# RELATION OF MANTLE CONDUCTIVITY TO PHYSICAL CONDITIONS IN THE ASTHENOSPHERE

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**Abstract.** Magnetotelluric soundings show that the conductivity increases in the asthenosphere. The depth of this conductivity zone decreases with an increase of the surface heat flow, i.e. in such cases the lithospheric plate is thinner. The depth of the velocity decrease of seismic shear wave (S waves) shows the same connection with the surface heat flow. The solidus of a mixed-volatile medium intersects the temperature curves belonging to different surface heat flows at depths where the conductivity increase and the velocity decrease appear. These connections point to partial melting in the asthenosphere, which can decrease the viscosity too, and help the movement of the lithospheric plates according to the ideas of global tectonics.

The melt fraction of peridotite and pyrolite determined by Shankland and Waff from the effective conductivity of the asthenosphere is about 3–4% at 30 kbar and at $\sigma^* = 0.1$ S m$^{-1}$.

In the upper mantle of old shields it is likely that there is no well-developed asthenosphere due to the low temperature. Over these so-called 'viscous anchors' the lithospheric plates do not move. It is supposed that the conductivity increases observed below crystalline shields at a depth of about 300 km indicate the phase transition of rocks. Thus in these areas the surface of the phase transition can be at a higher position than in the younger tectonic units.

## 1. Introduction

25 years ago, in 1953, Gutenberg confirmed finally the velocity inversion in the upper mantle, at depths between 70 and 80 km on the basis of the travel-time curves and amplitudes of seismic P and S waves. Lehman (1959, 1961) confined this velocity inversion to the S waves. Now it is generally accepted that the velocity decrease appears more distinctly in the velocity of the shear (S) waves than the P waves.

In 1963, when the first deep magnetotelluric soundings (DMTS) were carried out, Ádám (1963, 1965) and Fournier *et al.* (1963) pointed to an increase of the electrical conductivity at the depth of the low velocity zone.

The asthenosphere represented by the low velocity layer (LVL) and by the highly conducting layer (HCL) and the lithospheric plate above it are basic notions in the new global tectonics, in ocean-floor spreading hypothesis, i.e. in the new trend of geodynamics established in the late sixties.

The decrease of the velocity of shear waves and the increase of electrical conductivity show quite clearly that the physical changes are caused by partial melting of the rocks in the upper mantle. This supposition has been supported by theoretical temperature-depth curves which approach the solidus curve in the depth range of LVL and HCL.

Another feature of the upper mantle is similarly found both in seismic velocity and electrical conductivity at depths of about 300 to 400 km. This is the so-called seismic

*Geophysical Surveys* **4** (1980) 43-55. 0046-5763/80/0041-0043$01.95.

'20° discontinuity' or C layer which means a velocity increase and corresponds to the conductivity increase deduced from early geomagnetic induction studies (e.g. Lahiri and Price, 1939). The cause of these physical changes is a phase transition of the rock material (e.g. olivine → $\beta$–phase).

In the following, we shall investigate this initial qualitative physical-structural picture of the upper mantle to see how much it became a quantitative one as result of intensive field and laboratory work and what kind of conclusions can be drawn from it for the new global tectonics.

## 2. The Connection of the Conductivity Distribution in the Upper Mantle with Heat Flow

### 2.1. The Reliability of Magnetotelluric Data

Deep electrical conductivity data (down to several hundred km) can be obtained mainly from magnetotelluric soundings. Near-surface inhomogeneities, however, often distort the MTS curves and cause difficulties in the interpretation (Berchidevsky and Dmitriev, 1976). If the cause of the distortion is known, the distribution of the conductivity at great depths can be approximated by characteristic parts of the curves measured in different directions. In addition, there is another, much more expensive way of eliminating the effect of the near-surface distortions: measurements made in a network over the area to be studied (the geologic formation) and statistical treatment of the data. A comparison of the conductivity distribution of areas with different geophysical-tectonic character is enabled only if the soundings are processed using the same principles as has been stressed by Hutton (1976). There are some types of areas (e.g. rugged high mountains covered by thin sediments) where MTS cannot be interpreted due to the accumulation of disturbing effects.

These well-known principles are often neglected as many examples show when conductivity distributions are deduced from a single sounding, and therefore they are inexplicable and uncorrelated with other physical parameters, e.g. heat flow values.

In contrast to MTS, geomagnetic deep sounding (GDS) gives a relatively simple picture of the distribution of the conductivity in the upper mantle.

In order to obtain information about the usefulness of MT data in the Earth, especially in mantle physics, the data on the conductivity distribution published in the KAPG Monograph (Ádám (ed.), 1976) which are uniformly processed according to the method of the Soviet School (Berdichevsky, 1968) have been systematically studied.

