

The Nature of the Mohorovicic Discontinuity, A Compromise¹

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Abstract. The available experimental data and steady-state calculations make it difficult to explain the M discontinuity beneath both oceans and continents on the basis of the same phase change. The oceanic M discontinuity may be a chemical discontinuity between basalt and peridotite, and a similar chemical discontinuity may thus be expected beneath the continents. Since available experimental data place the basalt-eclogite phase change at about the same depth as the continental M discontinuity, intersections may exist between a zone of chemical discontinuity and a phase transition zone, the transition being either basalt-eclogite or feldspathic peridotite-garnet peridotite. Detection of the latter transition by seismic techniques may be difficult. The M discontinuity could therefore represent the basalt-eclogite phase change in some localities (e.g. mountain belts) and the chemical discontinuity in others (e.g. oceans and continental shields). Variations in the depth to the chemical discontinuity and in the positions of geotherms produce great flexibility in orogenic models. Intersections between the two zones at depth could be reflected at the surface by major fault zones separating large structural blocks of different elevations.

Chemical discontinuity. The conventional view that the Moho discontinuity at the base of the crust is caused by a chemical change from basaltic rock to peridotite has been expounded recently by *Hess* [1955], *Wager* [1958], and *Harris and Rowell* [1960]. Petrological and geochemical concepts related to the composition of the earth's mantle and problems of heat distribution have been discussed by *Bowen* [1928], *Buddington* [1943], *Ross et al.* [1954], *Verhoogen* [1954], *Birch* [1958], *Lovering* [1958, 1959], *Kuno* [1959], *MacDonald* [1959a, 1959b], *Harris and Rowell* [1960], and many others. A conclusion that the upper mantle is composed of material having the composition of a feldspathic peridotite is in reasonable agreement with the hypothesis that the over-all composition of the mantle is the same as that of the silicate fraction of chondritic meteorites. Although there are divided opinions about the validity of meteorite analogies, the chondritic model is favored in most recent reviews [*MacDonald*, 1959b; *Harris and Rowell*, 1960; *Vinogradov*, 1961; *Ringwood*, 1962a; *Mason*, 1962]. *MacDonald* [1959b], after summarizing arguments in favor of the chondritic model, concluded that material having radioactivity in-

termediate between dunite and basalt is qualitatively reasonable for the mantle.

Ringwood [1962a, c] adopted a specific model compounded from the concepts advanced and developed by many petrologists and geochemists, and he concluded that to a first approximation the mean chemical composition of the upper mantle and crust over any extensive region of the earth is similar to a mixture of 4 parts of dunite to approximately 1 part of basalt. *Ringwood* called this material 'pyrolite,' but I prefer to retain the terms 'feldspathic peridotite' and 'garnet peridotite' (for the same material in the eclogite facies) which were used long ago by *Bowen* [1928].

The main advantage of this model for the upper mantle is that it provides reasonable explanations for a wealth of petrological data. Petrogenesis demands that the mantle material be capable of supplying the basaltic magma which has been erupted so frequently at the earth's surface. Furthermore, it appears to be more likely that this magma is produced as a result of partial melting of crystalline material than by complete melting, which is what would be required if the mantle were composed of eclogite [*Bowen*, 1928; *Hess*, 1960b]. *Vinogradov* [1961] concluded that original mantle material of chondritic composition is affected by zone melting, which leads to a separation into

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basaltic magma and residual dunite, the basalt eventually forming the earth's crust.

