizontal compressive stresses existed in close proximity to zones such as the mid-Atlantic Ridge and the East African Rift where continental drift would seem to require horizontal tensions to be operating; as a result he stated that theories of convection currents were inconsistent with results from stress measurements in such places as Iceland, and, by implication, that continental drift was therefore dubious. Hast preferred to stay with his earlier mechanism for horizontal compressive stress evolution, a gradually contracting outer crust of the Earth.

Bulin (Ref. 6) attempted to define the measured stresses in terms of geological conditions, by separately plotting results for the crystalline and folded basement, for the sedimentary deposits on the platforms, and for salt and gypsum deposits. The trend of vertical stress versus depth was linear, and similar for all types of rock, corresponding to a gravity relationship $\sigma_v = \rho gz$, with ρ values of 2.5 to 3.0 tonnes/metre^3 encompassing most of the measured values. i.e. = 24.5 to 29.4kPa per metre depth. The trend lines of average horizontal stress ($\sigma_{x,y} = (\sigma x+\sigma y)/2$) versus depth could be differentiated into that for sedimentary cover deposits ($\sigma_{x,y}$ = 3.6MPa + 0.007MPa/m depth) and that for the basement rocks ($\sigma_{x,y}$ = 6.1MPa + 0.03MPa/m). Plotting the ratio of $\sigma_{x,y}$ to σ_v as a function of depth resulted in consistent ratios of 0.5 to 0.7 for sedimentary cover rocks and 0.6 to 1.0 for evaporite deposits, but the ratio varied with depth for the basement rocks. This indicated that the horizontal stresses in sedimentary cover and evaporites were a direct function of the vertical gravity stress: $\sigma_{x,y} = \rho gz \cdot \nu/(1-\nu)$ with implied Poisson's ratios of 0.33 to 0.41 in the former and 0.375 to 0.5 in the latter. No such relationship could be deduced for the basement rocks, and the horizontal stress was obviously caused by forces other than gravity.

Turchaninov et.al. (Ref. 7) reported several recent stress determinations throughout the U.S.S.R. In many places both horizontal compressive principal stresses greatly exceed the geostatic stress, ρgz, by as much as twenty times (in the Kola Peninsula).

Sbar and Sykes (Ref. 8) summarized the records of earthquake activity and recent stress determinations in North America. The observed pattern of stresses appears to indicate high horizontal compressive stresses, acting in an easterly direction, throughout eastern North America.

Sykes and Sbar (Ref. 9) examined the records of more than 80 intraplate earthquakes i.e. occurring in the interiors of crustal plates, away from the dominant seismic zones along plate boundaries. They found that broad scale patterns of compressive stress exist over the Earth's surface, with the earthquake focal mechanisms being consistent with measured stress directions and with directions of plate motions.

Ranalli and Chandler (Ref. 10) made a comprehensive synopsis of all previous rock stress determinations. They followed Bulin's practice of subdividing the reported measurements, according to

