RELATIONS OF ELECTRICAL CONDUCTIVITY TO PHYSICAL CONDITIONS WITHIN THE ASTHENOSPHERE

HARVE S. WAFF
Department of Geology, University of Oregon, Eugene, Oregon 97403, U.S.A.

Abstract. This paper examines the constraint placed by electrical conductivity on physical conditions existing within the mantle. Determination of bulk electrical conductivities of multiphase materials from knowledge of individual phase conductivities and their relative fractions is discussed in the light of recent studies of the equilibrium phase geometries of partial melts. It is concluded that existing models which are based on assumed geometries offer little refinement over Hashin–Shtrikman variational bounds. The possible effects of the gravitational field on phase geometry in partial melts and the resulting conductivity anisotropy are considered. At this time it appears that minimum melt fractions can be safely estimated from a knowledge of Earth conductivity combined with laboratory data on melt and crystalline conductivities and the Hashin–Shtrikman upper bound. The question of whether or not the asthenosphere corresponds to a zone of partial melting is also addressed.

Introduction

A frontier that remains for geophysicists during the next decade is to understand the dynamic processes involved in mantle convection and magma migration. The ability to model realistically the various aspects of these processes is critically dependent on correct specification of boundary conditions and physical properties of the upper mantle. Substantial progress has been made in delineating its composition and mineralogy via petrological and seismological studies. Other important parameters, however, such as oxygen fugacity, volatile content, temperature, and degree of partial melting are considerably less well known. The latter three of these variables are particularly important determinants of fluid and solid motion within the mantle. Most, if not all, dynamic processes directly result from thermal activation and are, therefore, strongly dependent on temperature. Geotherms estimated from petrological studies (c.f. Clark and Ringwood, 1964; Lambert and Wyllie, 1970a, 1970b; Wyllie, 1971; Ringwood, 1969, 1975; Boyd, 1973; Mercier and Carter, 1975) are useful for limiting possible excursions of temperature and melt fraction but lack sufficient precision or means for estimating local temperature variations which are significant in mantle dynamics. The effect of these variations on elastic properties is generally too subtle to be unambiguously separated from other effects present in seismic records. The same difficulty exists with regard to density variations and gravity interpretations. The electrical properties of rocks fall into another class, however. Electrical conductivity is extremely sensitive to temperature in a given material. Earth conductivity profiles derived from geomagnetic variation or magnetotelluric data, combined with knowledge of the electrical properties of mantle materials, represent an important source of additional information about the state and temperature distribution of the mantle. Recently, it has been recognized that electrical methods are potentially the most power-

Geophysical Surveys 4 (1980) 31-41. 0046-5763/80/0041-0031$01.65.

ful tools for addressing the question of whether or not partial melt exists at particular locations within the interior (Shankland and Waff, 1977). The past decade has seen rapid growth in the volume of high quality field data from which conductivity profiles can be derived. The same is true for laboratory data pertaining to the conductivities of the crystalline and liquid phases of the mantle. In addition, numerous techniques for modelling bulk conductivity in multiphase materials are now available in the literature.

It is now a sensible and timely task to assess critically the data and methodology from which evidence for constraints on the physical conditions within the mantle are determined by electrical methods. Specific attention is given here to the following topics: (1) the appropriateness of theoretical models for bulk conductivity in polyphase assemblages likely to be encountered within the mantle, (2) the suitability of conductivity measurements made on materials under laboratory conditions to describe their conductivities within the mantle, (3) the question of discriminating between segregated and associated partially molten phases, (4) the possibility of using electrical conductivity anisotropy as an indicator for thermodynamic stability of partial melts occuring within the mantle, and (5) directions for future work. Attention is also focused on the asthenosphere and in particular whether or not it is partly melted and its possible association with the seismic low velocity zone. The paper is divided into sections on theoretical modelling and phase geometries of partial melts, laboratory measurements on crystalline materials and liquids, and laboratory measurements on partial melts, as depicted in the flow chart of Figure 1.

