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Upper mantle temperature determined from combining mineral composition, electrical conductivity laboratory studies and magnetotelluric field observations: Application to the intermontane belt, Northern Canadian Cordillera

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Abstract

Using laboratory-derived temperature dependences of the electrical conductivity of mantle minerals coupled with appropriate mixing laws, we determine the bulk conductivity of mantle mineral assemblages for the ternary olivine–orthopyroxene–clinopyroxene (Ol–Opx–Cpx) system. We calculate physical property bounds (Hashin–Shtrikman bounds) as a function of the fraction of different phases present; these limits correspond to the extreme situations where the most conducting phase is either fully interconnected or fully disconnected. The relationships we present between temperature, mineral composition and bulk electrical conductivity allow constraining one of them given the other two. We apply this approach to an area of the North American Cordilleran Intermontane Belt in the Yukon Territory, northern Canada, where xenolith evidence indicates bimodal upper mantle mineral assemblages (harzburgite and lherzolite). This locality coincides spatially with an upper mantle region of low electrical conductivity determined by long period magnetotelluric data. Given the mantle mineral composition and the maximum and minimum bounds on the electrical conductivity, deduced by non-linear model appraisal, we determine the permitted extremal temperature bounds of the Intermontane belt mantle rocks directly below the Moho to a depth of some 80 km. We show that the mantle in this region is at a minimum temperature of 820 °C and a maximum temperature of 1020 °C; the latter is some 200 °C colder than that suggested in a recent interpretation of an observed collocated low velocity zone from a teleseismic survey.

Keywords: magnetotellurics; electrical conductivity; rock physics; mantle properties; northern Canadian Cordillera

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1. Introduction

The electrical conductivity of the continental mantle is a physical parameter that allows constraints to be placed on mantle properties and geometries, thereby aiding deduction of formation processes and evolutionary development ([1] and [2]). Regional and global studies of the mantle's electrical conductivity have been undertaken since Lahiri and Price's (1939) [3] groundbreaking work, and since then several radially symmetric global models had been presented. Early work primarily used geomagnetic arrays (e.g., [4]), but since the 1980s, and particularly through the 1990s, EM studies are now almost universally undertaken using the magnetotelluric method (see, e.g., [1]). Reviews of regional and global studies of the mantle's electrical conductivity can be found in [1,4-8].

Electrically, the mantle is considered to be formed mainly by silicates that behave as semiconductors at mantle temperatures below the adiabat. In the upper mantle olivine is the dominant mineral, and is assumed to control the conductivity of impurity-free, solid mantle rocks. The presence of impurities or defects, with a valency misfit in the crystal lattice, was long thought to be the dominant semiconduction mechanism [5]. More recently, the main defect responsible for electrical conduction in the temperature range 700–1300 °C has been associated with the polaron Fe^{3+} [9]. Support for this mechanism is provided by the experiments carried out by several authors [9–13].

The electrical conductivity of mantle-forming minerals can thus be described by the solid-state Arrhenius equation, depending on the appropriate activation energies, Boltzmann's constant and absolute temperature. Considering a pyrolitic bulk composition for the upper mantle [14] the amount and distribution of the minerals olivine (Ol), orthopyroxene (Opx) and clinopyroxene (Cpx) controls the bulk conductivity of the mantle. Early laboratory work on the electrical conductivity of mantle minerals was inconsistent, leading to questions as to its utility [15]. However, over the last decade and a half the temperature dependences of the electrical conductivities of these mantle minerals, and others appropriate for deeper mantle rocks, have been determined by careful laboratory measurements [9,11–13,16–18], and are summarized in [8].

Various mixing relationships can be used to quantify the bulk conductivity of a multiphase rock, and work in the past has primarily concentrated on two-phase assemblages, e.g., [19] Schmeling (1986). For our purposes we need to quantify a three-phase assemblage, namely Ol–Opx–Cpx rocks. There are many mixing laws possible to describe the interconnectivity, but with the use of the Hashin–Shtrikman [20] bounds one can constrain the electrical conductivity limits of the assemblage for a given specific petrology and temperature. Commonly, the Hashin–Shtrikman upper and lower bounds vary by orders of magnitude, as one is usually considering a resistive phase or phases with a highly conductive phase, such as partial melt (e.g., [19]) or conducting minerals (e.g., sulphides, [21]). In our case the three phases are all resistive that do not vary significantly between them—the electrical conductivity ratio among these mantle minerals is never higher than six. Thus, the consequence is that the upper and lower Hashin–Shtrikman bounds are close to one another, and all other possible mixing relationships lie in-between.