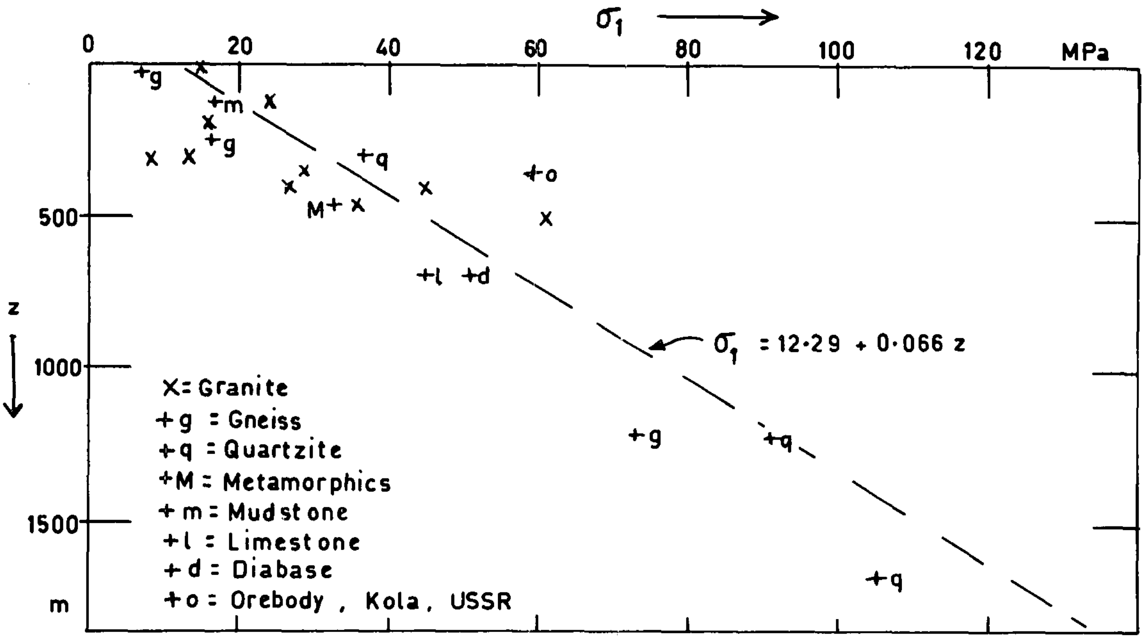

Figure 1

their geological setting. Hast's relationship, $\sigma_{x,y}$ = 9.31MPa + 0.05 z MPa was shown to be valid for shield areas and Palaeozoic folded belts, although there is considerable scatter on both sides of the line. The sedimentary cover of platforms has a relationship $\sigma_{x,y}$ = 2.50MPa + 0.013zMPa. As the vertical stress relationship is σ_v = 0.026zMPa it is evident that in these sedimentary cover deposits the vertical stress tends to exceed the horizontal stress below a depth of about 200 metres. Ranalli and Chandler show in their Table 2 a number of determinations where full details of each principal stress magnitude and direction, as well as the rock type, were published. Some of these values are shown on Fig. 1, a plot of maximum principal stress, σ_1, versus depth, z. Ranalli and Chandler, in their Fig. 3, show horizontal stress anisotropy ratio (σ_1/σ_2) versus depth. Analysis of these data show that there is no significant tendency for the ratio to change with depth. The mean reported ratio is 1.94, and half of the reported values lie between 1.35 and 2.5. If this mean σ_1/σ_2 ratio of 1.94 is applied to Hast's relationship $\sigma_{x,y}$ = 9.31 + 0.05z it yields an expression for σ_1 = 12.29MPa + 0.066zMPa. This line, when plotted on Figure 1, is seen to be in good agreement with the measured values. Predicted average principal values at several depths are as follows :

TABLE 1

Depth (m)	σ_1	σ_2	σ_v (MPa)
0	12.29	6.34	0
400m	38.69	19.94	10.58
1000m	78.29	40.36	26.46
1500m	111.29	57.37	39.69

If these values for σ_1 and σ_v are plotted as Mohr circles, as shown in Fig. 2 a straight line envelope can be fitted over the stress circles. The parameters of this Mohr envelope are S_o = 4MPa, ϕ = 25.5°. This envelope may represent the average strength of the crustal rocks (mainly granites) in which the stresses were measured.

2 EXTRAPOLATION OF NEAR-SURFACE STRESS MEASUREMENTS TO GREATER DEPTHS

If there is a direct causal relationship between the Hast relationship, as shown by the straight line on Fig. 1, and the straight line "rock strength" envelope on Fig. 2, it seems evident that there is a limit to their extrapolation as straight lines: the latter may be expected to