Birch [1952] showed that the elastic properties of feldspathic peridotite do not conform with those of mantle material at depths of several hundred kilometers. This is not an argument against the peridotite hypothesis, however, because at appropriate depths the basaltic portion of the peridotite will be converted to eclogite [*Bowen*, 1928, p. 318]. The mantle material then consists of garnet peridotite (eclogite of *Birch* [1952], garnet pyrolite of *Ringwood* [1962a]), composed of a mixture of dunite and eclogite (eclogite here being restricted in chemical composition to the range of basaltic compositions). *Birch* [1952] concluded that such material satisfies the elastic requirements even more fully than a pure dunite would, and *Bowen* [1928] concluded that the mineralogical constitution of the basaltic fraction of the mantle would make little difference in the generation of basaltic magma. (Recent experimental work by *Yoder and Tilley* [1962] indicates that this may have an important bearing on the nature of the basaltic magma produced.) Because of the similarity of elastic properties of feldspathic peridotite, garnet peridotite, dunite, and eclogite, it is possible that the existence of a discontinuity or transition zone at depth between any pair of these rocks cannot be detected with existing seismic techniques.

This hypothesis is satisfactory in many ways, but again there are difficulties. *Kennedy* [1959] cited four major observations which were inadequately explained by the traditional view that the earth's crust is separated by the M discontinuity from denser ultramafic material, such as feldspathic peridotite: (1) the relatively uniform values for heat flow in continental and oceanic basins (an explanation of this may be forthcoming when more heat-flow data are available [*Birch*, 1958]), (2) the persistence of continents and mountain ranges in spite of high erosion rates, which might be expected to cause dispersion of the continental rocks in the ocean in a relatively short span of geological time, (3) the subsidence of marginal troughs in response to loading by low-density sediments, and (4) the uplift of plateaus once worn to sea level. According to *Kennedy*, items 3 and 4 appear to require large masses of rock to be transferred laterally near the base of the

earth's crust. *Kennedy* proceeded to develop plausible explanations of these observations by assuming that the M discontinuity is represented by a phase change from basalt to eclogite. *MacDonald and Ness* [1960] also discussed some of the contradictions with the hypothesis that the upper mantle is composed of peridotite. In particular, they questioned the assumption that a sharp chemical discontinuity between peridotite and basalt could persist for periods longer than 10^9 years.

Phase change. The suggestion that the upper mantle is composed of eclogite appears to have originated with *Fermor* [1913, 1914], and the idea was supported by *Goldschmidt* [1922] and *Holmes* [1927]. This hypothesis has been revived by *Lovering* [1958] and *Kennedy* [1959]. *Lovering* compared a layered earth with a differentiated, parent meteorite body whose composition is represented by achondrites, and he concluded that the outer 100 km of the earth is of basaltic composition. The M discontinuity can then be explained only as a phase change from basalt to eclogite, its dense chemical equivalent. This hypothesis is attractive because vertical movements of isotherms cause M to migrate up or down, producing changes in crustal thickness and causing contraction or expansion, with consequent changes in surface elevation. This process has far-reaching implications for orogenetic theories. *MacDonald and Ness* [1960], *Wetherill* [1961], and *Noble* [1961] have since calculated the order of magnitude of possible effects produced by movement of the M discontinuity. *Hess* [1955] had earlier discussed similar processes caused by serpentinization or dehydration of the upper-mantle material (assumed to be peridotite) with specific reference to suboceanic topography.

The phase change from basalt to eclogite involves a change from the mineral assemblage plagioclase + pyroxene (+ olivine) to pyrope-rich garnet + jadeitic pyroxene (+ olivine). The basalt may be saturated, in which case it may contain some free quartz but no olivine, or it may be undersaturated, containing nepheline and olivine. Experimentally measured curves for transitions involving these minerals are plotted in Figure 1. Curve 1 for the reaction albite + nepheline \rightleftharpoons jadeite was measured by *Robertson et al.* [1957], and curve 2 for the same reaction at lower temperatures was meas-

