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CORRELATION BETWEEN ELECTRICAL CONDUCTIVITY AND OTHER GEOPHYSICAL PARAMETERS

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Anomalies of electrical conductivity are considered in relation to other geophysical parameters, such as seismic wave velocity, attenuation, seismicity and density, and to tectonic features. In the case of active subduction zones there appears to be a good correlation between low conductivity and the seismic quality factor Q. Beneath western North America, a conductive zone in the uppermost mantle apparently is controlled by the thickness and severity of the low-velocity layer. Anomalies in conductivity beneath rift valleys can be related to regions of intermediate seismic P-wave velocity, typically about 7.0 km/sec, which is suggestive of partial melting of mantle material. Within the continental crust, anomalies in conductivity are not, in general, thermally controlled, but they can show correlations with seismicity, and may indicate intra-plate boundaries.

1. Introduction

As there have already been a number of excellent reviews of the correlation of conductivity anomalies with other geophysical parameters (Uyeda and Rikitake, 1970; Law and Riddihough, 1971; Gough, 1973a; Schmucker, 1973) the emphasis in this paper will be on the results which have become available in the past two or three years. In some cases these results refer to new conductivity studies, in others to new complementary geophysical results. There have in addition been a number of papers synthesising the geophysical information on different tectonic areas, and where possible reference will be made to these, rather than to original works, in order to reduce the number of References. The past few years have seen a change in the philosophy of interpretation, especially in the recognition of the importance of near-surface features, and of current channelling. Bullard (1970) in introducing the 1969 symposium on the subject, stated that sources in the surface rocks above basement and in the basement rocks could usually be excluded for periods greater than a few minutes because of insufficient thickness and inadequate conductivity respectively. Recent experience suggests that channelled currents, even in suprabasement rocks, can produce effects at moderately long periods, and that basement rocks, locally, can be quite conductive. There has at the same time been a growing recognition of the very high conductivity that sedimentary rocks may possess (Garland, 1971). While it had long been recognized by those engaged in electric logging of boreholes that resistivities as low as a few ohm · m were usual in sedimentary basins, there was a reluctance on the part of many other geophysicists to accept such low values. This attitude appears to have changed.

Because the mechanisms of current flow in the crust and mantle are so different, a preliminary classification of anomalies is desirable before discussion of any correlation with other parameters. In what follows, consideration is first given to a group of anomalies from different parts of the world, which appear to have their sources mainly below the crust. In almost every case, while there may be important contributions to the anomaly from near-surface currents (the coast effect in the case of Japan and Iceland; the effect of conductive fill in the rift valleys), they appear to be largely mantle-controlled. The correlations that are found support this conclusion.

2. Mantle anomalies

With the above caution on the difficulty of separating crustal and mantle effects in mind, we proceed to pick out for discussion a group of anomalies which has a high probability of having their source in the mantle.

Any discussion of correlation of conductivity with other geophysical parameters must take into account the mechanism of electrical conductivity, and the equations which describe it. In the case of mantle anomalies the mechanism is most probably semi-conduction, although in extreme cases where a partial melt exists, ionic conduction may be present (Presnall et al., 1972). Laboratory work on the variation of conductivity with temperature for minerals believed to be representative of the mantle is the subject of a separate review (Shankland, 1975), but one or two comments on the recent results are in order. First, Tolland (1973) has shown that, while minerals other than olivine are almost certainly present in the upper mantle, their conductivities are such that an electrical model based upon olivine alone will not be seriously in error. Secondly, it is now evident that conductivity is not a single-valued function of temperature, even for olivine of a given composition. Duba (1972) has shown that olivines of the same fayalite content may have conductivities differing by an order of magnitude, at any given temperature up to 1,100°C, as a result of differing oxidation states of the iron. These findings place severe constraints on attempts to estimate mantle temperatures from the conductivity. On the other hand, a general correlation between conductivity and seismic wave attenuation and velocity diminution may be expected, and will be shown below. Correlations with surface heat flow exist, but care is required here because of the time lag involved in the flow of heat from depth to the earth's surface.

2.1. Japan

The Japanese anomaly in conductivity was one of the first to be recognized in the world and is one of the most completely described (Rikitake, 1966). It is manifested in strong variations of the $\Delta Z/\Delta H$ ratio across the island, observed at periods extending from a few minutes to many hours. The persistence of the effect with period and the obvious correlation with deep seismicity and volcanism argue for a mantle source. One uncertainty is the importance of the coast line effect in modifying the anomaly; the model study of Roden (1964) suggests that, at the longer periods, the coast effect can have an appreciable influence.