### 2.2. The Surface Heat Flow as a Systematizing Parameter

The connection of the electrical conductivity with the temperature shows (see e.g. Uyeda and Rikitake, 1970) that MT data are to be systematized according to a surface parameter characteristic for the inner thermal state of the Earth, if a general connection with other physical parameters is looked for in the electrical conductivity data. As the conductivity increase in the upper mantle has been attributed recently to other factors, too (Shankland (1975) and Duba (1976) mention e.g. disorder which causes time dependence of $\sigma$ prior to melting), the determination of the thermal effects seems very important.

Pollack and Chapman (1977) have empirically shown that about 60% of the average surface heat flow of any area ($\bar{q}_0$) comes from the upper mantle: $q^* = 0.6\ \bar{q}_0$. If it is really so the surface heat flow parameter is an adequate quantity to analyse the thermal effects in the distribution of the electrical conductivity in the upper mantle, too, if a state of equilibrium is reached.

The data on the depth of the conductivity increase of the asthenosphere (denoted by ICL as a hint to its situation between conducting zones) arranged according to the regional heat flow yielded an empirical formula for the dependence of this depth on the heat flow (Ádám, 1976, 1978a):

$$h_{\mathrm{ICL}} = 155\ q^{-1.46}\ . \tag{1}$$

As Figure 1 shows, the depth values for $q \leqslant 1$ HFU ($\approx 42$ mW m$^{-2}$) lie well above the $h_{\mathrm{ICL}}(q)$ curve and generally $h_{\mathrm{ICL}} > 200$ km.

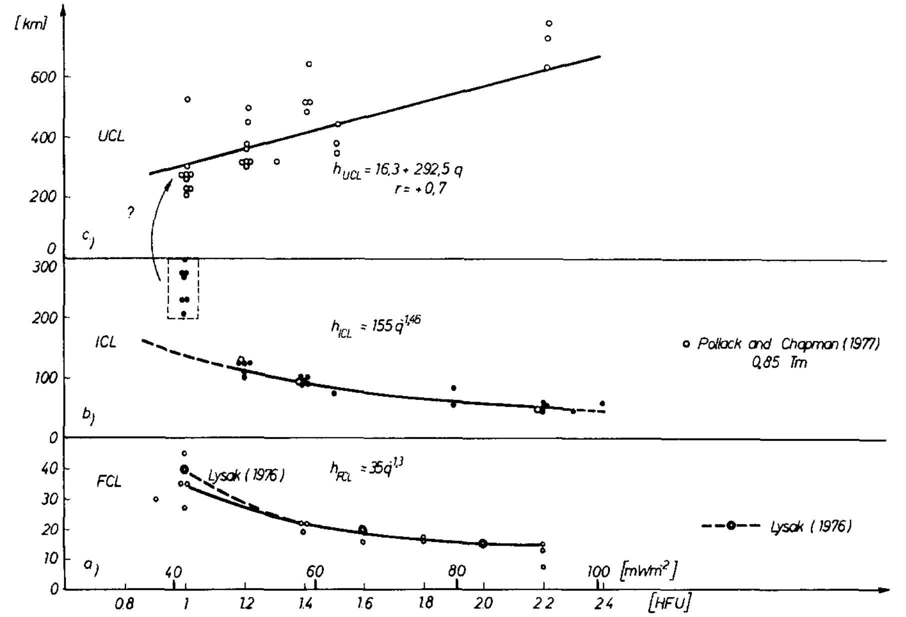


Fig. 1. Connection between the regional heat flow and depth of conducting layers (Ádám, 1976, 1978a). FCL = first conducting layer (in the Earth's crust); ICL = intermediate conducting layer (according to the asthenosphere or LVL zone); UCL = ultimate conducting layer (according to the phase transition).

The investigations were carried out for the depth of the conducting zone, as the conductivity of the zone cannot be determined accurately enough from MTS. It has been generally found that in the asthenosphere $\sigma = 0.1$ S m$^{-1}$ (e.g. in the Nagycenk observatory, Ádám, 1976). Vanyan *et al.* (1977) give also the value of 0.1 S m$^{-1}$ for the specific conductivity of a well-developed asthenosphere.

When computing the geoelectric parameters of the asthenosphere (ICL), the increase of conductivity due to temperature continuously increasing with depth has been taken into account generally only by an average $\sigma$ value. In the case of a well-developed asthenosphere (for its explication, see Vanyan *et al.*, 1977) this simplification seems justified as it was proven by the investigation carried out on Soviet data determined with this supposition.