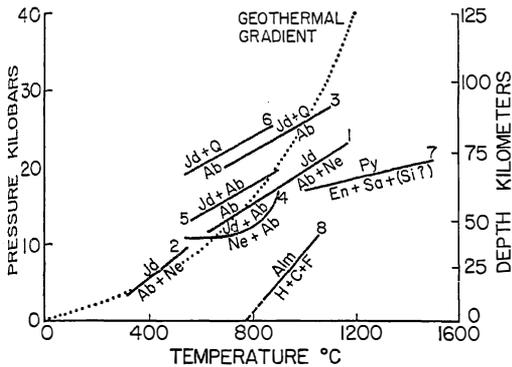


Fig. 1. Experimentally measured reactions involving dense silicate minerals. *Ab*, albite; *Ne*, nepheline; *Jd*, jadeite; *Q*, quartz; *En*, enstatite; *Sa*, sanidine; *Si*, sillimanite; *Alm*, almandine; *H*, hercynite; *C*, iron cordierite; *F*, fayalite. The dotted line is an average geothermal gradient after Howell [1959]. See text for references.

ured by Hoffer and Dachille, using apparatus in which a shear component had been added to the hydrostatic pressure in order to improve the kinetics of the reaction [Dachille and Roy, 1962]. The reaction albite \rightleftharpoons jadeite + quartz (curve 3) was measured by Birch and LeComte [1960]. Kennedy published preliminary curves 4, 5, and 6 for a more complex sequence of reactions involving solid solution between albite and nepheline, and conversion of these minerals to jadeite. Boyd and England [1959] determined the stability field of pyrope, bounded on its low-pressure side by less dense crystalline phases (curve 7). Yoder's [1955] preliminary curve for the stability of almandine (curve 8) suggests that the garnet in eclogites, which contains some almandine in solid solution, would be stable at somewhat lower pressures than pure pyrope.

Although these simple mineralogical reactions give an indication of the position and slope of the basalt-eclogite transition, they are not sufficient to permit us to locate it precisely. Robertson *et al.* [1957] and Birch and LeComte [1960] noted cautiously that their experimental data were too few to permit them to decide whether the M discontinuity was a phase change, and they pointed out the difficulty of accounting for the oceanic discontinuity in terms of the basalt-eclogite transformation. Boyd and England [1959] suggested that the pyrope and jadeite stability curves (7 and 1) could together be taken as an approximation of the basalt-eclo-

gite transition. However, the effect of other components (especially CaO and FeO occurring in solid solution in natural plagioclase and pyroxene) on these transitions is not known, and the position of the transition is obviously sensitive to the degree of silica saturation of the original basalt (curves 1 and 3). The experimentally determined curves do indicate that crystalline basalt would be converted to eclogite at no great depth within the earth, but there are large margins of uncertainty as to the depth at which the change occurs.

To locate the position within the earth of a phase change from basalt to eclogite, or from feldspathic peridotite to garnet peridotite, it is necessary to know not only the pressure-temperature range for the phase transition but also the geothermal gradient within the earth. Neither of these is adequately known, as is indicated by the two extreme estimates shown in Figure 2 [Kennedy, 1959; Ringwood, 1962a]. These estimated positions of the phase change were based partly on the transition curves of Figure 1 and partly on preliminary experimental work with natural basaltic glasses.

Kennedy [1959] reported the conversion of basaltic glass to a product with eclogitic affinities at 500°C and pressures just above 10 kb.

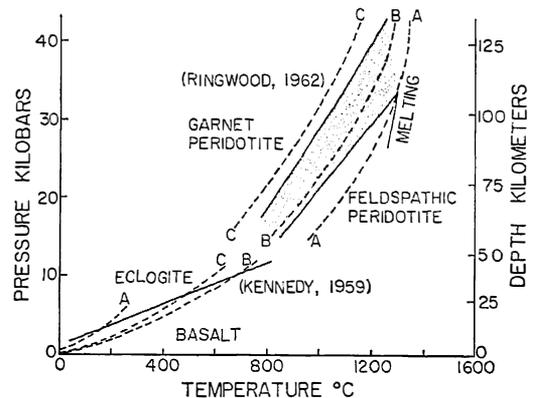


Fig. 2. Basalt-eclogite phase transition and geothermal gradients after Kennedy [1959] and Ringwood [1962a]. Estimated geothermal gradients: A, in oceanic regions; B, in orogenic regions; C, in continental shield regions. According to Kennedy, the M discontinuity could be caused by the phase transition in all three environments. According to Ringwood, the transition lies within peridotite of the mantle. Ringwood [1962c] has since modified this diagram.