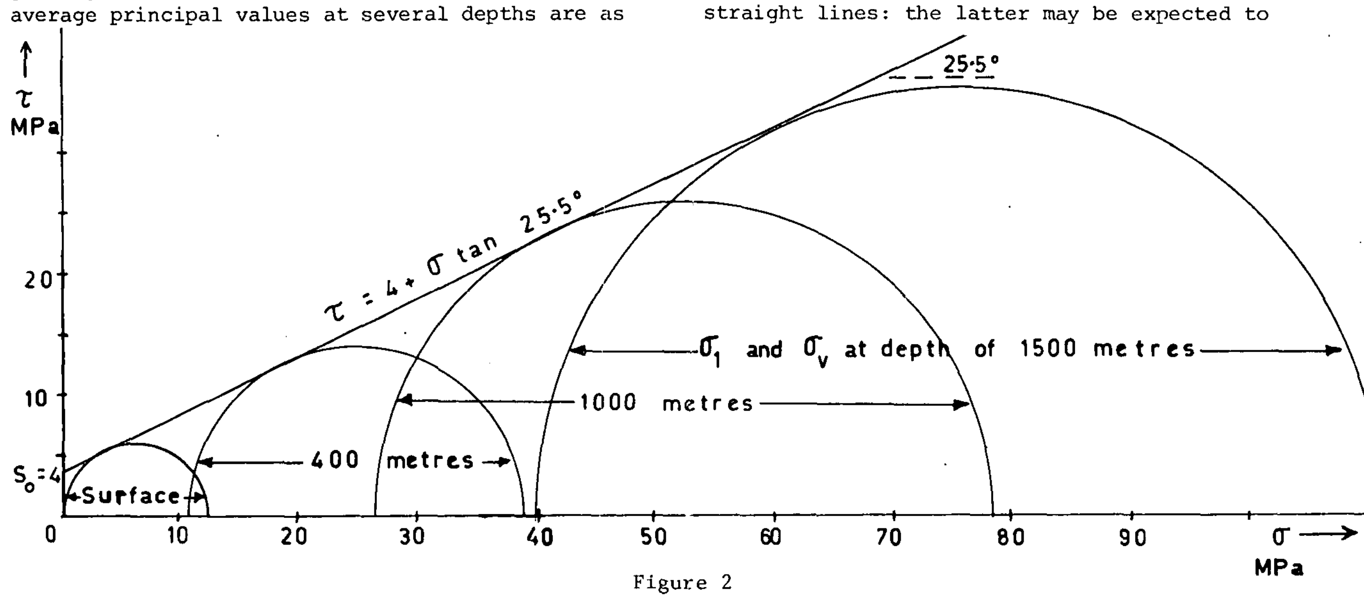

Figure 2

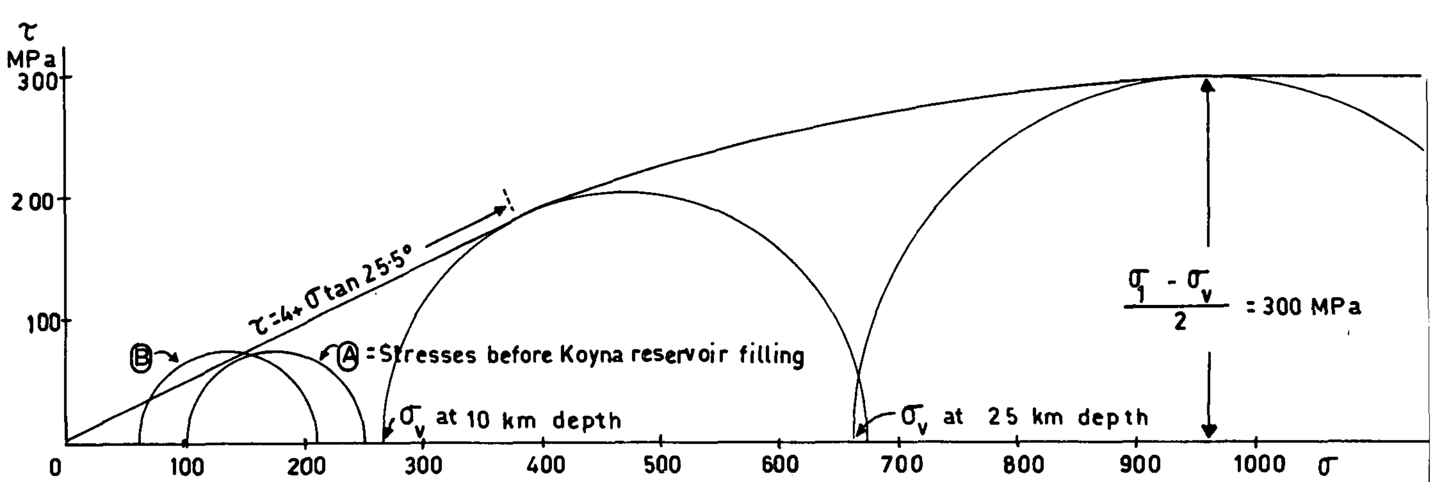

Figure 3

exhibit the well-known parabolic or elliptical shape under high confining pressures, while the former will consequently also become curved.

Kropotkin (Ref. 11) discusses the observed patterns of high horizontal compressive stresses near the surface. His Fig. 2 shows postulated relationships between $\sigma_{x,y}$ and σ_v and depth below the earth's surface. He shows a gradual departure from the Hast line at a depth of about 10km. The magnitude of $(\sigma_{x,y} - \sigma_v)$ continues to increase to a value of about 300MPa, at a depth of about 25km, after which the hydrostatic case is approached, at a depth of 50-60km. A plausible strength envelope may be drawn, as on Fig. 3, by extrapolating the envelope as derived in Fig. 2, with S_o = 4MPa, ϕ = 25.5°, until it is just tangent to a circle with $\sigma_v = \sigma_3$ = 265MPa, corresponding to overburden pressure at a depth of 10km. The envelope then becomes curved, and becomes a horizontal tangent to a stress circle with $\sigma_v = \sigma_3$ = 662MPa (corresponding to overburden pressure at a depth of 25km) and $(\sigma_1 - \sigma_3)/2$ = 300MPa (after Kropotkin).

