ELECTRICAL CONDUCTIVITY STRUCTURE IN THE LOWER CRUST

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Abstract. The subject is reviewed, notwithstanding the existence of a number of disagreeing and/or controversial results found in the literature. First, a brief critical reexamination of the methodology is presented. Second, it is attempted to put the results, or partial conclusions, by different authors, using different methods and referring to different geographical regions, into a working scheme. This is done by investigating, as far as possible, the relationships between the electrical conductivity information and other types of geophysical and geological information for each geographical area investigated. It appears almost impossible to draw general conclusions that hold for the entire Earth. Conclusions are given for those areas with some very well-defined geomorphological characters. Unfortunately, the available investigations still appear to give a poor coverage of several types of geographic areas with specific tectonic characteristics, and certainly the scientific coverage by electromagnetic methods of investigation cannot be compared with those available today from seismological methods. Investigating the electrical conductivity structure of the lower crust certainly opens relevant heuristic possibilities, but there appears to be a great need both for a refinement in the basic methodology, and for a better coverage of the investigated areas.

1. Introduction, Definition of Problem and Methodology

The electrical conductivity structure in the lower crust can be inferred by investigating the telluric currents flowing underground, because the electromagnetic (e.m.) induction within the solid Earth is a response to the time varying electromagnetic fields impinging on the Earth's surface from ionospheric and outer-space sources. There are a variety of different e.m. methods used which sometimes appear difficult to compare with one other. This is possibly one of the principle reasons why solid Earth geophysicists still prefer to rely predominantly on seismological techniques rather than on e.m. investigations.

E.m. methods begin by using geomagnetic (variometric) and/or geoelectric recordings. A classical approach, called magnetotelluric (MT) sounding (see for example Cagniard 1953a, b, 1956; Adam, 1976), makes use of the two horizontal components of the geomagnetic field plus the two horizontal components of the geoelectric field measured on the Earth's surface. The measurements are generally interpreted in terms of a horizontally-layered conductivity structure for the Earth below the recording site.

The telluric method uses the three components of the geoelectrical field alone, but it has been only seldom used (e.g. Keller and Frischknecht, 1966; Yungul, 1966; Angenheister *et al.*, 1967; Haak *et al.*, 1970; Yungul *et al.*, 1973; Reitmayr, 1975).

Geomagnetic Depth Sounding (GDS), sometimes also called magnetovariational (MV) sounding or profiling, makes use only of the three components of the geomagnetic field and has been extensively used in the past. GDS, however, has been tackled by a number

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of different analysis techniques: the literature is very large indeed (refer, e.g., to Schmucker, 1964, 1970a, b; Everett and Hyndman, 1967a; Schmucker and Jankowski, 1972; Banks, 1973; Frazer, 1974; Alabi *et al.*, 1975; Adam, 1976; Beamish, 1976, 1977; Hutton, 1976a; Gregori and Lanzerotti, 1979a, 1980a and references therein).

All of the investigation methods mentioned above start from some given experimental data set and then use some mathematical tools by which the underground conductivity structures can be promptly derived. However, different data sets, as well as different mathematical tools, are often found to provide different results for the same geographical location. The range of the errors and uncertainties from such analyses often appear large and not adequately understood.

A review of the present understanding of the conductivity structure of the lower crust requires a brief methodological foreword that is intended to help in evaluating the actual physical significance of a given quoted investigation. There is clearly no magical rule for selecting 'correct' results from 'incorrect' ones. The source of any error can be attributed largely to the specific mathematical tool used (provided, of course, that the experimental data base is reliable). Each paper or technique can be most conveniently analyzed in terms of its basic logical steps in the following manner.

Call $\mathbf{B}(t)$ the time varying geomagnetic field being recorded (after subtracting from the measured field the time independent field at the site, including the secular variation field). Henceforward, let us refer for simplicity to the geomagnetic field alone, because an accompanying geoelectric field must exist (by Maxwell's equations), and thus all methodology for the geomagnetic field can be repeated for the geoelectric field, and vice versa. $\mathbf{B}(t)$ has a spectrum covering the period range from ~1 s through several years. In reality, however, MT and GDS investigations have almost always been confined to periods shorter than a few hours, a time range that is suited for investigating the Earth's crust and upper mantle.

A simple, intuitive, and correct, procedure is the following. Let a $\mathbf{B}(t)$ field, having a given period T, impinge on the surface of a uniform conducting medium. Then $\mathbf{B}(t)$ is damped within the medium until, at some depth, it is practically cancelled. The 'skin depth' is the depth at which $\mathbf{B}(t)$ is damped by a factor $1/e$ and is given by $s = 30.2\sqrt{T/\sigma}$ (for T in hours; the conductivity* σ in S/m^{-1}; s is in km; see, e.g. Cagniard, 1956). Different frequency constituents of the natural $\mathbf{B}(t)$ penetrate to different depths, longer periods reaching larger depths. Differently stated, the Earth can be imagined to behave as a 'reservoir' of conductivity layers: a given $\mathbf{B}(t)$ (for a given period) penetrates as deep as required such that the total integrated telluric currents induced in the entire penetrated layer cancels $\mathbf{B}(t)$. Or, stated in yet another way, the outermost depth-integrated layer where the telluric currents flow screens, like a Faraday cage, the underlying inner portion of the Earth. Therefore, for any given period T there is some ultimate depth below which $\mathbf{B}(t)$ is totally damped.

The first logical step of a given analysis method is concerned with the search for a proper filter in order to select a given period (or, more precisely, a given period band) of

* We use either S or Mhos, being $1S = 1$ Mho.

$\mathbf{B}(t)$. Fourier series, Fourier transform, superimposed epoch analysis, or visual selection of events after visual interpolation (e.g., selecting geomagnetic bays of some given total time lag) are examples of such filters reported used. However, there appears to exist no general agreement on any standard method for this step.

The second logical step, which is often hidden within some implicit mathematical handling implied by the technique, is concerned with separating from $\mathbf{B}(t)$ the 'external' portion $\mathbf{B}_e(t)$ (i.e., that portion which originates from the electric currents in the ionosphere and/or magnetosphere) and the 'internal' portion $\mathbf{B}_i(t)$ (which is produced by the telluric currents). The separation problem allows, in principle, a unique solution, when it is assumed that no electric current crosses the Earth's surface; this was formerly shown by Gauss (1839). A few different practical methods for this have been proposed (Gauss, 1839; Vestine, 1941; Gregori and Lanzerotti, 1980b); but are not of concern here.

The next logical steps concern the solution of the inversion problem for both $\mathbf{B}_e(t)$ and $\mathbf{B}_i(t)$. Viz., provided that $\mathbf{B}_e(t)$ and $\mathbf{B}_i(t)$ have been separated, what is the pattern of the electric current densities $\mathbf{j}_e(t)$ and $\mathbf{j}_i(t)$ that produce $\mathbf{B}_e(t)$ and $\mathbf{B}_i(t)$, respectively? For the sake of completeness, it must be noted that one should be concerned with the determination of the conductivity σ of the underground layers, not with $\mathbf{j}_i(t)$. However, whenever σ is known, since $\mathbf{B}_e(t)$ is also known, $\mathbf{j}_i(t)$ will also be uniquely determined by solving the so-called 'forward problem'. Further, whenever $\mathbf{B}_e(t)$ and $\mathbf{j}_i(t)$ are known, σ can be inferred everywhere from Maxwell's equations. Thus, we consider here as analogous logical steps either the inferring of $\mathbf{j}_i(t)$ or the inferring of σ, and we call this the inversion problem for $\mathbf{B}_i(t)$.

Unlike the separation problem, the inversion problem does not allow a unique solution. Viz., let us compare the inverse problems for $\mathbf{B}_e(t)$ and for $\mathbf{B}_i(t)$.

Concerning the determination of $\mathbf{B}_e(t)$, a long debate was culminated in1968 when N. Fukushima circulated a short preprint, subsequently published in expanded form (Fukushima 1969, 1972), in which he showed the practical impossibility, under suitable assumptions, of distinguishing by means of ground geomagnetic recordings alone, a $\mathbf{j}_e(t)$ pattern containing also electric currents aligned along geomagnetic field lines (a so-called Birkeland-Alfvén current system) from a $\mathbf{j}_e(t)$ pattern composed only of currents flowing in a spherical shell concentric with the Earth, and representing the ionosphere (a so-called Chapman-Vestine current system). That is, the inversion problem for $\mathbf{B}_e(t)$ does not allow a unique solution.

Concerning $\mathbf{B}_i(t)$, first of all notice that there is a logical symmetry between the 'external' space and the 'internal' space, with respect to their dividing surface. Thus, Fukushima's arguments can be symmetrically applied also to the Earth's interior: the result is that a $\mathbf{j}_i(t)$ pattern, with some segment (in the $\mathbf{j}_i(t)$ loops) oriented along a radial direction, is indistinguishable from a $\mathbf{j}_i(t)$ pattern flowing uniquely over a spherical shell concentric with the Earth. The implications of such a conclusion are not, however, as dramatic as their equivalent in the case of $\mathbf{B}_e(t)$, because the $\mathbf{j}_i(t)$ must flow on the outermost (or shallowest) possible layers (compatible with the local conductivity and the skin depth for the given frequency). In fact, any current loop of $\mathbf{j}_i(t)$ will tend to become as broad as possible (see any book on college electromagnetism regarding a classical experiment by Laplace using moving contacts within a mercury filled vessel). (The same physical situation exists by virtue of the virial theorem in plasma physics, for a current-carrying plasma; the argument was given initially by Fermi and Teller, see, e.g., Rossi and Olbert, 1970.) Hence, if the Earth were perfectly spherically symmetric, $\mathbf{j}_i(t)$ should always flow on strictly concentric layers, so that the nonuniqueness argument of Fukushima would be physically ruled out by the Laplace-Fermi-Teller argument.

Moreover, in a series of important papers (Tikhonov, 1965; Weidelt, 1969, 1970, 1972, 1975; Bailey, 1970; Loewenthal, 1975) it has been shown that whenever the Earth is perfectly spherically symmetric (i.e., a perfect horizontal or spherical layering of the underground conductivity structure), and under a few suitable but very general assumptions, the inversion problem for $\mathbf{B}_i(t)$ does allow unique solutions. This result is remarkable, and, for symmetry reasons, it can be applied to the 'external' space as well (even though this will be more a matter of curiosity than of physics).