## 3. The Connection of the Low Velocity and Highly Conducting Zones in the Asthenosphere

The decrease of the velocity of seismic waves and the increase of electrical conductivity in the asthenosphere enables us to compare the connection $h_{\mathrm{ICL}}$ $(q)$ with the connection between the depth of the low velocity zone and the regional heat flow. Such a comparison is possible as Chapman and Pollack (1977) give the thickness of the lithosphere both for continents and oceans as a function of the surface heat flow (Figures 2 and 3). The values of the function $h_{\mathrm{ICL}}$ $(q)$ are also indicated at some heat flow values on these figures. These show that at any regional surface heat flow or at any stage of the tectonic development the changes of these two physical parameters occur at similar depths. The greatest scatter of the depth data occur in continental areas at $q < 40$ mW m$^{-2}$. The greatest

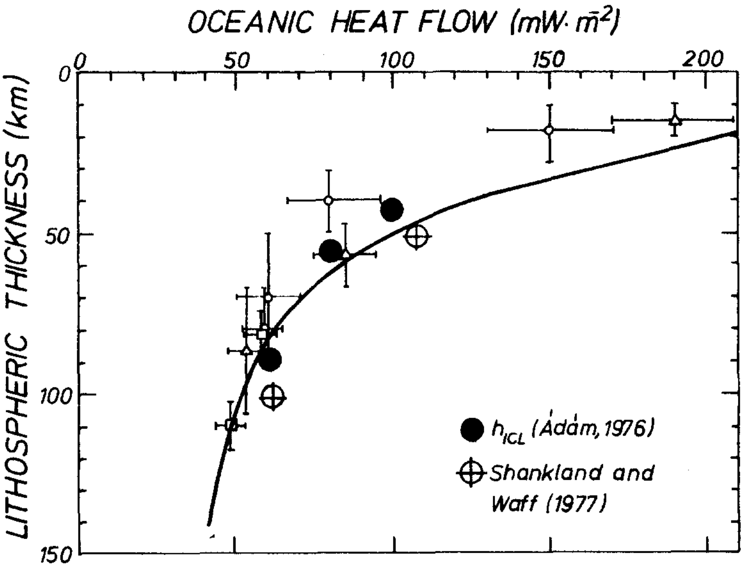


Fig. 2. Lithospheric thickness for oceanic region versus surface heat flow after Chapman and Pollack (1977). Data points with error bars are depths to seismic low-velocity zone from the following surface-waves studies: (o) Yoshii (1975); (Δ) Leeds *et al.* (1974); (□) Leeds (1975). Solid line is depth at which geotherms in Figure 4 intersect mixed-volatile solidus. (●) the magnetotelluric values $h_{\mathrm{ICL}}$ are from Figure 1 (Ádám, 1976). (⊕) data are derived from the diagrams of Shankland and Waff (1977, Figures 7 and 8) and from geotherms of Chapman and Pollack (1977, Figure 4).