Rikitake (1969) has shown that the anomaly can be explained, qualitatively at least, by undulations in the depth to highly conducting mantle. The important point is that the depth must increase, as one proceeds across Japan from the Sea of Japan, until, under eastern Japan, it abruptly becomes less. It is really a triangular wedge of relatively non-conducting mantle which produces the anomaly.

A very complete review of seismicity and seismic properties under the Japanese arc has been given by Utsu (1971). In addition to giving the location of earthquake epicentres, Utsu has outlined the zones of high and low wave velocity, and those of high and low Q. The latter have been determined from attenuation measurements. It was found (Fig. 1) that the zone of high Q coincided closely with that of high velocity, particularly S-wave velocity. The suggestion is that this zone represents the downgoing slab of the Pacific plate. Within the high-velocity zone, the uppermost-mantle P velocity is 8.2 km/sec or greater. A difference of 6% is found for both P and S velocities, between the high- and low-velocity zones. The quality factor Q, which may be as great as 1,000 in high-Q regions, falls to about 80 in the low-Q zones. On Fig. 1 the outline of Rikitake's non-conducting wedge has been superimposed, to show good agreement in general location, although the wedge thickens in the opposite sense to the dip of the slab. The conductivity profile shown in Fig. 1 is from further west in Japan than Utsu's section, but the general relationship is confirmed by more recent conductivity studies to the east (Nabetani and Noritomi, 1974). The suggestion is that the Japanese anomaly is as much the result of the poorly conducting subducted slab, as it is of abnormally high near-surface temperatures. This is an effect which clearly should be looked for in other subduction areas.

The distribution of heat flow in and around Japan (Watanabe et al., 1970; Uyeda and Rikitake, 1970) confirms that the conductivity anomaly is not simply related to an area of high heat flow. Contours of heat flow cut across the island arc, and the most prominent region of high flow is over the Sea of Japan to the

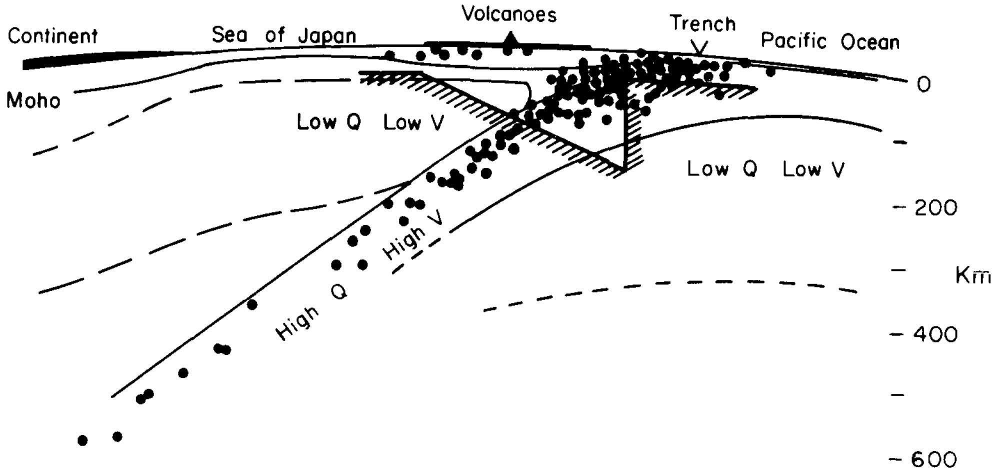

Fig. 1. Conductivity structure beneath Japan in relation to zones of high and low seismic velocity and seismic quality factor *Q* (after Utsu, 1971). The hatched line is the inferred surface of highly conducting mantle, according to Rikitake (1969).

west, where the conducting mantle is assumed to become shallow.

2.2. *The Andes*

The Andean anomaly may similarly be associated with a region of subduction along the western coast of South America. The effect is shown in $\Delta Z/\Delta H$ values, which appear to reach maxima along the crest of the mountains. Schmucker (1973) has interpreted the source of the anomaly as a block of highly conducting (resistivity 10 ohm · m) material, lying beneath the mountains at depths of 20–80 km. The block would presumably be partially within the thick crust known to exist beneath the Andes.