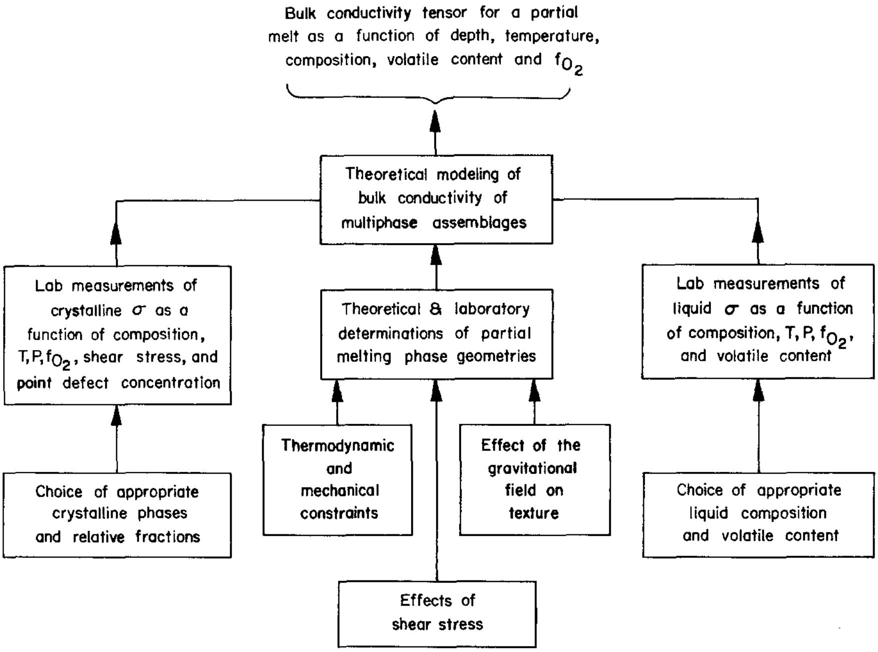

Fig. 1. General flow diagram for determination of bulk electrical conductivity of partial melts existting within the asthenosphere.

Theoretical Modelling and Phase Geometries of Partial Melts

The purpose of modelling in the present context is characterization, with suitable mathematical formalism, of electrical transport in multiphase assemblages so that bulk conduction in real materials existing within the mantle can be sensibly calculated. Bulk conductivity could, in principle, be modelled rather precisely in terms of individual phase conductivities and their relative volume fractions if precise information about the phase geometries were known. Little problem is encountered in modelling conductivity in solid materials (i.e. solid portions of the mantle) in which individual phase conductivities are of approximately the same order of magnitude, as is the case for the major upper mantle silicates (c.f. Duba *et al.*, 1973; Duba *et al.*, 1976; Duba and Nicholls, 1973). Reasonable agreement with experiment is obtained with existing theories of random mixtures such as the effective medium theory of Landauer (1952) or the geometric mean theory (c.f. Madden, 1976). On the other hand, the phase geometry assumes considerably more importance when the conductivity contrasts of the different phases is large, as is the case in partially molten silicates. Until very recently little information applicable to the phase geometries of partial melts in the mantle has come from laboratory petrological studies (cf. O'Hara, 1963a; Scarfe *et al.*, 1972; Arndt, 1977) or xenoliths brought to the surface in magma flows. This primarily results from lack of attainment of textural equilibrium in laboratory specimens. A pressure release melting in xenoliths obscures the primary textures of any partial melt which might have been present in situ. The net result has been that most attempts at theoretical modelling of bulk conductivity have purposefully or accidentally avoided investigations of which aspects of the topology of partial melts are important and which are unimportant determinants of conduction.