Accordingly, if the bulk electrical conductivity of a region of lithospheric mantle can be determined by the magnetotelluric (MT) method with a high degree of reliability and precision, the use of laboratory electrical conductivity measurements and the Hashin–Shtrikman bounds for a three component system can constrain the temperature of that region. The relationships presented here between temperature, mineral composition and electrical conductivity allows limiting one of them given the other two. A caveat of the previous reasoning is that a more conductive phase, e.g., partial melt [19,22–24], hydrogen diffusion [25,2], interconnected carbon [26] or sulphides [21] cannot be present.

The region discussed in this study (Intermontane Belt, Northern Canadian Cordillera) is a special case because of two important and unusual factors: 1) the lower crust is not conductive, and 2) the upper mantle is not conductive, i.e., in both regions there are no interconnected conductive phases. The existence of a conducting lower crust produces a shadow zone beneath it preventing determination of the true electrical conductivity [1]. Thus, as a conducting lower crust exists in almost all continental regions [27], usually only a lower bound can be set on the uppermost mantle's resistivity [1]. In locations where

the lower crust is resistive, such as the southern part of the Slave craton [28], the southern part of the Rae province [29], and the location discussed herein, then the resistivity of the mantle directly below the Moho can be determined reliably and, given high quality data, with precision.

The electrical conductivity model of the region obtained by Ledo et al. (2004) [30], shows a spatially defined zone of low electrical conductivity at mantle depths in the Intermontane belt that coincides with a zone of xenoliths having bimodal lherzolitic and harzburgitic composition [31]. In this paper, we take that mantle mineral composition and the observed electrical conductivity, combine them with laboratory studies of the temperature dependence of conductivity of mantle minerals and assumed mixing laws, to determine temperature bounds of the Intermontane belt mantle rocks. We demonstrate that the mantle in this region is at a minimum temperature of 820 °C and a maximum temperature of 1020 °C. This temperature range is some 200–400 °C colder than that suggested in an interpretation by Shi et al. (1998) [32] of an observed collocated low velocity zone from a teleseismic survey by Frederiksen et al. (1998) [33].

2. Electrical conductivity of mantle minerals

Determining the electrical conductivity of mantle minerals at appropriate conditions, both physical and chemical, is highly demanding. Early results on olivine crystals and composites showed a great degree of scatter within and between laboratories, leading to questions being raised about the usefulness of the measurements for calibrating the Earth [15]. After the role of oxygen fugacity was appreciated, then the observations from different laboratories began to show consistency, and reliable and repeatable results could be obtained. From even the earliest measurements it was recognised that the pressure dependence of electrical conductivity is far less than the temperature dependence [34,35].

Constable and Duba (1990) [13] , Shankland and Duba (1990) [12] and Constable et al. (1992) [16] provided the temperature dependence of electrical conductivity of olivine, and show that it obeys the solid state Arrhenius relationship with up to three branches with different activation energies associated to different conduction mechanisms. Thus, the electrical conductivity can be expressed as the sum of three thermally activated processes:

$$\sigma = \sum_{i=1}^{3} \sigma_i e^{-A_i/kT} \tag{1}$$

where σ is the conductivity of olivine in Siemens per metre (S/m), k is Boltzmann's constant, A is the activation energy, T is the temperature in Kelvin, and subscript i refers to the three branches or conduction mechanisms. The main conclusion from the results obtained from Constable and Duba (1990) [13] combining different datasets was that the electrical conductivity of olivine rocks between 640 and 1500 °C can be described with three different conduction mechanisms. For low temperatures (<720 °C) the conduction mechanism has very low activation energy, although the lack of data precluded its estimation. Between 720 and 1500 °C the conduction mechanism has activation energy between 1.60 ± 0.01 eV. At temperatures greater than 1500 °C the activation energy ranges between 7.16 ± 0.56 eV. The isotropic constants and activation energies derived by Constable et al. (1992) [16] that best fit their experimental data are:

$$\sigma_1 = 10^{2.402}\,\mathrm{S/m},$$

$$\sigma_2 = 10^{9.17}\,\mathrm{S/m},$$

$$A_1 = 1.60\,\mathrm{eV},$$

$$A_2 = 4.25\,\mathrm{eV}.$$

This equation is plotted in Fig. 1a and b in the temperature range of 800–1400 °C as the solid line marked CSD. Fig. 1a uses conventional laboratory data display of log(10,000/reciprocal absolute temperature) on the abscissa vs. log (conductivity) on the ordinate, whereas Fig. 1b uses a geophysical display of log(resistivity) on the abscissa vs. log (temperature in Celsius) on the ordinate, with temperature increasing downwards as a proxy for depth. Xu et al. (1998) [17] also derived a temperature dependence of olivine from experimental data, and fit them with a single activation energy of

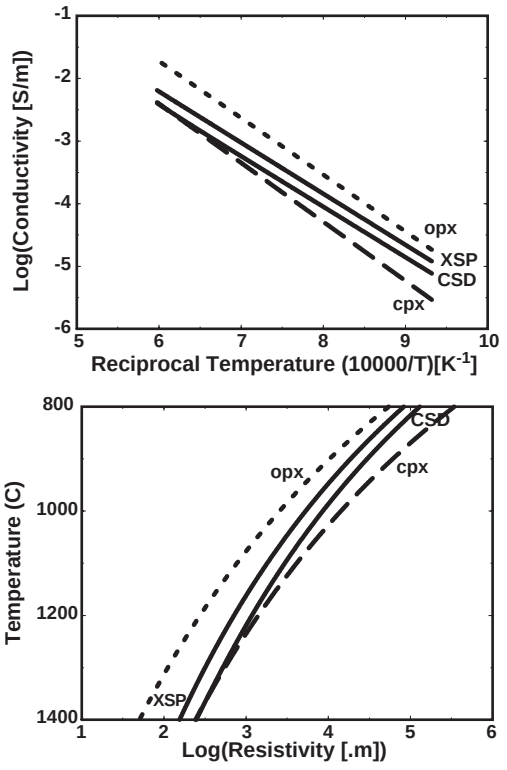

Fig. 1. Electrical conductivity versus temperature for mantle minerals. CSD: equation obtained from [17]; XSP: equation obtained from [18]. Top: conventional laboratory data display; Bottom: geophysical data display.

$A_1 = 1.62$ eV with a constant of $\sigma_1 = 10^{2.69}$ S/m. Their equation is plotted as solid line XSP on Fig. 1a and b.

Xu et al. (2000a) [8] presented the equations for the temperature dependence of a variety of mantle minerals, and for our purposes we take those for orthopyroxene and clinopyroxene given as:

$$\sigma_{\mathrm{opx}} = 10^{3.72}\exp(-1.80/kT),$$

$$\sigma_{\mathrm{cpx}} = 10^{3.25}\exp(-1.87/kT),$$

and these relationships are plotted on Fig. 1a and b as dotted (opx, orthopyroxene) and dashed (cpx, clinopyroxene) lines.

Note that at a particular temperature the ratio between the conductivities for the three minerals is never greater than six. Given the relatively small difference between the three minerals, the bulk conductivity will be less sensitive to the type of mixing law chosen to describe the assemblage.

3. Electrical conductivity of mantle mineral mixtures

Knowledge and understanding of the interaction between different rock components in an assemblage, and how that interaction controls bulk rock properties, are critical for both improved characterization and more meaningful interpretation of observed geophysical data. In the case of electrical conductivity we optimally would want to determine the mineral components present, their electrical conductivities, their abundances and their geometrical distributions. However, given the non-uniqueness of the solutions from such observations, we need to rely on external sources of information to give us the minerals and their abundances. From laboratory studies (reviewed above) we can assign electrical conductivities to the minerals for a given temperature, leaving the geometrical distribution as the unknown variable. Calculation of exact results for the bulk electrical conductivity of mixtures is mathematically complex, and the different formalisms that can be used to construct answers to this question can be classified in four broad categories: a fixed microstructure geometry, random distributions, empirical relations and exact bounds, or a combination of two or more of them.