Tectonic structure under the area has been reviewed by Kausel and Lomnitz (1969), who considered gravity anomalies and seismicity, Sumner (1967) who studied attenuation of P waves, also James (1971), and more recently by Plafker (1972). Plafker considered the surface displacement which resulted from the Chilean earthquake of 1960. His results are of considerable interest as they permit the boundary between the Pacific and American plates to be located. It is probable that the down-going portion of the Pacific plate coincides with the poorly conducting part of Schmucker's model. As in the case of the Japanese anomaly, there is the suggestion that the interruption of the normal mantle conductivity structure by a cold plate is as important in producing the anomaly, as is the upward movement of hot material produced by frictional heating along the side of the slab.

2.3. *Iceland*

We turn from a subduction zone to a mid-ocean ridge. Iceland is not only located on the Mid-Atlantic Ridge, but probably is a classic example of a hot spot or plume (Wilson, 1963; Brooks, 1973). That the electrical conductivity beneath it is anomalously high was shown by Hermance and Garland (1968) by $\Delta Z/\Delta H$ ratios, and the conductivity structure has been investigated in detail, using magnetotelluric methods, by Hermance and Grillot (1970, 1974). As in the case of Japan, there is undoubtedly a coastline effect at some periods and at some stations, but this is not believed to alter the main conclusions.

For a station in southwestern Iceland, Hermance and Grillot (1974) have applied a Monte Carlo inversion to the magnetotelluric observations. One conductivity interface is fixed at the crust–mantle interface, as located seismically (Palmason, 1971) at a depth of 10 km. The crust itself consists of layers, apparently of basaltic rock, underlain by a layer, 4–7 km thick, with a P velocity of 6.35 km/sec. This lower layer may represent intrusive material injected from the mantle. A feature of importance is the low upper-mantle velocity, 7.4–7.6 km/sec, and this value may extend as deep as

240 km (Tryggvason, 1964). Throughout most of the crust, the resistivity is found to lie between 20 and 50 ohm · m, while in the uppermost mantle it lies between 40 and 100 ohm · m, and is apparently almost constant to a depth of 100 km. The inferred temperature distribution is thus one of high gradient in the crust leading to a relatively high temperature at the crust–mantle boundary, underlain by a low gradient in the upper mantle. Measured borehole gradients reach values of over 150°C/km in the Reykjanes–Lanjökull zone of southwestern Iceland (Palmason, 1973) corresponding to a heat flow of approximately 8 hfu. Furthermore, the presence of a high temperature gradient underlain by a very low one is consistent with a kinematic model for plate spreading and heat flow related to dike intrusion, as developed by Palmason. Iceland remains as one of the best examples of correlation between electrical conductivity and heat flow. It is true, of course, that no information on the form of the anomaly is available, because of the limited area available for measurements. The possibility of defining the profile of the ridge-associated conductivity effect is a strong argument for sea-floor magnetic-variation measurements. Similarly, high values of mantle conductivity have been found beneath Hawaii (Larsen, 1974) but once again a complete profile including ocean-bottom measurements would be most desirable.

2.4. Western North America

The conductivity structure under western North America is complicated, but the pattern is well-defined as a result of traverses with single instruments (Schmucker, 1970; Cochrane and Hyndman, 1970; Caner, 1971), and arrays (Porath, 1971; Porath and Gough, 1971; Camfield et al., 1971; Camfield, 1973). The area now lies well within the American plate, but it is one of Cenozoic volcanic activity, and may have been associated with a down-going slab in Cenozoic and earlier times. For the southern part of the region at least, the extent and frequency behaviour of the anomalies argue for a mantle source. The outstanding characteristics of this southern portion are two belts of high conductivity, one associated with the southern Rocky Mountains and one with the Wasatch Fault Zone, separated by the Colorado Plateau. Gough (1973b) has emphasized the ambiguity of interpretation. The array results could be satisfied equally well by undulations in the depth to the highly conducting mantle (giving depths of between 100 and 400 km) or by variations in thickness of a conducting layer in the upper mantle, separated from the deep mantle. The latter interpretation is attractive because it allows a comparison with the seismic low-velocity zone.