The points of intersection of his estimated curve for the basalt-eclogite transition with estimated geothermal gradients give the depths to M in three environments. The three dashed curves represent geothermal gradients increasing from ocean basins (A) to continental shields (C), and reaching maximum values beneath mountain belts (B). Because the geothermal curves have approximately the same slope as the basalt-eclogite transition, the depths to M increase in the same sequence. According to this interpretation, the M discontinuity can be explained everywhere in terms of a basalt-eclogite phase transition.

Ringwood [1962a] adopted a standard chondritic model for the upper-mantle composition and concluded that the basalt-eclogite transition is located within the mantle, where it is expressed as a change from feldspathic peridotite ('pyrolite') to garnet peridotite ('pyrolite'). When Boyd and England [1959] crystallized a basalt glass at 1200°C between 33- and 40-kb pressure, they reported the presence of minor calcic plagioclase as well as garnet, clinopyroxene, and some free silica. Ringwood interpreted these results as indicating that the runs lay within the basalt-eclogite transition interval. His original estimated position for this interval is illustrated by the stippled band in Figure 2. This has a much steeper slope than Kennedy's estimate, and the transition therefore extends to much higher pressures before being intersected by melting curves. On the basis of more recent work by Boyd and England [1961] on the stability of anorthite, Ringwood [1962c] suggested that the transition zone between plagioclase pyrolite and garnet pyrolite would be wider, 'extending to lower pressures at the expense of plagioclase pyrolite.' He further suggested that the transition in pyrolite involved reactions somewhat different from those involved in the basalt-eclogite transition, with pyroxene predominating. Ringwood's later estimated transition is therefore closer to the estimate of Yoder and Tilley [1962], which is plotted in Figure 3.

Figure 2 illustrates not only the effects of uncertainties in estimating the position of the basalt-eclogite transition on the basis of available data but the uncertainties in estimates of the geothermal gradient at depth. In Kennedy's model, the geothermal gradient beneath the

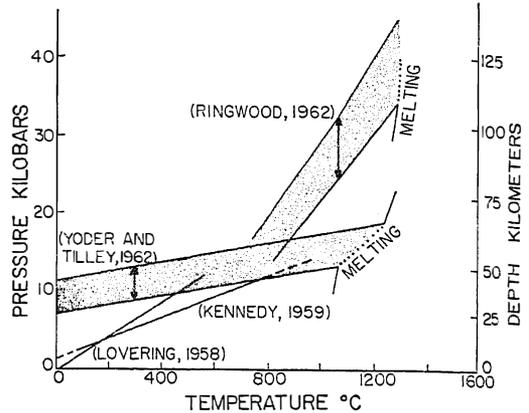


Fig. 3. Published estimates of the position of the basalt-eclogite phase transition.

oceans is less than it is beneath the continents and orogenic regions, whereas in Ringwood's model the geothermal gradient beneath the oceans is greater than the estimated gradients in the other two environments. If Ringwood's estimated geothermal gradient for the area beneath the oceans were used in Kennedy's model, the M discontinuity beneath the oceans would be deeper than M beneath the continents.

Four published estimates of the basalt-eclogite phase transition are compared in Figure 3; two of these have already been discussed in connection with Figure 2. Lovering [1958] concluded from his achondrite analogy that the M discontinuity must be a phase transition from basalt to eclogite, and he drew the boundary through two points with temperatures and pressures believed to exist at the base of the crust beneath (a) ocean basins and (b) continents. Yoder and Tilley [1962] presented a preliminary diagram for the transition between natural basalt and eclogite and for the melting relations of both rocks, based on their own experiments with natural samples as well as those of Boyd and England [1959] and Kennedy [1959]. The experimental data are meager, but the few runs completed provide limits for the gradient of the phase transition and show reasonable agreement with extrapolations from studies of the mineral components. The width of the transition interval remains uncertain.

