

outward from the moon, in accordance with the lack of detectable lunar fields at the distance of the orbiting Explorer 35 satellite.

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## Low-Velocity Zone of the Earth's Mantle: Incipient Melting Caused by Water

**Abstract.** *Experimental phase diagrams for the systems gabbro-water and peridotite-water indicate that, if there is any water in the upper mantle, then traces of hydrous interstitial silicate magma will be produced at depths corresponding to the beginning of the low-velocity zone. This explanation for the zone is more satisfactory than others proposed.*

Almost simultaneously with Kushiro *et al.* in 1968, we reported experimental data that suggested an explanation for the low-velocity zone in terms of incipient melting of mantle eclogite or peridotite in the presence of traces of water (1, 2). Anderson and Sammis and Ringwood independently deduced that incipient melting of peridotite in the presence of water was a likely explanation (3). The validity of this interpretation is strengthened by the recent publication of experimental data for the systems gabbro-water-carbon dioxide by Hill and Boettcher and peridotite-water by Kushiro (4, 5). We now consider that the model outlined below represents the most likely cause of the low-velocity zone.

The existence of a low-velocity zone in the upper mantle for most tectonic environments is now established for both *S* and *P* waves. The depth and thickness of the zone varies from one tectonic environment to another, and it is probably coincident with a layer of reduced viscosity (6, 7). There have been many attempts to explain this zone by departure of the geotherm from the critical temperature gradient for which the seismic velocity remains

constant, or in terms of chemical or mineralogical zoning; but these explanations have not proved adequate (3). Many geophysicists now conclude that partial melting of the upper mantle is required to explain the observations, and the assumption has usually been implicit that melting occurred because the geotherm rose above the dry solidus. Dry melting introduces a number of problems, and it requires that the geotherm be rather sensitively controlled and constrained close to the solidus to prevent the production of too much liquid. Interpretations of the low-velocity zone in terms of partial melting of the dry mantle, and review of the problems of this interpretation, have been presented recently by Ringwood, Knopoff, Anderson, and Birch (see 3, 6, 8).

The upper mantle contains peridotite of three types: undepleted (original), residual, and precipitated, with layers and pods of gabbro or eclogite (9-11). Residual peridotite may be dominant beneath the continents. According to Press, there is at least 50 percent eclogite in the suboceanic mantle between depths of 80 and 150 km (10). There is evidence that traces of

water are present, stabilized in amphibole and phlogopite in the uppermost mantle. Superimposed on this heterogeneous mantle is a concentric succession of mineral facies. The depths to transitions between facies are sensitive to temperature variations (9, 11).

Addition of water to material of gabbroic composition (as shown in Fig. 1) causes depression of the melting temperatures, increases the temperature interval between solidus and liquidus, and introduces one hydrous mineral, an amphibole. The gabbro-eclogite transition interval, shown below the solidus for the dry rock, is masked by the formation of amphibole in the presence of excess water. The slope ( $dP/dT$ ) of the solidus for the rock with excess water reverses at 15 kb, where plagioclase feldspar is replaced by jadeitic pyroxene (1, 4, 12). The hornblende-out curve for the breakdown of amphibole under these conditions also reverses slope, as predicted by Green and Ringwood and by Fry and Fyfe (13, 14), but our experimental data indicated that the change in slope is considerably more marked than anticipated (2).

This pattern of melting relationships has been confirmed by Hill and Boettcher (4). It is known that the hornblende-out curve extends to higher pressures and temperatures for amphiboles occurring in ultramafic rocks (4, 15), and to higher pressures and temperatures if water pressure is reduced compared with load pressure in the presence of a liquid phase (4) and in the vapor-absent region (16).

The solidus for dry peridotite is similar to that for gabbro in Fig. 1, and the solidus for peridotite in the presence of excess water is close to the liquids for gabbro-water in Fig. 1 (1, 2, 4, 5). The upper stability limit for hornblende in gabbro under these conditions thus barely overlaps the solidus for peridotite-water; Kushiro has shown that in a natural peridotite, the amphibole-out curve overlaps the solidus by a few tens of degrees within a pressure range of 8 to 17 kb (5).

Figure 1 is based on experiments with gabbros that become quartz eclogites at high pressures. For a gabbro undersaturated in silica to such an extent that it yielded olivine eclogite, or a simple garnet-pyroxene eclogite, we can expect that the solidus in the presence of excess water would increase in temperature rather sharply within a

short pressure interval above 15 kb, where plagioclase disappears; the mineralogy would then be similar to that of the high-pressure peridotite.

The upper mantle probably contains only traces of water. Given gabbroic material containing 0.1 percent water, we can deduce the general pattern of phase relationships from Fig. 1, and the resulting isopleth is shown in Fig. 2. The liquidus temperature is depressed only slightly compared with the dry liquidus. Within the stability field of hornblende, all the water is fixed in the hornblende and no melting occurs. There are two vapor-absent fields for hornblende-gabbro and hornblende-eclogite, with a transition interval indicated between them. The breakdown curve for hornblende in Fig. 2 should be located at somewhat higher temperatures than in Fig. 1 because of the vapor-absent conditions (16).

