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LOG Id: LOG_0034
LOG Titel: Electrical conductivity of the asthenosphere
LOG Typ: article

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J Geophys (1984) 55:179–181

Journal of Geophysics

Electrical conductivity of the asthenosphere

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Abstract. The lateral changes of the upper mantle are investigated by magnetotelluric soundings. Comparison with the reference apparent resistivity profile leads to the conclusion that there is no partial melting in the asthenosphere beneath the Precambrian cratons and old oceanic plates. The highest conductivity and the greatest melting occurs in the asthenosphere of young oceans, transition zones and tectonically active zones of continents. Soundings also indicate a low-resistivity zone in the continental crust which is probably due to water solution.

Key words: Asthenosphere – Electrical properties – Upper mantle

Introduction

Twenty years ago, A. Adam, H.G. Fournier, S.H. Ward and H.F. Morrison proposed the existence of a conductive layer corresponding to the seismic low-velocity channel in the asthenosphere (Adam, 1963; Fournier et al., 1963). Development of this idea led to some resistivity-depth models constructed by means of field results and laboratory measurements (Adam, 1976; Feldman, 1976; Shankland and Waff, 1977, etc.). A new stage in deep MT investigations began in 1978. The General Assembly of the International Association of Geomagnetism and Aeronomy adopted the International ELAS project (Electrical Conductivity of the Asthenosphere), "to concentrate effort during 1978–1985 on magnetic and magnetotelluric measurements and their comparison with heat flow and seismic measurements". The main goal of the ELAS project is to investigate the electrical conductivity of the asthenosphere for different geotectonic structures (Vanyan, 1980; Schmucker, 1981).

Reference apparent resistivity

The estimation of the electrical conductivity of the asthenosphere is restricted by experimental noises. Most of them are the distortions of the MT field due to surficial inhomogeneities. Often they can be assumed to be variations of the conductance of sediments or sea water. If these variations are small-scale compared with deep MT anomalies, their influence can be eliminated by averaging apparent resistivity along traverses. If the dimension of the surficial inhomogeneities is comparable with that of the deep anomaly then numerical modelling is necessarily used for investigation of the nature of the distortions. A third technique is the correction of the field apparent resistivity by a reference one. The most important part of the reference apparent resistivity is the global response obtained by spherical analysis of geomagnetic variations on continents (Berdichevsky et al., 1970; Fainberg, 1983). In the period range shorter than 3 h the global apparent resistivity coincides well with the averaged data from the Baltic Shield (Kovtun et al., 1981) and East European Platform (Vladimirov and Dmitriev, 1971). At the shortest periods, which correspond to penetration depths of several kilometres, information about apparent resistivity can be obtained from AMT, DC soundings and frequency dipole-dipole soundings. The apparent resistivity values are usually between 10^4 and 10^5 ohm.m.

Combining the three apparent resistivity bands yields a monotonically decreasing curve which is shown in Fig. 1. Since the magnetotelluric part of this curve was obtained in the shield area with a heat flow of about 40 mW/m^2 and the curve itself does not show pronounced minima, one can consider it as corresponding to the "cold" resistivity model (Vanyan et al., 1980).

It is reasonable to choose this apparent resistivity profile as the reference one (Rokitiansky, 1972).

According to geothermics, there is no partial melting beneath shield areas with low heat flow values. The reference "cold" apparent resistivity curve suggests that if a partially molten zone occurs, its conductance is not more than 10^3 S (Vanyan et al., 1977).

Oceanic asthenosphere

There are only a few sea-bottom MT soundings located in the North Pacific (Filloux, 1980, 1981, 1982). There is no possibility of obtaining average apparent resistivity curves in some areas.

However, the small anisotropy of the sea-bottom impedance suggests that most MT soundings are only slightly distorted by local inhomogeneities. Besides, one can check the level of distortion by comparing the experimental long-period apparent resistivity with the reference one. As shown in Fig. 1, most of the sea-bottom MT curves are in agreement with the long-period part of the reference profile. The long-period results of MT soundings in the North Central Pacific (Chave et al., 1981), which are close to those obtained by Filloux (1980), are shown in Fig. 1. If experimental errors are taken into account, sea-bottom apparent resistivity values at long periods are close to average continental