Bulk properties from simplified representations of material microstructures (spheres, tubes, periodic networks, fractal microstructure) for two-phase systems, principally a conducting phase and a non-conducting phase, have been derived for over four decades [20,36,37]. The problem with this approach is that if the exact tautology of the microstructure is not known a priori from petrological observations, or if known but cannot be approximated by a simple geometry, or if that geometry is not consistent over the whole region being investigated, then this is an ill-posed problem with a non-unique solution. In some cases knowledge of another geophysical observable (e.g., seismic velocity) can help constrain the microstructure geometry [20,38–40], but the reservations expressed above still remain.

In situations where a small degree of heterogeneity is present effective medium theories can be applied [41,42]. Effective medium theories aim to infer an average conductivity for heterogeneous disordered media from the statistics of local conductivity components. Thus, an effective medium is defined as the homogeneous equivalent structure for which the macroscopic physical properties are the same as for the heterogeneous system. Effective medium theories are limited by the fact that if the microstructure corresponding to a particular formula is not precisely known then agreement or disagreement with observable data can be neither confirmed nor rejected for a particular model of microstructure. Also, effective medium theories fail at high heterogeneity degree due to clustering effects, and the appropriate formalism to describe clustering effects is percolation theory [43–45]. Percolation is a random process and the percolation threshold, p_c, is that concentration at which an infinite network appears in an infinite lattice [45]. A combination of different formalisms, namely effective medium and percolation theories, was proposed by Bahr (1997) [46] to explain the observed electrical conductivity of the crust. The effective medium theory was used to calculate the bulk conductivity of the medium and the percolation theory was introduced to explain the results observed when the amount of one of the materials is close to the critical degree. Using this formulation Bahr (1997) [46] justified the macroscopic anisotropy of the bulk conductivity of the crust as result of distribution of micro cracks on a small scale when the conductive phase is close to the percolation threshold in a preferential direction. Another approach combining results obtained from random lattice simulations and micro structural models to calculate the electrical conductivity of saturated porous rocks was presented by Bigalke (2000) [47], comparing the results obtained from his models with Fontainebleau sandstone samples it concluded that the electrical conductivity of saturated porous rocks can be described by means of random lattice conduction.

A long-established empirical approach first adopted in sedimentary rocks is to correlate electrical properties to the volume fraction (ϕ) of the component phases in an exponential manner, e.g., $\sigma = a\phi^m$ for a single conducting phase within a highly resistive host matrix [48,22]. In this case all explicit information describing the material is ignored. These empirical relations are useful for correlating data but not for predicting properties. For sedimentary rocks Archie (1942) [48] found empirically that m is dependent on lithology and the degree of cementation.

Rigorous bounds on possible bulk properties are based on variational principles (Hashin and Shtrikman, 1962 [20], hereafter called HS) and require only information of phase fractions. These bounds for mixing two-phase materials are in use in many other fields with other names, notably Maxwell–Garnett (1904) [49] formulae for calculation of effective dielectric permittivity. A general form of the bounds for n-phases materials was given by