A comparison between the proposed conductor, based on this second interpretation, and the upper-mantle velocity structure, is given in Fig. 2. The velocity model shown for western North America is that of Helmberger and Wiggins (1971). Also plotted is a seismic velocity model for eastern North America, according to Massé (1973). The striking feature is the difference in thickness and intensity of the low-velocity zone between the two portions of the continent. In the west, the depth extent of the zone corresponds well with the required thickness of conducting material, while the much smaller low-velocity zone in the east is compatible with the fact that conductivity anomalies in eastern North America appear to be controlled by crustal rather than mantle, conditions.

Heat flow in the western United States (Sass et al., 1971) also shows a good correlation with the inferred thickness of conductor, as indicated on Fig. 2. The presence of two regions of high flux, separated by a relative low over the Colorado Plateau, is evident.

Granted that electrical conductivity, heat flow and seismic velocity show a correlation, it remains to relate all parameters to the tectonic framework. This is much more a matter of opinion, but Dickinson (1970) has argued that the depth of origin of andesitic volcanic rocks may be inferred from their potash content. On this basis, he has reconstructed the position of a down-going slab, which may have existed beneath western North America, as late as Quaternary time. The location is indicated in Fig. 2, from which it is seen that the western belt of high heat flow could be a vestigial effect of it. It is possible that volcanism and thermal effect in the eastern portion of this section of the Cordillera are evidence of a separate hot spot.

In the northwestern United States and western Canada the conductivity pattern is very different. High conductivities in the uppermost mantle or crust are found continuously, from near the coast to the front of the Rocky Mountains. In this area the effects are seen most strongly at periods of less than two hours, and while mantle conduction cannot be rules out, conductivities in the crust undoubtedly have an in-

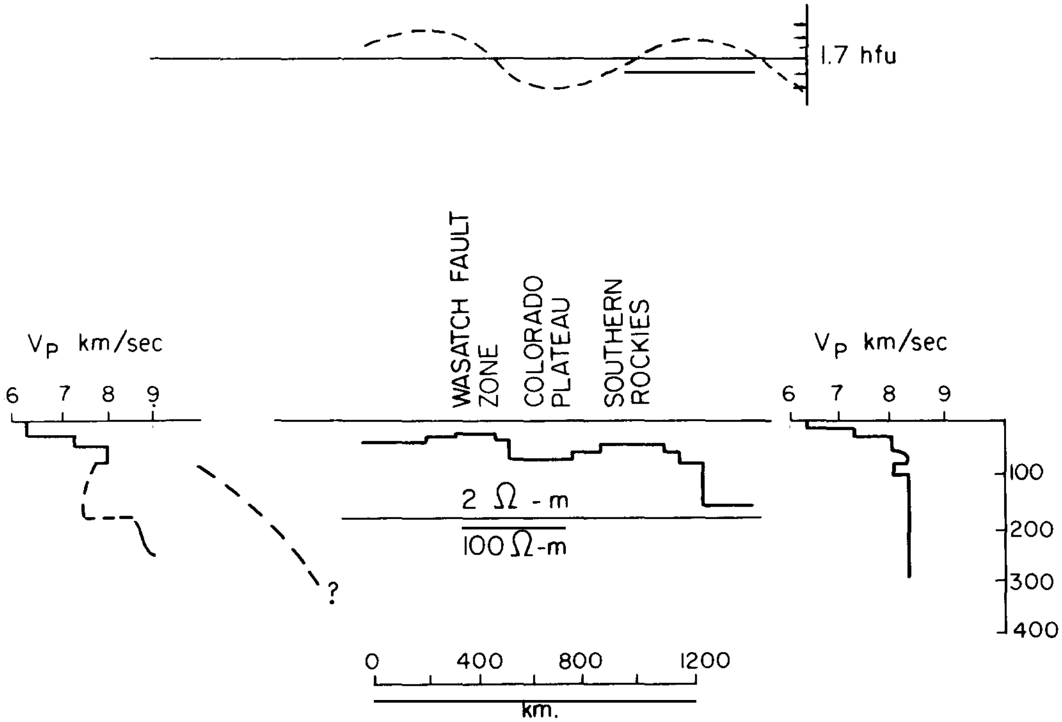

Fig. 2. One interpretation of the conductivity structure in western North America, in terms of a highly conducting upper-mantle layer of varying thickness. Seismic-velocity sections to the west (left) and east, and heat flow (top) are shown. The broken line marks the possible location of a former subduction zone. Sources as in text.

fluence. The region of increased conductivity lies to the west of the western edge of the covered Precambrian shield. Hyndman and Hyndman (1968) have suggested that the younger crust to the west has not been dehydrated to the extent of the Shield rocks, and is therefore more conductive.