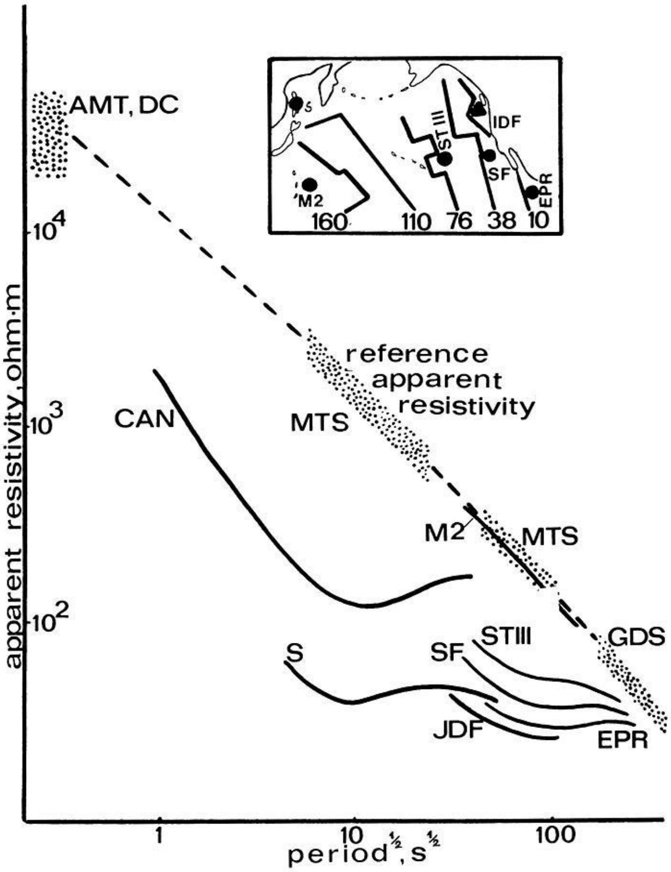

Fig. 1. A comparison of the apparent resistivity curves for different areas. CAN = average data for the Canadian shield (Osipova et al., 1978); S = average data for Sakhalin Islands; M2 = reduced curve for Marianna Island Arc (Filloux, 1982); SF and STIII = stations in the North Pacific Rise (Filloux, 1981); EPR = station near the East Pacific Rise (Filloux, 1981); JDF = curve for Juan De Fuca Ridge (Law and Greenhouse, 1980); AMT, DC = normal apparent resistivity band for the uppermost crustal rocks of the Baltic shield; GDS = global apparent resistivity band. *Insert:* Sounding sites. Lithospheric age, in 10^6 years, is shown by isolines

data. This suggests a spherical symmetry of resistivity distribution beneath the asthenosphere.

But in the period range shorter than 8–10 h the sea-bottom apparent resistivity values are significantly lower than the reference ones; at periods around 1 h the ratio reaches 3–5. This indicates the existence of the asthenospheric low-resistivity zone.

The only MT curve which does not agree with the reference apparent resistivity is the transversal apparent resistivity curve for the MT site M2. This sounding is located eastward of the Marianna Islands in the area where the oceanic depth changes rapidly. The results of two-dimensional numerical modelling, which will be described elsewhere, suggest that the transversal impedance is greater than the one-dimensional value by a factor of about 1.5–2.0. This factor is practically independent of frequency.

However, the apparent resistivity for M2 reduced in accordance with the numerical modelling results is close to the reference one. It means that near the Marianna Island Arc (160 my) the conductance of the asthenosphere does not exceed the threshold of the MT soundings which is about 10^3 S (Vanyan, 1981). Interpretation of the other North Pacific soundings allows estimation of the thickness and conductivity of the low-resistivity zone (Filloux, 1981). Due to the non-uniqueness of the MT inverse problem the most valid result is the conductance, i.e. the depth-integrated conductivity. Conductance values along the traverse from the ridge axis to the Marianna Islands are shown in Fig. 2. They indicate a decrease in thickness or conductivity of the low-resistivity zone (or both) with the age of the ocean floor (Filloux, 1982). The conductance decreases from 10^4 S near the axis of the East Pacific Rise to about 10^3 S near the Marianna Trough. Using the mean value of conductance (about 5×10^3 S) and the thickness of the seismic low-velocity zone (10^2 km) one can estimate the typical resistivity of the oceanic asthenosphere to be 20 ohm.m. Comparison with geothermics suggests that this low value has a thermal nature. It is well-known that resistivity decreases with temperature. The experimental data for ultramafic rocks were discussed by Haak (1980). An important feature of these data is that the resistivity value of about 10^2 ohm.m corresponds to the solidus. Thus the resistivity value of 20 ohm.m indicates partial melting in the oceanic asthenosphere. Comparing this result with the absence of the liquid phase beneath the Precambrian continental plates, one can deduce a significant lateral heterogeneity of the upper mantle.