This curve may be taken as a reasonable approximation to the strength envelope of the crustal materials in which stresses have been measured.

3 PLATE TECTONICS

As mentioned above, Voight (Ref. 4) suggested that a causal relationship may exist between high horizontal compressive stresses and plate tectonics.

Voight et.al (Ref. 12) stated that the available evidence favours the interpretation that these stresses represent existing tectonic phenomena, rather than "residuals" from ancient deformations. They quoted from the work of Gzovskiy (Ref. 13), in showing how the U.S.S.R. could be divided into zones with different magnitudes of stresses, with the directions of the maximum horizontal stresses in the highest stress zones being normal to actively-building mountain ranges and plate collision margins. They also quoted discrepancies in convection current models which mean that convection currents are an implausible driving mechanism for plate tectonics.

Turchaninov et. al. (Ref. 7) linked stress orientations with recent mountain building, and emphasized that present stress orientations appear to be different from those that created mountains in the geologic past. Hast, in his published discussion following Kropotkin's paper (Ref. 11), stated that it is clear that the horizontal stress field in the Earth's crust has changed in direction and magnitude, up to 3 or 4 times in some areas. This seemed to corroborate the hypothesis that the horizontal stresses and the plate motions were causally linked, considering that the present episode of plate motions and sea-floor spreading is considered to have commenced less than a quarter of a billion years ago, and that several previous episodes, on similar time scales, occurred previously.

Sbar and Sykes (Ref. 8) considered that the existing pattern of stresses in North America is post-Mesozoic in origin, and that they have been generated by the same mechanism as drives the movements of large lithospheric plates.

Fitch et.al. (Ref. 14) state that resistance of the Indian Ocean plate to subduction beneath the eastern end of the Alpine — Himalayan orogenic belt is believed to be a major source of tectonic stress in that plate. They also comment that mechanism solutions for earthquakes within the major plates generally show horizontal maximum compressive stress axes, often with nearly uniform trend. These preferred orientations may be interpreted as due to the stress conditions at the nearest interplate margin, or to tractions near the bottom of the plate.

Davies (Ref. 15), in commenting on Ref.9, states that both measurements of in situ stress and earthquake mechanism solutions imply that there are broad scale patterns of compressive stress over the Earth's surface. These observations are strongly linked to plate tectonics.

Jackson and Shaw (Ref. 16) discuss the linear island chains in the Pacific Ocean, and consider that they have been caused by rifting parallel to the direction of σ_1.. The Pacific plate is presently dominantly stressed with an in-situ maximum stress oriented NW-SE, uniformly oriented for the last 40 to 50 million years.

The recent literature, a selection of which has been quoted, strongly suggests that relationships between horizontal compressive stresses and plate tectonics have now become generally accepted.

4 DRIVING FORCES FOR PLATE TECTONICS

No unanimity of opinion exists, but some of the main ideas may be summarized.

Sbar and Sykes (Ref. 8) considered that the pattern shown in their Fig. 5, of the directions of in-situ stresses measured in North America, may result from the stresses applied to the lithosphere by some pattern of flow in the asthenosphere, and that stress measurements could help to define this pattern of mantle flow.

Forsyth (Ref. 17) concluded that "pushing from the ridges is a primary driving mechanism of plate tectonics". He studied the records of a 1971 earthquake in the Antarctic Plate, approximately 500km east of the Pacific-Antarctic Ridge, and calculated that the earthquake was caused by a horizontal compressive stress, striking at 85° to the ridge axis direction. The push from the ridges could arise from the injection of magma at the ridge crest, or to hydrostatic overpressure resulting from the elevation of the ridge above the ocean basins.

Bott and Dean (Ref. 18) showed that such horizontal pressures applied at or near ocean ridges would gradually diffuse across the plate: "the viscous shearing stress of the asthenosphere is a significant factor in causing stress to diffuse through the lithosphere". The implication is that periodic pushes from the ridges would not be perceived as fluctuating stresses in the interior of a plate. Persistent changes in pressure would take of the order of a million years to penetrate across a large plate.