In the subsolidus region, at pressures above the stability of hornblende, the water exists as an interstitial film in eclogite. The curve for the beginning of melting is the same as that for melting with excess water, as in Fig. 1, but, for an eclogite without quartz, this curve would be at a higher temperature. Because of the very small amount of water present, only a trace of liquid develops. At lower pressures, the solidus is the breakdown curve for hornblende; the subsolidus vapor-absent assemblages are stable until hornblende releases water, which then passes directly into a vapor-absent liquid phase. The light-shaded area represents gabbro or eclogite with a trace of interstitial liquid, undersaturated with water; its composition is probably intermediate rather than basic (17). The amount of liquid is controlled almost entirely by the water content, and it increases only very slightly with temperature increase. Melting increases when the temperature reaches the solidus for dry eclogite (heavy shading in Fig. 2).

On the basis of the solidus and hornblende-out curve in Fig. 1, we suggested in 1968 that the beginning of the low-velocity zone corresponds to the level where amphibole becomes unstable, because at greater depths traces of water in eclogite pods or layers would cause the formation of interstitial magma. This model is illustrated in Fig. 2. The geotherms show that the depth where the zone of incipient melting begins is sensitive to temperature and that variation in temperature at depth

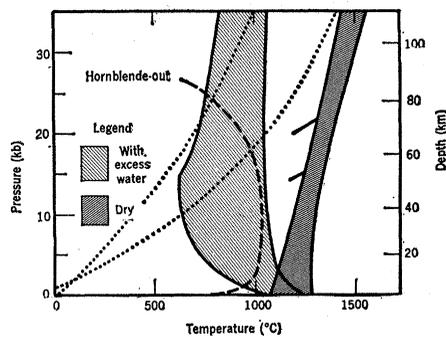


Fig. 1. Generalized diagram for the melting interval of gabbroic material, dry and in the presence of excess water [based on experimental work by Green and Ringwood (13), Cohen *et al.* (20), Lambert and Wyllie (2), and Hill and Boettcher (4)]. The dotted curves are estimated geotherms for oceanic and shield regions.

would cause the boundary between vapor-absent hornblende-eclogite and a partially melted eclogite to migrate up or down. Extrapolation of Fig. 2 indicates that eclogite with interstitial magma would extend below 110 km, as long as water is present.

The dominance of carbon dioxide compared with water in fluid inclusions of some mantle-derived materials (18) suggests that Fig. 2 may not provide a realistic model for mineral facies in the upper mantle. If carbon dioxide is present in upper mantle material, the water has to be distributed between a pore fluid and hornblende. Given water in the pore fluid, some liquid must form below the maximum temperature limit of hornblende, which is depicted as the solidus in Fig. 2. We have then to consider distribution of water among pore

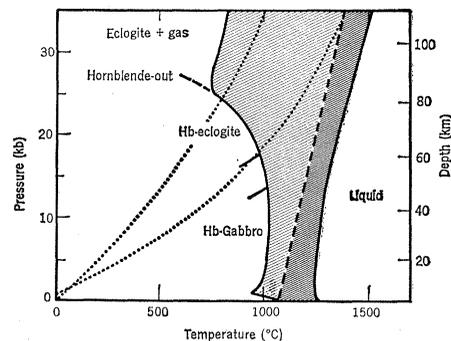


Fig. 2. Estimated isopleth for the phase fields intersected by gabbroic material in the presence of 0.1 percent by weight of water [deduced from Fig. 1 (9)]. Only a trace of liquid is present through the light-shaded interval; basic liquid is produced only within the dark-shaded interval, which corresponds closely to the dry melting interval in Fig. 1.

fluid, liquid, and hornblende. The general pattern of phase relationships would probably remain similar to that shown in Fig. 2, with incipient melting beginning at lower temperatures and with all facies, including a trace of a gaseous phase composed largely of carbon dioxide.

Consider now a mantle composed of peridotite with 0.1 percent by weight of water. This water would be stored in hornblende in the upper mantle, and a vapor-absent assemblage would therefore be produced. If carbon dioxide is present, an intergranular fluid would exist, but it would probably contain very little of the water. At depths greater than the hornblende stability limit, any water present would be distributed between an intergranular pore fluid and phlogopite. Phlogopite remains stable to depths of 100 km or more in the suboceanic environment and to much greater depths beneath the continents (16). Figure 1 shows that mantle peridotite with a trace of water will undergo incipient melting at a depth of 80 to 100 km in the suboceanic environment, but beneath the shield regions incipient melting will occur at very much greater depths. The amount of liquid developed would be extremely small, much less than in gabbro under comparable conditions, and would be strongly dependent upon the amount of water present.

The phase diagrams illustrated and discussed for the system peridotite-gabbro-water leave little doubt that, if there is any water present in the upper mantle, then traces of hydrous interstitial silicate magma will be produced at depths corresponding to the beginning of the low-velocity zone. The fact that the amount of liquid produced varies little through wide ranges of depth and temperature provides a satisfactory explanation for the existence of the low-velocity zone with similar properties in different tectonic environments with different depth-temperature distributions.