Before considering the specifics of phase geometry we shall briefly review the modelling techniques which are most relevant to partial melts. In all such theories, the reasonable assumption is generally made that the individual phases collectively fill space, and that significant potential drops do not occur across phase boundaries in the presence of an electric field. In addition, individual components, whether liquid or crystalline, are usually considered to have isotropic electrical properties and to be homogeneously distributed on a macroscopic scale. Madden's (1976) calculations using systems of embedded networks indicates, for example, that the effects of crystalline conductivity anisotropy will be supressed in an actual three-dimensional polycrystalline material. The assumption of crystalline isotropy is reasonable as regards interpretation of Earth conductivity profiles, even in view of possible stress-induced crystallographic orientational alignment. This is true at least until major additional refinements in the analysis of field data are possible. It also seems reasonable to assume that an approximately constant melt fraction exists over macroscopically large regions of the asthenosphere where evidence exists for partial melting, provided that the melt stays in intimate association with grain boundaries. In the light of recent studies, however, it seems improbable that the phase geometry can also be considered to be constant over extended vertical distances in partial melts which are texturally equilibrated. This possibility and its implications will be discussed later in this section. First we shall consider existing models. They fall into the three following general categories:

(1) *Variational Bounding Methods*

The variational principle is used to calculate absolute upper and lower bounds on bulk conductivity of a multiphase assemblage in terms of single phase conductivities and relative fractions. Individual phases are considered to have isotropic conductivities but no assumptions are made about their geometrical distribution. The tightest bounds theoretically realizable are given by Hashin-Shtrikman (cf. Waff, 1974, for conductivity application). This method is valid and useful for determining conductivity limits on all mixtures regardless of the individual phase conductivity contrasts.

(2) *Calculations Based on Specific, Assumed Geometries*

These models yield bulk conductivity values inside the Hashin-Shtrikman bounds. The extent to which they yield more realistic values than the bounding method is strictly a function of how accurately they reflect the actual phase geometry of assemblages occurring within the mantle. The simplest approach has been to assume a cubic array of grains of one phase, each of identical size, separated by a continuously connected second phase (Chan *et al.*, 1973; Waff, 1974). A somewhat different approach was used by Waff (1974) who determined bulk conduction in a spherical particle assemblage of an infinite number of different-sized composite spheres each containing an inner core of one phase surrounded by an outer shell of a second phase. Honkura (1975) has used yet another geometry, that of spheres of one medium imbedded within a second medium. All of these models yield nearly identical expressions to the upper or lower Hashin-Shtrikman bounds when the fraction of the continuously connecting phase is less than approximately 20 volume percent. Obviously, neither geometry is particularly close to anything expected in solid or partially molten rocks, and thus it can be concluded that they offer only slight improvement in estimating bulk conductivity over the bounding method itself. They do provide, however, some physical notion of the phase geometry requirements needed to realize maximum and minimum possible conductivities within a multiphase material.

(3) *Resistor Networks and Percolation Theory*

In partial melts the degree to which bulk conduction is determined by the liquid or solid phases is strongly a function of the connectedness of the highly conducting liquid phase, at least where mantle silicates are concerned. The models discussed thus far treat a given phase as being either completely connected or completely unconnected. A degree of connectivity intermediate between these two extremes may occur in partially molten rocks with multiple solid phases. This is so because the wetting characteristics of the liquid in contact with different crystalline phases may differ significantly. In this case network and percolation theories applied to random media are directly applicable. These methods are reviewed by Waff (1974) and Shankland and Waff (1974). The essential result, for our purposes, is that conduction will or will not proceed via connected liquid paths depending on whether the fraction of connected liquid bridges (i.e. fluid along edge channels) is less or greater than some critical concentration, P_c. For melt to enhance conductivity the value of P_c must be small enough so that it may be safely concluded that wetting of the grain edges associated with olivine crystals alone in partially molten peridotite will guarantee conduction via interconnected pathways regardless of the wetting characteristics of the volumetrically dominant phases. It is therefore the wetting characteristics of primitive liquids in contact with olivine which are most important in determining high conductivity paths for the upper mantle.

