4. Map Scales and Projections

a. Polar stereographic projections will be used for all chart exchanges.
b. Analysis and prognostic charts having a scale of 1:30 million or 1:40 million will be used.
c. Special charts exchanged on request would be on scales most convenient for the transmitting country.

The Mohorovičić Discontinuity and the Orogenic Cycle

The following report, by Peter J. Wyllie, Department of Geochemistry and Mineralogy, Pennsylvania State University, is based on a paper presented by the author at the Second Western National Meeting of the American Geophysical Union, held at Stanford University, December 1962. A similar, more-detailed version of this paper has been published in the Journal of Geophysical Research, August 1, 1963. *The version presented below includes an enlarged discussion of possible applications to the orogenic cycle; essentially the same version has also been issued as Pennsylvania State University* Mineral Industries Contribution No. 62-91.

The generally accepted view that the lower part of the earth's crust is composed of basalt (or gabbro) is supported by the measured velocity of 7.0 ± 0.6 km/sec for compressional seismic waves. The Mohorovičić discontinuity (or M discontinuity) separates the crust from the upper mantle, which is composed of material with seismic-wave velocities of 8.0 ± 0.4 km/sec (usually 8.1 ± 0.1 km/sec). Of rocks known at the surface of the earth, only dunite, peridotite, and eclogite have the elastic properties appropriate for this velocity. (Figures 2 and 3, and parts of the discussion below, provide information about the temperature, pressure, and depth conditions under which possible rock materials of the lower crust and upper mantle are formed, as well as about the conditions of formation of some of their major constituent minerals.)

The thickness of the earth's crust varies considerably. Beneath the ocean basins the M discontinuity is at a depth of about 12 km; beneath the continental shields it is about 35 km deep; and beneath mountain belts it reaches depths as great as 65 km.

No direct observations have been obtained of the composition of mantle material, and the Mohole deep-drilling project can provide only local samples of the upper mantle. Indirect evidence concerning the composition of the mantle is provided by analogy with meteorites, by the compositions of intrusive igneous rocks and of volcanic rocks and their inclusions (which may have been derived from the upper mantle), and by consideration of the distribution of radioactive elements required to explain the earth's thermal budget.

Two rival hypotheses exist concerning the composition of the upper mantle and the nature of the M discontinuity. The conventional view that the M discontinuity marks a *chemical change* from basalt, in the lower crust, to material with the composition of peridotite, in the upper mantle, is challenged by the view that the upper mantle is composed of eclogite—the denser chemical equivalent of basalt—and that the M discontinuity represents a *phase change* from basalt to eclogite. Each of these hypotheses has its advantages and each faces difficulties. Both hypotheses appear to satisfy the available geophysical evidence;