An important point, however, is whether or not an underground conductivity layering that significantly deviates from perfect sphericity can be uniquely evaluated by the inversion of $\mathbf{B}_i(t)$. An accurate reply requires lengthy discussion. A guess is that whenever the geometrical shape of the iso-conductivity surfaces underground has been suitably pre-chosen, the uniqueness for the solution for $\mathbf{j}_i(t)$ or σ can still be attainted. But, to our knowledge, this has still to be formally proven. In any case, the differences in the procedure for finding a solution are such that all authors agree that no unique solution can be found in practice.

In general, past investigations have evaluated the inversion solution by assuming, most frequently, a perfectly horizontal conductivity layer beneath the recording site. Other solutions have assumed some simple geometrical structure buried underground, such as a line current, or a cylinder of various cross-section, or an oblique planar fault, etc. (e.g. Porstendorfer, 1976). Actual structures are likely to be much more complicated. Such examples would appear to be quite common, as illustrated in any textbook on geology. In any case, it would appear definitely arbitrary to assume a very simple geometrical structure, even in those standard geographical regions characterized by typical tectonic features such as continental shelves, rifts, hot spots, volcanic areas, mid-oceanic ridges, etc., or in more complicated regions where there may be curiously shaped, deep-seated hydrated sediments, etc.

Summarizing, the inversion problem is a fundamental critical point for any practical application of e.m. methods, and several authors have clearly stated this. The work of Jones (1980) points this up clearly: an experimental data set, treated by means of several different inversion techniques, is found to provide completely different and contrasting results. Monte Carlo methods used for perhaps a little more than a decade for inverting seismic data, have been used only much more recently for inverting e.m. data (e.g., Jones and Hutton, 1979a and b discuss the amount of indeterminacy when using flat layered models).

Concluding, almost all papers in the literature contain a mixture of all the above mentioned logical steps within a unique mathematical data handling process, whereby a problem with a unique solution (i.e. the separation problem) is mixed up with the indeterminate inversion problem. This largely explains many of the controversies between different observational investigations made in the same or in analogous geographical areas.

However, notwithstanding such an important difficulty, an attempt can be made to prepare a catalogue of the conductivity structures of the lower crust being characteristic features related to some specific geomorphological patterns of the crust. This is the basic theme in the following section.

Attempting to classify geomorphological and tectonic features is sometimes embarrassing, because there appear to exist many different opinions and viewpoints among geophysicists themselves. We have attempted to adopt here a scheme that is fairly general, so that the different viewpoints, whatever may be the correct one, should fit in reasonably well. One should be able to recognize geomorphological structures in the lower crust by means of e.m. investigation alone. This is not yet possible, but it could be in the future. This review is an attempt toward solving such a problem. But the reader should be aware that since we cannot attack each problem in full detail, we only give a series of brief comments on some topics that appeared to us particularly significant for future developments.

Some of the items contain some speculative arguments, generally reported from solid Earth geophysics. In other areas treated, apparently no e.m. investigations have yet been reported. In such cases, we have mentioned them also, because we propose a tentative scheme where the available investigations, as well as future e.m. investigations of the crust, can be fitted within present understanding. The Earth's crust is quite a varied physical system, and without such a scheme, this review would be only a log of apparently randomly contrasting published results.

2. A Tentative Classification

The crust is defined as the layer above the Moho. Hence, this review should be concerned only with conductivity structures lying above the Moho. However, it is not yet completely clear what the relationships are between seismological information (like the Moho) and e.m. data. We refer to Figures 1, 2, and 3: in these cases the authors suggest that the conductivity layering (more specifically some ultimate conducting layer being inferred by some inversion technique) appears correlated with the 1000–1200 °C isothermal surface underground (being related to a presumed partial melting zone). Such a conducting surface would appear to be well below the Moho. Other authors (e.g. Oni and Agunloye, 1973; and Bailey *et al.*, 1974) suggest that one of their inferred surfaces, dividing layers of different conductivity, should be likened to the base of the crust. The problem is difficult, and it has to be considered in the framework also of geochemistry and petrology (see, e.g., Garland, 1975; Shankland and Waff, 1977; Wasilevski *et al.*, 1979). Summarizing, the present review should more appropriately be considered as referring to the lower crust plus upper mantle.

The Earth's crust can be quite different from site to site. Preparing a typological classification of the crust, even on the basis of the seismological evidence alone, is not

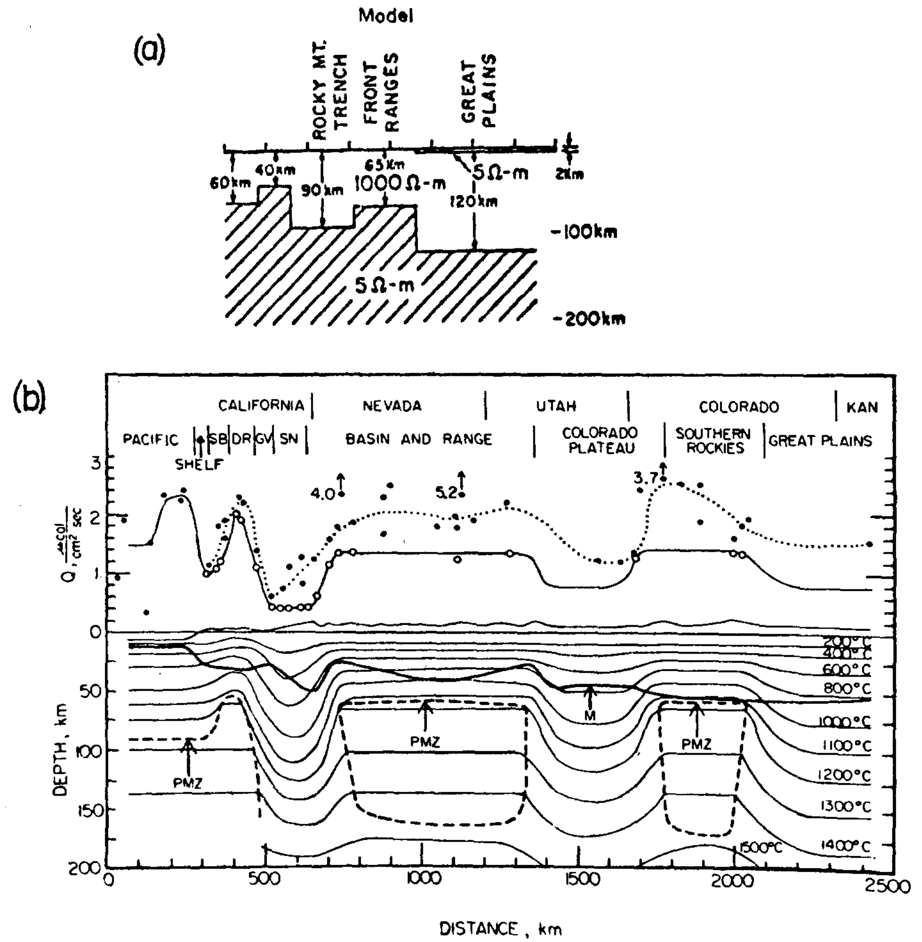


Fig. 1. (a) East-west section shows Deep Geomagnetic Sounding model deduced for Rocky Mountain front near U.S. – Canadian border (after Porath *et al.*, 1971). (b) East-west profile shows heat flow observations (above) and section (below) shows derived upper mantle model for the western United States. PMZ indicates partial melt zone (after Roy *et al.*, 1972). (Figure and captions from Chaipayungpun and Landisman, 1977).

simple; neither is an understanding of the reasons for such differences. It is important, however, that such seismological aspects be considered when dealing with the e.m. induction information in the crust at some given site; see for example Green (1977). The classification we propose here is an attempt to match in some way the observational complexity.

It is impossible, because of space limitations, to provide here a complete list of all the references for each subheading. We quote some relevant review papers, plus those of interest for the brief comments we make on some specific subject. A complete listing of references, including some systematic tables allowing cross-references to methods used, areas investigated, and results obtained, will be published elsewhere.

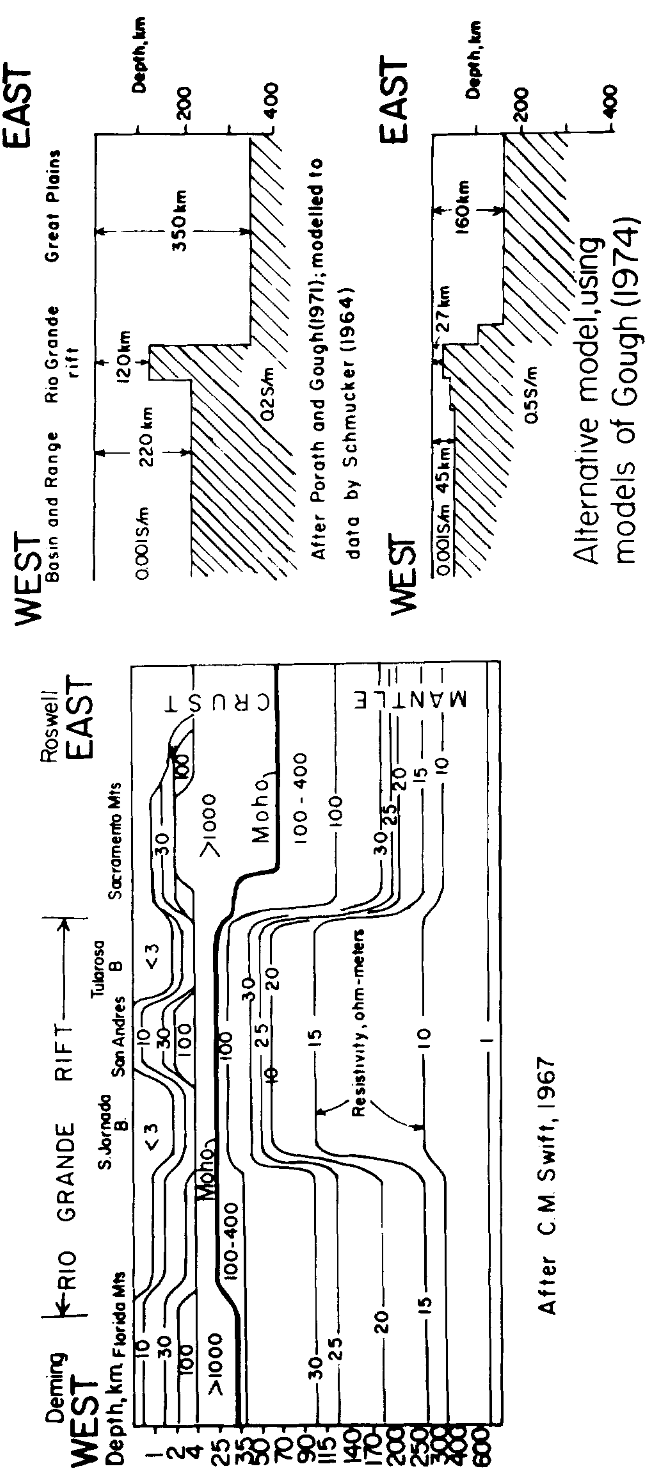


Fig. 2. Resistivity and conductivity models across the southern Rio Grande rift near latitude 33° N. (Figure and captions from Seager and Morgan, 1979).

