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Comparison of continental and oceanic mantle electrical conductivity: Is the Archean lithosphere dry?

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[1] **Abstract:** Electrical conductivity profiles derived from magnetotelluric and geomagnetic sounding methods provide a means of constraining upper mantle properties that is complementary to seismic studies. We analyze conductivity profiles for an Archean craton and an oceanic setting, in conjunction with independent constraints on mantle geotherms, to estimate the water content of the upper mantle in these very different geologic environments. Results from this analysis indicate that the Archean lithosphere contains less water than the oceanic mantle in the depth range between ~150 and ~250 km. Below ~250 km these oceanic and continental environments show similar conductivities, suggesting that the water content of the mantle does not vary significantly between ~250 km and the 410-km discontinuity. These observations indicate that the Archean lithosphere may be stabilized against convective instabilities partly because it has a high viscosity associated with a dry composition.

Keywords: Electrical conductivity; continental lithosphere; water; mantle; craton.

Index terms: High-pressure behavior; magnetic and electrical properties; dynamics of lithosphere and mantle-general; composition of the mantle.

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1. Introduction

[2] Global variations in the physical state of the upper mantle have been identified using seismological observations. The contrast in seismic properties between different tectonic environments is most pronounced in the depth range between ~100 and 300 km, where, for example, body wave velocities of Archean continental roots are significantly greater than those of the oceanic mantle. High velocities in the Archean regions are attributed to a combination of chemical depletion and conductive cooling to depths of up to ~350 km. Since Archean

terranes are stable and show few signs of significant subsidence, the upper mantle beneath them has been hypothesized to be buoyancy compensated through a depletion in Fe [*Jordan*, 1981]. Without this compensation, significant geoid anomalies would be expected between oceanic and continental environments. In addition, the roots might be expected to delaminate and become entrained in the thermal convection of the mantle [e.g., *Shapiro et al.*, 1999].

[3] Deep electrical conductivity profiles provide additional constraints on the thermal and chemical state of the mantle. Although the number of deep magnetotelluric profiles is limited, those that do exist reveal considerable lateral variation in the conductivity of the upper mantle in a manner consistent with seismic observations. In particular, the conductivity of the upper mantle in the depth range between ~100 and 250 km is significantly greater for oceanic regions than it is for old continental roots. In this paper, we discuss the implications of two deep-probing electrical conductivity profiles for the oceanic and continental upper mantle (Figure 1a). The first, obtained from analysis of data from a submarine cable extending from Hawaii to North America, provides what can be considered an average conductivity profile for moderately young oceanic mantle [*Lizarralde et al.*, 1995]. For comparison, the conductivity shown for the oceanic setting between ~150 and 400 km in Figure 1a is similar to that beneath the actively spreading East Pacific Rise over the same depth interval [*Evans et al.*, 1999]. The second profile comes from the stable Archean Superior Province in the Canadian Shield [*Schultz et al.*, 1993]. Details of the data collection and analyses used to calculate these conductivity profiles are described in the references cited above. Fundamental to our analysis is the demonstration by *Lizarralde et al.* [1995] that