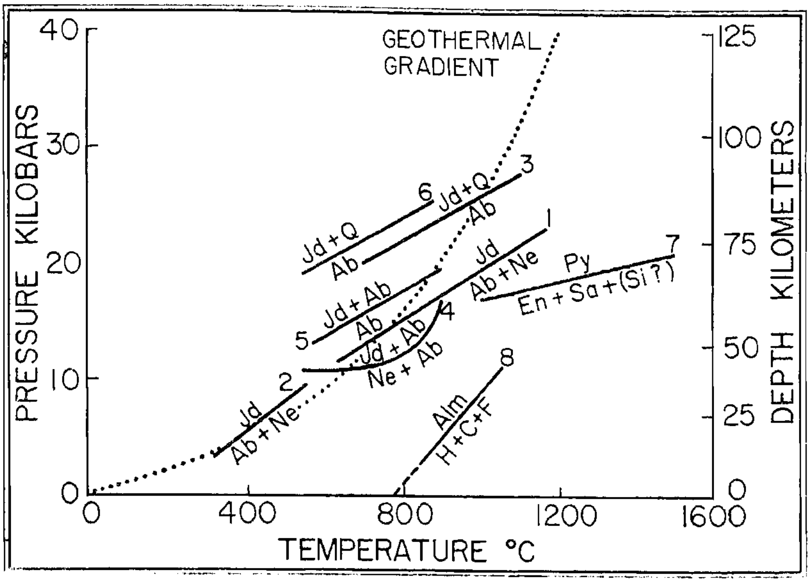

Fig. 2. *Experimentally Measured Reactions, under Varying Temperatures and Pressures, Involving Dense Silicate Minerals. Ab = albite; Ne = nepheline; Jd = jadeite; Q = quartz; En = enstatite; Sa = sanidine; Si = sillimanite; Alm = almandine; H = hercynite; C = iron cordierite; and F = fayalite. Dotted line represents an average geothermal gradient.*

most other indirect evidence, including experimental data on the stability of high-pressure modifications of common silicate minerals, can be adjusted to suit either interpretation.

There appears to be no good reason why these two hypotheses should exclude each other. In fact, as outlined in the following pages, it is quite possible that the M discontinuity is caused by a chemical discontinuity in some environments and by a phase change in others. Such a model combines the advantages and removes some of the difficulties of the two hypotheses considered separately. In addition, it adds an element for consideration in orogenic, or mountain-building, theories—namely, the effect on mountain-formation of intersections at depth between a chemical discontinuity and a phase-transition zone.

Chemical Discontinuity Hypothesis

The M discontinuity is generally believed to be caused by a chemical change from basaltic rock in the lower crust to peridotite in the upper mantle, the mean chemical composition of the upper mantle over any extensive region of the earth being similar to a mixture of about four parts dunite (variety of peridotite consisting chiefly of the mineral olivine [$(Mg, Fe)_2SiO_4$]) to approximately one part basalt. A conclusion that the upper mantle is composed of material with the composition of 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 (a type of stony meteorites).

The primary advantage of this conventional model of the upper mantle is that it provides reasonable explanations for a large amount of rock data. What is known of the origins of rocks demands that the mantle material be capable of supplying the basaltic magma that has been erupted so frequently at the earth's surface throughout geological time. Furthermore, it appears more likely that this magma is produced by partial melting of crystalline material than by complete melting; the latter would

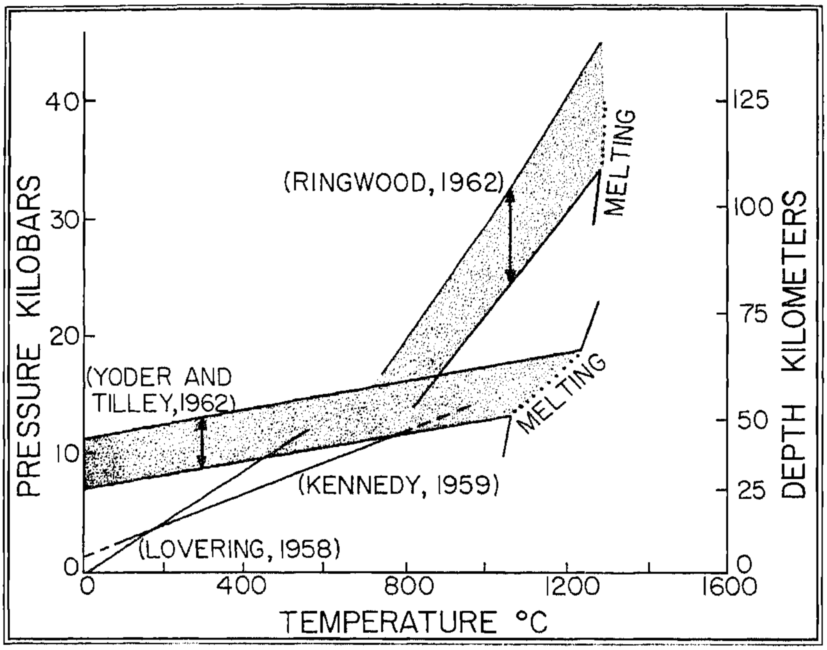

Fig. 3. *Position of Basalt-Eclogite Phase Transition, from Published Estimates.*

be required if the mantle were composed of eclogite.

