Geophys. J. R. astr. Soc. (1987), **89**, 7-18

MT and reflection: an essential combination

Alan G. Jones, *Lithospheric Geophysics, Geological Survey of Canada, 1 Observatory Crescent, Ottawa, Ontario, Canada, KIA OY3*

Summary. At many localities in the world there have been coincident comprehensive electromagnetic (EM) studies and seismic reflection profiles conducted. Unfortunately, over many more regions the seismic reflection images are interpreted without the constraints afforded by electrical conductivity information. This paper is an attempt to convince the reader that a collocated magnetotelluric (MT) study should, in almost every case, be made wherever a seismic reflection survey is undertaken. Examples are shown from six studies in which the EM results aided the geological/tectonic interpretations of the seismic sections.

Also, difficulties with the MT technique are discussed, and the interpretations of conducting zones within the lower crust are examined. Finally, a generalised model is proposed for the continental crust that may account for both the reflectivity and conductivity of the zone at the top of the lower crust.

1. Introduction

Knowledge of the structure of the continental lithosphere has increased substantially during the past decade with the advent of various national programmes of seismic reflection profiling. However, the very causes of the observed deep crustal reflections are, in general, unknown, although progress appears to have been made in excluding certain currently popular but possibly controversial hypotheses to explain the reflectivity (Klemperer *et al.*, this issue). Accordingly, one can perhaps argue that seismic "imaging", whilst being a powerful geological mapping tool, has not resulted in a significantly improved understanding of the nature and composition of the middle to lower continental crust. In order to make advances in these areas it is genenerally recognised that other geophysical information needs to be included in the interpretation, rather than considering the seismic reflection and geological information *in vacuo*.

Determination of coincident electrical conductivity structure, by electromagnetic (EM) means, provides powerful constraints on the interpretation of the deep reflecting horizons. Although EM responses represent an integration of the electrical conductivity structure from the surface down to the depth of maximum eddy current flow, and are thus analagous to surface wave studies, it must be recalled that conductivity can vary over seven orders of magnitude in the continental crust (10^{-1} - 10^{6} Ωm, Haak & Hutton 1986) whereas seismic parameters vary by less than an order of magnitude. This facet ensures that EM methods have a remarkable lateral resolution compared to other geophysical methods that determine an integrated response of the earth, and as a general rule-of-thumb one should think of the magnetotelluric (MT) technique as having a vertical resolution equivalent to the seismic refraction method, but a lateral resolution comparable to that of the seismic reflection method (see Fig. 1).

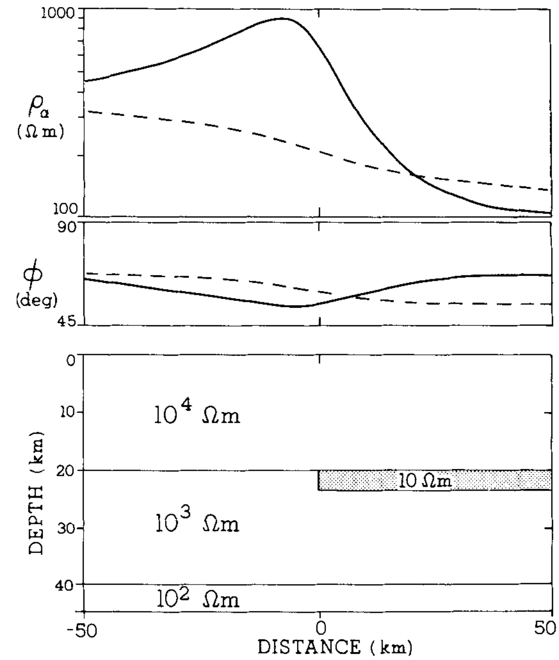

Figure 1. Theoretical MT responses at a period of 100 s to the *2D* model shown. Full lines are for the B-polarization mode of induction (i.e. current flowing across the model), and dashed lines are for the E-polarization mode (current flowing along the model). Note the sensitivity of the B-polarization responses to the edge of the lower crustal conducting zone.

Of the currently available EM techniques suitable for probing the middle and lower crust, MT offers the most advantages in terms of resolution, sophistication of interpretation, and ease of logistics. Geomagnetic depth sounding (GDS) interpretations are notorious for their lack of resolution and non-uniqueness, and controlled-source studies are both horrendous in their logistics and are currently simplistic (lD) in their interpretation.

Two difficulties beset MT data interpretation: resolution of vertical structure and "static-shift" of the apparent resistivity response curves. Space limitations do not permit a full discussion of the resolution inherent in MT data, this will appear elsewhere, but the essential points to make are:

(i) to discriminate between a single-layer lower crust and a two- or multi-layer lower crust requires highly precise response functions (standard errors < 1%), particularly in the so-called MT "dead-band" of 0.1 - 10 s periodicity (Fig. 2) where natural signal levels are low and noise levels high.