In any case, the boundary between the two areas of different behaviour in western North America, which must be an approximately east–west line near the Canada/United States boundary, may well be a line of significance in the former tectonics of the American plate.

2.5. Australia

Of a number of conductivity anomalies located in Australia that which is most probably mantle-controlled lies off the east coast in the vicinity of Sydney (Bennett and Lilley, 1974). Measurements of component ratios and phases at stations up to the coast suggest that a conductive body, perhaps 40 km thick, lies at a depth of 50 km or less beneath the sea floor. Because the observations are entirely to the side of the presumed body, the interpretation remains somewhat tentative. However, the presence of such a structure would explain peculiarities in the reception of S phases at Australian stations. In particular, the path from the Macquarie Rise to Sydney, along which S does not propagate well, would cross the anomalous body, while the path to Hobart, where S is recorded, would not necessarily do so. High temperatures in the upper mantle off eastern Australia may also be related to known Cenozoic volcanism and guyot formation.

2.6. Southern Africa

Gough et al. (1973) have located an east–west trending anomaly in southern Africa, over which the $\Delta Z/\Delta H$ ratios reach very large values at periods up to at least 100 min. The anomaly is not yet completely defined, since it is located at the southern margin of the array, but the amplitude is so large that current concentration, in addition to local induction, appears to be involved. It is located near the axis of the Cape Folded Belt and also near the Karroo basin, but model studies indicate that conduction in the thickened sedimentary rocks alone is probably not the cause of the anomaly. Gough (1973c) has pointed out a remarkable correlation with a negative isostatic gravity anomaly of similar trend, and has suggested that both may be the result of an east–west, linear plume. It would be dangerous to attempt a more detailed interpretation until the conductivity anomaly is more fully mapped, but the coincidence of gravity and conductivity effects is indeed remarkable. It must be noted that not all suspected plumes exhibit large negative anomalies; over Iceland, for example, departures from isostatic equilibrium are smaller (Einarsson, 1954). However, on the basis of topography and structure, Hales and Gough (1960) had already argued convincingly that the African gravity anomaly was due to a root from which the load had been removed by erosion. The plume origin for the root is a distinct possibility.

2.7. Rift valleys

Correlations between electrical conductivity, and either seismic velocity or density are found in the Rhine graben and the Rift Valley in Kenya. For the first, Winter (1973) has given the most detailed interpretation of magnetic deep-sounding measurements; magnetotelluric measurements have been discussed by Haak et al. (1970). Because of infilling of the graben by sedimentary material, there is a thin surface layer of high conductivity, but the most striking feature of Winter's interpretation is a conductive layer (30 ohm · m resistivity) extending in depth from 25 to 75 km. This range in depth extends across several layers defined seismically (Ansorge et al., 1970), as shown in Fig. 3, and appears to include both lower crust and upper mantle. The seismic profile indicates a complex layering in the crust, with at least two low-velocity layers, underlain by a thick layer with the intermediate P velocity of 7.6–7.7 km/sec. (More recent seismological work suggests