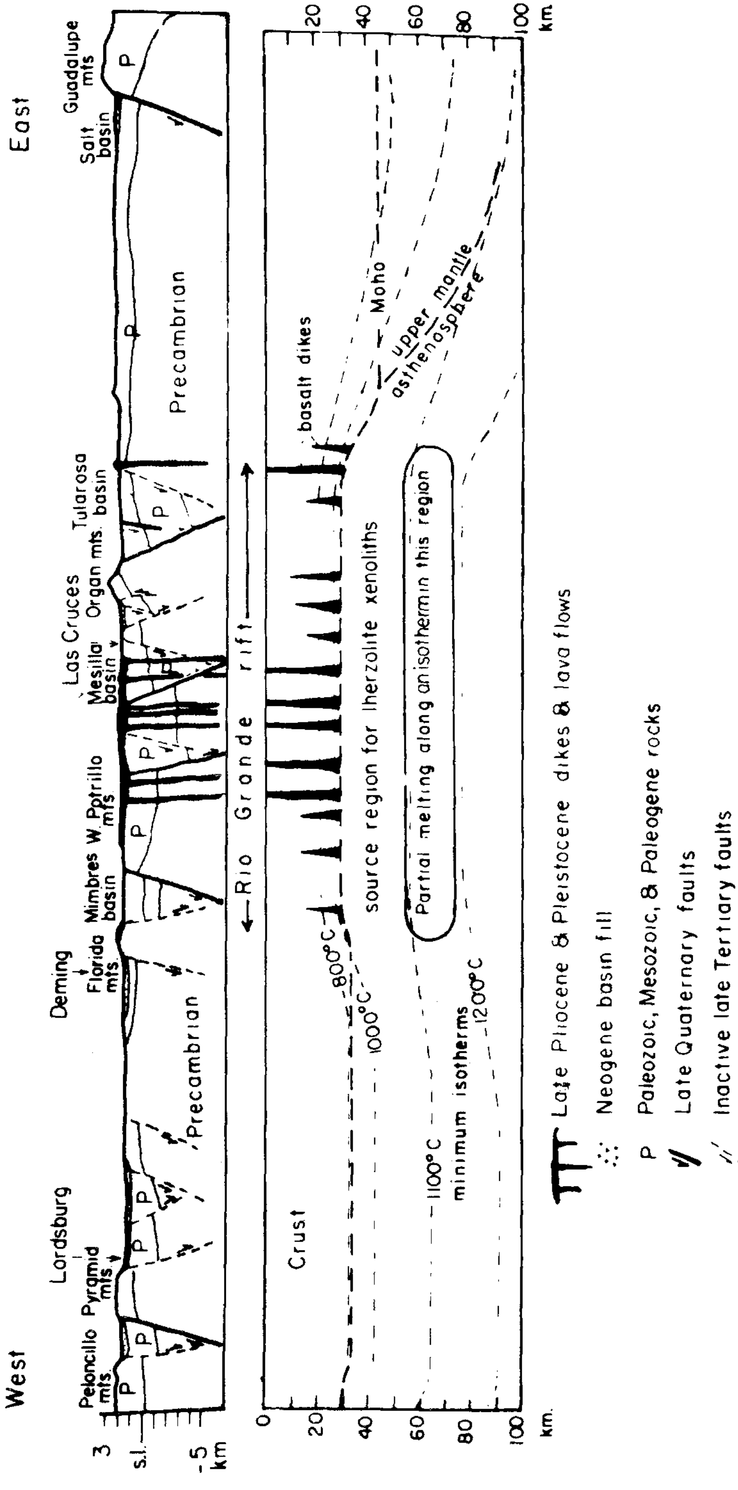


Fig. 3. Hypothetical cross-section through southern Rio Grande rift. (Figure and captions from Seager and Morgan, 1979).

2.1. Flat Conductivity Structures

2.1.1. *Continental Shields, Platforms and Cratonic Areas*

A review has been given by Kovtun (1976). All regions with a thick platform or continental shield, or cratonic areas, have a low-conductivity thick layer, and the ultimate conducting layer is always found at several hundred kilometers depth. It can occur at shallow levels (but always deeper than 100 km) whenever some tectonic process has been, or is still, active (e.g. Colorado plateau, some regions of Canada, Nigeria, etc.); in such regions the crust is therefore somewhat thinner. In general, flat conductivity structures extend over rather limited areas. See, e.g., the maps given by Ritter (1975) and by Berdichevskiy *et al.* (1976), or Figure 4, redrawn after Vakulin *et al.* (1971).

2.1.2. *Continental Borders*

Sometimes, strips of continents (being divided from main continental land by, for example, a fault) have the deepest conducting layer at ~100 km. A typical example is western Australia (Everett and Hyndman, 1967b). The transition regions on the border of continents are further discussed in Section 2.3.

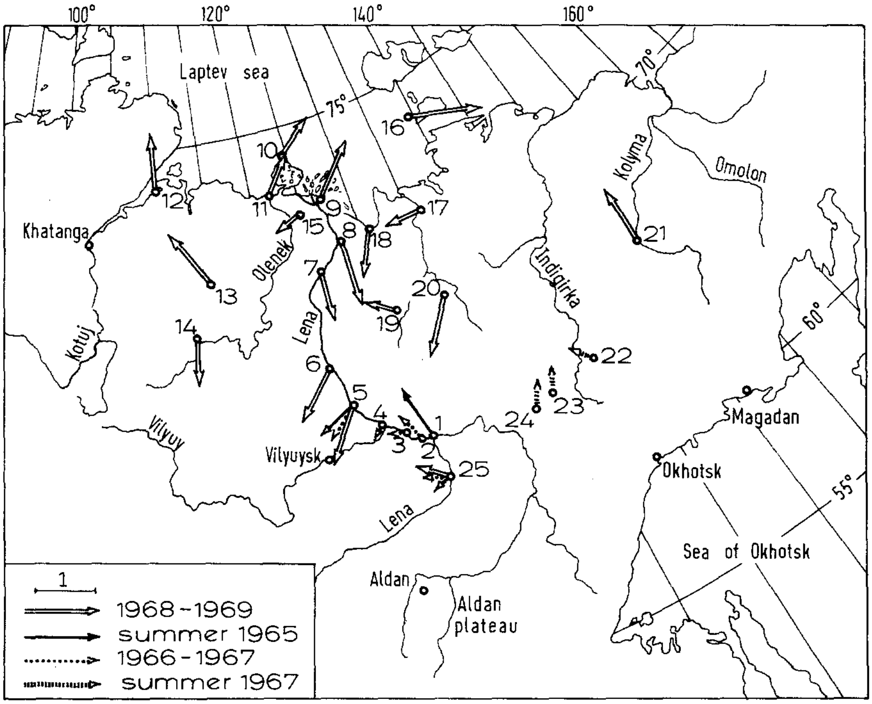


Fig. 4. Wiese vectors in the Siberian platform. Map redrawn after Vakulin *et al.* (1971). The names of the recording sites are: (1) Belyanka; (2) Sitte; (3) Sangar; (4) Prom'schlenniy; (5) Bestyak; (6) Zhigansk; (7) Siktjakh; (8) Kjusjur; (9) Sokol; (10) Dunaj; (11) S. -Khocho; (12) Khosistiy; (13) Dzelinda; (14) Olenek; (15) Sklab; (16) Khighilyakh; (17) Kazač'e; (18) Njajba; (19) Batagaj-Alyta; (20) Batagaj; (21) Zyrjanka; (22) Agayakan; (23) Nekyun'yakh; (24) Tepl'iy Klyuch; and (25) Yakutsk. For the Wiese vector definition refer, e.g., to Gregori and Lanzerotti (1980a).

2.2. SURFACE PHENOMENA – CHANNELLING

By this we mean all that is concerned with shallow (depths $\leqslant$ 10 km and, in some exceptional cases, somewhat greater) current flows. In general, these features are most clearly recognized, and have been most often reported, whenever some elongated structure produces a unexpected effect. Such elongated features nearly always appear to occur as narrow conducting bodies embedded in a less conducting environment. This most frequently occurs when water is present either in seas, lakes, rivers, etc., or as a relevant component within hydrated sediments. An example of this is shown in Figure 5, where the north-south sedimentary cover running eastward of the Rocky Mountains can be noted.

Such surface phenomena are often called channelling phenomena (e.g. Banks, 1973; Hutton, 1976a). Such effects have now been recognized in several regions: e.g., in the English Channel (Van Bemmelen, 1908); in the British Isles (several papers); in the Seine basin (Moureau, 1893; Rossignol and Le Mouël, 1971); in the Bonifacio Straits (Giorgi and Yokoyama, 1967; 1968); in the north German conductivity anomaly, extending eastward to Poland (Jankowski, 1967; Untiedt, 1970; and references therein); in the Ishikari plain in southern Hokkaido (Nishida, 1976); in the St. Lawrence river (several papers by Canadian workers; refer, e.g. to Bailey *et al.*, 1974; Kurtz and Niblett, 1978; and references therein). Figure 5, even though not greatly detailed, can help in recognizing the regions where hydrated sediments may eventually play some relevant role in channelling phenomena.

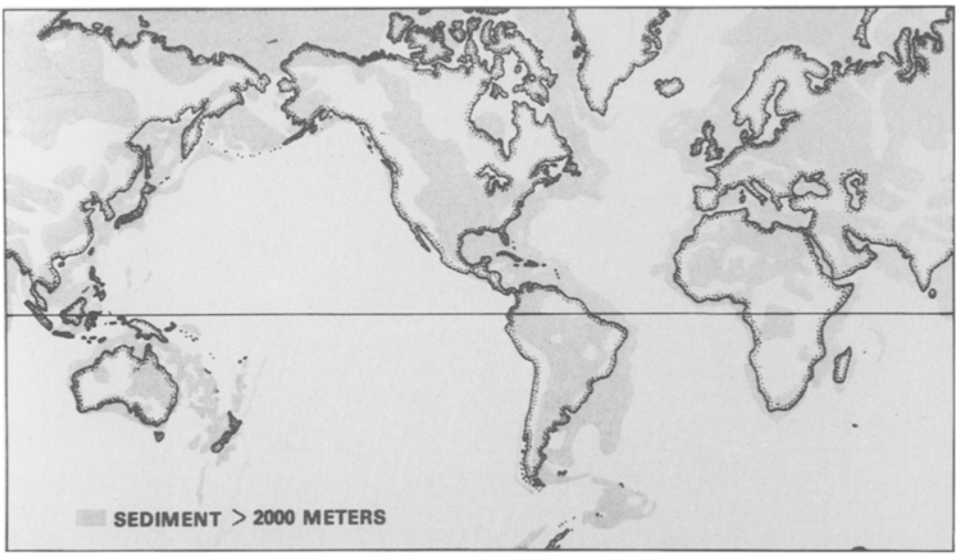


Fig. 5. Generalized sedimentary basins of the world (after H. R. Hopkins, personal communication, 1976). (Figure and captions from Green, 1977).

