Brief Report

The So-Called Folded Mountains

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We show that the usual model in which folded mountain chains are assumed to originate by lateral compression does not constitute a unique explanation. An alternative model, here only developed qualitatively, is proposed in which undulations of originally horizontal strata are produced by lumps of crustal material that rise from below and attach themselves to the bottom of continental plates. This model corresponds to the orogenic process that can be observed when basaltic material is molten, and then rises at a Gutenberg seismic fault zone that slopes down toward a continent.

The idea that mountain ranges are generated by lateral compression has a long and distinguished history. The model is, however, not unique as we shall demonstrate in this note. An alternate model is obtained by assuming that crustal material is added to a continental plate from below; this addition, by isostasy, leads to a buckling of the upper layer that in practice is indistinguishable from corrugations that could arise by compression. We make no claim that either the compression mechanism or our accretion mechanism is unique and excludes the other, but it appears likely on a variety of grounds that the accretion mechanism is the more widespread of the two.

The buckling of thin rods and plates under longitudinal compression was first treated by Euler. It is a case of 'geometrical' instability where the buckled plate has a lower energy than the merely compressed one, and therefore is the more stable configuration. If we are concerned with the buckling of a continental plate in orogeny, we are dealing with plastic rather than with elastic deformation. Compressive buckling is usually inferred in geology from the corrugation of strata that must originally have been flat-lying. But we should remember that any undulation of strata near the surface must, by isostasy, be accompanied by an undulation of opposite sign at the bottom of the continental plate and, with the usual ratio of densities of crust/mantle, the amplitudes of the latter will be about six times larger than the amplitude of the surface undulations. If the maximum amplitude of the bottom undulation were comparable to the thickness of the crust (say, for example, 36 km from peak to bottom), the undulations near the surface would have a vertical amplitude of 6 km, which seems very large indeed. We may conclude that in general the buckling of a continental plate as observed in terms of the undulations of geological strata is rather different from a geometrical instability: Unless the amplitude of the top strata approaches 6 km vertically, there will be a middle part of the continental layer that is only compressed while corrugations are extruded at the bottom by an as yet poorly understood process.

Since we shall show presently that an accretion mechanism leads to fairly uniform buckling of the top strata, it does not seem that one can discriminate between the two mechanisms on the evidence of warped layers alone. There is one unambiguous observable criterion that distinguishes between horizontal compression and horizontal tension: Thrust faults indicate compression at the time of their formation, and normal faults correspondingly indicate tension. But there seems to be no evidence that so-called folded mountain ranges are uniquely correlated with thrust faults; so the actual picture is likely to be much more complicated.

Consider now the alternate, the formation of a mountain by accretion of crustal material from below. We shall consider a somewhat schematical model in which the displacement of any particle of the crustal plate is thought of as purely vertical (Figure 1). Let there be an originally flat stratum, and let it be deformed into a layer of sinusoidal shape, say

$$y = h \sin (2\pi x/\lambda)$$

where $\lambda/2$ and h are width and height of the bulge, as indicated in Figure 1. The bulge is thought of as cylindrical in a direction perpendicular to the plane of the paper. A strip parallel to the cylinder axis of width dx will by the deformation be stretched to

$$dx' = (dx^2 + dy^2)^{1/2} = [1 + (dy/dx)^2]^{1/2}\, dx$$

or for small dy/dx, approximately

$$dx' = [1 + \tfrac{1}{2}(dy/dx)^2]\, dx$$

The stretching will be maximum at the points $x = 0$ and $x = \lambda/2$; at these points

$$dx' = \left[1 + \frac{\pi^2}{2}\left(\frac{2h}{\lambda}\right)^2\right] dx$$

Let now the curve in Figure 1 represent a deformed layer that was originally of uniform thickness, D. The equation of continuity requires that D decreases at the same rate as dx increases, that is,

$$D' = \left[1 - \frac{\pi^2}{2}\left(\frac{2h}{\lambda}\right)^2\right] D$$

at the points $x = 0$ and $x = \lambda/2$. As an example, let $2h/\lambda = 1/20$ that represents a slope of 9° at $x = 0$. The decrease in D is found to be 1.2%. Given the large random errors in geological field measurements, such a variation can hardly be identified. This would even be so if the amplitude of the undulation were appreciably larger than just assumed. We see therefore that the existence of undulations in originally flat layers does not constitute a criterion for distinguishing between mountain building by lateral compression and by accretion from below.

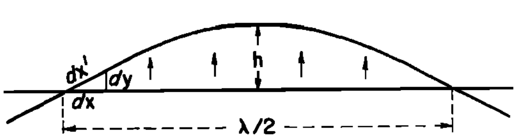

Fig. 1.

We now consider briefly the tectonic conditions under which the appearance of mountain ranges is observed. A particularly simple case is that of the Andes. It seems extremely difficult to conceive of compressive stresses that act only on a strip of land at the west coast of South America but leave all the remainder of the continent unaffected. On the other hand, there is clearly some relationship between the mountains, the trench off the coast, and the Gutenberg seismic fault that slopes down (under about 45°) toward the continent. Now, little doubt remains at the present state of geophysical knowledge that material of the lithosphere, a layer of about 60–75 km thickness at the top of the mantle, is sliding down along the Gutenberg fault zone [*Isacks and Molnar*, 1969]. A number of authors have proposed that this layer takes the thin oceanic crust down with it, by friction. At some depth the basaltic material of the oceanic crust melts and so does any basaltic material that may be contained in pockets of the lithosphere, not having had the time to rise all the way to the surface. Such pockets may develop whenever the lithosphere, on rising near submarine ridges, has cooled enough to prevent further penetration by basalt. *Oxburgh and Turcotte* [1968] have, moreover, suggested that the frictional heat of downsliding along the Gutenberg fault makes a major contribution to the heat of melting of the basalt.