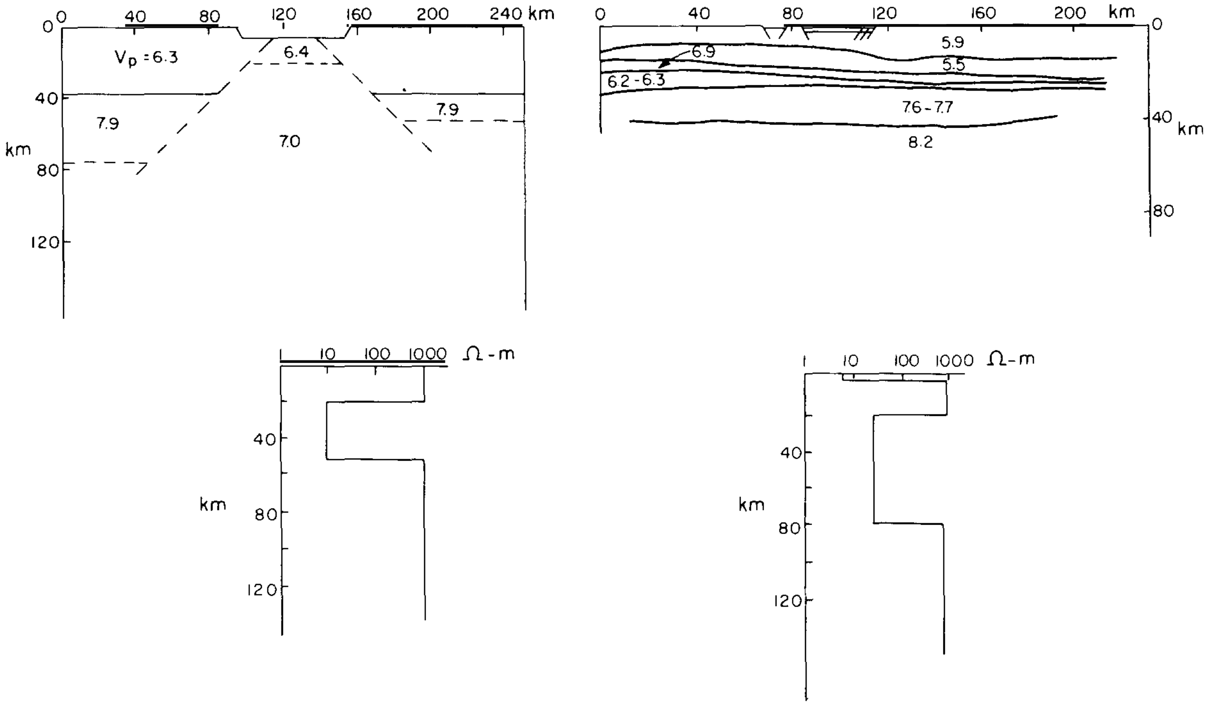

Fig. 3. Structure (top) and conductivity profiles for the African (left) and Rhine Graben rift structures. Figures on the structure sections are compressional wave velocities in km/sec. Sources as in text.

that these intermediate velocities will have to be modified.) This layer may represent an emplacement of basic material into the crust, the development of abnormally low velocity by heating or partial melting in the uppermost mantle, or a mixture of the two. In any case, it is in the depth range which appears to coincide with the increased conductivity.

A rather similar situation has been found by Banks and Ottey (1974) in Kenya. Once again, there is a surface layer of conductive material but the thickness of it appears to be insufficient to explain the anomaly. Banks and Ottey, who have also summarized the seismic and gravity information for the rift, favour a model which places a block of conducting material (resistivity 10 ohm · m) beneath the rift in the depth range 20–50 km. In this position it coincides with an anomalous seismic zone (Fig. 3) in which the P velocity, instead of increasing from normal crustal to normal mantle values, exhibits the intermediate range of 7.0–7.5 km/sec. As in the case of the Rhine graben there is the strong suggestion of a hot or partially molten uppermost mantle, perhaps extending upward into the crust. This picture is supported by the gravity anomaly pattern, which shows a local positive, the effect of basic rocks in the crust, superimposed on a broader negative, indicative of decreased density in the mantle.

The Gulf of California may be mentioned here, for while it is not strictly a rift valley, it is the locus of a series of lines of spreading offset by transform faults. White (1973a,b) has shown that although very high surface conductivities are present, the magnetic variation anomalies require the uplift of conducting mantle material from a normal depth of 160 km to as shallow as 50 km. In most cases the required uplift corresponds with spreading centres as suggested by the seismicity (Sykes, 1968), but under the central Gulf it is located under a supposed transform fault, and White has proposed that the pattern of spreading centres and faults may change with time.

3. Crustal anomalies

This class of conductivity anomaly has already been reviewed by Porath and Dziewonski (1971) but a good deal of information has become available since their paper was written.

The most important mechanism of current conduction in the crust is undoubtedly ionic, as the correlation between conductivity and porosity of typical sedimentary rocks of the crust shows. The conductivity of the crystalline portion of the crust probably depends on its state of hydration (Hyndman and Hyndman, 1968; Parkhomenko et al., 1972), reaching a minimum in the ancient shields. Within the shields conductivity may be locally increased by fracturing, or by concentrations of conductive minerals. The role of temperature is certainly less than in the case of mantle anomalies, although, as we have seen, heated or partially molten bodies beneath the rift zones may extend into the crust.