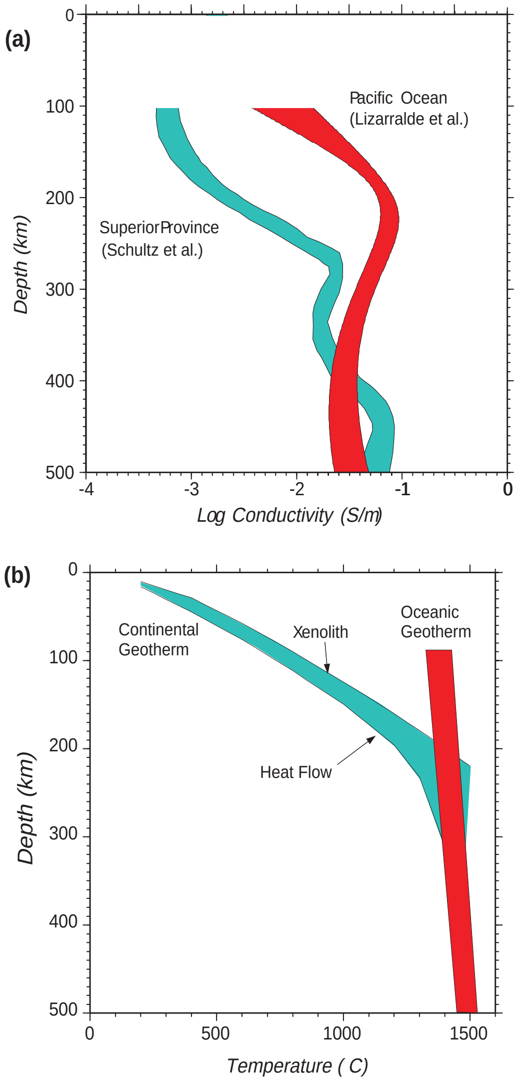


Figure 1. (a) Conductivity-depth profiles derived from magnetotelluric and geomagnetic depth sounding studies for an oceanic (northeast Pacific basin [*Lizarralde et al.*, 1995]) and an Archean (Superior Province [*Schultz et al.*, 1993]) setting. (b) Geotherms used for calculation of conductivity profiles shown in Figure 2. The geotherms used to calculate electrical conductivity profiles for the Superior Province are determined from thermobarometric data on xenoliths from the Superior Province [*Rudnick and Nyblade*, 1999] and a theoretical geotherm derived from surface heat flow [e.g., *Chapman and Pollack*, 1977; *Jaupart and Mareschal*, 1999] appropriate for the Superior Province. Geotherms for adiabatic mantle at potential temperatures of 1300°C and 1400°C are also shown.

the two data sets are distinct and can be described only by different conductivity-depth profiles.