2.3. SURFACE AND DEEP EFFECTS – COAST EFFECT

Close to sea coasts (or generally to water bodies, depending upon the frequency of the signal) there are well recognizable effects. Recently, three reviews have appeared on this topic (Fischer, 1979; Parkinson and Jones, 1979; Gregori and Lanzerotti, 1979b; see also Küppers *et al.*, 1979). The effect is generally called the coast or coastal effect, but also other names have occasionally been used (island effect, peninsula effect, straights effect, etc.). The effect is associated with sea water, but, at longer periods, it is definitely associated with continental borders. For example, Honkura (1974) and Honkura *et al.* (1974) show that at a 5 min period the coast effect is clearly recognizable on the islands of Miyake-jima and Hacijo-jima, while for longer periods (up to 120 min) the effect clearly reflects the nearby subduction zone.

The most important point to be emphasized is the 'reversed' coast effect occurring on the Andean coast (see Figure 2 in Gregori and Lanzerotti, 1979b): there appears to be a better conductor inland than oceanward. This has led Casaverde *et al.* (1969) to hypothesize a conductive half cylinder with upper surface at 60 km depth, lying over a flat horizontal conductive base 240 km deep, in order to explain the observed effect.

In this same respect, Law *et al.* (1980) refer to an investigation on an E-W profile

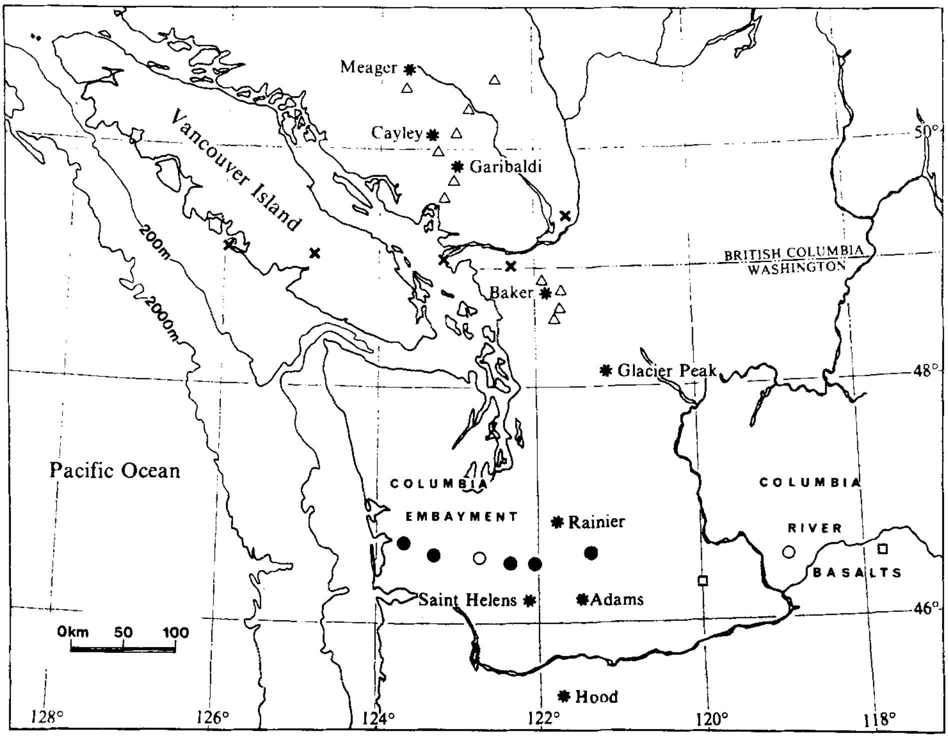


Fig. 6. Location of: the Geomagnetic Recording Stations, major volcanic centres in this region of the cordillera, the Columbia Embayment (after Davis, 1977) and the Columbia River Basalts. Stations of this study ●, stations of Cochrane and Hyndman (1970) X, other stations, Δ, O, □, ... Volcanos✱ (Figure and captions from Law *et al.*, 1980).

slightly north of the St. Helens volcano (Figures 6 and 7): they find a 'reversed' coast effect (Figures 8 and 9). They interpret the results in terms of a 'long, narrow conductor extending north-south in direction' that, however, does not extend as far as southern British Columbia. One could hardly hope to get better e.m. evidence of the uplifting 'magma chamber' underneath Mount St. Helens. That is, the results are suggestive of a 'point-like' magma chamber beneath Mount St. Helens, rather than an of elongated conductor. One could also suspect that in the Andes, too, there are several point-like magma chambers related to volcanos, that simulate an elongated north-south oriented conductor. Refer also to the Aldrich *et al.* (1978) investigation discussed in Section 2.7.3.

An open question concerns the longest period of **B**(t) for which a 'coast effect' is still

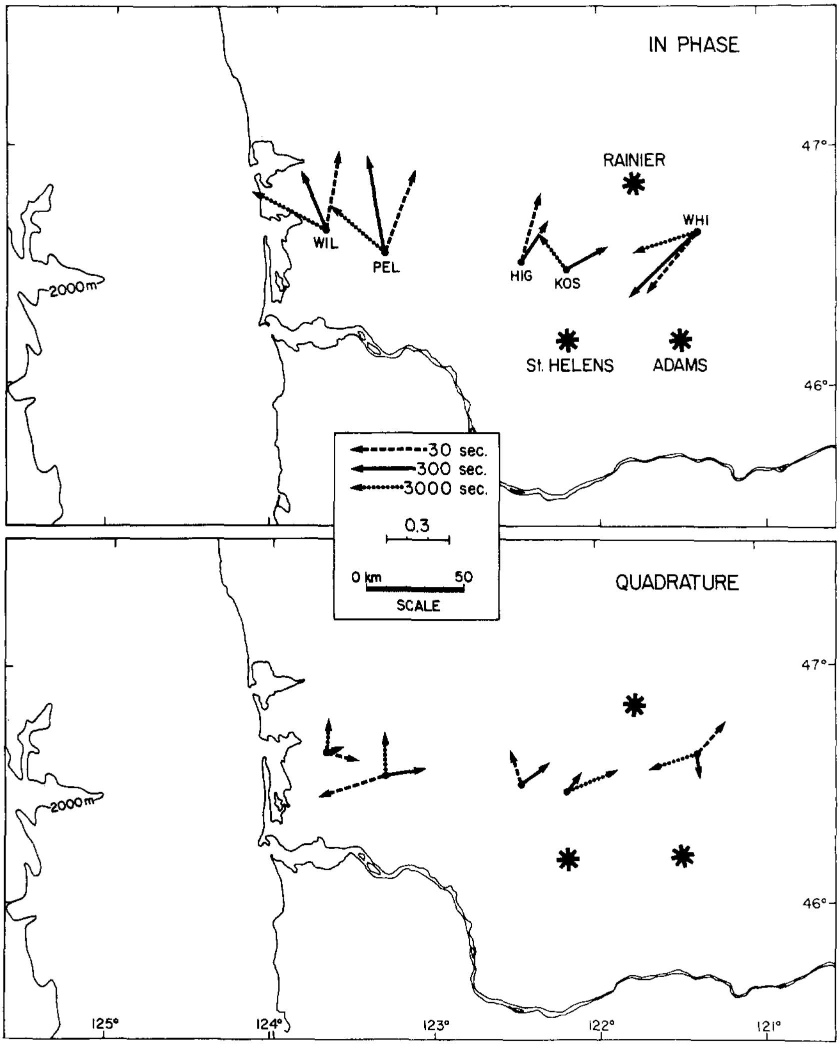


Fig. 7. In phase and quadrature induction arrows for 30, 300, and 3000 s periods. (Figure and captions from Law *et al.*, 1980).

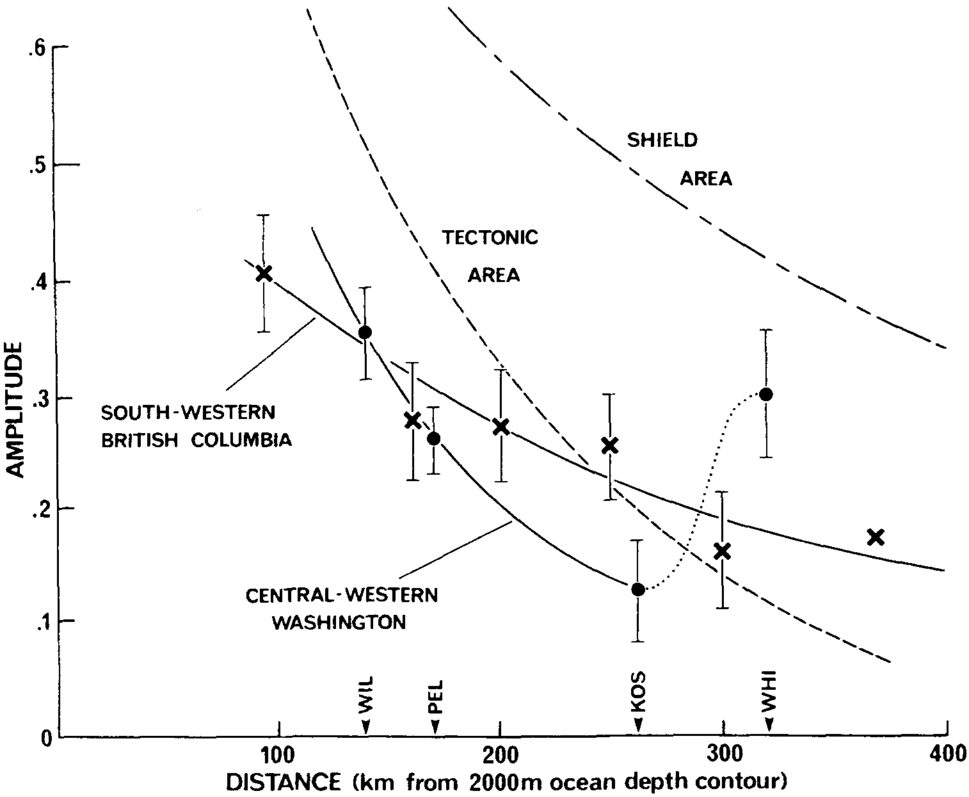


Fig. 8. Amplitude of the in-phase component of the transfer function resolved perpendicular to the coast at 50 or 60 min period in regions of different tectonic character as a function of distance from the 2000 m depth. (Figure and captions from Law *et al.*, 1980).

observed. Differently stated, the question is on the depth at which the solid Earth behaves as a uniformly layered body, no longer reflecting the continent/ocean anisotropies. The geophysical problem is very difficult and debated (see, e.g., Jordan, 1979; England, 1980). E.m. induction is likely to be able to provide very important information on this point. Some discussion is given in Gregori and Lanzerotti (1979b). Additional references discussing spatial anisotropies include Pecova and Praus, (1972); Pecova *et al.* (1977a, b, 1979); Faynberg *et al.* (1975); Lilley (1979); and Hvozdara (1980).