There is some evidence that, away from anomalies of small lateral extent, the conductivity of the continental crust shows a correlation with seismic wave velocity. Thus, Dowling (1970), on the basis of magnetotelluric measurements, found that beneath Wisconsin the resistivity decreased from values of the order of 1,000 ohm · m to below 100 ohm · m, at depths which corresponded closely to the increase in P velocity from 6.1 to 6.5 km/sec. The interface is presumably the top of a more basaltic part of the crust, within which the conductivity is actually greater than in the uppermost mantle. A similar decrease in resistivity within the crust beneath eastern Canada was found by Kurtz (1973), also on the basis of magnetotelluric measurements, and in a region where the crust contains a lower layer with a P velocity in the range of 6.9–7.0 km/sec (Berry and Fuchs, 1973). Conductivity anomalies could be expected in regions where this lower layer of the crust comes closer to the earth's surface. This may be the explanation for an anomaly over the uplifted Kirovograd block of the Ukrainian shield (Rokityansky and Logvinov, 1972). The conductive body apparently lies within the crust in a region where the Mohorovicic discontinuity is uplifted approximately 20 km. A puzzling feature, however, is that the Conrad discontinuity, or top of the basaltic portion of the crust, is shown as crossing the structure without uplift.

3.1. *Conductive structures, possibly ocean connected*

The significance of ocean linkages would be, of course, that currents induced in the oceans could leak into the continents and become concentrated in the process.

A major anomaly of this type is that extending northerly from the vicinity of Adelaide in Australia.

Magnetotelluric measurements (Tammemagi and Lilley, 1973) suggest the presence of a very low-resistivity body (0.1 ohm · m) in the upper five kilometres of the crust. Array studies (Gough et al., 1974) indicate a strong anomaly in Z amplitude, and a clear reversal in direction of induction arrows across the feature. The conductor has been traced along strike for about 700 km, and while the connection to the ocean is not established, the body almost certainly continues to the vicinity of the coast. There is a remarkable correlation with seismicity, which is believed to mark the boundary between two sub-plates (Cleary and Simpson, 1971) and this might suggest that major fractures in the lithosphere are responsible for the increased conductivity. Tammemagi and Lilley suggest that the structure is a remanent of a geosyncline, which developed between the former sub-plates, and which still contains a section of porous sedimentary rock bearing saline fluids.

The Alert anomaly in the Canadian Arctic now appears (Praus et al., 1971) to be of the same type. At least, a thick section of conductive sedimentary rock is present, and connections to the ocean are possible.

In the St. Lawrence region of eastern Canada, Bailey et al. (1974) have outlined, by means of induction arrows, a concentration of current which apparently flows inland from the ocean along a major fault zone. The fault, Logan's Line, marks the northern boundary of the Appalachians against the rocks of the Precambrian shield and covered shield. At longer periods the current concentration is probably an edge effect, related in a general way to the boundary of the more conductive Appalachian rocks. At the shortest periods the induction arrows appear to define very closely the location of the fault suggesting current flow along the fault plane itself.