(ii) detection of a conducting zone beneath another conducting zone is extremely difficult in lD, and only possible in 2D for highly precise response functions at a sufficient number of sites.

"Static-shift" is an effect akin to statics in reflection seismology whereby local small-scale lateral inhomogeneities cause a DC-like shift of the apparent resistivity values by the same multiplicative factor at all periods. Thus, on a log-ordinate scale the apparent resistivity curve is moved uniformly up or down, but the phase lead of the electric field over the magnetic field is unaffected (Fig. 3). The resulting lD interpretation of the resistivity and phase responses will have the correct structural shape, but the depths and resistivities of the layers will be in error (Fig. 3). Much progress has been made in the past few years at recognising the very existence of this problem, and of attempting to find solutions to it

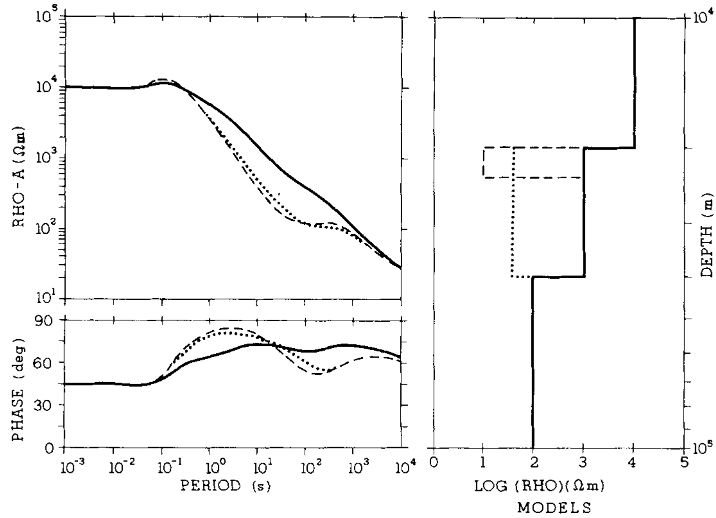

Figure 2. Theoretical MT responses to the three 1*D* models illustrated (with a 10 Ωm half-space at 100 km depth to represent the asthenosphere). Full lines are for the "reference" earth. Dashed lines are for the reference earth with the inclusion of a conducting zone at the top of the lower crust as an EM equivalent to the often observed suite of sub-horizontal reflections between typically 6.0 - 6.5 s TWT. Dotted lines are for a single-layer lower crust. Note that in order to discriminate between a single-layer moderately conducting lower crust and a two-layer lower crust, consisting of a highly conducting layer over a resistive one, it is necessary to obtain highly precise response functions.

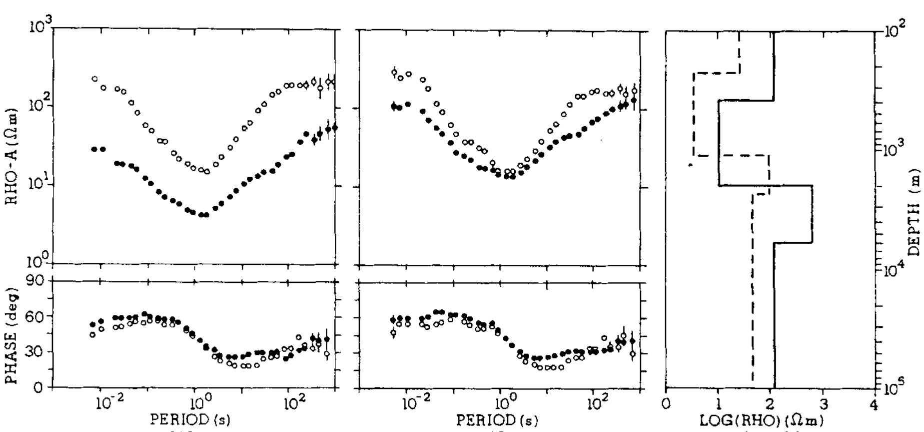

Figure 3. ρ_{xy} & ϕ_{xy} (open symbols) and ρ_{yx} & ϕ_{yx} (solid symbols) MT responses observed at two locations, 019 and *R*19, 200 m apart. The error bars represent 68% confidence intervals, where not plotted these intervals are smaller than the symbol. The phase information implies a 1*D* earth to a period of 1 s. Note the dramatic difference in the level of the two ρ_{yx} curves caused by static-shift. A 1*D* inversion of the two ρ_{yx} curves gives two models that are displaced in log-parameter model space (right-hand side). The solid line is the correct model, as derived from site *R*19's ρ_{yx} data, whereas the dashed line is an erroneous model determined from site 019's *yx* data.

(e.g. Jones 1987). If independent information can be used to constrain one of the model parameters then the phase response alone can be inverted to give the true model (Green *et al.*, this issue).

