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O.YU. SHMIDT'S HYPOTHESIS AND PROBLEMS OF GEOTHERMICS*

As we know, no area of earth physics has been influenced by the ideas of O. Yu. Shmidt as much as the one called geothermics, i. e., the study of the Earth's temperature and thermal history.

Before the advent of Shmidt's hypothesis, everything was usually reduced to the consideration of some variants of cooling of an initially white-hot Earth, and there were some attempts to develop a mathematical system, usually resulting in very slowly convergent series that made for a rather ineffective research tool. Shmidt's new ideas altered the situation radically. The research itself assumed a vastly more comprehensive and profound character. Shmidt's students carried out many studies along these lines, and today geothermics looks completely different from what it did prior to the advent of Shmidt's hypothesis.

It is a well-known fact that because of the lack of original data and uncertainty about much of the Earth's history, an evaluation of the Earth's thermal history yields very indefinite results. In Shmidt's time, this uncertainty appeared less pronounced than is known at the present time. Nevertheless, even then the question was raised whether a different statement of the problem on the Earth's thermal behavior might be possible; namely, whether it might be possible, instead of considering the Earth's history directly, to try to evaluate the present temperature of the Earth and its present distribution with depth by using a comprehensive approach to the solution of the problem, whose possibilities were repeatedly emphasized by Shmidt. In discussing the thermal history of the Earth, this would permit one to keep only those variants that agree with its present temperature. Such an approach could considerably reduce both the indeterminacy and the range of solution variants being obtained at the present time.

Unfortunately, there were practically no means available for such an approach at that time. However, the great progress in geophysics and in high-pressure and high-temperature physics made in the last ten years has considerably altered the situation, and it has now become possible to make an attempt to evaluate the present temperature of the Earth's interior, or, if not the temperature itself, then at least the possible limits of the distribution of temperatures inside the Earth.

The electrical conductivity at various depths inside the Earth would have to be considered as the prime and apparently the most natural source of information on the temperature of the Earth's interior, since the electrical conductivity is strongly temperature dependent. However, the strength of this method is also its weakness. This is because, just as the temperature strongly affects the electrical conductivity, the latter is influenced by those parameters which are included in the exponent together with the temperature (and these parameters are usually known very inadequately).

Several attempts in this direction have been undertaken. Possibly, the best known attempt was made by D. Tozer [1], who gave a temperature variation inside the Earth that was in accord with the electrical conductivity data available at that time. However, this temperature distribution curve naturally gives rise to many legitimate questions and doubts in view of the low accuracy of the parameters involved. Moreover, even the mechanism itself of electrical conductivity at a given depth is frequently unknown, so that many difficulties arise along this path. Another attempt at such an approach, made by V. N. Zharkov, made the difficulties involved even more apparent [2].

Another idea was naturally conceived: to use the same comprehensive approach proposed by Shmidt, while considering all the present-day possibilities, namely, to use all the available data to try to evaluate certain characteristics of the thermal field inside the Earth. These characteristics may be the temperature themselves or the temperature gradients. It turns out that it is very frequently more convenient to obtain the temperature gradients or at least their possible limits at various depths.

If we know the temperature gradient as a function of depth, further simple integration will yield the temperature. Everything will depend on the accuracy and detail with which we know the temperature gradients. The temperature gradients at the surface are determined from the heat flow. To date, heat flows have been studied very extensively on the continents and in the oceans. The thermal conductivity coefficients are known to a somewhat lesser degree, but in any case, one can obtain the temperature gradients near the Earth's surface that are characteristic of dry land and of the ocean. The temperature gradients obtained for the oceans are maximum ones (about 25° C/km^{-1}), and, as expected, for dry land (for the platform), minimum ones (about 18°C/km^{-1}). They may be considered the upper and lower limits of the temperature gradient at the Earth's surface. Special regions (such as regions of volcanism, hydrotherms) are not considered, as they are not characteristic of the Earth as a whole.

Farther down, the data are much more difficult to obtain. However, in the last few years we have been able in some cases to determine the temperature gradient at depths of the order of 15-20 km under the floor of the Earth's crust.

What has happened is that observations developed in the last few years, using bottom seismographs on the ocean bottom and deep sea troughs, where noise and interference are much lower than on the continents, have made it possible to determine the variation in the decrease of seismic wave amplitudes as a function of the distance from their source [3]. If one speaks of an ordinary wave sliding along the interface, its amplitude decreases according to a fairly simple law, shown by a solid curve in Fig. 1.