In this case also there is correlation with local seis-

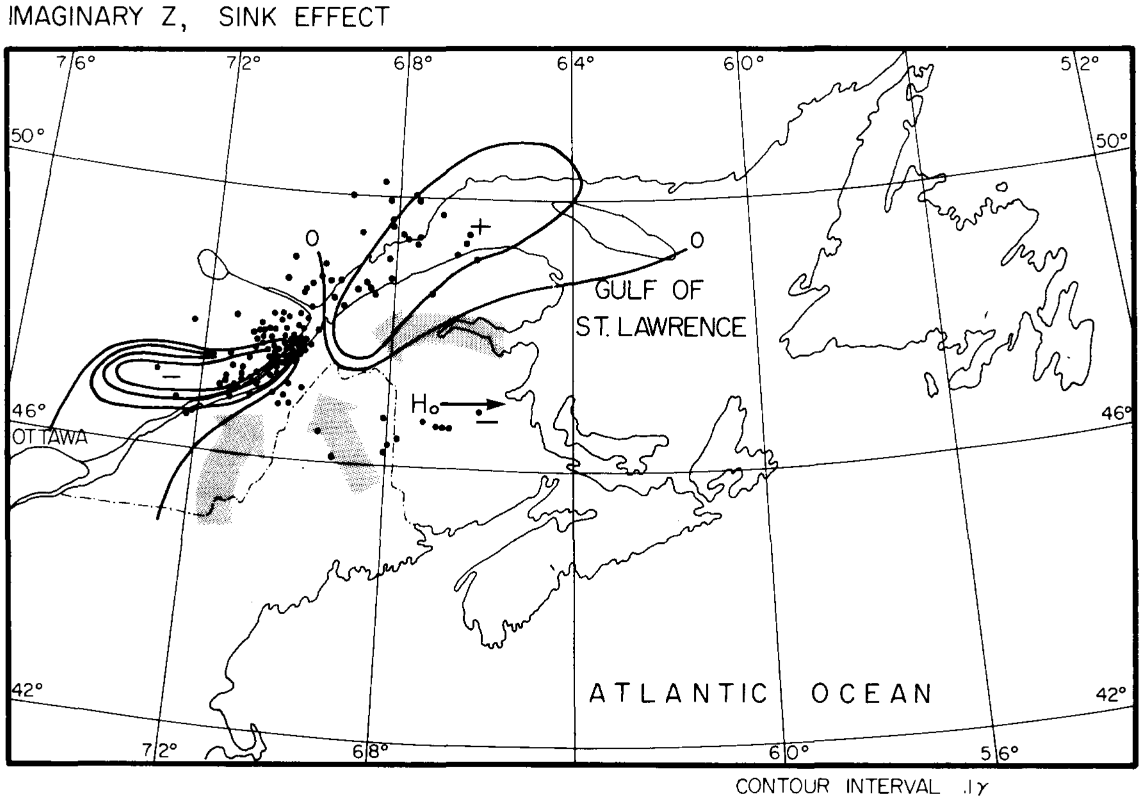

Fig. 4. Inferred current flow for a hypothetical magnetic event (H_0), according to the method of Bailey et al. (1974), compared with the seismicity of the lower St. Lawrence area of eastern Canada. Contours give the vertical field obtained by application of the event to the observed transfer functions. Large arrows indicate current flow; black circles are epicentres, reproduced for the central part of the region from Smith (1966).

micity. The application of hypothetical events (Bailey et al., 1974) to the imaginary induction arrows produces a pattern of Z fields which is suggestive of current leakage vertically to the mantle (Fig. 4). The site of this effect is close to the centre of seismic activity, and also to that of present-day vertical crustal movement (Smith, 1966; Frost and Lilly, 1966). An important question, not yet resolved, is the extent to which crustal conductive channels in general are linked to the conducting mantle. If there are multiple linkages, the phenomena of both induction and channelling become very involved.

3.2. Metamorphic zones

The Black Hills anomaly (Gough and Camfield, 1972) remains as one of the most striking elongated, intracontinental magnetic variation effects. Occurring over an area where the basement rocks are poorly exposed, the presence of the causative structure was indicated first by the array measurements, but Gough and Camfield have shown that there is supporting evidence for a metamorphic belt in the crust. On a much smaller scale, shear zones and fractures are well-known to result in the development of graphite and to act as conductors. Indeed, in the electromagnetic exploration for ore minerals, graphitic shear zones often produce the most abundant anomalies. The existence of the phenomenon on such a large scale is more unusual. Rokityansky (1972) has proposed that an elongated anomaly, extending 1,000 km along strike and found over the flysch zone of the Carpathians, is related to metamorphic changes in the crustal rocks. In particular, he suggests the development of an amphibolite melt in the deformed belt as providing the conductive channel. It appears, however, that one cannot rule out the possibility of porous sedimentary rocks alone being responsible for the effect.

4. Conclusions

While we have progressed beyond the stage of accepting every conductivity anomaly as indicating high temperatures, there remains a group of effects, from different parts of the world, that do appear to be related to important variations of properties in the mantle. It has been pointed out that in the case of subduction zones the interruption of the normal mantle by a relatively insulating slab is probably the dominant cause of anomaly. Observations over oceanic rifts and suspected plumes are seriously hampered by a lack of observing sites, and sea-floor variation measurements remain high priority.

A growing number of anomalies is recognized as having its origin in crustal rocks. These should not be dismissed as being without major tectonic interest, since correlations with seismicity suggest that some at least are related to plate fractures, or to ancient boundaries between sub-plates.

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