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THE CORE--MANTLE DISCONTINUITY

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THE CORE--MANTLE DISCONTINUITY

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Stishov, S. M. O granitse yadro—mantiya. Geokhimiya, no. 11, 1962, 989-992.

According to current concepts, the earth's core consists of metallic matter, a large part of which (the outer core, or E zone) is in the liquid state.

The chemical composition of the core is not completely known. The overwhelming majority of geophysicists and geochemists feel that the core is predominantly iron in composition. Others postulate that the material of the core is identical in composition with that of the mantle, but is in a metallized state. Both viewpoints can be regarded as equally tenable because at the present time neither can be fully confirmed or positively refuted.

This brief article discusses the hypothesis of a metallized silicified core, [illegible]

In postulating a phase transition at the boundary of the core, it is necessary to assume that the seismic boundary separating the mantle from the core is at the same time a phase boundary. If the outer core is liquid, it follows that a low-pressure* solid phase and a high-pressure** liquid phase coexist (are in equilibrium) at the core—mantle discontinuity.

This circumstance creates certain difficulties, because in an ordinary phase diagram of matter with transformations in the solid phase (see Fig. 1), there are no monovariant curves corresponding to such equilibrium. Other examples of phase diagrams are well known. Fig. 2 is a schematic representation of the phase diagram of indium antimonide InSb. In its normal state, InSb is a semiconductor with a structure like zinc blende, but at high pressures it transforms into the metallic phase and takes on a structure apparently similar to NaCl [1; 2]. It should be emphasized that indium antimonide melts at

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* The terms "low-pressure phase" and "high-pressure phase" are used in the same sense as the terms "low-temperature phase", "high-temperature phase", etc.; that is, to denote a completely determined physical state of a substance stable within a defined region of temperatures and pressures. These terms are only relative. In our case, the lower mantle is the low-pressure phase and the outer core the high-pressure phase.

** By "high-pressure liquid phase" is meant a liquid with a close correspondence to the crystalline structure of the high-pressure solid phase.

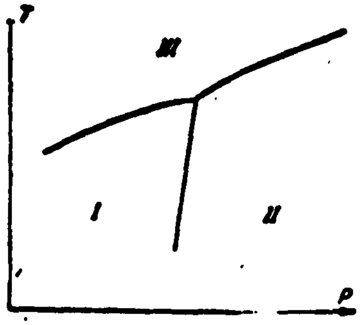

Fig. 1. Part of an ordinary phase diagram of matter with transformation in the solid state

I - low-pressure solid phase; II - high-pressure solid phase; III - liquid.

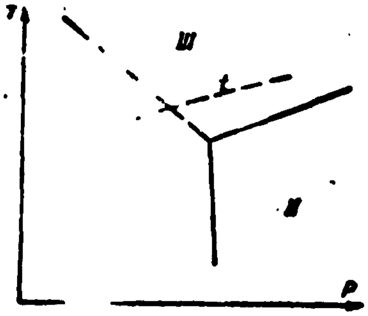

Fig. 2. Schematic phase diagram of indium antimonide

t - temperature distribution curve; other notations are the same as in Fig. 1.

normal pressure with reduction in volume. In the molten state, it is characterized by a structure identical with the NaCl-type structure and metallic conductivity [1-3]. In this system there is apparently no liquid phase corresponding to the nonmetallic phase, that is, the low-pressure phase.

If there were a diagram of this type for terrestrial material, the abovementioned difficulty would not exist, because the low-pressure solid phase and the high-pressure liquid phase would be in equilibrium along the phase I melting curve (see Fig. 2). However, this diagram is unsatisfactory because it was necessary to assume that the melting temperature of the mantle decreases with depth for the entire distance — in contradiction to known data [4; 5]. This difficulty can be avoided apparently by only one method — by postulating diagrams of the following types (Figs. 3 and 4), in which the melting curve of the material in the mantle has a "break", or peak. Since the entropy of the liquid phase in any case is greater than the entropy of the solid phase, the Clausius-Clapeyron equation,

$$\frac{dT}{dp} = \frac{\Delta V}{\Delta S} \; ,$$

would indicate that a change in the sign of the derivative dT/dp can be related only to a decrease in volume in the case of melting of the mantle close to the core.

Both diagrams of Figs. 3 and 4 are essentially identical and differ only in that the transition between the two liquid phases in Fig. 3 is gradual, whereas in Fig. 4 it is sharp — as can happen if the liquid phases are immiscible.

The following facts can be stated to support a diagram of this type:

1) Metals with a so-called irregular structure (Ga, Bi, Sb) and a covalent metallic nature of bonding melt with a reduction in volume

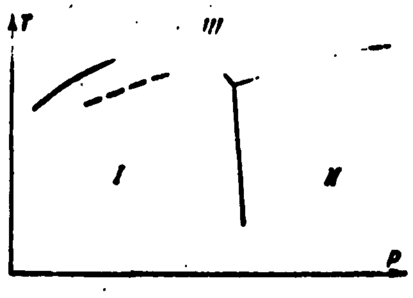

Fig. 3. Variant of the proposed phase diagram of matter in the mantle

For notations, see Fig. 2.