In resistor networks conductivity is modelled by representing each individual conducting channel in real material by a single resistor in a three-dimensional grid. Most network models have used equivalent resistor values on all bridges of the network. However, one would expect to observe a distribution of resistance values of individual liquid channels in a partially molten rock due to the variability of grain size and other aspects of the phase geometry. Madden (1976) has shown, using pseudo-random networks, that no significant variation from geometric mean behavior results when the range of individual resistance values of elements varies by as much as 1000:1. This result is confirmed by application of effective medium theory to resistor networks with a normal distribution of element resistance values (Waff and Shankland, unpublished results). Experimental observation of liquid edge channel dimensions in an ultramafic partial melt closely approaching equilibrium indicates a distribution of individual resistances much too narrow to cause significant variations in bulk conductivity over that of an idealized system with single valued elements, each having the mean conductance of the above distribution. It can, therefore, safely be concluded that variation in individual fluid channel geometry will not, by itself, cause any appreciable lowering of bulk conductivity below the upper Hashin-Shtrikman bound for a partial melt of a given melt fraction under specified thermodynamic conditions, provided that wetting conditions prevail.

PHASE GEOMETRIES OF PARTIAL MELTS

In recent laboratory investigations, Waff and Bulau (1979) succeeded in holding ultramafic partial melts at stable pressure-temperature conditions for sufficient time durations to allow close approach to textural equilibrium. In systems consisting of dunite plus a small fraction of basalt they found that the melt phase is confined to triangular grain edge and corner intersections, forming a continuously interconnected network. All triple junctions were observed to be wetted, regardless of the associated crystalline phases. However, the prism-like edge channels were observed to narrow or 'neck off' near their midpoints. In other words, channel cross-section was not constant. Depending on the degree of necking-off, this will lower bulk conductivity from the Hashin-Shtrikman upper bound. At this time it is difficult to ascertain the magnitude of this effect. Preliminary calculations by this author suggest that it will be small, less than half an order of magnitude. An additional observation in the above experiments was dry intergranular contacts (i.e. containing no glass), at least within the 200 Ängstrom resolution of a scanning electron microscope. Dry interfacial contacts are necessary to provide constant chemical activity of dissolved species throughout the liquid phase (Bulau, Waff, and Tyburczy, 1979). It may be concluded that the grains are in interfacial mechanical contact with each other throughout partially molten assemblages in textural equilibrium. However, the aforementioned experimental results, obtained for a specific sample composition held at a specific temperature and pressure, obviously cannot be considered to be representative of all silicate partial melts which might be encountered in the mantle. Significant effects could result from variation of surface energies, and therefore phase geometries, with composition, pressure, temperature, and perhaps pressure-induced coordination changes in the molten phase (Waff, 1975). Nevertheless, it seems clear that one of the following two configurations will prevail locally in texturally equilibrated, unsegregated, partial melts subject to hydrostatic confining pressure. The liquid will occur: (1) as an interconnected network of channels along grain edge intersections which connect at corners if the wetting or dihedral angle is less than 60 degrees, or (2) as isolated pockets at corner intersections when this angle exceeds 60 degrees (cf. Smith (1964); Bulau, Waff and Tyburczy (1979)). The latter distribution would not yield large enough bulk electrical conductivities to account for the high conductivity anomalies inferred from induction studies in the suboceanic mantle and that beneath certain continental regions (Shankland and Waff, 1977). Therefore, some form of the first general configuration of partial melting seems to be required for the anomalous zones of the mantle unless melt segregation has occurred.

Conditions existing within the upper mantle differ from those under which Bulau *et al.*, (1979) obtained texturally equilibrated melts as follows. Firstly, shear stress exists within the mantle. Although relevant experimental work has not been performed on silicates, Nye and Mae (1972) have observed the behavior of texturally equilibrated partially molten ice when subjected to pure shear. They observed the formation of small water lenses perpendicular to the direction of compressional stress at the expense of liquid formerly confined to crystalline edge intersections. A fraction of the edge channels close down, but apparently not enough to destroy liquid connectivity. In addition, the water lenses do not destroy mechanical contact between the crystalline grains. With regard to the upper mantle, shear stresses are thought to be small, probably less than 5 to 10 bars (Schubert *et al.*, 1978; Yuen *et al.*, 1978; Hagger and O'Connell, 1979). It seems improbable that shear could modify the phase geometry of partial melts very strongly without destroying highly conducting liquid pathways which are regarded as necessary to account for the aforementioned electrical conductivity anomalies at depth.