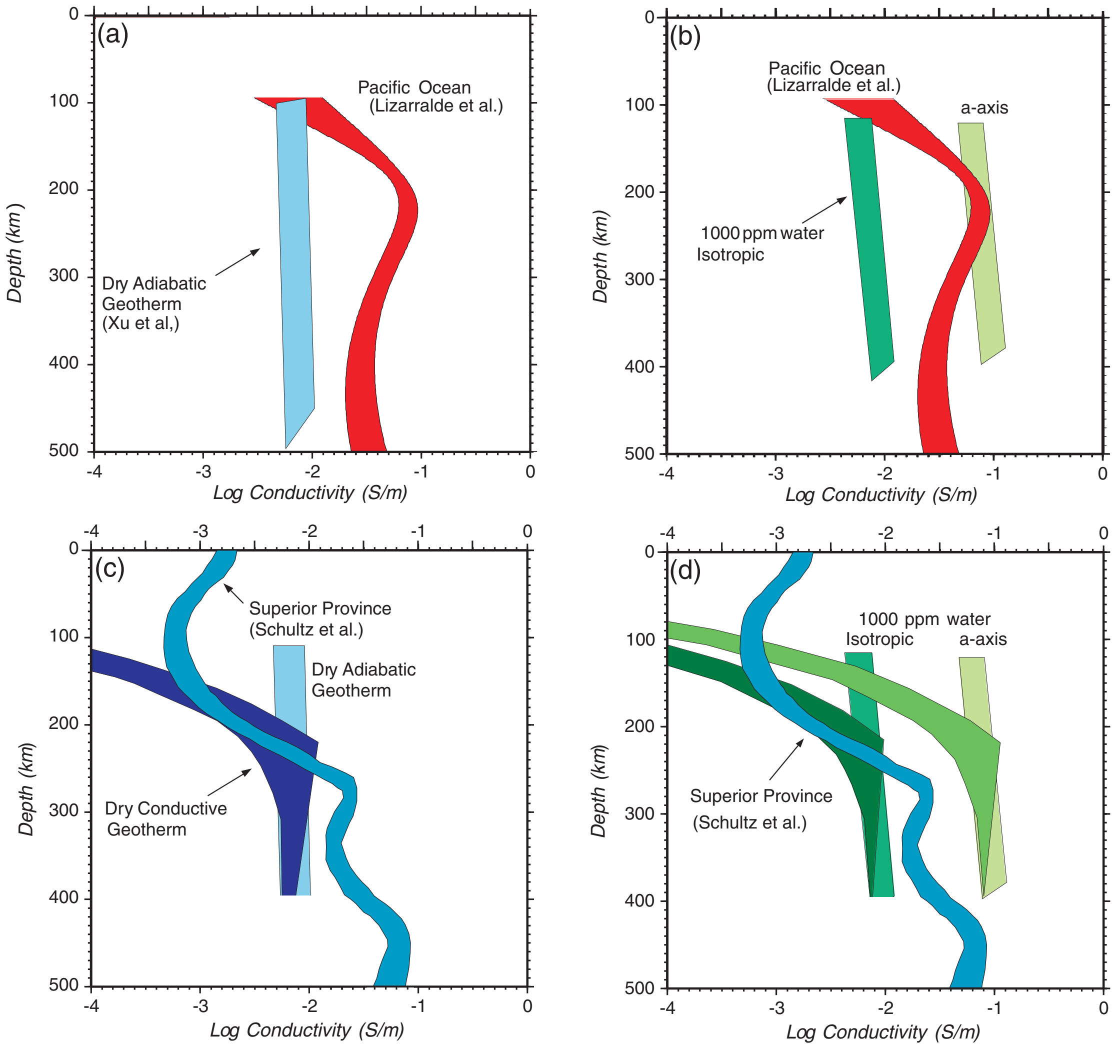
[4] We reexamine the Canadian craton and oceanic mantle conductivity profiles in the context of different conduction mechanisms and independent constraints on the geotherm of the Archean lithosphere, as shown in Figure 1b. We focus on the conductivity structure in the depth interval between 100 km and the 410-km seismic discontinuity, where the structure represented in both electrical conductivity profiles is well resolved. Finally, we examine the implications of these results for the interpretation of the seismic velocity structure of both the oceanic and continental mantle and the evolution of Archean cratons.

2. Mantle Conductivity

[5] Laboratory measurements made on peridotites and olivine single crystals under controlled temperature, pressure, and oxygen fugacity conditions provide a basis for the interpretation of mantle conductivity. Rather than use the conductivity data to constrain thermal profiles in the lithosphere, we use constraints on continental geotherms, derived from thermobarometry and geochemical analyses of xenoliths [e.g., *Rudnick et al.*, 1998], to predict resistivity structure under dry conditions. Such conductivity-depth profiles provide a reference against which field data can be compared. In these calculations we use the high-pressure and high-temperature conductivity data of *Xu et al.* [1998]. These data are generally consistent with previous conductivity models based on lower-pressure experimental data (for example, the SO_2 model of *Constable et al.* [1992]). Motivated by previous studies, we also explore the role of dissolved hydrogen on mantle conductivity. In this case we follow previous analyses [*Karato*, 1990; *Lizarralde et al.*, 1995] by using the Nernst-Einstein relationship to estimate conductivities in the presence of different water contents. For these calculations we use the recently analyzed hydrogen diffusion data of *Kohlstedt and Mackwell* [1998], extrapolating where necessary. In all calculations we assume that mantle conductivity is controlled by the properties of olivine, the dominant and interconnected phase in the upper mantle at depths above the 410-km discontinuity.