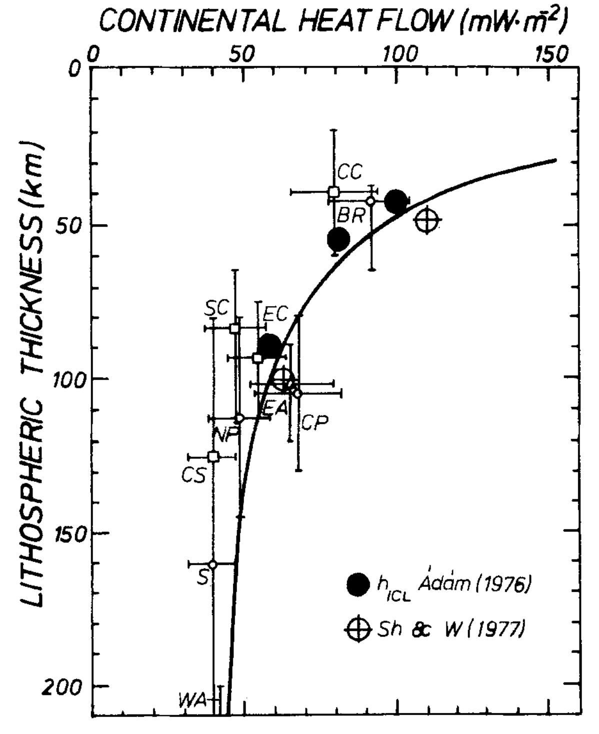


Fig. 3. Lithospheric thickness for continental regions versus surface heat flow after Chapman and Pollack (1977). Data points are depths to seismic low-velocity zone from the following surface-wave studies: (o) Biswas and Knopoff (1974); (Δ) Gončz and Cleary (1976); (□) Wickens (1971). Solid line is depth at which continental geotherms in Figure 4 intersect mixed-volatile solidus. Labels indentify the following physiographic provinces: CC, Canadian Cordillera; SC, southern Canada; EC, eastern Canada; CS, Canadian Shield; BR, Basin and Range; CP, Colorado Plateau; NP, northern Plains of United States; S, shield; EA, eastern Australia; WA, western Australia. (●) the magnetotelluric values $h_{ICL}$ are from Figure 1 (Ádám, 1976). (⊕) data are derived from the diagrams of Shankland and Waff (1977, Figures 7 and 8) and from geotherms of Chapman and Pollack (1977, Figure 4).

depth was found in Western Australia at $h > 200$ km (WA on Figure 3).

On Figure 4 geotherm families computed by the same authors for oceanic and continental areas in the case of different heat flows are also illustrated. The family parameter is heat flow in mW $m^{-2}$. Supposing the material of the upper mantle to be of peridotitic composition, three solidus-curves are shown on this figure, as the quantity of the volatiles influences considerably the temperature of the solidus, and there are only suppositions about the volatile content of the upper mantle. According to Chapman and Pollack:

Laboratory experiments have shown volatile-free melting to be the most refractory, and $H_2O$ to be the most effective in promoting melting at lower temperature. Experiments in a mixed-volatile environment (see for example, Mysen and Boettcher, 1975) principally with $CO_2$ and $H_2O$, show that the presence of other volatiles reduces the activity of $H_2O$, resulting in a solidus intermediate between the hydrous and volatile-free curves. We believe the mixed-volatile environment to be the common situation in the Earth's mantle.

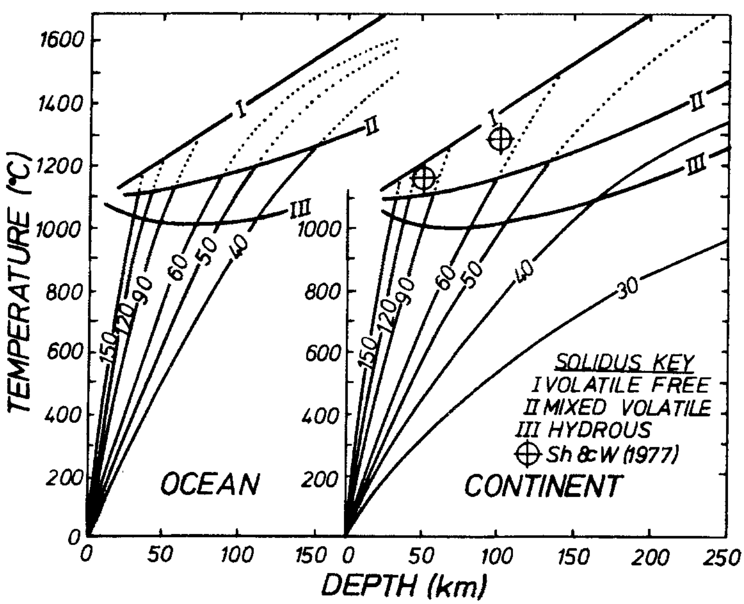


Fig. 4. Geotherm families for oceanic and continental areas. Family parameter is heat flow in mW m$^{-2}$ (42 mW m$^{-2}$ is about 1 cgs heat-flow unit = HFU) after Chapman and Pollack (1977).

With the exception of the curves $q < 45$ mW m$^{-2}$ of continental areas, the curves of both geotherm families intersect the mixed-volatile solidus indicating a zone of partial melting. This zone is the asthenosphere. Chapman and Pollack have connected the depths corresponding to the intersections on the figure representing the thickness of the lithosphere (the depth of the low velocity zone) as a function of the surface heat flow (Figures 2 and 3). This theoretical curve approximates well the measured data.

The geotherm families deduced by Chapman and Pollack for oceanic and continental areas differ from each other for $q < 50$ mW m$^{-2}$. The computations made in this connection by the authors will not be treated here.

The velocity decrease is most marked in the shear (S) waves. In recent years subsurface nuclear explosions and the development of the techniques of seismic explosions enabled significant results to be obtained on the structure of the lithosphere using the velocity distribution of P waves. Ansorge (1975) found several velocity inversions in the lithosphere both on old crystalline shields (Early Rise, Manitoba) and on normal continents (Bretagne SE). The velocity increase is attributed to dunite and eclogite intruded into the peridotite (see $P_d$, $P_{\mathrm{I}}$, $P_{\mathrm{II}}$ in Figure 5). In my opinion the low-velocity zones of the P waves cannot be identified with the conducting layers deduced from MTS. It is not likely that such a change in the composition of the solid rocks in the temperature range corresponding to the lithosphere is accompanied by a change of the electrical conductivity which can be detected by the soundings. In connection with the last velocity inversion in Figure 5 (the low-velocity zone before $P_m$), Ansorge hints already at the role of partial melting.