A second, more important factor, whose effects are not observable in laboratory scale experiments, is the effect on phase geometry of the gravitational field (Waff, unpublished manuscript). As a result of gravity and the density contrast between the liquid and crystalline phases, pressure in the liquid will increase relative to lithostatic pressure with increasing elevation above the base of a partially molten zone whose fluid phase is connected vertically and whose crystalline grains maintain mechanical contact with each other. In the absence of fluid motion this excess fluid pressure or hydraulic head must be exactly balanced by the effect of surface tension acting along the curved liquid-solid interfaces. This is analogous to the case of surface membrane tension in a stable gas bubble balancing excess internal pressure. Essentially, increased excess internal pressure can only be mechanically compensated by increased positive curvature of the liquid-solid interfaces for mechanical equilibrium. In partial melts, this ultimately results in closure of liquid pathways when the pressure differential exceeds a critical value which is dependent on surface energies and other parameters. This critical value, at which connectivity of the liquid phase is destroyed, will be reached at some finite vertical distance above the base of the partially molten zone. Above the elevation at which the fluid becomes unconnected, the pressure differential, due to buoyancy, can no longer be transmitted from below, and the melt will once again be interconnected upwards through another limited vertical column until the excess fluid pressure again forces closure of connected channels. The net result is vertical stratification of connectivity of the fluid phases from zero to some value probably close to 100 percent. The result will be horizontal layers of partial melt with high liquid path conductivity separated by smaller regions in which the melt fraction remains the same but in which the melt occurs in isolated pockets. The bulk conductivity will, therefore, be highly anisotropic, low in the vertical and high in the horizontal directions. This conclusion is predicated, of course, on the existence of thermodynamic equilibrium conditions within the mantle. Such conductivity anisotropy for partially molten regions of the mantle would not be discernable in induction studies that are sensitive primarily to horizontal telluric currents.

Laboratory Conductivity Measurements

CRYSTALLINE MATERIALS

Olivine, with an approximate composition $Mg_{1.8}Fe_{0.2}SiO_4$, is generally recognized as the major constituent of the upper mantle (Fujisawa, 1968). As such, it will control bulk electrical conduction in regions where solidus temperatures are not exceeded. The presence of pyroxene will cause little alteration since its conductivity is about that of olivine (Duba *et al.*, 1973). When measurements are made within the temperature-f_{O_2} range appropriate to maintain the stability of olivine crystals, conductivities generally fall within a range of one order of magnitude at a given temperature (Duba *et al.*, 1974; Duba *et al.*, 1976; Schock *et al.*, 1977). This is observed to be true for single crystals and polycrystalline material at pressures from one to 50 kilobars. These authors have noted, however, the difficulty of distinguishing changes due to temperature and oxygen fugacity effects from pressure effects in the girdle-anvil pressure apparatus. No data have actually been taken above 8 kilobars under controlled oxygen fugacity. Nevertheless, it seems quite unlikely that conductivity would vary outside the range indicated above because of the variations in these parameters encountered experimentally. An order of magnitude uncertainty in the physical property translates into a temperature uncertainty of approximately 180°C if bulk conductivity were known precisely. In any event, the conductivities of the crystalline phases apparently contribute relatively little to overall conductivity where partial melting occurs, and their uncertainties are considerably less important. It should be mentioned, however, that the effects of shear stress and point defects have not been investigated experimentally in a quantitative way. The production of line defects under shearing stress could enhance conduction. The San Carlos olivine specimen studied by Duba and Nicholls (1973) had an edge dislocation density of 2–3 $\times$ $10^5/\mathrm{cm}^2$, which is similar to that estimated for mantle olivine under 50 bars of shear stress by Kohlstedt *et al.*, (1976). In addition, no significant enhancement was observed in olivine conductivity by Schock *et al.*, (1977) in the girdle-anvil apparatus which produces nonhydrostatic stresses larger than that expected in the mantle. The presence of other phases can alter the transport properties of olivine through their influence on its point-defect chemistry (Stocker and Smyth, 1978). The possible significance of this effect has not been demonstrated to date and needs further experimental investigation.