[6] We do not incorporate the effects of iron content or the presence of melt on conductivity in our calculations. Chemical analyses of xenoliths indicate that olivine compositions vary between ~Fo88 and Fo93 in the upper mantle [e.g., *Boyd*, 1989; *Kelemen et al.*, 1998]. Experimental studies indicate that at a constant oxygen fugacity, this range in Fe content can result in approximately a factor of 2 difference in conductivity [*Hirsch and Shankland*, 1993]. The iron content (Fo90) of the samples used by *Xu et al.* [1998] is in the middle of the expected variation in olivine Fe content. The electrical conductivity of the mantle can also be enhanced in the presence of melt [e.g., *Roberts and Tyburczy*, 1999], provided that the melt forms an interconnected network. While this mechanism is likely beneath an active spreading center [e.g. *Evans et al.*, 1999], the depth range where melts are present away from spreading centers remains somewhat poorly constrained. The presence of small amounts of volatiles can induce melting at depths around 100−300 km [e.g., *Planck and Langmuir*, 1993; *Hirth and Kohlstedt*, 1996] in the oceanic mantle. However, it is unlikely that melt is present in the lithosphere beneath stable Archean cratons.

[7] As illustrated in Figure 2a (and further discussed by *Lizarralde et al.* [1995]), the conductivity of the oceanic mantle in the depth range of ~100−400 km is too high to be explained by conduction in a dry pyrolite mantle at a potential temperature of 1300°–



1400°C. A possible explanation for this observation is that the conductivity of the mantle is significantly enhanced in the presence of small amounts of water [*Karato*, 1990; *Lizarralde et al.*, 1995]. The enhancement of mantle conductivity due to the presence of water has been estimated by incorporating experimental data on the diffusivity [*Mackwell and Kohlstedt*, 1990; *Kohlstedt and Mackwell*, 1998] and solubility [*Kohlstedt et al.*, 1996] of hydrogen in olivine into the Nernst-Einstein relationship. In the Nernst-Einstein relationship the conductivity is directly proportional to the product of the concentration of the charge-carrying species and the square of its charge. Thus, for conduction accommodated by diffusion of protons, the conductivity is directly proportional to concentration. The applicability of the hydrogen conduction mechanism remains unverified in the laboratory owing to the difficulty of making reliable conductivity measurements on hydrous mantle aggregates at high pressure. In addition, uncertainties arising from the anisotropy of hydrogen diffusion in olivine must be considered [e.g., *Constable*, 1993].

[8] The conductivity of the oceanic mantle, as described by *Lizarralde et al.* [1995], is consistent with an olivine water content of $\sim$1000–3000 H/10^{6}Si (Figure 2b). This range is within the bounds of the water content of olivine in the oceanic mantle estimated by *Hirth and Kohlstedt* [1996] based on independent laboratory [e.g., *Kohlstedt et al.*, 1996] and petrological [e.g., *Bell and Rossman*, 1992] constraints.

[9] The conductivity structure of the Archean mantle is consistent with the properties of dry olivine on a conductive geotherm to a depth of $\sim$250 km. The predicted conductivity for a dry mantle on a conductive geotherm, calculated using the Arrhenius relation given by *Xu et al.* [1998], is shown in Figure 2c. We used a range of conductive geotherms bracketed between end-member values constrained respectively by thermobarometric data on xenoliths from the Superior Province [*Rudnick and Nyblade*, 1999] and a theoretical geotherm derived from surface heat flow [e.g., *Chapman and Pollack*, 1977; *Jaupart and Mareschal*, 1999] appropriate for the Superior Province (Figure 1b). The two calculated profiles for the conductive geotherm bracket the electrical conductivity profile determined by *Schultz et al.* [1993] over the depth range between 150 and 250 km. The lower bound on the conductivity is given by the heat flow geotherm. Recent calculations of the temperature and pressure dependence of thermal conductivity suggest that the temperature in the deep portions of the conductive lithosphere may be greater than previously estimated [*Hofmeister*, 1999]. Thus the electrical conductivity calculated using the geotherm constrained by heat flow should be considered a minimum.