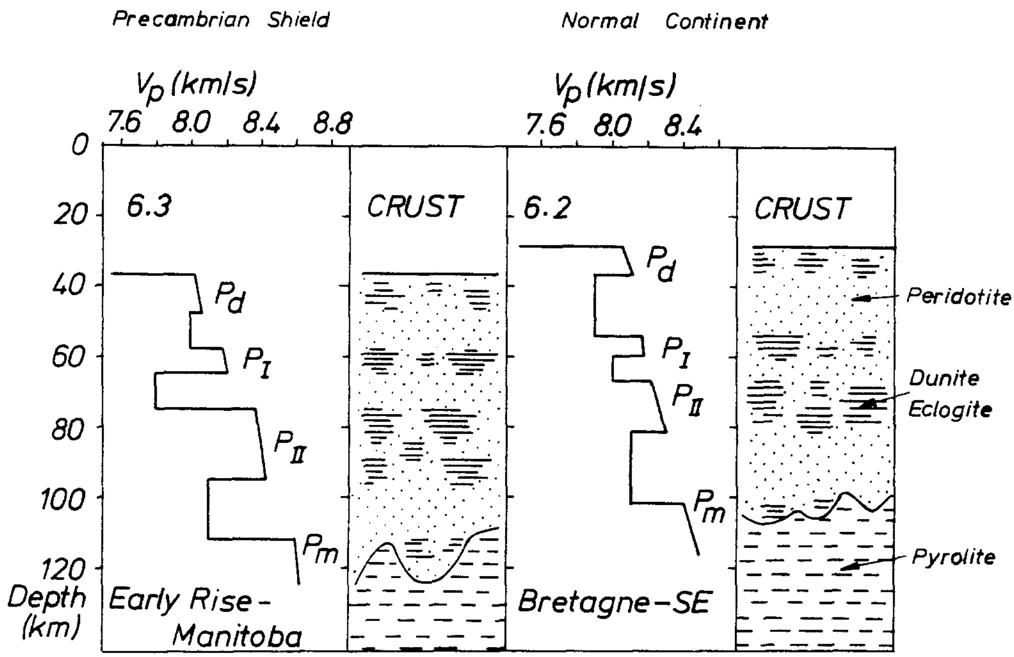


Fig. 5. Velocity of P waves versus depth and mantle pyrolite model of Clark and Rindwood (1964) and Ringwood (1969) after Ansorge (1975).

## 4. The Degree of Partial Melting and the Temperature in the Asthenosphere

Up to now we have used the intersection of the temperature curves with the solidus – after Chapman and Pollack – for the determination of the theoretical depth of the asthenosphere. The melting is, however, only beginning at the solidus temperature. The quantity of the liquid phase and the conductivity increase with a further increase of the temperature thus this temperature increase can be found from the results of the sounding.

According to Shankland and Waff (1977) if we make suppositions concerning the rock material of the asthenosphere and its volatile content, then both the temperature and the quantity of the liquid phase can be determined from the conductivity.

These authors approximate the bulk conductivity by the effective conductivity $\sigma^*$ computed according to an effective medium theory (Waff, 1974) in case of partial melting:

$$\sigma^* = \frac{\sigma_m + (\sigma_s - \sigma_m)(1 - (2/3)f)}{\{1 + f/3\,[\sigma_s/\sigma_m - 1]\}} \qquad (2)$$

where $\sigma_m$ and $\sigma_s$ are melt and solid conductivities, respectively, and $f$ is the melt fraction. Equation (2) is functionally equivalent to the Hashin and Shtrikman (H–S) (1962) upper bound formula. As conduction is pratically possible only with interconnect melt parts the $f$ value expresses their fraction in the whole medium. Equation (2) can be solved for $f$ at a given temperature and $\sigma^*$:

$$f = 3\,\sigma_m\,(\sigma^* - \sigma_s)\,/\,(\sigma^* + 2\,\sigma_m)\,(\sigma_m - \sigma_s)\,. \tag{3}$$