SILICATE MELTS

Melt conductivities at atmospheric total pressure show a variation with composition which is less than half an order of magnitude for most natural compositions (Waff and Weill, 1975; Rai and Manghnani, 1976). Moreover, their conductivities are nearly independent of f_{O_2} (Waff and Weill, 1975), so that these variables contribute little to the uncertainties of conductivity interpretations. Conductivities of basaltic liquids measured in different laboratories are in excellent agreement (Murase and McBirney, 1973; Presnall *et al.*, 1972; Waff and Weill, 1975; Rai and Manghnani, 1976). Pressure apparently has little effect on magmatic liquid conductivities. Very nearly identical values to those cited above were found for basaltic liquid by Khitarov *et al.* (1970) at 28 kilobars. In preliminary experiments in piston cylinder apparatus Waff (unpublished data) found a drop in conductivity of about 20 percent in a basaltic liquid between pressures of zero and 55 kilobars. All the measurements indicated above were made on anhydrous melts. The effect of water on melt conductivity has not been determined in a quantitative way. The addition of H_2O to a melt will have the essential effect of adding hydroxyl ions or complexes and not free protons. This would increase conductivity, but probably no more than addition of alkalis in comparable molar amounts (cf. Waff and Weill (1975)). Watanabe's (1970) measured conductivity values for basalt under finite but undertermined water pressure at 22.4 kilobars were close to the anhydrous melt values cited. Lebedev and Khitarov (1964) reported the conductivity of molten granite increasing with increasing water pressure, but less than an order of magnitude between 1 and 8000 atm at 1200°C.

PARTIALLY MOLTEN MATERIALS

Measurements of bulk conductivity on partially molten assemblages themselves rather than on their component phases could be valuable provided that their phase geometries were appropriate for partial melts existing within the mantle. This would involve the following requirements: (1) establishment of textural equilibrium with the small but significant surface energies within the system, (2) maintenance of appropriate liquid composition, and (3) determination of the possible effects of shear stress. The first requirement assumes the greatest importance since the conductivity resulting from a random nonequilibrated phase geometry cannot be expected to be relevant. Liquid composition may be important with regard to variations in surface energies and, therefore, phase geometries.

Application to the mantle of the two recently reported studies of bulk conduction in partial melts (Murase *et al.*, 1977; Rai and Manghnani, 1976) is doubtful owing to run durations too short to attain equilibrium textures. In addition, it is probable that a gas phase was also present in the partial melts. It would be useful to perform similar experiments under equilibrium conditions in the future. Hence, at the present time it seems more productive to use theoretical models based on knowledge of phase geometries plus single phase conductivities to determine bulk conduction. Even if experiments can be performed under equilibrium conditions and nonhydrostatic stress, the effects of the gravitational field must be dealt with theoretically.

Summary and Conclusion

(1) Existing theory is adequate for determining bulk conductivity for solid regions of the mantle in terms of individual crystalline phase conductivities and relative fractions.

(2) For partially molten regions, existing models based on idealized geometries offer little significant improvement in estimating bulk conduction over use of Hashin-Shtrikman variational bounds. This is due to inaccurate reflection of the actual phase geometries of assemblages occurring within the mantle.

(3) Laboratory measurements of crystalline and liquid phase conductivities have been shown to be highly reproducible under anhydrous conditions and controlled atmospheres. The precise effect of water on magmatic liquid conductivity is still uncertain, and needs attention in the future. Limited existing experimental work suggests that the effect will be small, and it can safely be neglected for regions of the mantle for which petrological and geochemical evidence indicates water contents less than one or two percent.