2.4. Surface or Deep Phenomena? – Conductivity Anomalies

There are 'conductivity anomalies' (CA) (i.e. elongated heterogeneities in the local conductivity environment, located at some unknown depth), all over the world. They often appear difficult to interpret as either surface (or shallow) or deep structures. Several of the conductivity anomalies are well known; e.g. the Eskdalemuir CA (tectonic), several CA's in Europe (tectonic, and nontectonic), in Japan (tectonic, island arc processes, see Section 2.7.2), the Alert CA and the Great Plains CA in North America. Two other prominent CA's are less frequently referred to in the literature: a CA in Greenland (Wilhjelm and

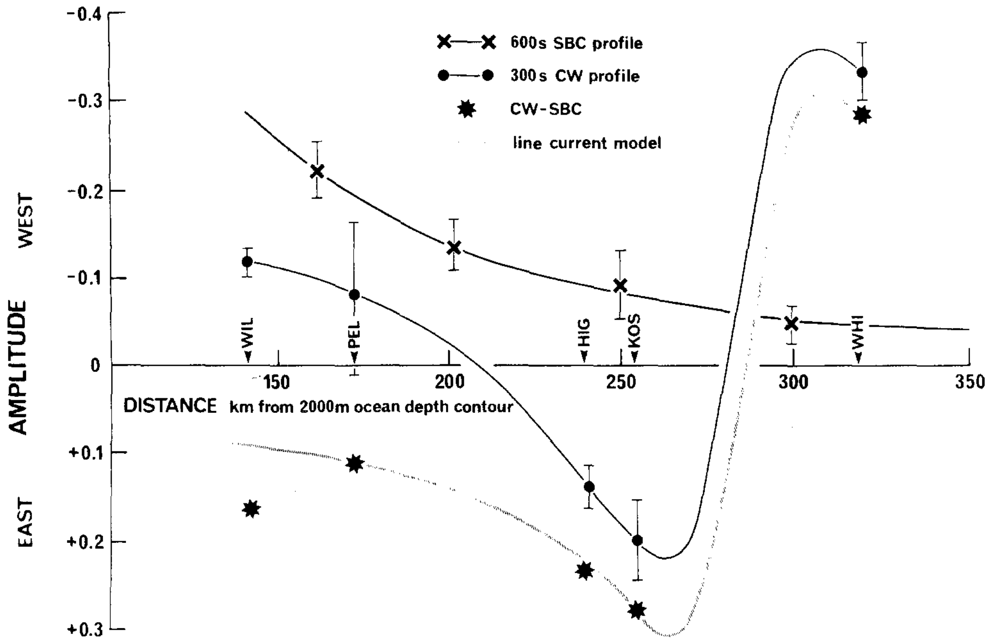


Fig. 9. Amplitude of the in-phase component of the transfer function resolved perpendicular to the coast at 300 or 600 s period for the SBC and CW profiles. Values of station differences: CW – SBC, and model curves of the transfer function response of a north-south line current. (Figure and captions from Law *et al.*, 1980. SBC means Southern British Columbia, and CW means Central Washington).

Friis-Christensen, 1973) that seems to be very shallow, and a CA in the Alboran Sea (western Mediterranean) entering inland in Morocco (Le Borgne and Le Mouël, 1975; see also the discussion in Gregori and Lanzerotti, 1979a), that has been interpreted in terms of a deep seated current line, 60 km deep. However, as is well known, depth estimates by means of a simple line model can be misleading (e.g., Bartels, 1957, evaluated an equivalent wire at 50–100 km depth for the north German CA which now appears to be just the effect of a surface hydrated sediment).

Moreover, two additional CA's are the subject of very recent investigations. One of them, in South Africa, (Gough and DeBeer, 1980; De Beer and Gough, 1980) appears to be correlated with the local geomagnetic anomaly, coinciding also with contours of equal age basement provinces. The other one is the well known Pyrenean CA (Galdeano *et al.*, 1979; 1980) (see Figure 10) that is interpreted as the sum of three different features: electric currents flowing in sediments, in deep seated conductive structures (a western and an eastern one, connected by a fault line), and an inclined-plane planar current distribution.

A mention should be made also of very shallow CA's, related to specific mineral ores. Such a one is the Flambeau anomaly (Sternberg and Clay, 1977). This type of anomaly is said to occur rather frequently on continental shields.

Basically, a CA is an anomalous feature, compared with its environment. Whenever interpreted, a CA should be included within some specific tectonic class as herein considered under one of the subheadings.

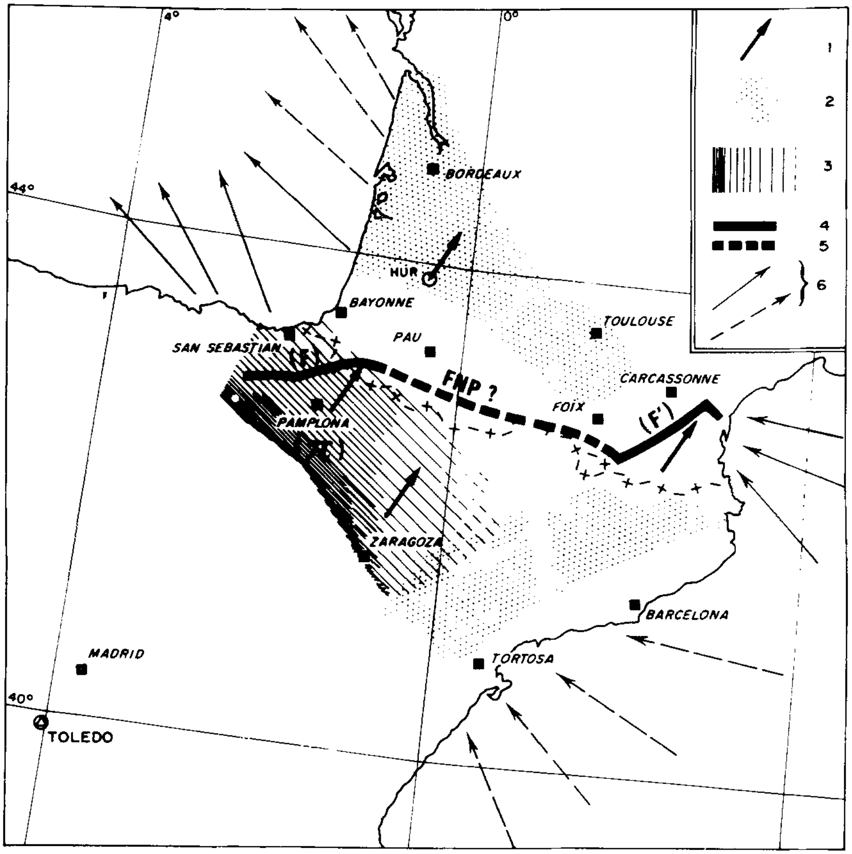


Fig. 10. Simplified sketch of the electrical structure of the Pyrenees. (1) Parkinson vector computed for each considered site (the vector at HUR is unique for all of Landes). (2) Sedimentary basins where currents are probably flowing. (3) Conductive structure, recognized as having a large dimension, a first order approximation model of which is an inclined plane (its steepening is indicated by a decrease in the density of the lines). (4) Recognized deep conductive linear structures (*F*) and (*F*′). (5) Probable linear conductive structure following the track of the north-Pyrenean fault (FNP) acting as a link between (*F*) and (*F*′). (6) Regions where the currents channelled within (π), (*F*), and (*F*′) are being either concentrated or spread out. (The current direction can be inverted). (Figure and captions from Galdeano *et al.*, 1980; captions have been here translated from French).

2.5. Fold Belts

Since mountain belts did not originate in the same way all over the world, one must expect that different belts should respond differently to e.m. induction analysis. We have already pointed out in Section 2.3 that the Andes region is anomalous, suggesting the existence of a linear conductor underneath them. It should be noticed, however, that the Moho under the Andes is by no means shallower than under other mountains (see, e.g., Figure 14 in

Green, 1977, his classes 22 and 23). This fact clearly envisages the heuristic potential of the e.m. method as an adjunct to, and unifier of, the seismic evidence. It is also remarkable that the California coast and the British Columbia coast behave 'regularly'; see, e.g., Lienert and Bennett (1977), their Figures 1 and 8; also Schmucker (1964). However, notice that Porath and Gough (1971) show an upheaval of the deep conductive layer underneath the Southern Rockies (both with respect to the Colorado plateau and to the Great Plains). See also Figure 3a of Stegena (1976). On the contrary, the profile slightly north of the St. Helens mountain, mentioned in Section 2.3, behaves similarly to the Andes.

These features can be tentatively and rather speculatively explained by supposing that the Rocky Mountains behave 'regularly' except along some limited segments of their extension, where the subduction process is active. The structure of the Rocky Mountains can be explained by supposing that North America, while drifting westward, is also 'corking' the west Pacific ridge. This causes an apparent segmenting of the spreading ridge (see, e.g. Handschumacher, 1976). But, the 'corked' segment appears to be actually stopped. In fact, Gilluly (1969) has investigated the problem extensively, concluding that during ~35 million years the continent rifted and spread by ~50 km, whereas, according to sea floor spreading, the spread had to be ~1300 km. A tentative conclusion is that, as long as the spreading ridge is stopped, the Rocky Mountains have a deep low-conductivity layer beneath. However, in those segments where subduction is still active, there is upwelling of conductive material (or in any case, an upheavel of the isothermal surfaces).

The Alps do not show any anomalous behaviour. However, in the wider region, there are several anomalies: this is a very complex region tectonically (e.m. anomalies include the Carpathian anomaly, Lake Balaton anomaly and Kirovograd anomaly; from a tectonic viewpoint the crust underneath the Caspian Sea depression is very thin, even though it is loaded by a large amount of sediments; see Green, 1977).