An attempt was made previously at correlating conductivity and seismic parameters, determined from refraction studies, for the lower continental crust (Jones 1981) and the combined observations fell into three classes of response. However, given the much higher resolution of reflection studies, and that there are now quite a few localities from which seismic reflection images and electrical conductivity models are available we are now in a position to assess the contribution that conductivity information has made to seismic and/or geological interpretations. I will consider EM and reflection data from six localities, chosen on their merits of quality and general acceptance of the results, and will give a brief summary of each. Finally, I will conclude with some general remarks concerning high conductivity layers in the continental lower crust, and present a possible general model for the continental crust.

2. EM and reflection data

2.1 VANCOUVER ISLAND

Green *et al.*, (this issue) descibe the remarkable correlation of the depth to the top of an electrically conducting zone with the depth to the top of the so-named "E-reflector" (Green *et al.* 1986), a zone of reflectors that is believed to lie near the top of the modern descending Juan de Fuca plate (Fig. 2 of Green *et al.*, this issue). Given the probable environmental conditions believed to exist in this zone, its interpreted electrical conductivity is consistent with trapped saline fluids in a rock matrix of porosity 1.6 - 3.6% (Kurtz *et al.* 1986). Thus, the notion of trapped sediments not being totally scraped off at the accretionary wedge, but also being subducted is possibly re-inforced by the MT interpretation. Also of importance is that the "C-reflector" appears to have no EM counterpart, and thus the reflectivity cannot be associated with fluids in interconnected pores in the same manner as for the E-reflector.

The other potentially major contribution made by MT is the indication (Fig. 2 of Green *et al.*, this issue) that the conducting zone associated with the E-reflector continues further eastwards of the point where the E-reflector appears to die out. Is this latter effect due to lack of penetration of the seismic energy to these depths, is it caused by absorption and scattering by the more inhomogeneous material between the faults, or is it due to a "knee-bend" in the plate such that the steeper dip cannot be seismically imaged? The MT results appear to favour the last explanation.

It is conceivable that the interpreted conducting zone is, in fact, the EM equivalent to the C-reflector which is erroneously located in depth due to static-shift of the MT responses, and that the underlying conducting layer equivalent to the E-reflector is not resolved. However, this would require the same static shift factor on the six responses from three widely differing locations, and such a coincidence in nature is improbable.

2.2 SILJAN RING

The Siljan Ring meteoritic impact structure in Sweden has been the subject of intense and diverse geophysical studies during the last two years in connection with Gold's mantle methane hypothesis. Seismic results (L.B. Pedersen, pers. comm. 1986) show a series of shallow reflectors (1-2 km) that deepen (2-3 km) towards the centre of the crater, and a deeper reflector which shallows from $\approx$ 9 km on its flanks to $\approx$ 6 km in its centre. The deeper reflector is interpreted as a pre-impact feature which was uplifted by some 3 km in the cratering process. MT results show a remarkable correlation with this lower reflector, with a conducting layer rising from about 10 km to about 5 km in the centre.

Recent drilling to these upper reflectors has shown that they are due to dolerite intrusives, which must be "dry" or they would also be electromagnetically imaged. In contrast, Pedersen believes that the deeper reflectors and associated conducting zone are due to "wet" fractures.

2.3 RHENISH MASSIF

Seismic investigations in the Rhenish Massif (Meissner *et al.* 1983) show strong Conrad (20 km) and Moho (30 km) events, with a low velocity zone between them. On the reflection profile, the Hunsrück fault is clearly imaged, as is the top of the Variscan front at its outcrop along the Aachen thrust fault.

The extensive MT study of Jödicke *et al.* (1983) inferred "thin" conducting layers at depths equivalent to the Conrad discontinuity, and no lower crustal conducting zone. Also very apparent in the responses was a dramatic change across the Hunsrück fault, with the conducting zone at a depth of ≈ 8 km south of it, and 18-20 km north of it (Fig. 4a).

Xenolith studies in the eastern Eifel and the northern Hessian depression apparently preclude the presence of large amounts of free water or high-conductive minerals in the middle and lower crust as an explanation of the conducting layers, and the correspondence between the seismic and MT results led Giese *et al.* (1983) to infer that these layers are well-foliated mica shists and/or augengneisses in deep-reaching shear zones. This interpretation supports a model of thin-skinned tectonics with crust stacking along the shear zones.