(4) Laboratory measurements of conductivity in partially molten materials representative of the upper mantle offer no refinement over theoretical modelling combined with individual phase conductivities in estimating mantle conduction unless such measurements are made under conditions achieving textural equilibrium. Otherwise the criticisms made of current geometrical modelling apply. Experiments reported to date do not meet equilibrium requirements and must therefore be regarded with caution.

(5) Additional modelling refinements for bulk conduction in partial melts must incorporate thermodynamic constraints, the effects of nonhydrostatic stress, and the gravitational field on phase geometry. The resulting reduction in conductivity from values predicted by the Hashin-Shtrikman upper bound for ‘interconnected’ liquid is expected to be less than one order of magnitude in the horizontal direction. The gravitational effect on fluid phase distribution is, however, expected to stratify fluid phase connectivity. This will be the case for thermodynamically stable regions of the mantle. Strong electrical anisotropy should result with considerable reduction in vertical over horizontal conductivity. Detection of this anisotropy with appropriate field techniques is an exciting

possibility. It could offer a means for distinguishing between partial melts whose liquid phase is contiguously associated with individual crystalline grains and segragated melt bodies amidst refractory residua. The latter configuration would not be expected to exhibit the same sort of anisotropy as the former in bulk conductivity. This is true at least on the scale of resolution of induction methods.

(6) Some comment is due regarding the question of whether or not the asthenosphere is a zone of partial melting. Recent studies of the phase geometries of partial melts indicate that when textural equilibrium exists, the liquid phase will be confined to corner or edge intersections and will not wet the intergranular facial contacts under any circumstances, provided that the melt fraction is less than about 25 percent. There is no compelling reason to suppose that a liquid phase, present in this sort of geometry, will accelerate creep processes appreciably over those which normally occur via grain boundary or bulk diffusion. It therefore seems plausible that the rheology of the asthenosphere is determined primarily by the crystalline phases alone, and that its boundaries need not correspond to a zone of partial melting. This further implies that seismic, rather than electrical methods, are more useful for defining the boundaries of the asthenosphere.

Acknowledgements

The author gratefully acknowledges support by the Division of Earth Sciences, National Science Foundation, NSF Grant EAR 78-19379. Thanks are also due T.J. Shankland for many stimulating and helpful discussions.

References

Arndt, N.J.: 1977, Carnegie Inst. of Washington Yrbk 76 (Ann. Geophys. Lab. Rpt.), 424-428.

Boyd, F.R.: 1973, *Geochim. Cosmochim. Acta.* 37, 2533.

Bulau, J.R., Waff H.S., and Tyburczy, J.A.: 1979, 'Mechanical and thermodynamic constraints on fluid distribution in partial melts', *J. Geophys. Res.* (in press).

Chan, T., Nyland, E., and Gough, D.I.: 1973, *Nature Phys. Sci.* **244**, 89-91.

Clark, S.P. Jr., and Ringwood, A.E.: 1964, *Rev. Geophys.* **2**, 35-88.

Duba, A.G., Boland, J.N., and Ringwood, A.E.: 1973, *J. Geol.* **81**, 727-735.

Duba, A.G., and Nicholls, I.A.: 1973, *Earth Planet. Sci. Lett.* **18**, 59-64.

Duba, A., Heard, H.C., and Shock, R.: 1974, *J. Geophys. Res.* **79**, 1667-1673.

Duba, A., Piwinskii, A., Heard, H.C., and Schock, R.N.: 1976, 'The electrical conductivity of forsterite, enstatite and albite', in R.G.J. Strens (ed.), *The Physics and Chemistry of Minerals and Rocks,* John Wiley and Sons, New York, pp. 249-260.

Fujisawa, H.: 1968, *J. Geophys. Res.* 73, 3281-3294.

Hagger, B.H., and O'Connell, R.J.: 1979, *J. Geophys. Res.* **84**, 1031.

Honkura, Y.: 1975, *Phys. Earth Planet. Int.* **10**, 128-134.

Khitarov, N.I., Slutsky, A.B., and Pugin, V.A.: 1970, *Phys. Earth Planet. Int.* **3**, 334-342.