Concerning the Urals, we are not aware of any direct investigation. However, the regions of Perm and of Sverdlovsk (Bobrov, 1959; Rotanova, 1963a, b; Matveev *et al.*, 1969) seem to behave regularly. Moreover, in the region that extends southward to the southernmost extension of the Urals, i.e. in Kazakh (A'lmukhanbetov *et al.*, 1967; 1978), the deep conductive boundary appears shallower under plains (90 km) than under mountains (210 km), thus suggesting that the Urals should not be anomalous, or that they should have a thick low-conductivity layer underneath. However, this argument could not be fully significant, because Kazakh could already have an anomalously thin crust, being close to the Caspian Sea depression (which has been investigated by Berdichevskiy *et al.*, 1970a, b; 1971; 1972).

There appear to be no reports of investigations in the Himalayas. This region is very interesting because, unlike the Alps and the Urals, there is a general agreement on their folding mechanism (i.e., by a collision between India and Asia, started ~39 million years ago; see, e.g., Norton and Sclater, 1979). The mechanism should have some resemblance to the present Andean folding mechanism. Moreover, the Himalayan folding could now be either stopped, or in any case much less active than in the Andes at present. Hence, it would be interesting to know whether the Himalayas have a shallower, or deeper, high-conductivity layer beneath them, compared with Asia north of the Himalayas.

A recent investigation on the Lomonosov ridge (Camfield *et al.*, 1980) has been reported. This is, actually, an oceanic ridge. However, it resembles a fold belt much more than a mid-oceanic ridge. In fact, it is aseismic and amagnetic (there are other two ridges in the Arctic ocean, viz., the Alpha ridge or cordillera, which is magnetic but aseismic, and the Nansen ridge, which is the prolongation of the mid-Atlantic ridge and, as such, is both magnetic and seismic; further details can be found, e.g., in Vogt and Ostenso, 1970; Burke and Wilson, 1976; Lowman and Frey, 1979; and Vogt *et al.*, 1979).

Camfield *et al.* (1980) operated several different instruments at a station fixed on, and drifting with, the Arctic ice pack. They suggest that the Moho becomes deeper under the Lomonosov ridge. The ridge appears to behave 'regularly' for a folded belt, because it has a thicker low conductivity layer underneath than does the oceanic crust around it. In fact, the induction arrows show a clear 'coast effect', pointing away from and perpendicular to the ridge (for induction arrow definition see Gregori and Lanzerotti, 1980a).

An interesting mountain belt is the Transantarctic Mountains. Their e.m. induction characteristics have never been investigated. One is tempted to guess that the Transantarctic Mountains are the result of upstream folding, when Antarctica rapidly moved to its present position. Hence, their structure should be very similar to the Andes. However, Antarctica reached its present position ~80 million years ago (at least) (Norton and Sclater, 1979). This means that the folding mechanism should have been quiescent since that time. On the other hand, notwithstanding such a long time lag, the Erebus volcano is still very active: is it a remnant volcano of such an ancient folding process, or is it a hot spot (see Section 2.7.3)?

Summarizing, the Andes, Himalayas, and Transantarctic Mountains could have similar structures underground. However, the folding mechanism is presently active in the Andes (and in a few segments of the Rocky Mountains), it started to be active in the Himalayas ~39 million years ago, but, at present, it could be quiescent, while it should have been quiescent for ~80 million years in the Transantarctic Mountains. Comparing the e.m. characteristics of the three cases would be very enlightning in order to infer information on the time scale needed for disappearance of crustal anomalies within the underlying mantle. One should be aware, however, that the foregoing is largely speculative: e.g., some authors have even suggested that Antarctica resulted from the collision of two formerly distinct continental plates (Jurdy, 1979, and references therein).

In general, it should be emphasized, that a geomagnetic depth sounding investigation could be one of the most viable practical geophysical investigations in many inhospitable areas.

2.6. RIFTS

Recent reviews have been given by Hutton (1976b) and Jiracek *et al.* (1979). Refer also to the monograph by Riecker (1979) on the Rio Grande rift. Presumably, this rift originated within some complex tectonic processes involving the westward drift of North America interacting with the expanding Pacific floor (Cocos plate) (see in particular the figures on pages 15, 89, 204, and 205 of Riecker, 1979). Figures 2 and 3 of this review show how a partial melting zone is believed to be associated with this rift. The spatial extension of the 'magma body', and elongated plutons, are mapped in the figure on page 211 of Jiracek *et al.* (1979); they are interpreted there as being as shallow as 18–22 km.

The conductivity structures of the four most investigated rifts are compared by Jiracek *et al.* (1979) (see Figure 11 herein). Refer also to Figures 2 and 4 of Jiracek *et al.* (1979). However, these authors warn about the non-uniqueness of the inversion. Indeed, it appears difficult to relate the Jiracek *et al.* (1979) plot for the East African rift (Figure 11 herein) with the conclusions by Banks and Ottey (1974), Beamish (1976 and 1977), Rooney (1976) and Rooney and Hutton (1977) (on the basis of which Figure

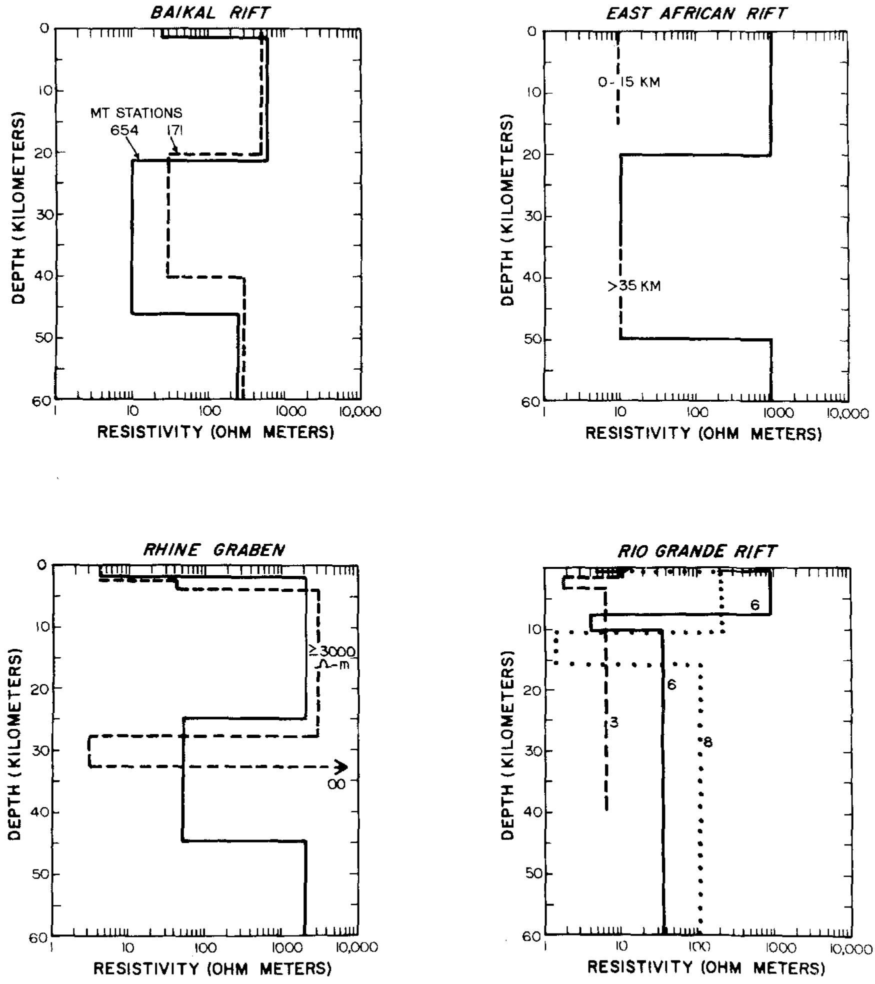


Fig. 11. Geoelectric sections interpreted for upper 60 km in major continental rift zones. Results for the Baikal rift from Gornostayev (1972). Dashed results for the East African rift are from Rooney and Hutton (1977); solid curve is from Banks and Ottey (1974). Dashed profile for the Rhine graben is from Losecke (1970), whereas, solid curve is from Reitmayr (1975). (Figure and captions from Jiracek *et al.*, 1979).

11 has been drawn). This is just one example of how difficult it is to compare just a few different investigations of the same or of analogous areas.

A transverse cross-section of Israel from the Mediterranean Sea to the Dead Sea rift does not show any relevant changes (Shoham *et al.*, 1978). They report a rapid increase in conductivity (to 0.2–1 Mhos m^{-1}) at a shallow depth (21–23 km), consistent with the results by Goldberg and Rotstein (1978) (who find at 12–20 km more than 0.1 Mhos m^{-1}).

It appears that there is a real requirement for fitting all different types of information in order to get a unique and consistent picture of each rift. Concerning the East African rift, for example, Burke (1977) reviews several evidences of 'an axial dike of basaltic material about 10 km wide, reaching nearly the surface and extending along the rift valley for a distance of over 100 km'. As well in the Ethiopia rift, at the latitude of Addis Ababa, three similar basaltic dikes have been reported, about 75 km wide altogether. These conclusions have been supported by refraction seismic studies, gravity observations, igneous rocks, and outcrop patterns. E.m. studies have probably not yet attained a sufficient spatial resolution in this area for correlation with such specific features.

However, e.m. methods have been applied on a very detailed spatial scale; for example, see the investigation by Stanley *et al.* (1977) in a complex geothermal area in the Yellowstone region. It is likely that such detailed investigations will be needed in rift areas for a better incorporation of e.m. information with other geophysical data.

A last point to be emphasized is that rifts are a very common feature in the Earth's crust. Very often they occur in sets of 3 rifts starting from a common point and spreading out at about 120° between each other. These structures have been called 'aulacogenes' (Burke and Wilson, 1976). They have been interpreted as the evolution of a former doming of the Earth's crust. An extensive catalogue of them has been prepared by Burke (1977).

2.7. VOLCANIC AREAS

We have found at least five different types of volcanism reported in the literature. It should be stressed, however, that this discipline appears to be still rapidly evolving, so that this scheme may not be accepted by all volcanologists. Some authors favour an explanation of several phenomena related to volcanism in terms of some hydrothermal cycle in the crust, rather than in terms of phenomena related to tectonic processes. An important point to be stressed is that it would be illogical to attempt to compare the conductivity structure of the crust in two volcanic areas where the volcanism has different origins.

In general, highly conductive layers occur underneath volcanic areas at a very shallow depth (a few kilometers to, at most, 25 km deep).