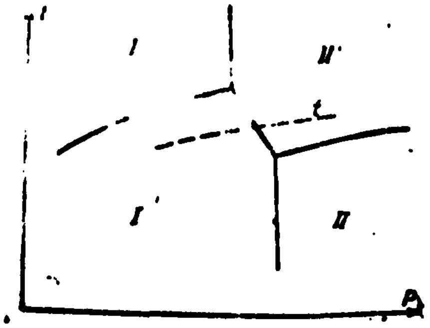

Fig. 4. Variant of the proposed phase diagram for matter in the mantle

I' - low-pressure liquid phase; II' - high-pressure liquid phase; for other notations see Fig. 2.

and an increase in coordination in the molten state [6-8]. The electrical conductivity of these metals in the molten state exceeds the electrical conductivity of the solid phases. This [phenomenon] is related to an increase in the effective number of free carriers [8].

2) Some semiconductors with a forbidden zone of the order of 1 ev or less (Si, Ge, InSb, GaSb, and others) behave similarly in the molten state; that is, they melt with a reduction in volume and an increase in coordination [6-8]. These semiconductors in a molten state are characterized by metallic conductivity.

3) A number of semiconductors (PbTe, Bi_2Te_3, PbSe, ZnSb) show a transition into the metallic state with a close-order change not at the melting point itself, but rather when the molten material is superheated to a certain point.

These facts, considered from the viewpoint of the zone theory — which apparently can also be applied to the molten state [7; 8] — once again confirm the fact that the heating of material leads to the expansion of energy zones. As a result, there is an overlapping of zones in the semiconductors mentioned and an increase of this overlapping in metals with an irregular structure during melting. In the terms of the theory of chemical bonding, these facts can be interpreted as an increase of the bonding during the heating of the metallic component in compounds with a covalent-metallic character of interaction. This leads to the formation of more compact structures because the principles of metallic bonding come into play — nonsaturation and a tendency to maximum coordination.

As a result, it may be assumed that material with a quite small forbidden zone and a crystalline structure far different from compact metallic structures will have a molten state with metallic properties and a greater density than the solid phase.

Therefore, if the probable reduction in width of the forbidden zone of the mantle material under the action of pressure and temperature is taken into account,* it can be expected that pressure will increase the melting temperature of the mantle to a fixed limit, after which the slope of the melting curve will reverse direction due to the appearance of a more compact structure in the molten material.

It should be noted that the structure of the phase diagrams shown in Figs. 3 and 4 supports the assertion that the metallization of matter in the molten state under pressure occurs sooner than it does in the solid phase.

We note in conclusion that from the viewpoint of the proposed diagrams of the state of matter in the mantle it is possible to explain the nature of the D" zone, in which there is a strong decrease in the gradients of seismic wave velocities (see Fig. 5).

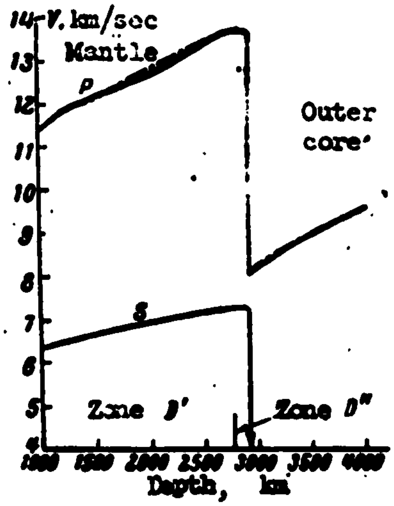

Fig. 5. Velocities of seismic waves in the lower mantle and outer core

The explanation is essentially as follows. According to Lindeman [11],

$$\nu = c m^{-1/2} V^{-1/3} T^{1/2}, \qquad (1)$$

where ν is the oscillation frequency of solid-state atoms, c is a constant, m is atomic weight, V is atomic volume, and T is melting temperature. The Lindeman oscillation frequency of atoms can be identified with the Debye frequency characteristic ν_{max}. The latter is equal to

$$\nu_{max} = \left(\frac{9N}{4\pi V}\right)^{1/3} \left(\frac{1}{V_l^3} + \frac{2}{V_t^3}\right)^{-1/3}, \qquad (2)$$

where V is the volume occupied by N molecules or atoms, and V_l and V_t are the velocities of longitudinal and transverse waves.

If we take into account the relative constancy of the ratio V_l/V_t in the mantle and designate the constant values K_1 and K_2, we

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* This is supported by the experiments of H. Drickamer and others on the displacement of the edge of the principal absorption band of certain substances, including olivine, under the action of pressure and temperature [9; 10].

obtain from equations (1) and (2)

$$V_l = K_1T^{1/2}, \quad V_t = K_2T^{1/2} . \tag{3}$$

Therefore, from the viewpoint of the concepts developed in this paper relative to the type of state diagrams of material in the mantle, it is possible to predict a decrease in velocity gradients and even a decrease in the velocities themselves of seismic waves in zones of the mantle close to the core such as are actually observed (see Fig. 5).

Equations (3) cannot be regarded as completely correct in our case because of the limited applicability of the Lindeman formula and the Debye theory. It is therefore impossible to expect complete agreement between the shape of the melting curve and the velocities of seismic waves in the mantle. It is to be hoped, however, that equations (3) represent qualitative tendencies quite well.

In all probability, the very fact of a decrease in velocity gradients in the D" zone is evidence in support of a metallic transition at the core-mantle discontinuity, provided there is experimental proof of the above-stated postulates.*

In conclusion, the author thanks V. A. Kalinin and A. A. Yaroshevskiy for their consideration of a number of problems discussed in this brief article.

The author is also grateful to Academician A. P. Vinogradov and Professor V. A. Magnitskiy for reading the paper in manuscript.

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* After this article was in print, the author and N. A. Tikhomirova succeeded in experimentally demonstrating the reality of one of the proposed phase diagrams (Fig. 3) for the case of tellurium.

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