[10] The conductivity in the depth interval of 150–250 km is consistent with the dry model; however, the presence of water cannot be ruled out owing to the effects of anisotropy. While dry olivine does not show substantial anisotropy in conductivity between the principal crystallographic axes, the diffusion of hydrogen is significantly anisotropic, with $D_{[100]} \approx 10 D_{[010]} \approx 100 D_{[001]}$ at a tempera-

Figure 2. Comparison of experimentally based predictions for mantle conductivity to profiles shown in Figure 1a. The conductivity-depth profile beneath the northeast Pacific basin [*Lizarralde et al.*, 1995] is compared to (a) a conductivity-depth profile calculated for a dry adiabatic mantle using the data of *Xu et al.* [1998] and (b) conductivity-depth profiles for an isotropic (dark green band) and anisotropic (light green band labeled a-axis, for the fast hydrogen diffusion direction) mantle containing olivine with 1000 H/10^{6}Si calculated using the Nernst-Einstein relation. The isotropic model was determined using the mixing relationship employed by *Constable* [1993]. The peak in conductivity around 200 km is consistent with an anisotropic mantle containing olivine with $\sim$1000 H/10^{6}Si. The width of these bands illustrates the range in conductivity calculated for an uncertainty in temperature of 100°C (i.e., a range in potential temperature of 1300°–1400°C). In Figures 2c and 2d the conductivity-depth profile beneath the Superior Province [*Schultz et al.*, 1993] is compared to conductivity-depth profiles calculated using the conductive geotherms shown in Figure 1b for dry (purple band in Figure 2c) and wet (similar bands in Figure 2d) conditions, respectively. The upper bound for the conductivity calculated using the conductive geotherm is constrained by thermobarometry of xenoliths from the Superior Province [*Rudnick and Nyblade*, 1999]. The lower bound is calculated using a geotherm inferred from surface heat flow [*Chapman and Pollack*, 1977]. Conductivity-depth profiles calculated for an adiabatic mantle with a potential temperature of 1300°–1400°C are also shown in Figures 2c and 2d. The conductivity in the depth interval of $\sim$150–250 km beneath the Superior Province is well fit by either the dry model or the isotropic wet model. On the basis of the predicted effects of anisotropy discussed in the text, we favor the dry model.

ture of ~1200°C [*Kohlstedt and Mackwell*, 1998]. Thus, in the presence of water, high conductivities are expected in regions with a strong alignment of olivine [100] axis. During deformation by dislocation creep, olivine [100] axes generally become aligned in the direction of mantle flow. Such fabrics can be identified by the presence of seismic anisotropy. By contrast, if the mantle is isotropic, the influence of the fast hydrogen diffusion direction on conductivity is significantly mitigated [e.g., *Constable*, 1993]. As indicated in Figure 2d, olivine water contents as high as 1000 H/10^6Si cannot be ruled out on the basis of conductivity profiles alone.

[11] Below 250 km the conductivities in the model of *Schultz et al.* [1993] are more similar to those determined for the oceanic setting and are significantly greater than those predicted for a dry pyrolite mantle. The increase in conductivity below 400 km is consistent with laboratory measurements that indicate an increase in conductivity associated with the phase changes of olivine to wadsleyite and ringwoodite [*Xu et al.*, 1998]. In the depth range between 250 and 400 km the conductivity determined for the continental region approaches that predicted for an isotropic mantle containing olivine with 3000 H/10^6Si (i.e., as shown in Figure 2d, the conductivity in this depth interval is approximately a factor of 3 greater than that calculated for an isotropic mantle containing olivine with 1000 H/10^6Si).