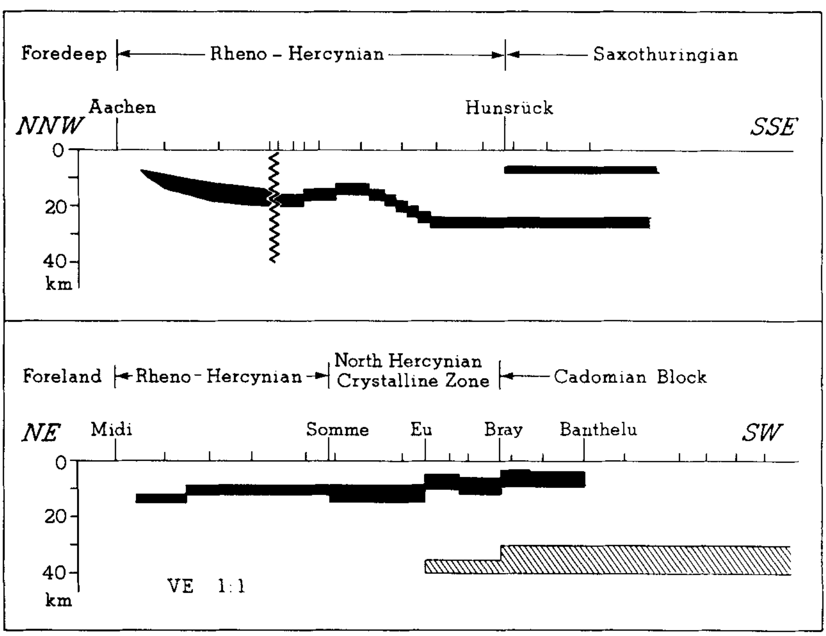

Figure 4a. The 2*D* model presented by Jödicke *et al.* (1983), supplemented to the NNW by 1D inversions from sites along strike, across the Rhenish Massif. **Figure 4b.** The 2*D* model presented by Cazes *et al.* (1986) across the equivalent major tectonic units beneath the Paris Basin. The solid layers are of high conductivity (0.1 S/m) whereas the shaded zone is of moderate conductivity (0.0025 S/m). The site locations are indicated by ticks along the surface, and major faults are shown and named.

Two points are worthy of note here.

(i) Although the shear zones can be mapped to their surface expression by the seismic reflection data, the conducting layers do not correspondingly rise to the surface.

(ii) Interpretation of the continuation of the mid-crustal conductor across the Hunsrück fault is questionable (Fig 4a), given the presence of the upper conducting layer.

2.4 NORTHERN FRANCE

The tectonic setting of the northern France ECORS profile is similar to that of the Rhenish Massif in crossing the Rheno-Hercynian zone and the Variscan front. Essentially, the seismic and MT results (Bois *et al.* 1986; Cazes *et al.* 1985, 1986) are similar to those obtained across the Rhenish Massif with both seismic and EM imaging of the Variscan front (Fig. 4b). Again, however, the top of the seismic reflections associated with the Variscan front rises to the surface at the Faille du Midi (Aachen fault), but the interpretation of the MT results appear to indicate that the associated high conductivity layer does not approach the surface (Fig. 4b). Also, there is a variation in the depth to the crustal conducting zone on either side of the Faille d'Eu, which may be the Hunsrück fault (see Fig. 1 of Cazes *et al.* 1985). Given the discussion of resolution in the Introduction, the 10 km thick moderately resistive zone of 400 Ωm (conductivity-thickness product of 25 S) beneath the Cadomian Block could in fact be a 1 km thick zone of 40 Ωm.

2.5 ADIRONDACKS

EM results (controlled-source EM, Connerney *et al.* 1980; horizontal spatial gradient, equivalent to MT, (Connerney & Kuckes 1980) in the Adirondacks have been interpreted to show the presence of a lower crustal conducting layer beginning at a depth of around 20 km and of conductance (thickness x conductivity, which is usually a well-resolved parameter, (see, e.g., Ilkisik & Jones 1984) ≈ 500 Siemens. COCORP profiling (Klemperer *et al.* 1985) shows a reflective zone (Tahawus complex) between 18 and 26 km. Various candidates which would be acceptable to both observations were suggested by Klemperer *et al.* (1985), including the presence of fluids, and igneous, gneissic or metasedimentary/metavolcanic layering.

An 8 km thick zone of 500 S implies a resistivity of 16 Ωm, which is consistent with a porosity of the order of 2%. Unfortunately, the EM data are of rather poor quality (phase error > 5°) and accordingly a detailed comparison and joint interpretation leaves a large margin for speculation. Certainly, the results are intriguing enough that a high-resolution wide-band MT survey should be undertaken in the Adirondacks.

2.6 SOUTHERN SCOTLAND

Recent 1D interpretations of responses from three long-period MT sites in southern Scotland by Beamish & Smythe (1986) were shown to be consistent with a conducting layer parallel to and beginning at the same depth as a north-west dipping reflection horizon seen on the BIRPS WINCH-2E line. This was interpreted as being the seismic and EM expression of the Iapetus suture.