The position of this transitional interval illustrates more clearly than the scattered curves in Figure 1 that basalt, or the basaltic portion of

feldspathic peridotite, must undergo a transition to eclogite at depths within the earth which are roughly equivalent to, or somewhat deeper than, the position of the M discontinuity beneath the continents. It does not support the contention of *Lovering* [1958] and *Kennedy* [1959] that the M discontinuity at shallow depths beneath the oceanic crust could be caused by the basalt-eclogite phase change (compare Figures 2 and 3). The calculations of *MacDonald and Ness* [1960] and *Wetherill* [1961], using steady-state or equilibrium approximations, also indicate that the M discontinuity beneath the oceans is unlikely to be caused by the same phase transition. There remains a possibility that M beneath the oceans could be caused by a different phase transition, such as one from partially serpentinized peridotite to unserpentinized peridotite [*Hess*, 1960a]. This would imply that the M discontinuity beneath the oceans is a 'fossil isotherm.'

The available evidence thus indicates that the M discontinuity beneath the continents, but not beneath the oceans, *could* be caused by a phase transition from basalt to eclogite. The width of the transition interval appears to be quite appreciable (Figure 3), but *Yoder and Tilley* [1962] suggested that the part of the reaction producing garnet might make the largest contribution to the seismic velocity change, so that if a phase change from basalt to eclogite does occur at the M discontinuity the effective change in seismic velocity might be realized over a much smaller depth interval than is indicated by the transition band in Figure 3. There appears to be some question as to just how sharp the M discontinuity may be [*Yoder and Tilley*, 1962; *Tuve et al.*, 1954].

The advantages of a model in which the M discontinuity is caused by a phase transition from basalt to eclogite were outlined by *Lovering* [1958], developed in detail by *Kennedy* [1959], and placed on a semiquantitative basis by *MacDonald and Ness* [1960], *Wetherill* [1961], and *Noble* [1961]. (See also *McMath* [1962] and *Noble* [1962].) The model provides reasonable solutions for major geological problems such as the difference between continents and ocean basins, the permanence of the continents, the elevation of large plateaus, the formation of geosynclines, and the origin of mountain belts. The steady-state calculations provide con-

siderable insight into some aspects of these problems. Results obtained for the thicknesses of sediments which can accumulate in a sinking geosyncline, the variation in the thickness of the crust in various environments, the amount of elevation in plateau and mountain regions, and the time span for these processes are of reasonable orders of magnitude.

The available evidence does not favor the hypothesis that the M discontinuity beneath the oceans is represented by the transition from basalt to eclogite. Wide variations in heat-flow measurements from the Pacific Ocean reported by *Von Herzen* [1959, 1963] indicate that the M discontinuity beneath the oceans is not caused by a phase change. If M beneath the oceans is a phase change, the wide range of heat-flow measurements should be accompanied by variations in thickness of the oceanic crust. However, initial seismic studies indicate no variation in the depth to M which can be correlated with the heat-flow variations. For petrogenic arguments in continental regions this hypothesis is less satisfactory than the chemical discontinuity hypothesis. It is difficult to reconcile *Lovering's* [1958] suggestion that the upper 100 km of the mantle are composed of eclogite with the widely accepted model of a chondritic mantle. Eclogite, which is the chemical equivalent of basalt, would have to be completely melted to provide basaltic magma. As was pointed out earlier, it is more likely that magma derived from the earth's mantle is generated by partial fusion [*Bowen*, 1928; *Hess*, 1960b]. It has been suggested that, if the M discontinuity is a phase change dependent upon pressure and temperature, there should be a correlation between crustal thickness and mean surface temperature, and between crustal thickness and surface elevation, although these could be masked by other effects such as compositional variations. So far, no significant correlations have been established [*Steinhart*, 1960; *Howell and Woodtli*, 1961]. The problem of the width of the phase transition compared with the width or sharpness of the M discontinuity as measured by seismic techniques has already been discussed.