The material thus released rises to the bottom of the continental plate, and a bulge at the top will be formed as a consequence of isostasy. In folded mountains there may be more than one bulge; several chains can occur in parallel. In such cases it is probably best to imagine that there is originally a periodicity in time, for instance an intermittent release of basalt at succeeding time intervals. This can be converted into a periodicity in space if this process is combined with a uniform horizontal sliding. For instance, the continent may grow at its edges and the trench and Gutenberg fault may correspondingly migrate toward the ocean. But it seems premature to work out a too specialized model; such a model will eventually have to grow out of the interpretation of concrete geological observations.

It is uncertain how many mountain chains are to be explained in terms of an accretion mechanism, but this might well be the majority of those known. Consider specifically the vast system of mountain ranges that extends from Western Europe all along the southern part of the Eurasian continent until well into China. In accordance with current ideas on continental drift we may conceive of Africa, together with Arabia and India, as having drifted northward from the southern hemisphere until these continental blocks abutted against the Eurasian continent. Before this collision of continents the vast system of mountain ranges would everywhere have been very close to the southern coast of Eurasia. A string of Gutenberg faults near the coast will have two dynamical effects. In the first place there will be a migration of ocean bottom northward, the ocean bottom carrying the continental blocks with it; it may even be presumed that the abutment of the blocks created a sufficient counterforce to terminate this system together with the related east-west trenches, of which trenches no trace seems to be left at present. In the second place, such a mechanism would provide a source for the basaltic material that produced the mountain chains by accretion from below.—Another case of a folded mountain range that comes to mind are the Appalachians. Their creation by a similar process would require a Gutenberg fault zone to have existed at the east coast of North America during the period of the Paleozoic where these mountains originated. This would most likely lead to the conclusion that the histories of the North and South Atlantic were quite different. There is no evidence that would contradict the view that South America and Africa for a long time formed one continent that then broke up with the pieces drifting apart; but clearly the processes around the North Atlantic must have been far more complex.

We cannot conclude these suggestions without inquiring into the statistical distribution and the averages of horizontal stresses over the earth. The general impression is that with a scheme of orogeny of the type proposed, tensile stresses averaged over the earth might be considerably in excess over compressive ones. This idea is not in contradiction to theory. It is only if one contemplates a model of a chemically homogeneous mantle driven purely by thermal instability that a symmetry between compressive and tensile stresses should exist. There are several effects that would introduce asymmetry, of which the two most significant ones seem to be: First, a thermal asymmetry owing to the low heat conductivity; thus sinking material remains cold for a long time, whereas rising material can cool more readily because it ends up near the surface. A second mechanism favoring asymmetry of stresses is the rising of basaltic material from the interior into the crust, there being no reverse to this process. If mantle convection as we know it at present has been going on at a steady rate throughout the life of the earth this last-named effect might be rather small; but if, as is quite possible, mantle convection has been much stronger during the last sixth of the earth's life than before, then this effect of asymmetry may be far from negligible.

We are therefore led to consider an earth model in which tensile stresses are more widespread and usually stronger than compressive ones. This view should by no means be interpreted as implying an overall expansion of the earth such as would be caused by a decline of the constant of gravity on a cosmological scale, an idea proposed by a number of physicists. Such decrease of gravity, if rapid enough to produce and maintain significant stresses in the solid earth as against relaxation, would have observable astrophysical consequences. These latter have been investigated [*Pochoda and Schwarzschild*, 1964], and evidence has been given that no more than a minute rate of decline of gravity would be admissible, not enough to have a significant influence upon the dimensions of the earth. We are therefore disregarding the possibility of this effect.

The mechanically simplest way of producing a widespread system of horizontal tensile stresses near the surface is by having localized forces *that pull material down* in certain limited regions. It may be shown that the down-pull does occur at the Gutenberg fault zones [*Isacks and Molnar*, 1969]. The mantle material there becomes heavier because it loses its basaltic component, either the oceanic crust or other material enclosed in pockets of the lithosphere, as already mentioned. Furthermore the mantle material may well undergo a transformation into a denser phase; and this will occur at lower pressures, that is, closer to the surface, when the material is cold than it would occur in a static mantle.

The lithosphere will now tend to equalize the horizontal stresses by suitable deformations or motions. A simple case is that of a plate of lithosphere sliding over an asthenosphere thought of as viscous [*Elsasser*, 1969]. In more complicated cases isostatic adjustments will come into play. It seems that, between the stresses themselves and the related isostatic adjustments, stress propagation can take place over very long distances on the earth as *Elsasser* [1969] has emphasized previously. Again, *Orowan* [1969] has pointed out on other evidence that horizontal stresses on the ocean bottoms seem to be largely tensile. Such tensile stresses make it much easier to understand the appearance of rather flat abyssal planes on apparently young ocean bottoms; it would be much harder to obtain these if the stresses were compressive. (By stresses we mean of course always deviator stresses. The isotropic mean hydrostatic stress changes the bulk properties of the material but has little effect on plastic properties that involve any sort of anisotropy.)

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