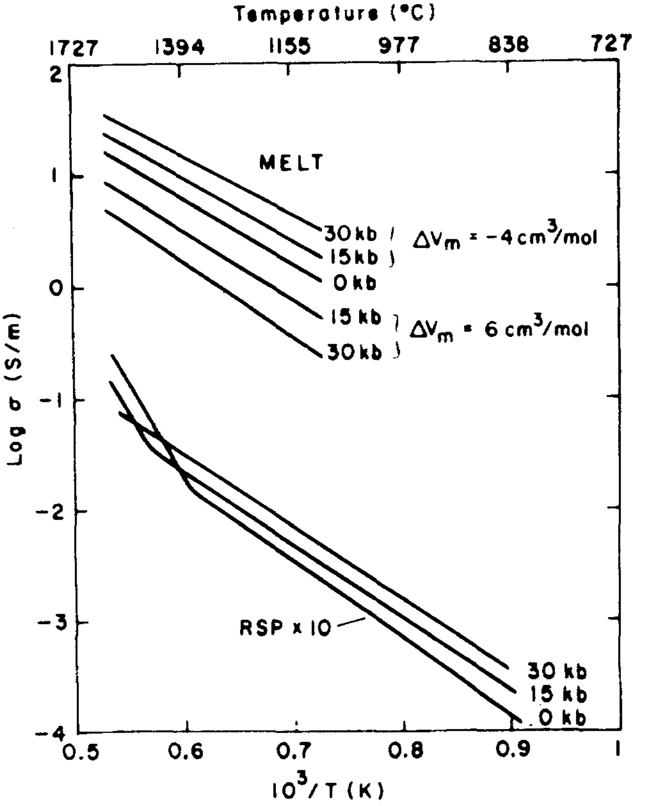


Fig. 6. Electrical conductivities as functions of temperature and pressure, starting from the basalt melt and Red Sea Peridotite (RSP) X 10 curves from Shankland and Waff (1977). With increasing pressure the presumably electronic mechanism having a decreasing activation energy dominates the conduction process in the olivine.

Figures 7 and 8 represent the line of equal effective conductivity $\sigma^*$ of a partial melt according to the H–S upper bound formula computed from the change of the conductivity of the basalt as a function of the temperature (Figure 6) by Shankland and Waff. These values of $\sigma^*$ give the temperature and the melt fraction for 0, 15 and 30 kbars and $\Delta V = 0$ (the activation volume, i.e. the pressure coefficient of the activation energy $\Delta V$ is uncertain at present and it depends on the choice of a conduction mechanism). Figures 7 and 8 show also the temperature above the solidus needed to produce a given melt

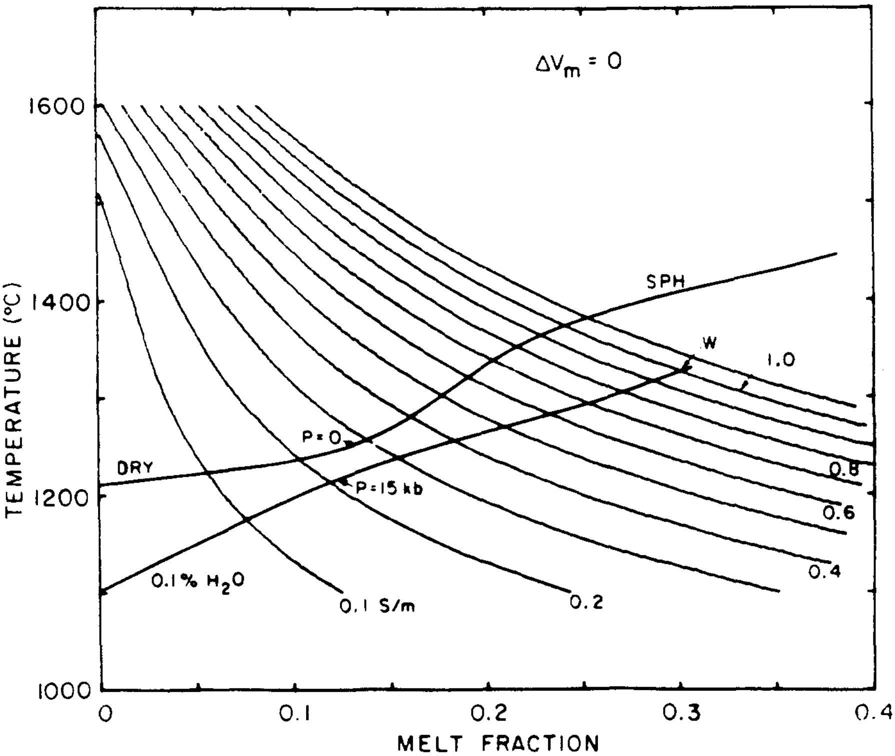


Fig. 7. Lines of equal effective conductivity $\sigma^*$ of a partial melt according to the H–S upper bound after Shankland and Waff (1977). Curve SPH is from Scarfe *et al.* (1972), and curve W is from Wyllie (1971).

fraction in peridotite (Scarfe *et al.*, 1972; Wyllie, 1971) and in pyrolite (Ringwood, 1975) for the cases of the dry solidus and solidus in the presence of 0.1% water.