However, the current interpretations of Hutton (pers. comm. 1986; see also Ingham & Hutton 1982, and references therein) indicate that this conducting layer is closest to the surface beneath the Northumberland Basin, and not only dips NW, in agreement with Beamish & Smythe, but also dips to the SE. This latter feature is also apparent as a

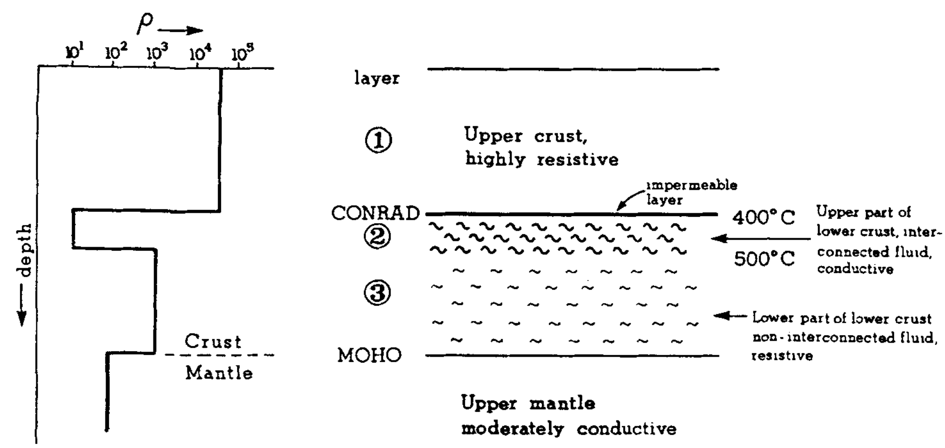

Figure 5. Schematic diagram of the proposed general model of the continental crust with a resistive upper crust underlain by a two-layer lower crust. The two are divided by an impermeable zone at a temperature of the order of 400°C. The top part of the lower crust contains interconnected free water, and thus is an electrically conducting zone which may also be responsible for both the "Conrad' discontinuity and the often observed suite of sub-horizontal reflections between typically 6.0 - 6.5 s TWT.

reflecting horizon on the migrated depth section from WINCH-2E (see Fig. 6 of Beamish & Smythe 1986). Thus, the appropriate tectonic model for the closing of the Iapetus ocean may not be a simple single dipping suture zone, but may in fact be closer to the model proposed by Phillips *et al.* (1976) of two Benioff zones during the Llandeilo-lower Caradoc (450 MYa).

This particular conducting zone does not explain the well-known 'Eskdalemuir anomaly" in electro-magnetic fields (for example, Edwards *et al.* 1971 and Hutton & Jones 1980). It is apparent that there is another feature in the Southern Uplands of Scotland causing the observed anomalous EM fields, and this feature is in a location where the seismic reflection data (LISPB, Bamford *et al.* 1976) is uninterpretable, and the seismic reflection section exhibits a "transparent" crust.

3. General remarks, lower crustal conductivity, temperature and conclusions

In the six examples discussed above, consideration of the EM results had an important effect on the interpretations of the seismic reflection sections. There are many other areas for which joint seismic and MT datasets are available, e.g., the Rio Grande Rift, the Long Valley Caldera, the Basin and Range Province, and the Georgia Piedmont; and in many of these cases there is a strong correlation between the relevant seismic image and the geoelectric model. However, as discussed above there are certain structures that do not correlate, e.g., the "C-reflector" on Vancouver Island. Accordingly, an identification scheme that might be of use when attempting to interpret zones within the continental crust is one whereby on the seismic image the zone is classed as either transparent or reflective, and from the electrical conductivity model is classed as either resistive or conductive. It is relatively easy to interpret zones that are transparent/resistive, in terms of "normal" continental crystalline rock, and there are a number of candidates for zones that are reflective/conductive, e.g., fluids in inter-connected pores. Obviously, the enigmas are zones that are reflective/resistive, for which mylonites may be one acceptable explanation, or layered intrusives as exhibited at the Siljan Ring, and those that are transparent/conductive, although the latter appears to be relatively rare (Eskdalemuir anomaly). Interpretation of these zones represents the next challenge to both the geomagnetic induction and the seismic reflection communities.

Conducting coincident MT and seismic reflection surveys can have additional benefits. For example, MT data, as mentioned in the Introduction, are highly sensitive to lateral variations in conductivity. In particular, sub-vertical faults, which are not easily detected by standard reflection techniques, are well-resolvable if the faults are fluid-filled or if they juxtapose blocks of differing conductivity (e.g., Poll *et al.* 1987).

It must be emphasised that in order to make rather specific conclusions regarding the lower continental crust from MT studies the data need to be highly precise. I believe that given today's sophisticated MT systems, a standard error of better than 1% is not only obtainable but also should be a requirement. Certainly, differentiating between a moderately conducting single layer lower crust and a two-layer lower crust consisting of a "thin" highly conducting layer over a more resistive one requires responses with errors of this order.