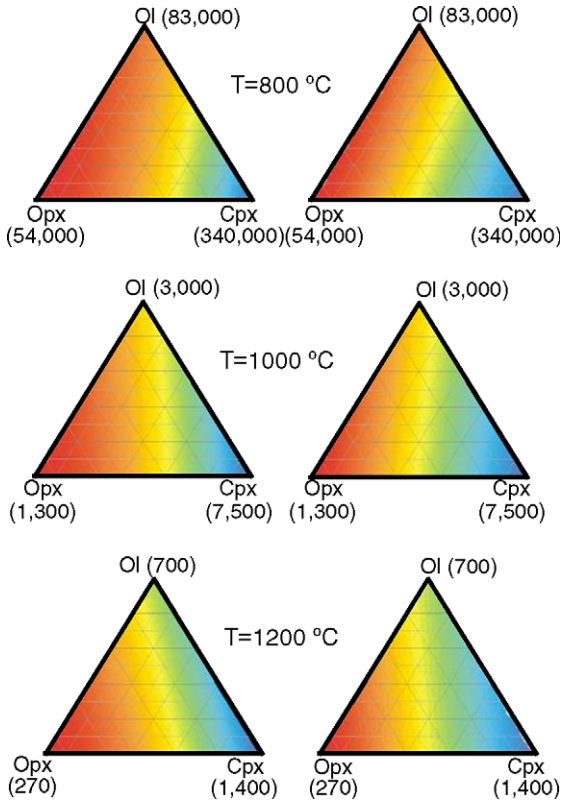

Fig. 2. Hashin–Shtrickman lower (left column) and upper (right column) bounds for Ol-Cpx-Opx mantle rocks. At each temperature the colour scale for the bounds is the same, values between brackets correspond to the electrical resistivity in Ω m for each mineral. Red corresponds to the minimum value (Opx) and blue to the maximum (Cpx). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Berryman (1995) [50], and using his formulae the HS bounds for a three component system have the following expression:

$$\sigma_{HS^+} = \frac{1}{\left(\frac{X_{ol}}{\sigma_{ol}+2\sigma_{opx}}\right)+\left(\frac{X_{opx}}{3\sigma_{opx}}\right)+\left(\frac{X_{cpx}}{\sigma_{cpx}+2\sigma_{opx}}\right)} - 2\sigma_{opx}$$

$$\sigma_{HS^-} = \frac{1}{\left(\frac{X_{ol}}{\sigma_{ol}+2\sigma_{cpx}}\right)+\left(\frac{X_{opx}}{\sigma_{opx}+2\sigma_{cpx}}\right)+\left(\frac{X_{cpx}}{3\sigma_{cpx}}\right)} - 2\sigma_{cpx}.$$

We have used the laboratory-derived temperature-dependence of electrical conductivity of olivine, orthopyroxene and clinopyroxene [18,8] to calculate the electrical conductivity bounds for mantle rocks at different temperatures for Ol–Opx–Cpx compositions. In this case, given that the maximum difference between the electrical conductivity of the three minerals is only a factor 6, the Hashin–Shtrikman bounds are very close between them. Fig. 2 shows the variation of the HS electrical conductivity bounds with temperature in ternary diagrams for all the possible distributions of Cpx–Opx–Ol for temperatures of 800 °C, 1000 °C and 1200 °C.

4. Temperature bounds for the intermontane belt mantle

As an example of the application of our approach, we discuss an area in the Yukon, northwestern Canada (Fig. 3), where there is xenolith evidence for a bimodal upper mantle mineral assemblage (harzburgite and lherzolite). This locality coincides spatially with an upper mantle region of low Vp, determined from teleseismic data [33], and a low electrical conductivity, determined by long period magnetotelluric data (Fig. 4). The teleseismic data