Compromise. There is no convincing evidence to support the view that the M discontinuity beneath the oceans is caused by a phase change from basalt to eclogite, and there are few objections to the hypothesis that it is a

composition change from mafic to ultramafic material. If the upper-mantle material beneath the oceanic crust is composed of feldspathic peridotite, it is reasonable to conclude that the upper mantle beneath the continents has a similar composition. This implies that there is a chemical discontinuity of global extent between material of basaltic composition and material with the composition of feldspathic peridotite. The depth to this discontinuity certainly differs between oceanic and continental areas, and it probably differs between continental shield areas and orogenic regions.

In addition to the chemical discontinuity, it is now well established that there must be another discontinuity, at the appropriate depth, marking the position of the basalt-eclogite phase transition. This may be expressed as a transition from basalt to eclogite or as a transition from feldspathic peridotite to garnet peridotite, depending upon the depth to the chemical discontinuity. The depth to the phase transition zone varies according to the geothermal gradient. Where the chemical discontinuity occurs at a higher level than the phase transition, as in the oceanic regions, the chemical discontinuity is recorded as the M discontinuity by seismic measurements. It would probably be difficult, using present seismic techniques, to detect the deeper transition from feldspathic peridotite to garnet peridotite, because the change in the velocity of seismic waves between these rocks would be small. If the phase transition occurs at a higher level than the chemical discontinuity, the transition from basalt to eclogite would be recorded by seismic measurements as the M discontinuity, and the deeper chemical discontinuity between eclogite and garnet peridotite might be undetected. Only the major discontinuities involving elastic properties and density would be detected by seismic methods, i.e. the discontinuities between basalt and feldspathic peridotite, or between basalt and eclogite. Refinement of seismic techniques or of other geophysical methods may ultimately provide a test for the existence of a second discontinuity below the M discontinuity. Recent crustal magnetotelluric measurements in Massachusetts are of interest in this connection [Cantwell and Madden, 1960]. The results indicate that a rapid change of resistivity must occur around 70 km, which is deeper than the M discontinuity in this region.

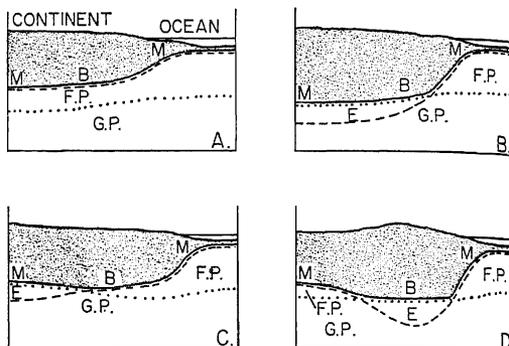


Fig. 4. Possible arrangements within the earth of a chemical discontinuity (dashed line), a phase transition zone (simplified to a boundary, the dotted line), and the M discontinuity (the lower solid line *MM*). *B*, basalt; *E*, eclogite; *F.P.*, feldspathic peridotite, *G.P.*, garnet peridotite. The crust is stippled.

The model for the upper mantle and crust presented here is a compromise between the rival hypotheses discussed earlier. Four possible arrangements for the two discontinuities are illustrated schematically in Figure 4. The phase transition zone is shown as a dotted line, and the M discontinuity, the solid line *MM*, may be a chemical discontinuity (dashed line) in some localities (e.g. beneath ocean basins and parts of the continents, such as stable continental shields), and a phase transition in other localities (e.g. in orogenic belts and other active regions of the continents).

The occurrence of intersections between the chemical discontinuity and the phase transition zone introduces an additional element to be considered in the discussion of orogenic processes. Regional variations in the depth to the chemical discontinuity, and local variations in geothermal gradients which cause variations in depth to the phase transition zone, produce great flexibility in orogenic models.