Sykes and Sbar (Ref. 9) show in their Fig. 3 the states of stress inferred from 80 focal mechanism solutions of intra plate earthquakes. Thrust faulting (the failure expected when σ_1 and σ_2 are horizontal and σ_3, the minimum principal stress, is vertical) is involved in : 49% of the total number of earthquakes; all of those in the Pacific plate; all of those in the Atlantic plate well away from the mid-Atlantic ridge; 73% of all events away from ridges, subduction zones, and East Africa. Their Fig. 4 indicates that normal faulting only seems to occur in oceanic crust younger than 20 million years old (or within about 400km of the ridge, at a typical spreading rate of 2cm/year). Thrusting, rather than strike-slip faulting (when σ_2 is vertical), seems to be predominant in rocks older than 20 million years. Great horizontal compressive stress is indicated seaward of several Pacific trenches. A single mechanism is not evident, but gravitational sinking seems to be acting only near island arcs, and is considered to be a contributory, not the primary driving mechanism. Plates may be driven from below by flow, or by gravitational sliding or pushing from the general area of ridge crests.

Harper (Ref. 19) considers that plates are pulled along on top of a viscous asthenosphere by their cold dense leading edges, and that they also tend to slide down the flanks of ocean ridge systems. For reasonable physical properties he calculated that a typical strong subduction zone pulls about seven times as hard as a typical mid ocean ridge pushes. Harper's Fig. 1 shows the velocity profile through the lithosphere and asthenosphere, with a return current in the asthenosphere, flowing in the opposite direction to the lithospheric plates. This is an interesting reminiscence of convection currents, providing the necessary mass transfers, without the major inconsistencies mentioned, for instance, by Hast (Ref. 5)

Solomon et.al. (Ref. 20) analysed the absolute velocities of individual plates, which they found indicated that pull by subducted lithosphere at trenches is an important driving force and that drag may be greater beneath continental than oceanic lithosphere. They also deduced that the driving forces at ridges must be at least comparable in magnitude to other forces in the system. The various driving forces they considered included negative buoyancy forces at subduction zones and at ridges, viscous drag on the bases of plates, and resistance forces adjacent to sinking slabs. They tested numerical models, using varying assumptions as to the relative magnitudes of these forces, against measured stress patterns. A model consisting of buoyancy forces exerted symmetrically about ridges and trenches, and viscous drag at the base of the lithosphere, gives inferred principal stress directions in good agreement with those measured, if the ridge force is approximately equal to the trench force, and the drag = 0.01 to 0.001 of the trench force. A model with negligible driving forces at the ridges gave predictions not in agreement with measurements, and hence is unacceptable. No model considered could match the measured principal stresses in North America and Europe unless the driving forces at the ridges are comparable to thos exerted at subduction zones.

Forsyth and Uyeda (Ref. 21) attempted to choose the most plausible mechanisms for driving the motions of the lithospheric plates, by determining a set of forces that would make the sum of the torques acting on a plate equal or close to zero (as each plate must be in dynamic equilibrium). They concluded that the forces acting on the downgoing slab control the velocity of the oceanic plates and are an order of magnitude stronger than any other force. The forces acting on a downgoing slab control the velocity of the oceanic plates, but the net force from the slab is small. The horizontal part of the plate should be under a weak compressive stress due to the push from the ridges, which is balanced by resistance at trenches and weak drag on the base of the plate – this drag is stronger under the continents than the oceans. Drag forces are passive, i.e. there are no convection currents.

The magnitude of the push from the ridges has been estimated as of the order of 23 to 30MPa; this is the mean excess pressure exerted on the lithosphere due to the elevation of the ridges above the surrounding sea floor.

Finally, the recent work of Lister (Ref. 22) may be quoted. The observed ridge topography, a square-root deepening of the oceanic basement away from the ridge, can be due solely to thermal contraction of uniformly flowing material. He calculated that lateral compressive stresses of the order of 36MPa can be developed in the plate by its becoming rigid after a relatively small decrease in temperature. This driving force is not an edge force associated only with actively rifting mid-oceanic ridge crests.

It is interesting to recall that Hast originally postulated that thermal contraction of the earth's crust was the mechanism which generated horizontal compressive stresses. It now seems that, although much evidence is against any contraction of the earth's total circumference, thermal contraction maybe a plausible mechanism for driving plate motion. The measured in-situ compressive stresses in continental plates are greater than the magnitudes for mid-oceanic driving forces stated by Forsyth and Uyeda, and Lister. However, the downward subduction forces, regarded by some of the authors as up to an order of magnitude higher, could very well produce large compressions of the continental plates. A simple calculation shows a possible magnitude of a continental compression, by a slab downgoing at 45° to the horizontal, under a buoyancy stress of 10x36MPa (quoted by Lister as the thermal contraction driving stress). Horizontal stress = 10x36 cos 45° = 255MPa.