If the effective conductivity of the asthenosphere is $\sigma^* = 0.1$ S m$^{-1}$, then at a pressure of 30 kbar, i.e. at a depth of about 100 km and in the presence of 0.1% $H_2O$, the expected temperature is 1300°C and the melt fraction 0.03 (see the intersection of the curves W and R in Figure 8 with the 0.1 S m$^{-1}$ line). At 15 kbar, i.e. at a depth of about 50 km similar conditions mean 1180°C and 0.07 melt fraction. These values are denoted on Chapman and Pollack's figure showing geotherm families for continental areas (Figure 4). The points lie as a maximum by 80°C and 120°C above solidus II for a mixed-volatile enviroment on the geotherms corresponding to 63 and 110 mW m$^{-2}$. The depths of the asthenosphere (50 and 100 km) drawn on Figures 2 and 3 at the corresponding heat flows lie inside the scatter of the data.

The choice of the solidus is problematic. It was shown by the last example that results can be achieved in agreement with field data if computations of the thickness of the lithosphere are made on the basis of Chapman and Pollack's solidus for a mixed-volatile environment or a temperature is supposed for the rocks of the asthenosphere in the presence of 0.1% water which makes the conductivity equal to 0.1 S $m^{-1}$. The latter choice seems to be more realistic.

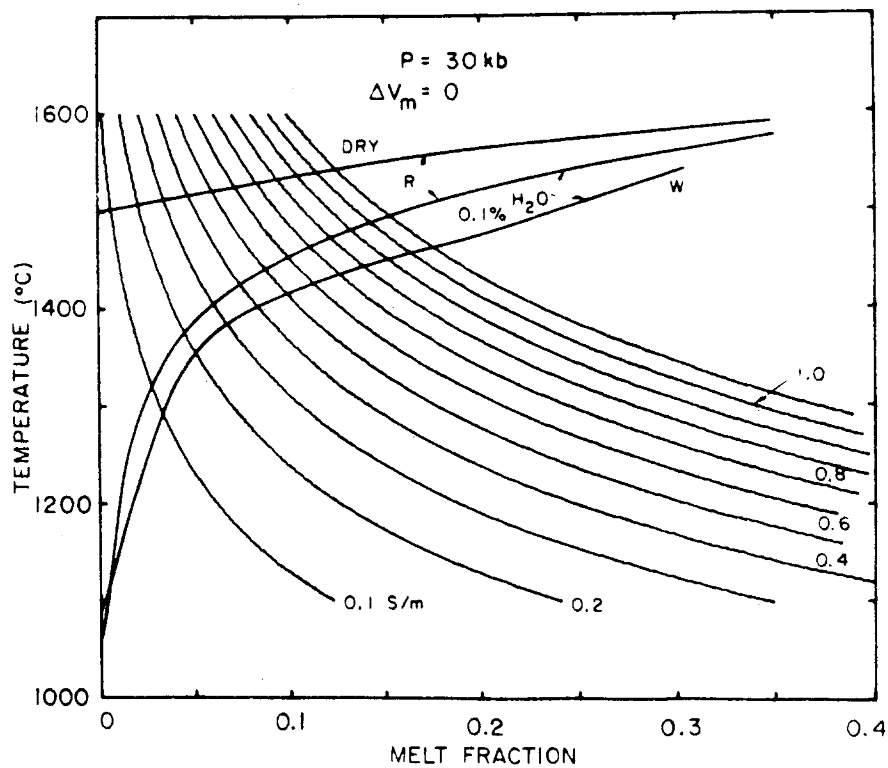


Fig. 8. Lines of equal $\sigma^*$ of a partial melt according to the H–S upper bound at 30 kbar pressure, roughly equivalent to the depth of 100 km from Shankland and Waff (1977). Curve W is from Wyllie (1971), and curve R from Ringwood (1975) for pyrolite, both based on data by G. Green.