At appropriate depths, according to this hypothesis, the basaltic portion of the peridotite making up the upper mantle would be converted to eclogite. The mantle material thus would consist of garnet peridotite, composed of a mixture of dunite and eclogite (eclogite here being restricted in chemical composition to the range of basaltic compositions). Because of the similarity in the elastic properties of feldspathic peridotite, garnet peridotite, dunite, and eclogite, it is possible that present seismic techniques would not record the existence of a discontinuity or transition zone between any pair of these rocks at depth.

This hypothesis is satisfactory in many ways, but it also presents difficulties, some of which are more easily explained by the phase-change hypothesis for the M discontinuity.

Phase Change Hypothesis

The suggestion that the upper mantle is composed of eclogite is not new, but it received little support until revived following recent theoretical and experimental studies. If it is concluded that the outer 100 kms of the earth are of basaltic composition, the M discontinuity can be explained as a phase change from basalt to eclogite. The great attraction of the phase-change hypothesis lies in the fact that vertical movements of isogeotherms cause the M discontinuity to migrate upward or downward, producing changes in crustal thickness and causing contraction or expansion, with consequent changes in surface elevation. This process has far-reaching implications for orogenic theories.

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 complete conversion of basalt to eclogite probably involves a series of rather complex mineral transitions. Experimentally measured curves for transitions involving these minerals are plotted in Figure 2 with respect to pressure, temperature, and depth beneath the earth's surface.

Although the simple mineralogical reactions shown in Figure 2 give an indication of the position and slope of the basalt-eclogite transition relative to the physical factors, they are not sufficient to locate it precisely. 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 regarding the actual depth at which the change would occur. In order 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 as yet adequately known.

Figure 3 compares four published estimates of the basalt-eclogite phase transition. The estimate of H. S. Yoder and C. E. Tilley (1962), based on their own experiments with natural samples as well as on those of other investigators, is regarded as the best estimate yet available. 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 position of the Yoder and Tilley transitional interval illustrates more clearly than the scattered curves in Figure 2 that basalt, or the basaltic portion of feldspathic peridotite, must undergo a transition to eclogite at depths within the earth roughly equivalent to, or somewhat deeper than, the position of the M discontinuity beneath the continents. It does not support the view that the M discontinuity at shallow depths beneath the oceanic crust could be caused by the basalt-eclogite phase change, nor do various published calculations support this view. There remains a possibility that the M discontinuity beneath the oceans could be caused by a different phase transition, such as one from partially serpentinized peridotite to unserpentinized peridotite. This would imply that the M discontinuity beneath the oceans is a "fossil isotherm"—the preserved evidence of an ancient surface of equal temperature.

The available evidence thus confirms 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 (Fig. 3), but it has been suggested that the part of the reaction that produces garnet might make the largest contribution to the seismic-wave 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 occur over a much smaller depth interval than that indicated by the transition band in Figure 3. There appears to be some question as to just how sharp the M discontinuity may be.

The advantages of a model in which the M discontinuity is caused by a phase transition from basalt to eclogite are many. The phase-change model provides reasonable solutions for major geological problems such as the differences 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. Steady-state calculations provide considerable insight into some aspects of these problems. Using this model, calculated estimates obtained for the thicknesses to which sediments 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 phase-change model also faces difficulties. First, available evidence does not favor the hypothesis that beneath the oceans the M discontinuity is represented by the transition from basalt to eclogite. For continental regions, the phase-change hypothesis is less satisfactory with respect to petrogenetic arguments than the chemi-