3. Discussion and Conclusions

[12] The potential for using EM data to constrain the composition and temperature of Earth's mantle is emphasized by our comparison of oceanic and old continental regions. As illustrated in Figure 2, first-order differences in electrical properties between these two tectonic settings can be explained by differences in water content. There are certainly other variables that can influence conductivity. However, we emphasize the role of water (and in particular evidence for low water contents in Archean settings) owing to its potential importance for controlling the evolution of the mantle through its effects on viscosity [e.g., *Pollack*, 1986; *Hirth and Kohlstedt*, 1996]. Deep conductivity profiles from different continental settings show significantly higher conductivities than those in the *Schultz et al.* [1993] model [e.g., *Egbert and Booker*, 1992; *Jones*, 1999]. The conductivity in some of these regions can be influenced by postemplacement reworking or ongoing tectonic processes. For example, a profile from Tucson, Arizona [*Egbert and Booker*, 1992], shows a highly conductive upper mantle that can be explained by mantle hydration by the subducted Farallon plate and subsequent upwelling and melting.

3.1. Evidence for a Dry Archean Continental Lithosphere

[13] While the oceanic conductivity profile is consistent with the presence of water, the situation for the Archean mantle is more ambiguous. In the depth interval between ~150 and 250 km the Archean structure is consistent with the dry model, but water contents as high as ~1000 H/10^6Si cannot be ruled out if the mantle is isotropic. However, a combination of two observations leads us to prefer the "dry" model. First, the electromagnetic (EM) data collected at Carty Lake are approximately consistent with a one-dimensional (1-D) structure [*Schultz et al.*, 1993] and do not show evidence of anisotropy. Second, seismic data from this region show that the upper mantle is strongly anisotropic [*Silver and Kaneshima*, 1993]. The seismic data do not constrain the depth extent of anisotropy. However, studies of other Archean terranes show that anisotropy is generally confined above ~250 km [e.g., *Gaherty and Jordan*, 1995].

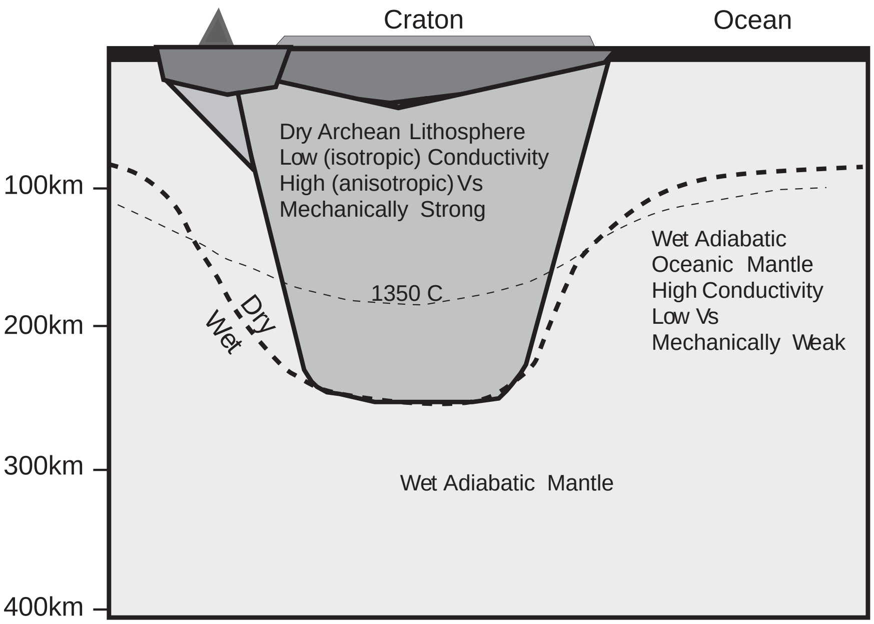


Figure 3. A self-consistent model for the mantle structure beneath the Superior Province and its schematic relation to oceanic mantle. An ~250-km-thick continental root is consistent with both seismic [*Van der Lee and Nolet*, 1997] and electromagnetic data. The craton is inferred to have a dry composition and an anisotropic structure to reconcile the electrical resistivity data and observations of seismic anisotropy. The thick dashed line indicates a transition to a wet underlying mantle. The depth of the wet-dry transition in the oceanic mantle is based on the study of *Hirth and Kohlstedt* [1996]. The depth of the 1350°C isotherm beneath the craton is constrained by thermobarometric analyses of xenoliths from the Superior Province [*Rudnick and Nyblade*, 1999]. The dry composition of the continental root increases its viscosity relative to adjacent oceanic mantle and therefore increases its stability against buoyancy-driven delamination and convective "erosion."