Generally, crustal conducting zones are now interpreted as somewhat "thin" zones of high conductivity rather than "thick" zones of moderate conductivity, e.g., Jödicke *et al.* (Fig. 4a). This may be an expression of the inverse solutions approaching the delta-like D^+ solutions of Parker (1980), which are the best-fitting (i.e., smallest χ^2 misfit) attainable, or it may be that we are now resolving the parameters with greater precision.

The very causes of conducting layers within the continental crust is a source of continued debate, and there have been a variety of explanations including hydrated minerals, serpentinization, carbon, CO_2, partial melt, and free water from dehydration reactions. Recent work by Olhoeft (1981) appears to exclude hydrated minerals per se; it is the effect of released fluid that causes the enhanced conductivity. Also for serpentinized rocks, Stesky & Brace (1973) have shown that the high conductivity is a result of the presence of free water. Carbon may be acceptable under certain circumstances (e.g., Shankland & Ander 1983), but not generally. The nonpolar nature of CO_2 makes it a poor conductor (Kay & Kay 1981), and temperatures of at least 600°C are required for partial melting of "wet" rock (Lambert & Wyllie 1970). Thus, with the exception of somewhat exotic effects such as of metal oxides, the presence of fluids is the principle candidate for explaining zones of enhanced conductivity in the lower crust.

Temperatures less than 400°C are below the critical limit required for the onset of dehydration reactions (Ringwood 1975; Walther & Orville 1982; Spear & Selverstone 1983; Haak & Hutton 1986), and yet above 500°C plasticity of the rocks would seem to ensure that no inter-connectivity of fluid is possible (Brace 1972, 1980; Tullis & Yund 1977). Accordingly, there may be a rather narrow temperature range of 400 - 500°C within which free water becomes available by release from dehydration reactions and which is interconnected. Etheridge *et al.* 1983, (see also Etheridge *et al.* 1984) believe that minerals in the upper part of this zone precipitate out causing an impermeable layer through which the released water cannot pass. Thus, there appears to be an acceptable scenario by which fluids are released, then become trapped beneath an impermeable layer.

This model leads to a three-layer electrical conductivity structure for the "cold" continental crust (Fig. 5);

Layer 1 : the upper crust is "dry", no fluids, and hence resistive (10^4 Ωm),

Layer 2 : the top part of the lower crust at depths where the temperatures are in the range 400 - 500°C contains interconnected free water, generated by dehydration reactions and trapped by an impermeable layer above, which, by Archie's Law, causes a zone of high conductivity (possibly around 10 Ωm), the fluid in this zone may be in "active circulation" according to the schematic model of fluid circulation systems presented by Etheridge *et al.* 1983),

Layer 3: the lower part of the lower crust also contains free water, but this water is not interconnected and exists in isolated pockets with the result that the conductivity of the layer is moderate (perhaps 10^2-10^3 Ωm), also this water does not circulate according to Etheridge *et al.*'s (1983) model.

The indication from a number of studies, particularly Jödicke *et al.* (1983), is that the top of Layer 2 coincides with both the "Conrad" discontinuity and with the top of the often observed suite of sub-horizontal reflections between typically 6.0 - 6.5 s TWT. Accordingly, perhaps at this location the Conrad discontinuity is the seismic expression of the impermeable zone at 400°C.

In an independent investigation of the possible relation between continental heat-flow and the seismic reflectivity of the lower crust, Klemperer (1986) derived an isotherm for the top of the reflective lower crust of 300 to 400°C, with a preferred value of 390°C for western U.S.A. Also Klemperer (pers. comm.) has analysed Adám's (1976) correlation of depths to conducting layers within the crust (h) with surface heat flow (Q) in terms of $Q = \lambda T/h$, where λ is the thermal conductivity of the crust, and has determined from Adám's limited data set that crustal conducting layers are at a temperature of ~ 470°C.

From Lachenbruch & Sass (1977), the depth range for 400-500 °C is 25 - 30 km for their "stable reference crust". However, the Kola hole results, of 180°C at 10-12 km with a gradient of 25°C/km, imply a depth range of 20 - 24 km for temperatures of 400 - 500°C. These depths compare well with the depth to the conducting zone beneath the Adirondacks (approx. 20 km) and with the depth and thickness extent of the reflective Tahawus complex (18 - 26 km).

For the Rhenish Massif, Haenel's (1983) geotherm gives a depth range of 14 - 18.5 km for temperatures in the range 400 - 500°C, and Jödicke *et al.*'s conducting zone is between 14 - 18 km with a reflecting horizon between 15 - 17 km (Fig. 2, Meissner *et al.* 1983).

For Vancouver Island, it is believed that the top of the E-reflector, which correlates well with the top of the conducting zone, represents a 400°C isotherm (Lewis 1986, pers. comm.). Also, the 2D model that satisfies the observed MT responses (Kurtz *et al.* 1986) includes a shallower conductor beneath the B.C. mainland, and it is noteworthy that the geothermal model includes a rapid rise in the isotherms beneath the mainland such that 400°C is at about 15 km depth (Lewis, pers. comm.).