Kohlstedt, D.L., Goetze, C., and Durham, W.B.: 1976, 'Experimental deformation of single crystal olivine with application to flow in the mantle', in R.G.J. Strens (ed.), *The Physics and Chemistry of Minerals and Rocks,* John Wiley and Sons, New York, pp. 35-49.

Lambert, I.B., and Wyllie, P.J.: 1970a, *Science* **169**, 764.

Lambert, I.B., and Wyllie, P.J.: 1970b, *Phys. Earth Planet. Int.* **3**, 316-322.

Landauer, R.: 1952, *J. Appl. Phys.* **22**, 779-784.

Lebedev, E.B., and Khitarov, N.I.: 1964, *Geochem. Int.* **2**, 193-197.

Madden, T.R.: 1976, *Geophysics* **41**, 1104-1125.

Mercier, J.–C.C., and Carter, N.L.: 1975, *J. Geophys. Res.* **80**, 3349.

Murase, T., Kurshiro, I., and Fujii, T.: 1977, 'Electrical conductivity of partially molten peridotite', Ann. Rpt. of the Director, Geophys. Lab., Carnegie Inst. of Washington, 416-419.

Murase, T., and McBirney, A.R.: 1973, *Geol. Soc. Amer. Bull.* **84**, 3563-3592.

Nye, J.F., and Mae, S.: 1972, *J. Glaciology* **11**, 81-101.

O'Hara, M.J.: 1963a, Carnegie Inst. of Washington Yrbk. 62 (Ann. Geophys. Lab. Rpt.)., 71-76.

O'Hara, M.J.: 1963b, Carnegie Inst. of Washington Yrkb. 62 (Ann. Geophys. Lab. Rpt.), 76-77.

Presnall, D.C., Simmons, C.L., and Porath, H.: 1972, *J. Geophys. Res.* 77, 5665-5672.

Rai, C.S., and Manghnani, M.H.: 1976, (abstract), EOS Trans. AUG, 57, 1005.

Ringwood, A.E.: 1969, 'The Earth's crust and upper mantle', *Amer. Geophys. Union Monograph* 13.

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

Scarfe, C.M., Paul, D.K., and Harris, P.G.: 1972, *N. Jb. Miner. Mh.* **H-10**, 469-476.

Schock, R.N., Duba, A.G., Heard, H.C., and Stromberg, H.D.: 1977, 'The electrical conductivity of polycrystalline olivine and pyroxene under pressure', in M. Manghnani and S. Akimoto (eds.), *High Pressure Research Application in Geophysics*, Academic, New York, pp. 39-51.

Schubert, G., Yuen, D.A., Froidevaux, C., Fleitout, L., and Souriau, M.: 1978, *J. Geophys. Res.* **83**, 745-758.

Shankland, T.J., and Waff, H.S.: 1974, *J. Geophys. Res.* 79, 4863-4868.

Shankland, T.J., and Waff, H.S.: 1977, *J. Geophys. Res.* **82**, 5409-5417.

Smith, C.S.: 1964, *Met. Rev.* 9, (33) 1-47.

Stocker, R.L., and Smyth, D.M.: 1978, *Phys. Earth Planet. Int.* **16**, 145.

Waff, H.S.: 1974, *J. Geophys. Res.* 79, 4003-4010.

Waff, H.S.: 1975, *Geophys. Res. Lett.* **2**, 193-196.

Waff, H.S., and Bulau, J.R.: 1979, 'Equilibrium fluid distribution in an ultramafic partial melt under hydrostatic stress conditions', *J. Geophys. Res.* (in press).

Waff, H.S., and Weill, D.F.: 1975, *Earth Planet. Sci. Lett.* **28**, 254-260.

Watanabe, H.: 1970, *Spec. Contrib. Geophys. Inst. Kyoto Univ.* **10**, 159-170.

Wyllie, P.J.: 1971, *The Dynamic Earth: Textbook in Geoscience,* John Wiley, New York.

Yuen, D.A., Tovish, A., and Schubert, G.: 1978, *J. Geophys. Res.* **83**, 759-765.