Applications. As previously stated, the phase change hypothesis for M is attractive because vertical movements of isogeotherms cause M to migrate upward or downward with resultant changes in surface elevation. A regional depression of isogeotherms converts basalt to eclogite (Figure 3), which is accompanied by upward movement of M, contraction, and downward sinking of the surface. Conversely, regional uprise of isogeotherms converts eclogite to basalt,

which is accompanied by expansion, downward movement of M, and uplift of the surface. In the compromise model outlined in the preceding section, an additional element is introduced by the existence of intersections between a chemical discontinuity and a phase transition zone.

Kennedy [1959], discussing applications of the phase change hypothesis, concluded that the uplift of extensive regions, such as the Colorado plateau, could be effected by a regional uprise of isogeotherms. The lateral limits of such uplifts would coincide with the limits of the temperature increase at depth, and the elevated regions would grade into the surrounding areas. In fact, many elevated areas are terminated laterally by faults or fault zones. The model illustrated in Figure 5 shows how lateral boundaries of this kind could be provided by the intersection at depth of a chemical discontinuity with a phase transition zone, without a necessity for rather abrupt changes in the distribution of isogeotherms.

A regional rise of isogeotherms causes the phase transition zone to move downward from its original position in Figure 5A to the lower position illustrated in Figure 5B. The position of the intersection between the chemical discontinuity and the phase transition zone migrates laterally down the slope of the chemical discontinuity. Conversion of garnet peridotite to feldspathic peridotite causes a moderate amount of expansion and surface elevation, but conversion of eclogite to basalt causes very much more expansion and correspondingly greater surface elevation. The crustal blocks on either side of

the intersection of the chemical discontinuity and the phase transition zone are thus elevated by greatly different amounts and a fault, or fault zone, would tend to develop between the two blocks. Lateral migration of the intersection at depth (whose amount depends upon the steepness of the chemical discontinuity) tends to favor the formation of a fault zone rather than a single fault plane. The crust thickens beneath the elevated block as the phase transition zone migrates downwards. Figure 5 illustrates what can happen when the phase transition zone migrates without appreciable change in the position of the chemical discontinuity. Much more flexibility is introduced if changes in the position of the chemical discontinuity are considered as well.

In the conventional picture of the orogenic cycle, the chemical discontinuity is moved downward, possibly as a result of the action of convection cells, with the formation of a tectogene. Sediments accumulate in the subsiding trough which is formed at the surface. If the initial situation is as illustrated in Figure 4A, and if the formation of the tectogene is accompanied by cooling at depth, then, as the chemical discontinuity moves downward, the phase transition moves upward to meet it. When the two intersect, a pocket of eclogite is developed at the root of the tectogene corresponding to the condition illustrated in Figure 4D. Once this stage is reached, continued conversion of basalt to eclogite accentuates the subsidence of the trough at the surface. Subsequent heating at depth would cause the phase transition zone to move downward relative to the chemical discontinuity, and the sediments accumulated in the trough would be elevated. When the phase transition zone passes below the chemical discontinuity at the base of the tectogene, the continued depression of the phase transition in peridotite ceases to have much effect on the surface level. The intersection of the phase transition zone with the chemical discontinuity could thus provide a beginning and an end to the more vigorous changes in surface level occurring during orogenic cycles. This model will be discussed in more detail elsewhere.

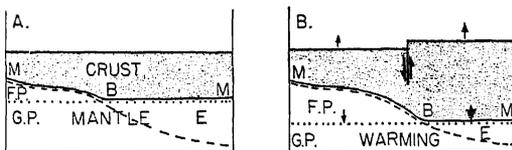


Fig. 5. The effect of an intersection between the chemical discontinuity (dashed line) and the phase transition zone (simplified to a line, dotted) when the regional geoisotherms are raised. The phase transition migrates downward, causing conversion of eclogite to basalt with resultant surface elevation. Differential elevation occurs between the crustal blocks overlying eclogite and peridotite, with the formation of a fault (or fault zone) between two blocks of different elevation. The crust (stippled) thickens beneath the elevated region.

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