If the low-velocity zone is caused by incipient melting in the presence of water, the question arises as to why the zone terminates downward. There would be no liquid below the zone if the water content became vanishingly small or if the water was stored in high-pressure hydrous crystalline phases (19). If the bottom of the zone coincided with the lower limit of the eclogite-bearing peridotite (10), for the same amount of water there would be very

much less liquid in the underlying peridotite than in the eclogite. The melting interval of hydrous eclogite or peridotite begins to trend almost parallel with the dry melting intervals at higher pressures (Fig. 1), and it is conceivable that at depth, where the temperature gradient is less, the geotherm may pass through the solidus into the subsolidus region.

Where peridotite is present in the upper mantle between 60 and 100 km or deeper, the instability of hornblende and the small proportion of phlogopite permitted by potassium abundances suggest that there may be an interstitial, hydrous pore fluid (Fig. 1). This fluid may contain a high proportion of elements not readily accommodated in the peridotite minerals, including K, U, and Th, the elements important in the thermal budget of the earth. Where eclogite occurs in the upper mantle below 50 km, the same elements may be concentrated in interstitial silicate magma. The quantity, composition, distribution, and migration of such pore fluids and interstitial magmas are important for major geological processes (20).

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contain crystalline inclusions that were identified as zircon and chromite by x-ray diffraction. During further investigations, quartz and possibly coesite were identified by x-ray diffraction in frothy grains from the lightest fractions.

Microprobe analysis of several grains from each specific gravity fraction showed that the tektite has a wide range in composition (approximately 64 to 80 percent SiO<sub>2</sub>), but its average composition is similar to that of other previously analyzed Muong Nong-type tektites (2). A thin section from the tektite shows highly contorted flow lines and numerous frothy and sub-angular lechatelierite particles, as well as a layered structure that is also evident in the hand specimen.

All of the mineral inclusions were completely surrounded by glass. Two chromite crystals were recovered; they are opaque and have a bronze color and submetallic luster. One is an octahedral crystal about 75 μm in width (Fig. 1); the other is an irregular grain (56 by 87 μm). These crystals were identified from x-ray diffraction patterns obtained with a Debye-Scherrer camera. Fourteen lines were present and all match lines for chromite. No eskolaite (Cr<sub>2</sub>O<sub>3</sub>) lines were observed. The composition of one of the chromite crystals was determined by electron microprobe analysis (Table 1). The grain containing the chromite crystal was mounted in epoxy, ground down to expose the crystal, and then polished. Nine chromites of known compositions were used for standards. The silica content of the chromite inclusion is rather high (average, ~ 2 percent) and variable (increasing toward the edges); otherwise the grain was fairly homogeneous, and the chromite-glass interface seemed to be rather sharp. Unfortunately, the grain was lost in an attempt to polish down to the maximum diameter of the chromite crystal; therefore no spectrometer traces or counts across the interface are available.

Approximately 15 zircon crystals were recovered. The largest dimension for each crystal is between 60 and 100 μm. They are generally white and opaque—although one euhedral crystal is partially translucent with an opalescent appearance. They vary in shape from euhedral, doubly terminated crystals to rounded grains and to irregular but rounded grains (Fig. 2). X-ray diffraction patterns were obtained for five different grains. Approximately 25 lines were observed for each pattern;

## Zircon and Chromite Crystals in a Muong Nong-Type Tektite

**Abstract.** *Chromite, zircon, and quartz crystals (identified by x-ray diffraction) have been recovered from a 2.07-gram sample of Muong Nong-type tektite. The absence of eskolaite (Cr<sub>2</sub>O<sub>3</sub>) and baddeleyite (ZrO<sub>2</sub>) supports a previous conclusion that Muong Nong-type tektites were not heated as intensely as other tektite groups. X-ray asterism studies indicate that the crystals are shocked, which supports an impact origin. The presence of chromite and zircon together suggests that the Muong Nong-type tektite was produced from sedimentary material.*

During the investigation of the chemical variation within a Muong Nong-type (layered) tektite from Indochina, several crystalline inclusions, identified as chromite and zircon, were discovered. The discovery was not entirely unexpected, however, since previous work had indicated that the Muong Nong-type tektites were formed at lower temperatures than the splash-form types were and thus provide the logical place to search for minerals included in tektites (1). The minerals described in this report are believed to be relict and are therefore of obvious importance

in indicating the nature of the parent material from which and the process by which the tektite was formed.

The chromite and zircon inclusions were discovered by crushing and sieving a 5.4-g sample of Muong Nong-type tektite. The fraction consisting of particles 110 to 149 μm in size (2.07 g) was then separated into 14 fractions based on specific gravity by use of heavy liquids (Bromoform and *N,N*-dimethyl formamide). Microscopic examination of each fraction revealed that many of the grains in the heavier fractions (specific gravity, 2.42 to 2.75)