## 5. Some Petrographical and Tectonic Conclusions about the Asthenosphere and the Phase-Transition Zone

Below old crystalline shields with low heat flow there is no well developed asthenosphere (Ádám, 1976, 1978a, 1978b), as the temperature in the upper mantle remains below the solidus. This has already been hinted at by Chapman and Pollack (1977) when they called these rigid areas of high viscosity 'viscous anchors'. The tectonic development proceeds toward thickening of the asthenosphere, decrease of the heat flow and increase of the viscosity, i.e. the movement of the plates is stopped. From the temporal distribution of the thickening of the asthenosphere the age of the lithosphere can be concluded. E.g. according to Crough's figure (Figure 9) the lithosphere of the Carpathian Basin – supposing its thickness is 60-70 km – developed at the Oligocene-Miocene boundary (25 million

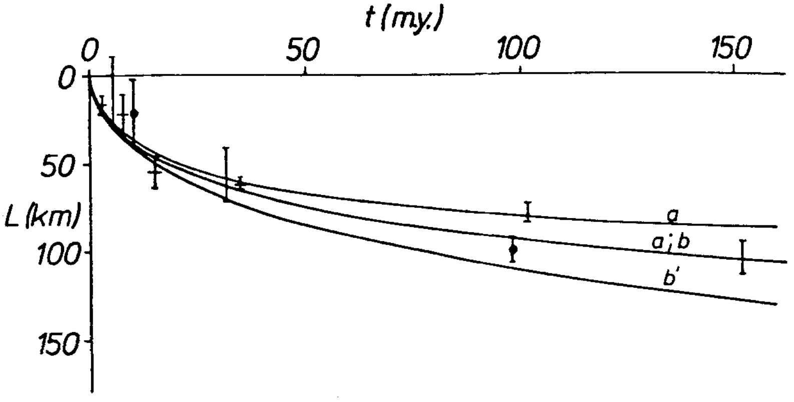


Fig. 9. Predicted and observed lithospheric thickness in the oceans as a function of time after Crough (1977). Solid lines, theoretical predictions of thermal model (a, Q = 0.80 HFU; b, Q = 0.56 HFU; a′ and b′ same total asthenospheric heat flux as a, b but 0.25 HFU of the flux is caused by a temperature gradient in the asthenosphere). Symbols, depth to the seismic low-velocity zone. Vertical bar, Pacific (Leeds *et al.*, 1974; Leeds, 1975); bar with slash, East Pacific (Forsyth, 1975); bar with dot, Atlantic (Weidner, 1973).

years ago). This supposition is supported by the important Miocene volcanism accompanying the development of the lithosphere (Stegena *et al.* 's (1975) theory on the mantle diapir).

In areas with low heat flow ($q < 45$ mW m$^{-2}$) the first conductivity increase was detected at depths of 250-300 km (see the data in Ádám, 1978a). This change of the conductivity might already be attributed according to Akimoto and Fujisawa's (1965) results to the phase transition of rocks (Ádám, 1978b). This increase of the conductivity has depth values which do not fit into the $h(q)$ curve determined for the asthenosphere (Figure 1). These depth values however, together with the depth values ($h_{\mathrm{UCL}}$) of the deepest conductivity increase (UCL), point to the positive gradient $\mathrm{d}P/\mathrm{d}T$ (bar/°C) characterizing the phase transition according to the empirical formula (Ádám, 1978b):

$$h_{\mathrm{UCL}} = 16.3 + 292.5\, q, \tag{4}$$

supposing the pressure to be proportional to the depth and the temperature to the heat flow. Thus the depth of the phase transition below crystalline shields seems to be smaller than below other younger great tectonic units. This is a continuing problem and has to be considered along with the new laboratory data.

According to latest data (Annual Report of the Carnegie Institution for 1976/1977) the structure is not so simple everywhere. E.g. a velocity inversion has been observed below the Baltic shield at a depth of 250 km and this has been attributed to the partial melting of the asthenosphere (Sacks *et al.*, 1977). It should be further mentioned that Mayer-Rosa and Mueller (1973) observed below the asthenosphere two further velocity inversions for S waves at depths of 160-210 km and 260-310 km in SE and SW Europe.

The cause of these inversions and their possible connection with the velocity inversion at a depth of 250 km below the Baltic shield must be further studied.

If a small melt fraction is still present below areas of low heat flow, then its effect of causing a conductivity increase cannot be separated from that corresponding to the phase transition, as their depths are too near to each other (Ádám, 1978b).

There are other factors, too, which can increase the conductivity of the mantle. In this connection we quote Shankland and Waff (1977):

> While other mechanisms for mantle conductivity enhancement may exist, e.g. contribution from contaminated grain boundaries or high volatile contents, these explanations associate a chemical differentiation in the mantle with thermal manifestation and in most cases create conditions that favour melting.

In conclusion we add two remarks about the interpretation of the MT data:
– the $h(q)$ curves must be made more accurate;
– it is not necessarily the consequence of a methodological-measurement error if some regional data differ significantly from the general trend. Such areas must be further studied, and possible transition zones can be very interesting for geodynamics.

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