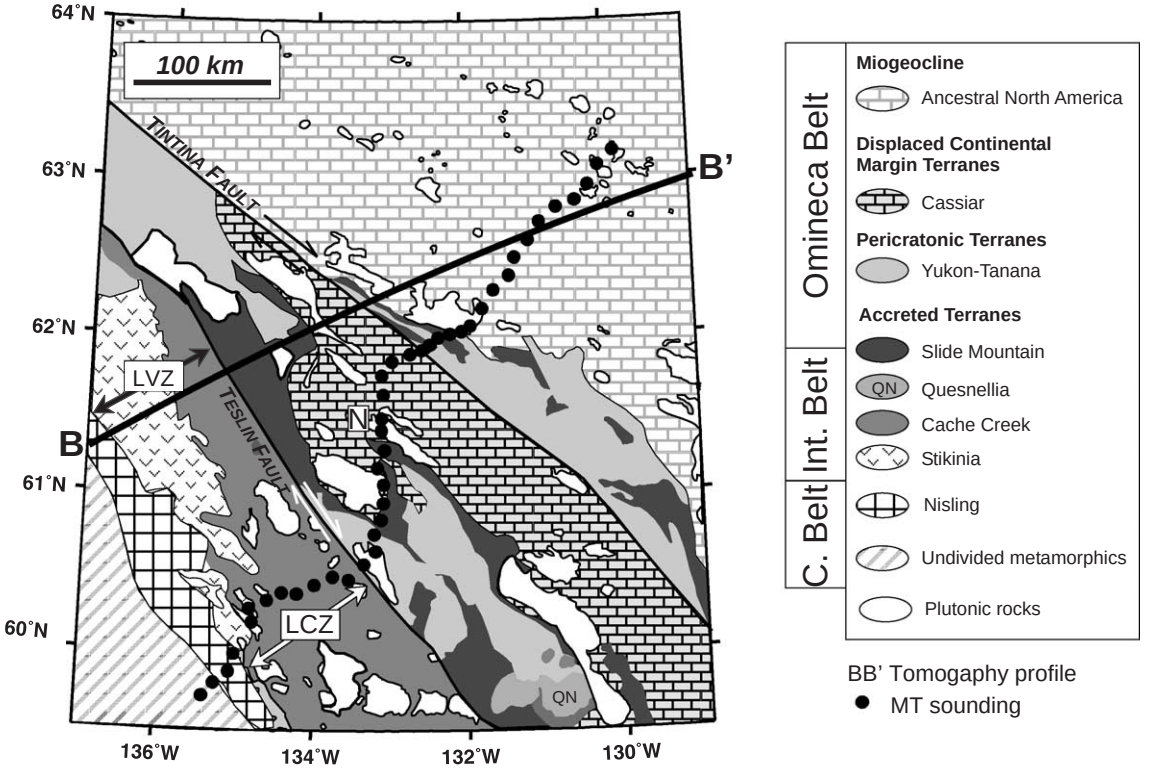

Fig. 3. Terranes and tectonic elements map of the northern Canadian Cordillera. The black dots represent the location of the magnetotelluric stations. Line BB′ tomography profile from Frederiksen et al. [33]. LVZ: low velocity zone at mantle depths, LCZ: low conductivity Zone at mantle depths.

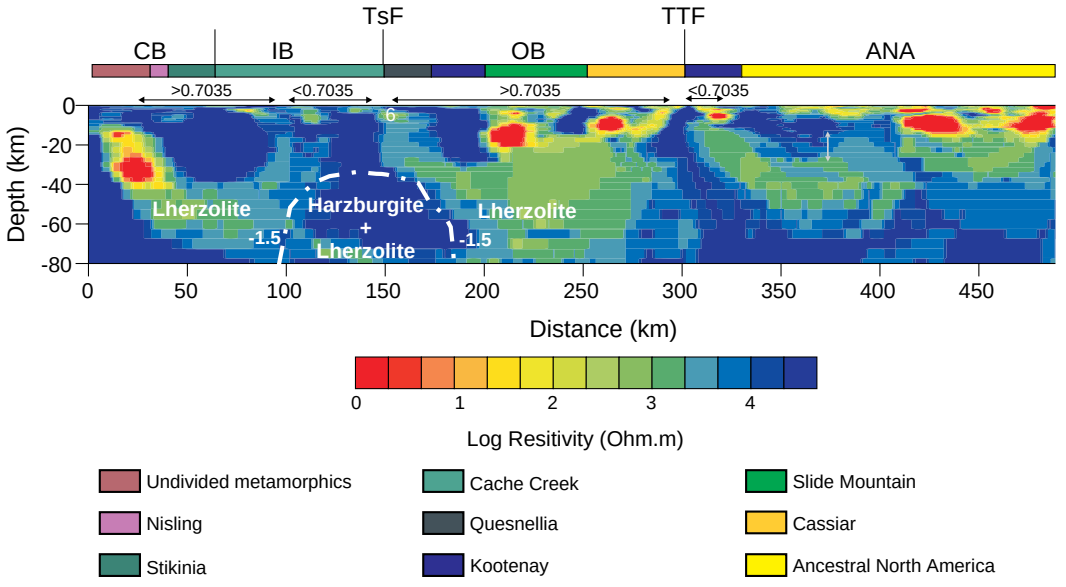

Fig. 4. 2D MT resistivity model obtained by inversion using both TE-and TM-mode resistivities and phases (from [30]). Dashed-dotted white line: P-wave velocity (%) anomaly of Frederiksen et al. [33].

were taken to suggest an up to 200 °C localized increase in mantle temperature, compared to neighbouring regions that are more lherzolitic (Cpx-rich) in nature [32].