The circles in this figure indicate the observed variation of amplitudes as a function of the distance to the source. It is evident that in the beginning, the observational data fall satisfactorily on the calculated curve. However, starting at a certain distance, they veer sharply away from this curve. This effect is explained by the fact that in addition to the wave sliding along the interface of the two media, there will also be waves penetrating into the lower medium. The amplitudes of these waves change in accordance with the law represented by dashed

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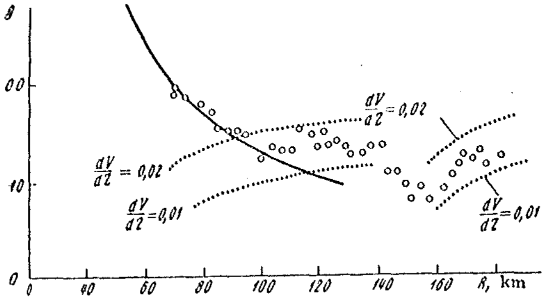

Fig. 1. Decrease in amplitude of seismic waves vs. distance.

curves in Fig. 1. The position of these curves depends on the magnitude of the velocity gradient of seismic waves in relation to depth (dv/dH). Thus, knowing the position of the observed points in relation to the theoretical curves, and using the data of Fig. 1, one can find the velocity gradients dv/dH, and hence, by using a known procedure, also the temperature gradients dT/dH. The gradients in the upper mantle at 15-20 km depths under the floor of the Earth's crust were calculated in this manner. Obviously, the existing information does not permit one to obtain the gradient values uniquely; only the values of their upper and lower limits could be estimated.

The following estimate of gradients pertains to 100-200 km depths, corresponding to a layer of low seismic wave velocities, or the asthenosphere.

While the low-velocity layer is associated with a partial fusion of the mantle substance, the temperature gradient coincides with the solid curve gradient of the corresponding rocks and minerals, which have been studied in laboratory experiments. If the low-velocity layer is associated with a direct effect of the temperature gradient, the latter is estimated from the extreme condition of the velocity curve of the seismic wave. It is thus possible also to estimate the limits of the temperature gradient values at 100-200 km depth.

It may now be considered established that the sharp increase in seismic wave velocities at a depth of about 400 km is due to the transition of olivine from the rhombic to the spinel modification. This transition has been adequately studied, both experimentally and theoretically. In Fig. 2, curves AA and BB are the boundaries of the transition band of olivine from the rhombic to the spinel modification, containing 10% iron and 90% magnesium. Points a and b denote the pressures for the beginning and end of the layer of sharp increase in seismic wave velocities, its width being taken as 50 km, and points a and c, if the width is taken as 80 km. Then, as is evident from Fig. 2, from the points of intersection by the transition band (AABB) of the pressure interval corresponding to the layer of steep increase of seismic wave velocities (a, b, c) one can determine the limits for the temperature gradient dT/dH. Obviously, the width of the transition band (AABB) itself depends on the composition of olivine, and this introduces a certain additional indeterminacy.

Finally, the use of the law of corresponding states makes it possible to evaluate the temperature gradient at a depth of the order of 1000 km or so. However, the use of the law of corresponding states requires a qualification.

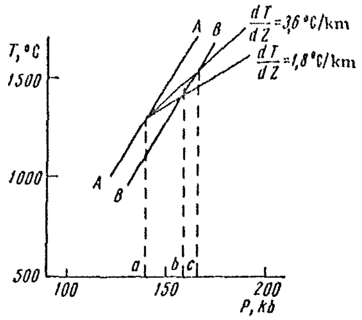

Fig. 2. Band of transition of olivine from the rhombic to the spinel modification.

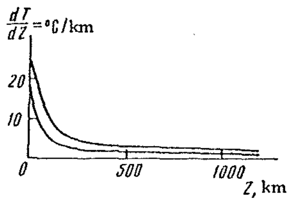

Fig. 3. Character of change of the temperature gradient with depth.

It is satisfactorily obeyed for oxides and not as well for more complicated compounds. It is true that recent extensive studies by Al'tshuler's group [4] dealing with the behavior of substances of a series of rocks and minerals at very high pressures showed that this law is completely verified in this case. This makes it possible to make the corresponding estimate.

As a result, the pattern shown in Fig. 3 was obtained, where curves for the limits of the temperature gradient are given. What is most surprising is that such diverse methods gave points that are connected by extremely smooth curves without any noticeably breaks.

If one now tries to perform the integration, the corresponding temperatures are obtained which will give, for example, the following limits: at a depth of 150 km, 1200-1800°C; at a depth of 1200 km, from 3000 to 4900°C. The scatter is very great, but this is natural, since it is only a first attempt, using very scant and not very reliable data. However, it is of some interest to note that the temperature curve obtained by D. Tozer from the electrical conductivity lies within the following limits: at a depth of 150 km, 1300°C, and at 1200 km, 3300°C, i.e., always slightly above the lower limit.

Of course, the significance of these results must not be overemphasized. There are obviously many other such sites requiring an additional examination. However, O. Yu. Shmidt's basic idea of trying to find the temperature distribution at a given present moment and to use this distribution as the criterion for selecting various theories of the Earth's thermal history deserves the continuation of such studies. Success may justify the effort and energy expended on this research.

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