This sampling of the literature indicates a general consensus in favour of plates being driven by both push from the vicinity of ridges and pull by the cool dense sinking subducted slabs. The latter driving forces are variously estimated by different authors as equal to or up to an order of magnitude larger than the former. It seems reasonable that high compressive stresses will be generated in a continental plate when an oceanic plate pushes against it and is dragged beneath it by subduction.

5 EVIDENCE FOR FAILURE CAUSED BY HORIZONTAL STRESS FIELD

Hast (Refs. 3 and 5) quoted several examples of large scale rock failures which he attributed to horizontal maximum principal compressive stresses. Several other examples may be quoted from more recent literature, which confirm Hast's ideas.

Brown et.al. (Ref. 23) report the presence at a dam site in Quebec of tension fractures, more or less parallel to the surface and extending to great depths in the precambrian gneiss. These appear to be very similar to the horizontal fissures, created by a process like axial cleavage fracturing in response to dominant horizontal compressive stresses, described by Hast (Ref. 3).

Balakrishna and Gowd (Ref. 24) studied the disastrous earthquake which followed the filling of the Koyna reservoir, in 1967. They inferred that the earthquake epicentre was at a depth of 4.2km, and that the horizontal tectonic stress was of the order of 210MPa. At a depth of 4.2km the vertical gravity stress may be expected to be about 110MPa. For transcurrent faulting to occur the vertical stress must be the intermediate principal stress, so the minimum horizontal principal stress must have been less than 110MPa. The effect of reservoir filling could be expected to develop pore fluid pressure of the order of 40MPa.

The stress conditions before reservoir filling may have been:

σ_1 = 250MPa $\sigma_2(=\sigma_v)$ = 110MPa σ_3 = 100MPa
i.e. $\sigma_{x,y}$ = 175MPa (c.f. $\sigma_{x,y}$=9.3+0.05z=220MPa)

After reservoir filling :

σ_1' = 250-40 = 210MPa σ_3' = 100-40 = 60MPa

That is, before reservoir filling the stresses (of the same general order of magnitude as Hast's relationship) gave stress circle A lying slightly to the right of the inferred strength envelope of Fig. 3. After the reservoir was filled the effective stress circle B intersected the strength envelope and a failure resulted. This seems to be evidence that the crust was under a state of stress very close to failure before being disturbed by man's activity. This observation has of course been confirmed by many other earthquakes induced by reservoir filling.

Sbar and Sykes (Ref. 8) described several examples of pop-ups caused by high horizontal compressive stresses in eastern North America; quarrying reduces the vertical lithostatic load σ_3 to lower than the value required to resist the horizontal stress σ_1, and the rock buckles upward.

They also described a series of small man-made earthquakes in 1971, generated by high pressure injection of fluids into a salt recovery well in New York; the seismic activity virtually ceased when injection ceased. The incident supports the presence of high tectonic stresses in equilibrium with rock strength, until the fluid pressure decreased the effective normal stresses in the rock, as in the Koyna example above.

Saull and Williams (Ref. 25) replied to Ref. 8 by describing several more pop-ups occurring near Montreal under the action of east-west compression, and in response to reductions in lithostatic load, caused by quarrying.

Voight (Ref. 26) further develops the theme that fluid pressures in rock masses can lead to failure, and conversely that the dissipation of fluid pressures can arrest the failure and "lock in" the horizontal stresses. He speculates that low angle thrust faults, or décollement zones, are mobilized under a condition of interstitial fluid pressures approximately equal to overburden pressure, and allow overthrust movements of many kilometres. Once the fluid pressure dissipates, the overburden pressure imposed on the décollement zone develops its frictional strength, prevents further movement, stabilizes the thrust block and locks in the tectonic stresses. In the terminology used in the Koyna dam example above, the thrust fault slips when effective stresses are $\sigma_1'=\sigma_h-\rho gz$ $\sigma_3'=0$. The rock mass returns to stability when stresses become $\sigma_1 = \sigma_h$ $\sigma_3 = \rho qz$

To sum up, evidence for the assumption that the crust of the earth is often in a metastable state of equilibrium between the rock mass strength and the tectonic stress fields falls into 2 main categories:

(i) the presence of subhorizontal fissures parallel to the ground surface (indicating an axial cleavage type of failure when both horizontal principal stresses are greater than overburden pressure) or of subvertical shear fractures striking at 20 - 30° to the major principal stress direction (indicating that overburden pressure was greater than the smaller horizontal principal stress). Both occurrences show that horizontal stresses equal to the rock's strength have been imposed.