In conclusion therefore, it is without doubt that MT and Reflection are *"an essential combination"*.

Acknowledgements

The author wishes to acknowledge with thanks both the offer to present this review paper and the financial support received from the BIRPS group. He is also indebted to colleagues at the Geological Survey of Canada for many discussions on this most interesting of topics, particularly Dr. Alan Green for his comments on an earlier version of this manuscript. Dr. Simon Klemperer is thanked for a preprint of Klemperer (1987).

Geological Survey of Canada Publication 36886.

References

Adám, A., 1976. Quantitative connections between regional heat flow and the depth of conductive layers in the earth's crust and upper mantle, *Acta Geodaet., Geophys. et Montanist. Acad. Sci. Hung.*, **11**, 503-509.

Bamford, D., Faber, S., Jacob, B., Kaminski, W., Nunn, K., Prodehl, C., Fuchs, K., King, R. & Willmore, P., 1976. A lithosphere seismic profile in Britain. I - Preliminary results, *Geophys. J.R. astr. Soc.*, **44**, 145-160.

Beamish, D. & Smythe, D.K., 1986. Geophysical images of the deep crust: the Iapetus suture, *J. geol. Soc. Lond.*, **143**, 489-497.

Bois, C., Cazes, M., Damotte, B., Galdéano, A., Hirn, A., Mascle, A., Matte, P., Raoult, J.F. & Torreilles, G, 1986. Deep seismic profiling of the crust in northern France: the ECORS project, in *Reflection Seismology: A Global Perspective: Geodynamics Series*, vol. 13, pp. 21-29, eds Barazangi, M. & Brown, L., American Geophysical Union, Washington, DC.

Brace, W.F, 1972. Pore pressure in geophysics, *Am. Geophys. Un. Geophys. Monogr.*, **16**, 181-195.

Brace, W.F., 1980. Permeability of crystalline and argillaceous rocks, *Int. J. Rock Mech. Min. Sci. Geomech. Abstr.*, **17**, 241-251.

Cazes, M., Torreilles, G., Bois, C., Damotte, B., Galdéano, A., Hirn, A., Mascle, A., Matte, P., Van Ngoc, P. & Raoult, J.-F., 1985. Structure de la croûte hercynienne du Nord de la France: premiers résultats du profil ECORS, *Bull. Soc. géol. France*, **8**, 925-941.

Cazes, M., Mascle, A., Torreilles, X., Bois, Ch., Damotte, X., Matte, Ph., Raoult, X., Pham, V.N., Hirn, A. & Galdéano, X., 1986. Large Variscan overthrusts beneath the Paris Basin, *Nature*, **323**, 144-147.

Connerney, J.E.P. & Kuckes, A.F., 1980. Gradient analysis of geomagnetic fluctuations in the Adirondacks, *J. geophys. Res.*, **85**, 2615-2624.

Connerney, J.E.P., Nekut, A. & Kuckes, A.F., 1980. Deep crustal conductivity in the Adirondacks, *J. geophys. Res.*, **85**, 2603-2614

Edwards, R.N., Law, L.K. & White, A., 1971. Geomagnetic variations in the British Isles and their relation to electrical currents in the ocean and shallow seas, *Phil. Trans. R. Soc. London*, **270**, 289-323.

Etheridge, M.A., Wall, V.J. & Vernon, R.H., 1983. The role of the fluid phase during regional metamorphism and deformation, *J. metamorphic Geol.*, **1**, 205-226.

Etheridge, M.A., Wall, V.J., Cox, S.F. & Vernon, R.H., 1984. High fluid pressures during regional metamorphism and deformation: implications for mass transport and deformation mechanisms, *J. geophys. Res.*, **89**, 4344-4358.

Giese, P., Jödicke, B., Prodehl, C. & Weber, K., 1983. The crustal structure of the Hercynian mountain system - a model for crustal thickening by stacking, in *"Intracontinental Fold Belts"*, pp. 405-426, eds Martin, H. & Eder, F.W., Springer-Verlag Berlin, Heidelberg.

Green, A.G., Clowes, R., Yorath, C.J., Spencer, C., Kanasewich, E.R., Brandon, M.T. & Sutherland Brown, A., 1986. Seismic reflection imaging of the subducting Juan de Fuca plate, *Nature*, **319**, 210-213.

Haak, V. & Hutton, V.R.S., 1986. Electrical resistivity in continental lower crust, *J. geol. Soc. Lond.*, (in press).

Haenel, R., 1983. Geothermal investigations in the Rhenish Massif, in *"Plateau Uplift"*, pp. 228-246, ed. Fuchs, K., Springer-Verlag Berlin, Heidelberg.