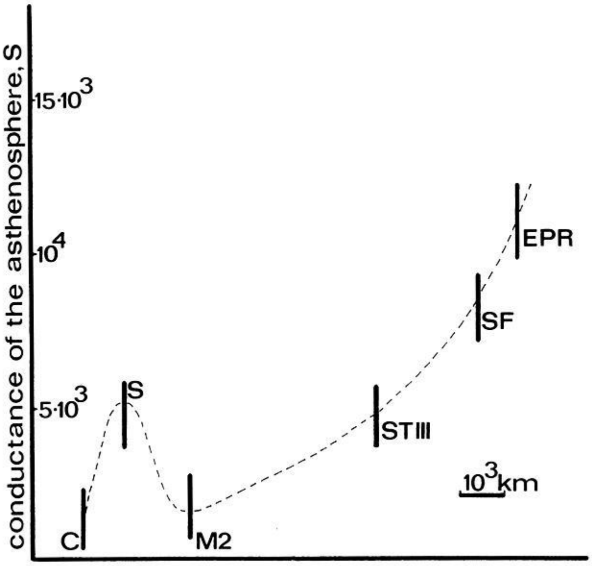

Fig. 2. Conductance of the asthenosphere along a traverse from the Asian continent to the East Pacific Rise. C labels the mean continental data. For other abbreviations see Fig. 1

Transition zones and tectonically active continental areas

The transition zone between the North Pacific and the continent of Asia was investigated by MT soundings on Sakhalin Island, Kamchatka Peninsula and the Japanese Islands. An average apparent resistivity curve, calculated by means of some hundreds of MT soundings performed on Sakhalin Island, is shown in Fig. 1 (Alperovich et al., 1983). Since the structure of this area can be considered as two-dimensional, parallel apparent resistivity was used, corresponding to a north-south electric field (Berdichevsky and Dmitriev, 1976). Note that the apparent resistivity values are reduced to the zero conductance of sediments by means of the equation:

$$Y = Y_o - S,$$

where Y is the observed admittance, Y_o is the reduced admittance, S is the conductance of sediments.

Reduced apparent resistivity clearly indicates the existence of the low-resistivity partial melting zone at asthenospheric depths. Similar features are observed in the Pannonian basin (Adam, 1976) and in the Basin and Range Province (Shankland and Waff, 1977). Low resistivity of the asthenosphere of transition zones and tectonically active areas is in accordance with high heatflow values.

Crustal low-resistivity zone and its correlation with the asthenosphere

Another interesting feature of the "Sakhalin" curve in Fig. 1 is a pronounced apparent resistivity minimum at periods of about 100 s. This minimum indicates the existence of the low-resistivity zone at depths of 15–20 km; i.e. in the middle and lower crust. Almost 20 years ago it was proposed that the anomalously low resistivity is due to supercritical water solutions in micropores (Elansky, 1964; Hyndman 1968; Feldman 1969; Caner, 1970; Berdichevsky et al., 1972).

There are some suggestions on the correlation of the crustal low-resistivity zone with the asthenospheric one. As mentioned above, beneath the Precambrian shields the asthenosphere has a conductance lower than 10^3 S. The crustal conductance for some shield margins does not exceed 200–300 S (Osipova et al., 1978). For the Sakhalin Island asthenospheric conductance is about 5×10^3 S and the crustal low-resistivity zone conductance exceeds 8×10^2 S.

Conclusion

MT soundings clearly indicate a strong lateral heterogeneity of the physical properties of the asthenosphere. Beneath Precambrian shields and platforms, as beneath old oceanic plates, there is no partial melting zone, or it is so small that it cannot be detected by EM fields. Beneath young oceans, transition zones and tectonically active continental areas there is evidence of well-developed partial melting. Observations also show the crustal low-resistivity zone which may indicate hydration of the continental and transition crust (Shankland and Ander, 1982). The conductance of this zone increases with tectonic activity.

Thus the significant feature of deep resistivity which greatly influences MT soundings is the existence of fluids (basalt melt in the upper mantle and water solution in the crust).

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Received November 21, 1983; Revised April 13, 1984
Accepted April 18, 1984