(ii) indications that increases in pore fluid pressure in a rock mass, by injection into wells or by saturation under a reservoir, can cause sudden failures, as the effective normal stresses acting on the rock mass are reduced from a just-stable state to an unstable state; conversely, that dissipation of fluid pressure can transform an unstable rock mass into a just-stable mass, in equilibrium with the tectonic stress field.

6 EXPECTED ROCK MASS STRENGTHS

To predict the strength of a mass of rock of the order of a lithospheric plate, under load for geological time periods, attempts may be made to deduce the effects on the strength of a rock sample of increasing the volume subjected to loading, and of decreasing the loading rate (or of increasing the duration of application of a sustained load). There have been several recent publications on both aspects, but this author will not try to summarize them here, but will quote his deductions from them.

Protodyakonov (Ref. 27) proposed the relationship for the ratio of the strength of a rock sample (a cube of side d) to the strength of an effectively infinite rock mass,

$$\frac{\sigma d}{\sigma m} = \frac{m-1}{(d/b)+1} + 1$$

where b = the spacing between discontinuities in the rock mass. Hoek (Ref. 28) stated that m could be assumed to be between 2 and 5, for hard rocks in compression. An NX core (54 mm diameter) with a length to diameter ratio of 2.5 has a volume of $3.1 \times 10^{-4} m^3$, which is the same volume as a cube with a side length of 68 mm. Assuming an average joint spacing of 1 metre, the term d/b is approximately 0.07 and the range of probable values for $\sigma d/\sigma m$, for m = 2 to 5, becomes 1.9 to 4.7 with a mean of 3.3.

Bieniawski and Van Heerden (Ref. 29) list a series of recent large scale compression tests, showing that for hard rocks the measured ratios of laboratory strengths to large scale strengths were 2 to 18, with the mean of the values they reported being about 7. As these large scale tests were carried out on specimens of finite size, the strength reduction factors would if anything be conservative when applied to larger volumes, so this estimate of 7 will be used below.

Estimation of time-dependent strength can be attempted

(i) by extrapolating the failure strengths of samples at various loading rates, to an effectively infinitely slow loading rate; or

(ii) by subjecting samples to different sustained stress levels, plotting the time taken for failure at each stress level, extrapolating time to infinity, and deducing the apparent stress level which would cause failure after an infinitely long time.

Obert (Ref. 30) quotes examples of strength reductions of up to 50%, as time to failure is increased from 0.03 seconds to 30 seconds. This represents a halving of strength with a thousand-fold decrease in loading rate. A laboratory quasi-static test, carried out at a loading rate of 700kPa stress increase per second, would take 2 to 3 minutes to break rocks in a typical strength range of 80 to 130MPa. The relative strengths at longer times to failure may then be calculated as :

Relative Strength	Time to Failure
100%	2 minutes
50%	2 days
25%	5 years
12.5%	5 thousand years
6%	5 million years

This prediction, of a tenfold reduction in strength when loading over geological time-scales, is not in good accord with other experimental work. John (Ref. 31) shows experimental data for granite, where a reduction in loading rate by a factor of 10^8 results in a 46% decrease in strength. This suggests that we may perhaps follow the lead of Gzovskiy (Ref. 13), who suggested taking long-term strength as 50% of the laboratory value.

Rough predictions may now be made. If the effect of increasing the stressed volume from a laboratory sample to a lithospheric sample is to reduce the strength to 14% of the quick compressive strength, and the effect of long-term loading is to halve the strength, it may be reasonable to expect the strengths of lithospheric plates, under loads for millions of years, to have only about 7% of the laboratory strengths of their constituent rocks.

The most common rock type in which measured maximum horizontal principal stresses were reported by Ranalli and Chandler (Ref. 10) was granite. Bamford (Ref. 32), in a comprehensive tabulation of published physical properties of rocks, found that the reported range of unconfined compressive strengths of granites was 54 to 290MPa, with a median value of about 150MPa.

The unconfined compressive strength of the lithospheric plates might then be deduced as being of the order of 150x0.07 = 11MPa. This is in reasonable agreement with the maximum horizontal stress at the surface calculated in Table 1 and shown on Fig. 2, and provides strong evidence for the conclusion that measured horizontal stress values are in effect, also the strength values of the rocks in which they are measured. This hypothesis is illustrated in Figure 4.