Hutton, V.R.S. & Jones, A.G., 1980. Magnetovariational and magnetotelluric investigations in S. Scotland, in *"Electromagnetic Induction in the Earth and Moon"*, ed. Schmucker, U., pp. 141-150, AEPS-9 Centr. Acad. Publ. Japan, Tokio & D. Reidel Publ. Co., Dordrecht, Suppl. Issue J. Geomagn. Geoelectr.

Ilkisik, OM. & Jones, A.G., 1984. Statistical evaluation of MT and AMT methods applied to a basalt-covered area in south-eastern Anatolia, Turkey, *Geophys. Prosp.*, **32**, 706-724.

Ingham, M.R., Hutton, V.R.S., 1982. Crustal and upper mantle electrical conductivity structure in southern Scotland, *Geophys. J.R. astr. Soc.*, **68**, 579-594.

Jones, A.G., 1981. On a type classification of lower crustal layers under Precambrian regions, *J. Geophys.*, **49**, 226-233.

Jones, A.G., 1987. The problem of static shift of magnetotelluric data and its removal in a sedimentary basin environment, (submitted to) *Phys. Earth planet. Inter.*

Jödicke, B., Untiedt, J., Olgemann, W., Schulte, L. & Wagenitz, V., 1983. Electrical conductivity structure of the crust and upper mantle beneath the Rhenish Massif, in *"Plateau Uplift"*, pp. 288-302, ed. Fuchs, K., Springer-Verlag Berlin, Heidelberg.

Kay, R.W. & Kay, S.M., 1981. The nature of the lower continental crust: inferences from geophysics, surface geology, and crustal xenoliths, *Rev. Geophys. Space Phys.*, **19**, 271-297.

Klemperer, S., 1987. A relation between continental heat-flow and the seismic reflectivity of the lower crust, *J. Geophys.*, (in press).

Klemperer, S.L., Brown, L., Oliver, J.E., Ando, C.J., Czuchra, B.L. & Kaufman, S, 1985. Some results of COCORP seismic reflection profiling in the Grenville-age Adirondack Mountains, New York State, *Can. J. Earth Sci.*, **22**, 141-153.

Kurtz, R.D., DeLaurier, J.M. & Gupta, J.C., 1986. A magnetotelluric sounding across Vancouver Island sees the subducting Juan de Puca plate, *Nature*, **321**, 596-599.

Lambert, I.B. & Wyllie, P.J., 1970. Melting in the deep crust and upper mantle and the nature of the low velocity layer, *Phys. Earth planet. Inter.*, **3**, 316-322.

Lachenbruch & Sass, 1977. Heat flow in the United States and the thermal regime of the crust, in *"The Earth's Crust"*, ed. Heacock, J.G., Am. Geophys. Monogr. **20**, 626-675

Meissner, R., Springer, M., Murawski, B., Bartelsen, B., Flüh, E.R. & Dürschner, B., 1983. Combined seismic reflection-refraction investigations in the Rhenish Massif and their relation to recent tectonic movements, in *"Plateau Uplift"*, pp. 276-287, ed. Fuchs, K., Springer-Verlag Berlin, Heidelberg.

Olhoeft, G.R., 1981. Electrical properties of granite with implications for the lower crust, *J. geophys. Res.*, **86**, 931-936.

Parker, R.L., 1980. The inverse problem of electromagnetic induction: existence and construction of solutions based on incomplete data, *J. geophys. Res.*, **85**, 4421-4425.

Phillips, W.E.A., Stillman, C.J. & Murphy, T., 1976. A Caledonian plate tectonic model, *J. geol. Soc. Lond.*, **132**, 576-609.

Poll, H.E., Weaver, J.T. & Jones, A.G., 1987. Calculations of voltage differences for magnetotelluric modelling of a region with near-surface inhomogeneities, (submitted to) *Phys. Earth planet. Inter.*

Ringwood, A.E., 1975. *Composition and Petrology of the Earth's Mantle*, McGraw Hill, New York.

Shankland, T.J. & Ander, M.E., 1983. Electrical conductivity, temperatures, and fluids in the lower crust, *J. geophys. Res.*, **88**, 9475-9484.

Spear, F.S. & Selverstone, J., 1983. Water exsolution from quartz: implications for the generation of retrograde metamorphic fluids, *Geology*, **11**, 82-85.

Stesky, R.M. & Brace, W.F., 1973. Electrical conductivity of serpentinized rocks to 6 kilobars, *J. geophys. Res.*, **78**, 7614-7621.

Tullis, J. & Yund, R.A., 1977. Experimental deformation of dry Westerly granite, *J. geophys. Res.*, **82**, 5705-5718.

Walther, J.V. & Orville, Ph.M., 1982. Volatile production and transport in regional metamorphism, *Contrib. Min. Pet.*, **79**, 252-257.