Thus, if the mantle were wet in this region, the EM data would be predicted to show a pronounced anisotropic signature if conduction was accommodated by diffusion of protons. At face value, the lack of this signature indicates that the water content of the mantle olivine beneath the Superior Province is <100 H/10^6Si (i.e., as illustrated in Figure 2d, the conductivity is at least 10 times smaller than that predicted for an anisotropic mantle containing olivine with 1000 H/10^6Si). In contrast, *Lizarralde et al.* [1995] showed that the high conductivity observed at a depth of ~200 km depth in the oceanic profile (e.g., Figure 2b) is consistent with conduction by hydrogen in an anisotropic mantle. Seismic observations indicate that the Pacific mantle is anisotropic to a depth of ~200 km [*Gaherty and Jordan*, 1995; *Ekström and Dziewonski*, 1998].

[14] Both the electrical conductivity and the seismic properties of the continental and oceanic mantle are similar in the depth interval of 300–400 km. The conductivities beneath both the Superior Province and the oceanic mantle from the *Lizarralde et al.* [1995] profile in this depth interval are consistent with an olivine water content of ~3000 H/10^6Si in an isotropic mantle. Seismic data from both oceanic and continental environments indicate that the mantle is isotropic over this depth interval and that the velocities are similar in both settings

[*Grand and Helmberger*, 1984a, 1984b; *Gaherty et al.*, 1996].

3.2. *Implications of a Dry Continental Lithosphere*

[15] The observation of a dry Archean lithosphere has several implications for the origin and evolution of the continental cratons. Our conceptual model consists of a root that extends ~250 km beneath the Superior Province (Figure 3), in contrast to other models of Archean roots that extend to depths of 350 km but in agreement with regional teleseismic studies in this area [*Van der Lee and Nolet*, 1997]. The conductivity model illustrated in Figure 2d suggests that there is a transition from a nominally dry to a wet mantle at a depth of ~250 km. Owing to the influence of water on the viscosity of the mantle [e.g., *Mackwell et al.*, 1985; *Karato and Wu*, 1993; *Hirth and Kohlstedt*, 1996], this transition could also result in a rheological boundary. Such a boundary could be important for understanding the origin and stability of the continental root [e.g., *Pollack*, 1986].

[16] The continental geotherm we used to compare with electrical resistivity data indicates that the mantle is somewhat hotter than predicted by models of cold, deep cratonic roots. In spite of the higher temperatures, the viscosity of the lithospheric mantle can be increased relative to oceanic mantle at the same depth owing to its dry composition. This higher viscosity will help stabilize the continental root against buoyancy-driven delamination and "erosion" due to convection of adjacent mantle [e.g., *Shapiro et al.*, 1999]. The higher temperature also helps provide buoyancy required by geoid data. Thus, while there is a contribution to buoyancy from Fe depletion, the amount of depletion required to satisfy the geoid constraint is not as great. The higher seismic velocities observed for continental roots relative to oceanic mantle at the same depth (i.e., ~200 km) are more difficult to explain if the mantle temperature is as high as indicated by the thermobarometric analysis of xenoliths. However, the dry nature of the continental roots suggested by the analysis of conductivity profiles could help reconcile this problem. The presence of water can result in a significant decrease in seismic velocity at high temperature through anelastic effects [e.g., *Karato*, 1995; *Karato and Jung*, 1998]. Thus a possible explanation for the higher velocity of a relatively high temperature continental root is that the effects of anelasticity are decreased owing to the dry composition of the mantle.

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