Fig. 4 shows the electrical resistivity model of the region, taken from Ledo et al. (2004) [30]. The feature of interest is the low electrical conductivity upper mantle region (20,000 Ω m) beneath the central part of the Intermontane Belt. This resistive region coincides spatially with the Cpx-poor harzburgitic mineralogy described by Abraham et al. (2001). The neighbouring more conductive regions coincide with more normal lherzolitic mantle. To determine the lower limit of the mantle resistivity below the Intermontane belt compatible with our model, the response of the model was calculated for progressively increasing values of the mantle resistivity. Fig. 5 shows the average maximum difference for the different models from our reference model (Fig. 4). The magnetotelluric mode for currents flowing along the profile, the TM (transverse magnetic) mode, is affected by the decreasing of the resistivity of the mantle; the lower limit for the mantle resistivity is 5000 Ω m for an averaged misfit of 3 degrees in phase, which is approximately double the measured phase one sigma error.

According to Abraham et al. (2001) [31], the harzburgite xenoliths contain 2% Cpx, 18% Opx and 80% olivine on average. Taking these values and using the equations of Xu et al. (2000a) [8] together with Hashin–Shtrickman bounds, the electrical conductivity extreme values determined indicate that the upper mantle temperature must lie between 820 and 1020 °C (Fig. 6).

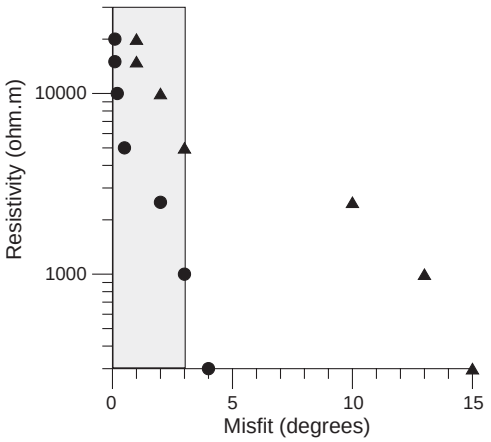

Fig. 5. Average maximum misfit for different Intermontane Belt mantle resistivities.