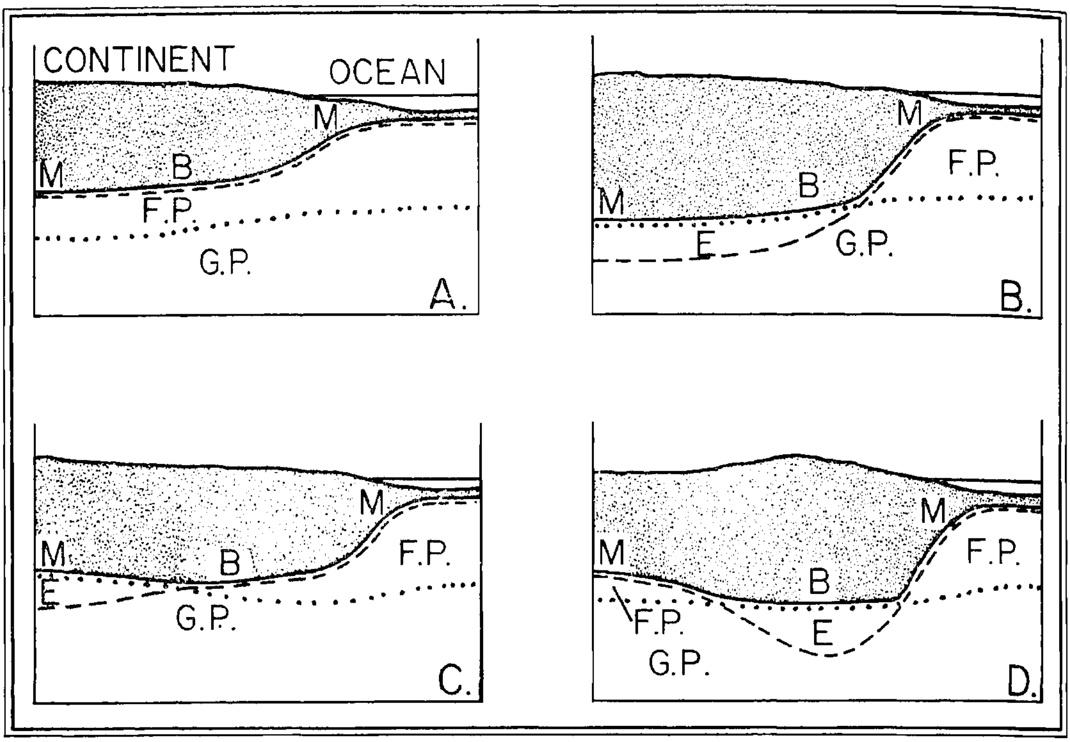

Fig. 4. *Possible Arrangements Within the Earth, and Possible Associated Structural Patterns, of a Chemical Discontinuity, a Phase-Transition Zone, and the M Discontinuity. The chemical discontinuity is represented by dashed line, the phase-transition by dotted line, and the M discontinuity by solid line MM; B = basalt, E = eclogite, F.P. = feldspathic peridotite, and G.P. = garnet peridotite; earth's crust is stipled.*

cal discontinuity hypothesis. It is difficult to reconcile the widely accepted model of a chondritic mantle with the suggestion that as much as 100 km of the upper mantle are composed of eclogite. Eclogite would have to be completely melted to provide basaltic magma; it is more likely, however, that magma derived from the earth's mantle is generated by partial fusion.

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. Thus far, no significant correlations have been established.

Compromise Hypothesis

There is no convincing evidence to support the view that beneath the oceans the M discontinuity is caused by a phase change from basalt to eclogite; on the other hand, there are few impediments to the view that the suboceanic M discontinuity represents a compositional change from mafic to deeper-lying ultramafic material. If the upper-mantle material beneath the oceanic crust is composed of feldspathic peridotite, then it is reasonable to conclude that the upper mantle beneath the continents has a similar composition. This implies that a chemical discontinuity of global extent exists, between material of basaltic composition at the base of the crust and material with the composition of feldspathic peridotite in the upper mantle. The depth to this discontinuity in oceanic areas certainly differs from the depth in continental areas, and it probably differs from continental shield areas to orogenic regions.