2.7.1. Andean or Cordilleran

This is the volcanism that arises whenever two plates are colliding, as in the Andes. This case was dealt with in Section 2.5.

2.7.2. *Island Arcs*

Island arcs are one of the best investigated and mapped structures of the Earth's crust. See, e.g., Talwani and Pitman (1977). The interested reader should refer, for fixing the relative nomenclature, to Figure 7 of Green (1977), reproduced from Karig (1971), and to Figure 1 of Dickinson (1973).

From the e.m. viewpoint, Japan has been the most investigated island arc. However, it is rather atypical for two reasons: first it has a considerable transverse cross-section (unlike typical island arcs that are formed by a sequence of small islands, often apparently equally spaced, and regularly aligned along a circle); and second, it is associated with the subduction of two oceanic plates, the Pacific plate northward of the Sagami trough (running approximately east-west slightly south of Tokyo), and the Philippine Sea plate south of it. Moreover, these two plates are subducting with different directions of tectonic movement. The literature is very large, but it is worthwhile to show in Figure 12 a result of Yoshimatsu (1964), suggestive that at Kanoya the skin depth is such that a highly conductive layer is reached by all geomagnetic field variations having a period $T \gtrsim 10$ min.

This figure, redrawn after Yoshimatsu (1964), can be tentatively interpreted as suggesting that e.m. signals with periods 10 min $\lesssim T \lesssim 200$ min penetrate down to a layer of such large conductivity that their skin depths are practically independent of T. Differently stated, e.m. signals of $T \sim 10$ min reach such a good conducting layer that even signals with $T \lesssim 200$ min also do not appear to penetrate it significantly. An alternative interpretation would be that deeper and deeper layers are parallel.

Accepting the validity of this first interpretation, we can tentatively suppose that

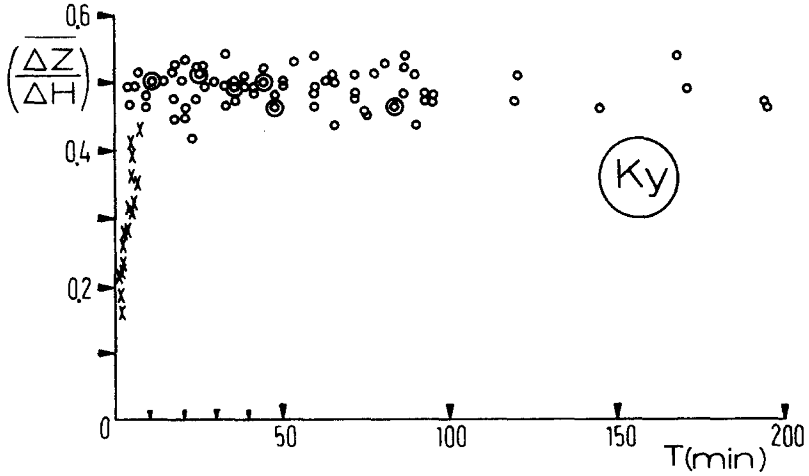


Fig. 12. For T longer than a few minutes, each plotted point refers to a bay-like magnetic variation event (T being the total time duration of the bay), the ordinate being the ratio $\Delta Z/\Delta H$ where ΔZ is the total range spanned during the bay by the Z component (i.e., vertical, positive downward), and ΔH is the analogous value for the H component (i.e. horizontal, positive northward). For T shorter than a few minutes, pc 3 (T~15–30 s) and pi 2 (T~35–90 s) events have been used by considering $\Delta\dot{Z}/\Delta\dot{X}$, which are evaluated by considering the peak to peak amplitudes. The recording station is Kanoya, in southern Japan.

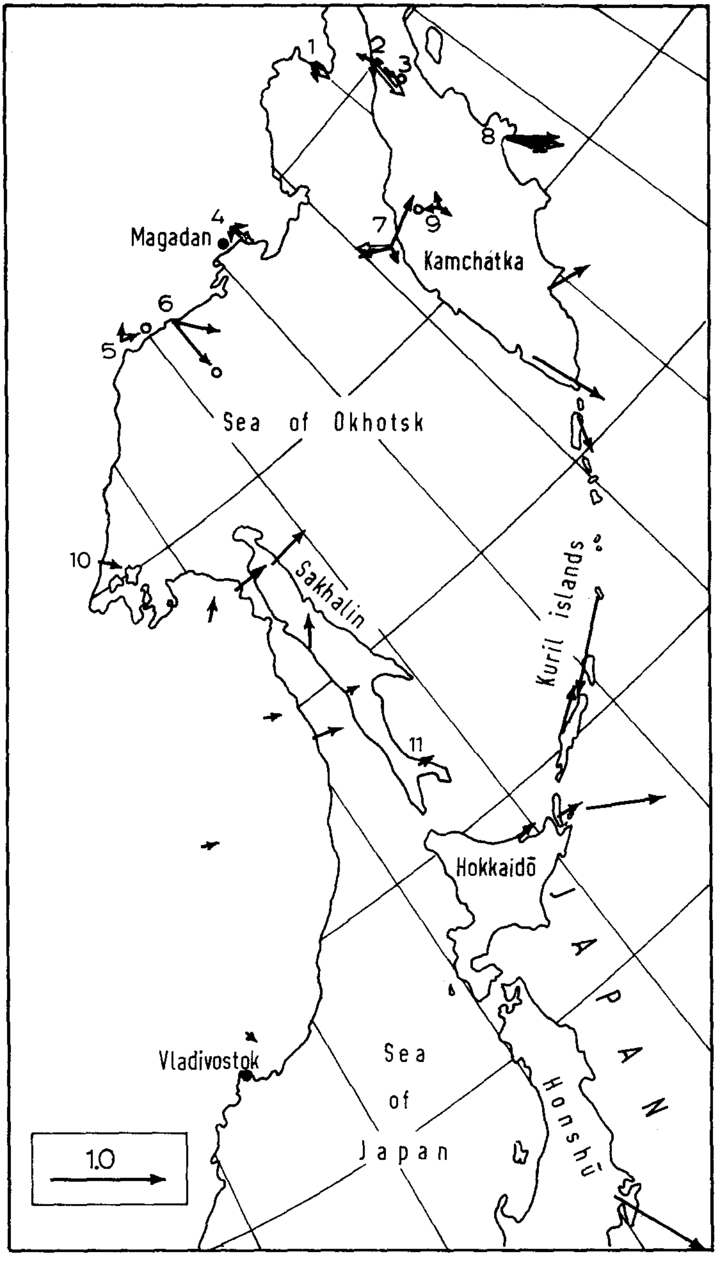


Fig. 13. Wiese vectors in the area encircling the sea of Okhotsk. Map redrawn after Vnuchkova and Vnuchkov (1971). At 10 sites the Wiese vector has been computed several times, by selecting different sets of bay-like events, depending upon the sign of ΔH, ΔD, and ΔZ (symbols as defined in the caption of Figure 12, D being horizontal, positive eastward). The average Weise vector, computed from all the available events is drawn as an open arrow or, when the average vector coincides with one of the individual vectors, as an open circle in front of the coincident solid vector.

such a highly conducting layer is the asthenosphere. Using the expression for the skin depth of penetration of an e.m. signal of period T within a medium of uniform conductiviy σ we find for T = 10 min, and s = 80 km, σ = 0.024 Mhos m^{-1}, and for s = 100 km, σ = 0.015 Mhos m^{-1} (for $T \sim$ 20 min, the preceding values of σ will be just doubled). Such values for σ are consistent with the structure proposed by Yanagihara (1965) for Kakioka (σ = 0.1 underneath 30 km depth), with the highly conducting layer suggested by Kuboki and Oshima (1966a, b) at about 30 to 100 km depth in the Kanto district, north-east of Tokyo (for 10 s $\lesssim T \lesssim$ several hours), with the sea bed estimates (σ = 0.06 or 0.022) in Japan by Teramoto (1971), with the value σ = 0.01 given by Honkura (1974, 1975) down to ~80 km in central Japan (10 min $\lesssim T \lesssim$ 2 hours), with the value $\sigma > 0.1$ underneath 30 km suggested by Yanagihara and Nagano (1976) for central Japan. Hence, the interpretation of the data of this figure is consistent with the available literature and suggests that e.m. signals of period $T \gtrsim$ 10 min induce telluric currents flowing within the asthenosphere beneath the Japan area.

Concerning other island arcs, we mention Hamilton (1979) for a recent preliminary investigation in the Scotia arc. Finally, Figure 13, redrawn after Vnuchkova and Vnuchkov (1971), refers to the Kurile island arc: notice the remarkable reversal of the induction arrow (for bay-like events) between the islands of Iturup and Urup. For induction vectors in Hokkaido island, see Mori (1975).

2.7.3. *Hot Spots*

These are generally conceived as 'pipes to deep mantle' (Morgan, 1971), and envisaged as being something like a fixed frame of reference for all solid Earth geophysics. Their relative motion has been reported to be of 0.5–2 cm yr^{-1} (e.g. Burke *et al.*, 1973; Chase *et al.*, 1975; Bonatti *et al.*, 1977). It is remarkable that McDougal (1971) has reported a speed of ~15 cm yr^{-1} (with a scatter between 9.6 and 17.0 cm yr^{-1}) of the Pacific floor with respect to the Hawaiian hot spot.

The Hawaiian hot spot is perhaps the most typical and most investigated hot spot (Larsen, 1975; Hermance *et al.*, 1978). The e.m. induction features should obviously be quite different from other types of volcanos.

A mention should be made of the investigation by Bonatti *et al.* (1977) on a volcanic chain extending both eastward and westward of Easter Island. They envisage the existence of a 'mantle hot line', extending from Pitcairn Island through Sala y Gomez, San Ambrosio, and San Felix islands, and perhaps extending even inside the South American continent (Ojos del Salado lineament). Aldrich *et al.* (1978) have attempted to investigate by e.m. induction methods whether there is any singular behaviour at the point of crossing of the Andean coast with such a supposed 'mantle hot line'. They did not find anything noteworthy and different with respect to what occurs in other sections of the western coast of South America.

2.7.4. *Oceanic Volcanos*

There are several other volcanic islands that do not behave like hot spots. Their growth rate is much slower, they appear to start close to mid-oceanic ridges, they move down, slowly, on the gentle slope outward from their parent ridge. Occasionally, they appear to be overriding some mantle uplifts. Thus, it happens that they can be occasionally above water level, occasionally underneath it. In these cases, they appear like flat-topped submarine pyramidal mountains (named 'guyots'). (Such mountains appear, however, very similar to the flat-topped, pyramidal mountains that are very frequent features of the landscape of Eritraea, on the borders of the Danakil depression, where they are called 'amba' in old Ge'ez, the old classical Ethiopic language.) Refer for information on such oceanic volcanos to Menard (1969a; 1969b; 1973) and Menard and Dorman, (1977).