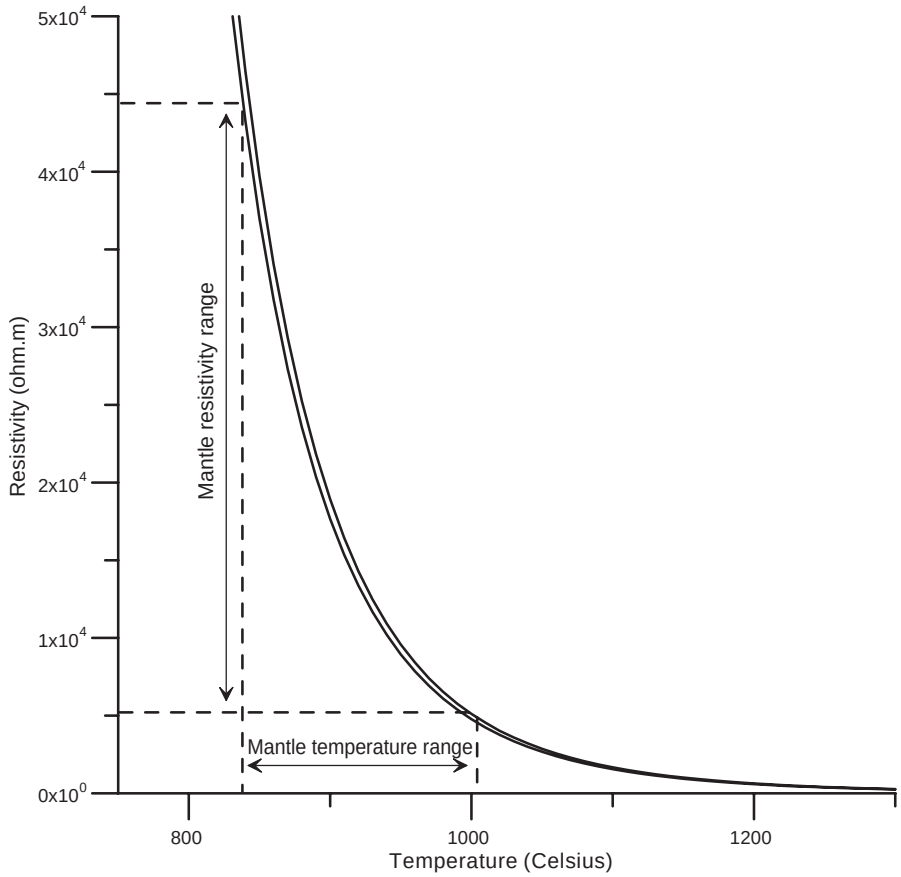

Fig. 6. Resistivity–temperature relation for the harzburgite xenoliths.

We also can verify the hypothesis about the maximum temperature of the uppermost part of the lithospheric mantle assuming that the observed composition of the xenoliths at surface does not correspond to the present day composition at mantle depths. In this case, we are limited by the minimum value of the resistivity determined by the magnetotelluric method (5000 Ω m). The extreme and unrealistic case is considering that the mantle is totally composed of clinopyroxene (the most resistive of the three lithospheric mantle minerals) will yield a maximum temperature of 1050 °C.

Thus, the resistive region in Fig. 4 cannot be any hotter than 1020 °C, or the resistivity would be <5000 Ω m and we would have resolved it. Similarly, it cannot be any colder than 820 °C or its resistivity would be >20,000 Ω m.

The maximum difference in equilibration temperatures calculated for the lherzolites and harzburgites is 60–80 °C, being 1040 °C for the harzburgites, as compared to 956 °C for the lherzolites [32]. The preferred explanation by Frederiksen et al. (1998) [33] for their velocity anomaly is the presence of asthenospheric material upflow driven by the opening of a slab window beneath the Northern Cordillera [51,52]; the velocity anomaly is explained by a 100–200 °C mantle temperature increase [32]. The temperature determined at the Moho of the northern Cordillera lithosphere from heat flow data [53,56] gives 950 ± 100 °C. Thus, our MT model support a small increase in mantle temperature below the Intermontane Belt more in accordance with the equilibration temperatures calculated for the lherzolites and harzburgites, but not an increase of the order of 200 °C

suggested by Frederiksen et al. (1998) [33] and Shi et al. (1998) [32].

5. Conclusions

There are a number of mechanisms for enhancing electrical conductivity, falling into two basic groups of either ionic conduction (dominantly in a fluid phase such as saline waters or partial melt) or electronic conduction (e.g., sulphides, graphite or iron oxides). Results from the German Deep Drilling Program (KTB) demonstrate that both may be operating simultaneously [54,55], but there is no possibility of determining the cause of enhanced conductivity from the MT data themselves. This inherent ambiguity in interpretation of conducting regions has raised questions about the utility of magnetotelluric surveys, with the most well-known debate centred on the cause of lower crustal conductivity [1]. A more defensible position is when an MT survey can demonstrate that an interconnected conducting phase cannot exist and can be excluded unequivocally. Similarly, MT studies can be far more significant when they falsify hypotheses. An example of this is the lack of a conductor in the lower crust of the southwestern part of the Slave craton [28] which excludes the presence of metasedimentary sequences containing sulphides, carbon or iron oxides thereby addressing questions concerning tectonic processes in the Paleoarchean.

In this paper we have examined a region beneath the central part of the Intermontane Belt in the Yukon Territory, Canada. Given the lack of a lower crustal conductor in the region, we are able to resolve the resistivity of the uppermost mantle directly below the Moho. We have shown that the minimum permitted resistivity is 5000 Ω m. From laboratory studies of the temperature dependence of the electrical conductivity of lithospheric mantle minerals, and from maximum and minimum bounds of the resistivity of mineral assemblages, this resistivity range translates to temperature bounds of 820 °C and 1020 °C. Thus, in certain specific situations, MT is able to provide absolute values of temperature.

Our data and results agree with the interpretations of [56] where the Moho temperature estimates using heat flow data, Pn velocity, thermal isostasy and lithosphere thickness in this area ranges between 800 and 1000 °C.

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