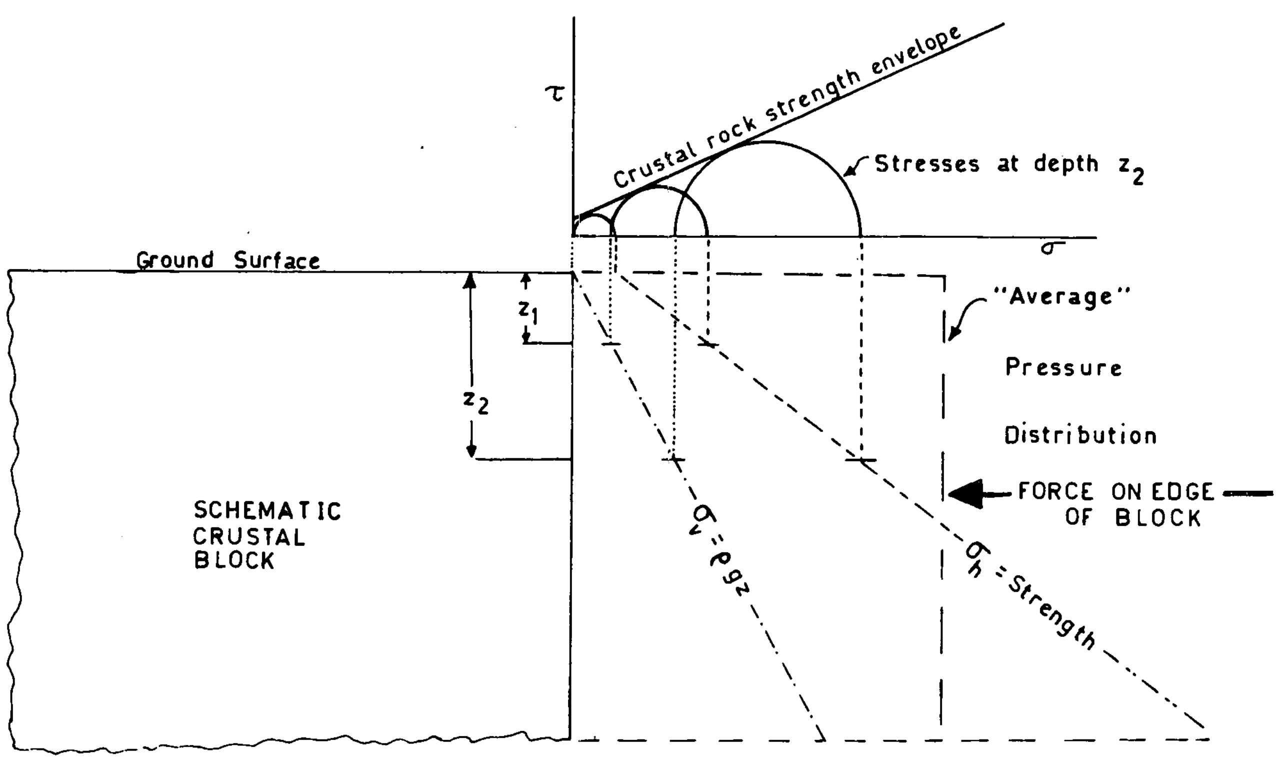

Figure 4

7 CONCLUSIONS AND PRACTICAL IMPLICATIONS

An argument that a strong causal relationship exists between plate tectonics and horizontal compressive stresses in the outer crust of the earth has been presented. Implications are that reasonable estimates of the magnitudes of such stresses in Palaeozoic and older rocks may be made, commencing from laboratory strength tests on typical samples of rocks from the region of interest; and that the likely directions of the principal stresses may be estimated from the regional directions of plate movements and the pattern of subduction zones. For examples, the Australian-Indian plate, moving in a northeasterly direction, is colliding with the Eurasian plate along the Sunda arc and with the Pacific plate along the northern coast of New Guinea and the Solomon Islands, while the Pacific plate moving westwards is colliding with the Australian plate along the Tonga and Kermadec trenches. The stress fields are a result of these collisions; maximum principal stresses are oriented easterly in south-eastern and southwestern Australia, and north-easterly in northern Australia. c.f. Fitch et.al. (Ref. 14).

It is hoped that reporting of in-situ stress measurements in future will also include data of strength tests of the rocks in which they were conducted, in order to test the hypothesis argued in this paper.

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