In addition to the chemical discontinuity, there exists at the appropriate depth another discontinuity, marking the position of the basalt-eclogite phase transition (Fig. 4). This second major discontinuity 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 this 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, then the chemical discontinuity is recorded as the M discontinuity by seismic measurements (Fig. 4A). It would probably be difficult, with present seismic techniques, to detect the deeper transition, from feldspathic peridotite to garnet peridotite, because the change in seismic-wave velocity 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 may be undetected (Fig. 4B). Only the major discontinuities, involving elastic properties and density (i.e. the discontinuities between basalt and feldspathic peridotite, or between basalt and eclogite), would be detected by seismic methods.

Refinement of seismic techniques or of other geophysical methods may ultimately provide a test to determine whether a second discontinuity actually exists below the M discontinuity. Recent crustal magnetotelluric measurements in Massachusetts are of interest in this connection. The results indicate that a rapid change of resistivity must occur at a depth of about 70 km, which is deeper than the M discontinuity in this region.

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

The occurrence of intersections between the chemical discontinuity and the phase-transition zone introduces an additional

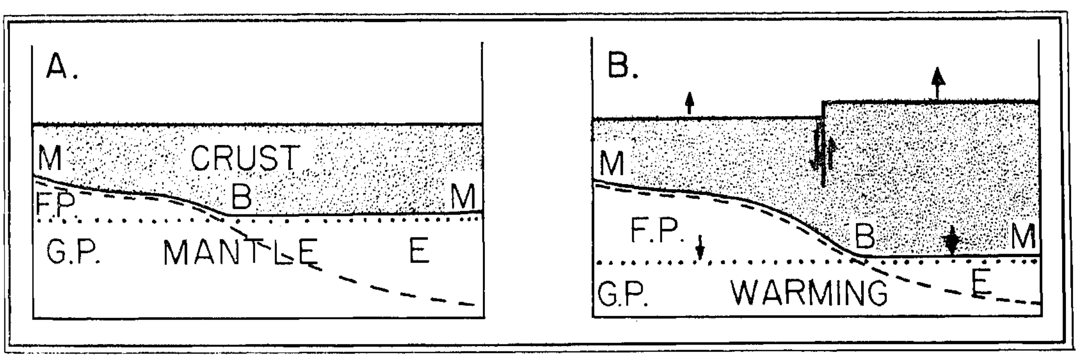

Fig. 5. *Effect of Intersection between a Chemical Discontinuity (dashed line) and a Phase-Transition Zone (dotted line) when Regional Geoisotherms are Raised. Phase transition migrates downward, causing conversion of eclogite to basalt and resultant elevation of surface. Differential elevation occurs between crustal blocks overlying eclogite and peridotite, with formation of fault (or fault zone) between the two blocks; crust (stippled) thickens beneath elevated region.*