Such volcanos should have a much shallower 'root' than hot-spot volcanos, and should behave accordingly from the e.m. viewpoint. However, there appear to be no reported e.m. investigations on islands that are generally believed to be of this type. Perhaps the best candidates are the islands of Oshima, of Miyake-jima, and of Hacijo-jima, located off the Japan coast, slightly south of Tokyo. Magma may be 'squeezed' up within them a few years prior to a strong earthquake in Japan, thus possibly envisaging that there is some internal pressure effect propagating westward (Kimura, 1976). Also, the reported variation of the distance of the Oshima island from the Japanese mainland (by relevant amounts occurring presumably at the time of a strong earthquake) would indicate that the island is not deeply rooted. E.m. induction investigations in these islands have been carried out on by Honkura (1973, 1974) and by Honkura *et al.* (1974).

2.7.5. *Mid-oceanic Ridges*

Mid-oceanic ridges span a wide network all over the globe, and possibly they extend even where it was formerly believed that there is just a simple fracture zone (Handschumacher, 1976). These ridges are here considered to be a class of volcanism because they are associated with a slow, but large, outflow of material from underground. All investigations on Iceland should be included in this class. Iceland, however, is rather anomalous, being a spot where the upwelling ridge branches into a wide transverse cross-section.

One should also properly refer to some more typical ridge segments. A very recent investigation has been reported by the RISE Project Group (1980). They estimate a conductivity of 0.004 Mhos m^{-1} for the ocean bottom, close to the Easth Pacific Rise (offshore Baja California). This should refer to an actual skin depth of ~8 km underneath (frequency ~1 Hz). Direct drilling had given 0.03 Mhos m^{-1}: this fact suggests that the upper layers are much more conductive than the average crust underneath, because of the role of water penetrating within cracks and fractures.

We want here to treat a mid-oceanic ridge as a natural elongated, conductive structure, something like a natural submarine 'telephone cable'. The first problem is to evaluate the structure's geometrical cross-section; the second, its conductivity.

A ridge cannot be likened to a mountain chain overlying a plain. In fact, ocean bathymetric profiles generally show a gentle slope on the flanks of a ridge (see, e.g., Vogt *et al.*, 1969; Riecker, 1979, p. 24). This trend is now well recognized in a vast literature as being the result of lithospheric cooling, differentiated vs age. A current debate is concerned with the existence, or not, of a 'magma chamber' underneath a ridge (Menard, 1969a; Nisbet and Fowler, 1978, and references therein). We will assume that the cross-section is as computed by Kusznir (1980), who modelled mathematically the thermal evolution of the oceanic crust spreading out from a ridge. He considered two typical spreading rates: 1 cm yr^{-1} for the Atlantic ridge and 6 cm yr^{-1} for the Pacific ridge. The result is a rhomboidal cross-section (see Table I).

The conductivity, as well as the depth of the layer overlaying the rhomboidal magma chamber, have been evaluated by scanning the literature on volcanic areas, Iceland, rift zones and ocean floors (see also Section 2.8). The figures quoted in Table I are certainly nonprecise, but should be indicative of the orders of magnitude. Notice that the mid-Atlantic ridge is roughly equivalent to $\sim 10^3$ standard submarine telephone cables, and the mid-Pacific ridge to $\sim 10^4$. Notice also that the existence of such an elongated 'magma chamber' could probably be most easily and convincingly evidenced by correlating geomagnetic recordings performed simultaneously on oceanic islands located close to the same mid-oceanic ridge, but very far from each other.

2.8. OCEAN FLOOR

The published results appear somewhat conflicting with one other. The shallow (down to 8 km beneath the ocean bottom) structure close to the East Pacific Rise has already been mentioned in Section 2.7.5.

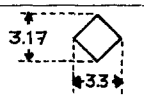
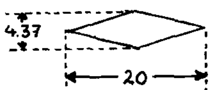
The north western Atlantic has a conductivity of 0.05–0.14 $S\,m^{-1}$ down to 100 km and 0.5 $S\,m^{-1}$ underneath (Poehls and Von Herzen, 1976).

The northeastern Pacific ocean has a conductivity of 0.3–0.4 $S\,m^{-1}$ between 15 and 35 km (Cox *et al.*, 1970).

For the Pacific, 450 nautical miles NNE of Hawaii, Filloux (1977) estimates 0.004

TABLE I

The 'magma chamber' of mid-oceanic ridges

Geographical location	Cross-section: shape (distances in km)	Cross-section: area (km^2)	Estimated depth of the upper side (km)	Conductivity (Mhos m^{-1})	Conductance per unit length (Mhos m)	Resistance per unit length ($\Omega\,m^{-1}$)
Atlantic ridge		5.25	$\lesssim$10–25[a]	0.1 – 0.3	0.5 – 1.6 10^6	0.6 – 1.9 10^{-6}
Pacific ridge		43.7	$\lesssim$10–25[a]	0.1 – 0.3	0.44 – 1.3 10^7	0.8 – 2.3 10^{-7}

[a] Macdonald and Luyendyk (1981) infer, by several different methods, this depth to be only a very few kilometers underneath the East Pacific Rise.

$S\ m^{-1}$ (maximum 0.01 $S\ m^{-1}$) down to 60 km, then 0.06 $S\ m^{-1}$ at 180 (± 40) km, then 0.3 $S\ m^{-1}$ at 500 km.

Off the California coast, Greenhouse (1972) estimates 0.014–0.1 $S\ m^{-1}$ beneath 20 to 30 km. Marderfel'd *et al.* (1970) and Trofimov (1975) estimate an abrupt increase to 5.3 $S\ m^{-1}$ at 120 km depth, while Van'yan *et al.* (1976) state the existence of a well conducting layer (0.3–0.5 $S\ m^{-1}$) at 70–170 km.

Such large differences could well be the product of different inversion techniques. However, they might also be a function of distance from the parent spreading ridge, associated with different lithospheric cooling vs age (similarly to bathymetry, see above).

3. Conclusion

Drawing any definite conclusions seems to us to be still premature, or largely arbitrary and speculative. First, the Earth's crust varies from site to site. Second, the definition of the Moho is based on seismological evidence; the definition from e.m. information of a similar surface that can be approximately likened to the Moho remains quite uncertain. Third, the presently available methods of investigation of the conductivity structure rely on such approximations and indeterminacies that disparate results can still be found from different authors using different methods in the same or in analogous geographical areas.

This review was prepared after scanning all the literature available to us, which we believe is a large fraction of the existing literature. We have attempted to evaluate, as far as possible, all the evidence and partial conclusions. We have searched for some methodological standardizing procedure for such a critical reevaluation, as we have briefly explained in Section 1. We have become progressively aware of the strict necessity for interpreting any e.m. induction investigation only within the framework of the more general geophysical, tectonic, geological and geothermal understanding of the area under investigation. Hence, we have proposed in Section 2 a tentative work scheme for such a purpose.

Some conclusions can be reliably drawn, but only when making reference to areas with clear geomorphological and tectonic characterization. Hence, the interested reader should refer to the specific subheading corresponding to a specific interest.

From a more general, i.e. 'planetary' viewpoint, continental shields, platforms and cratonic areas appear underlain by a thick low-conductivity layer. Whenever some tectonic process is (or has been) active, an apparent upwelling of conductive layers is observed. Such high-conductivity layers appear to occur at several hundred kilometers depth underneath continental shields, rising to ~100 km underneath tectonically perturbed continental areas, to a few to several tens of kilometers beneath rifts and grabens, to a few tens kilometers, and maybe even to a few or several kilometers, underneath some volcanic areas.

Essentially nothing can be learned about what happens underneath such a conducting layer because, as it is well known, the inversion problem has even larger errors whenever one attempts to evaluate the conductivity of a layer overlain by a more conductive one. One should use for this purpose much longer period variations (say longer than several hours) for probing the mantle, but this is not of concern here.

For the sake of completeness, we want also to mention a general electric structure as a global overall pattern of the Earth, in terms of four typical layers as proposed by Hermance (1979): (i) conducting sediments and/or oceans, variation period 0.1 to 100 s, penetration down to 5 km, conductivity 0.2–5 $S\ m^{-1}$; (ii) resistive crust, 100–1000 s period, penetration to 30–40 km, 0.0001 $S\ m^{-1}$; (iii) less-resistive mantle, 100–10000 s period, penetration to 400 km, 0.01–0.05 $S\ m^{-1}$; (iv) conducting mantle, periods 100 s to 27 days, penetration 400 to 1200 km, 1–10 $S\ m^{-1}$.

Other experts in the field claim that a conductive layer of ~0.1 $S\ m^{-1}$ should be considered as a typical feature at the base of the crust. In the literature one finds several papers mentioning a conductive layer of ~0.1 $S\ m^{-1}$ at some intermediate depth (depending on site). However, quite a few other investigations do not find it. Our overall impression is that considerable confusion presently exists on this point.

We can neither confirm nor refute any of the published conclusions noted above. Those conclusions are the results of specific critical evaluations by each author on the basis of his own experience, as well as on the area of investigation. It may not even be possible in the end to give any general or greatly simplified organization scheme. While the disparate results could be due to the lack of a properly standardized methodology, they could also reflect real geophysical differences. It is premature to decide at present from the published works.

The conductivity in the crust appears controlled by hydration and by the geothermal field (in addition to geochemical composition). Generally, an uppermost hydrated layer appears more conductive than the underlying 'insulating' dry layer, which in turn overlays deeper layers where the increasing temperature, associated with a possible partial melting, produces a substantial increase in conductivity.

In this respect, we should mention the possibility suggested in the past, of using for communications the natural wave guide existing in the crust (i.e., comprised between the conductive uppermost layer and the mantle underneath; Heacock, 1971; Levin, 1964, 1971; Wait, 1971; Wait and Spies, 1971, 1972; see also Berdichevskiy *et al.*, 1972). In the same spirit, one could perhaps think in terms of the use of the magma chamber, possibly underlying all the mid-oceanic ridges, as an extended natural network of huge submarine 'telephone' cables.

These conclusions, however, as well as an appropriate implementation of e.m. induction data within the general understanding of solid Earth geophysics, require first a better definition and agreement on some standard analysis methods. We believe, nevertheless, that e.m. induction methods can provide some basic and important information on the Earth's crust and lithosphere that other methods can not; therefore, e.m. methods provide an important additional data source for arriving at geophysical conclusions.

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