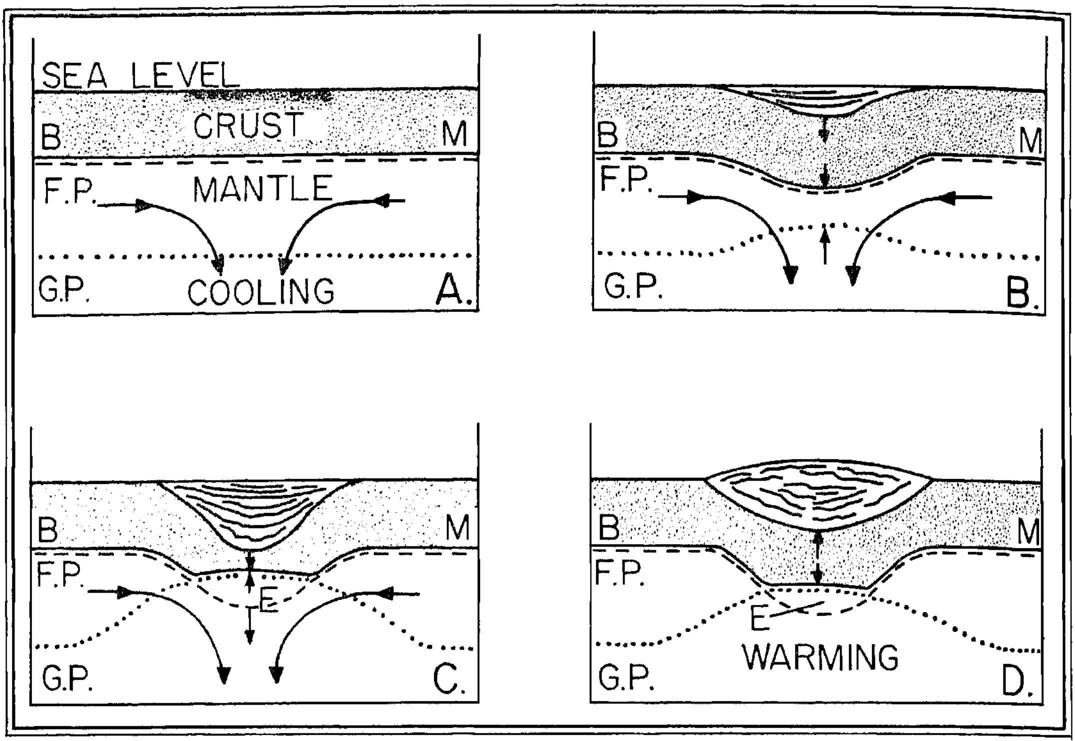

Fig. 6. *Schematic Representation of Possible Sequence of an Orogenic Cycle. B = basalt; E = eclogite; F.P. = feldspathic peridotite; and G.P. = garnet peridotite. Chemical discontinuity is represented by dashed line; phase-transition zone by dotted line; and M discontinuity by solid line M. Crust is stippled. Convection cells are operative in A, B, and C.*

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, permit great flexibility in the construction of orogenic models.

Applications of Combined M-Discontinuity Model

As stated above, an advantage of the phase-change hypothesis for the M discontinuity lies in the fact that vertical movements of isogeotherms cause the M discontinuity to migrate upward or downward, producing contraction or expansion of the crustal and upper-mantle rock material, with resultant changes in surface elevation. A regional depression of isogeotherms, for example, converts basalt to eclogite (Fig. 3), which is accompanied by upward movement of the M discontinuity, contraction, and downward sinking of the surface. Conversely, regional uprise of isogeotherms converts eclogite to basalt, which is accompanied by expansion, downward movement of the M discontinuity, and uplift of the surface. In the compromise model outlined above, the additional element of the existence of intersections between a chemical discontinuity and a phase-transition zone is introduced.

One immediately obvious application of the phase-change hypothesis is the idea that the uplift of extensive regions of the earth's crust, such as the Colorado Plateau, could be effected by a regional upward movement of isogeotherms. The lateral limits of such uplifts would be coincident with the limits of the temperature increase at depth, implying that the elevated regions would grade into the surrounding areas. In fact, many topographically 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 abrupt changes in the distribution of isogeotherms.

Conversion of garnet peridotite to feldspathic peridotite causes moderate expansion and surface elevation; conversion of eclogite to basalt, however, causes very much greater 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 them.

A regional rise of isogeotherms would cause the phase-transition zone to move downward from its original position, as shown 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. Such lateral migration of the intersection at depth (the 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 greater 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, or large downfold in the crust (Fig. 6). Sediments accumulate in the subsiding trough formed at the surface.

If the initial situation corresponds to that illustrated in Figure 6A, and 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 (Fig. 6B). If the two intersect, a pocket of eclogite is developed at the root of the tectogene, as shown in Figure 6C. After this stage is reached, continued conversion of basalt to eclogite accentuates the subsidence of the trough at the surface. Subsequent warming at depth would cause the phase-transition zone to move downward relative to the chemical discontinuity, with resultant elevation of the sediments accumulated in the trough (Fig. 6D).

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. 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.

Figure 6 is obviously an oversimplified picture of the possible effects of superposition of two basic models of the M discontinuity. More-detailed consideration is needed. It is evident from Figure 6 that, according to this compromise model, the structure of the upper mantle should be more complex and variable than present geophysical measurements indicate. This is a subject for further study as techniques become more refined.

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