Deep electrical structure of the northern Cascadia (British Columbia, Canada) subduction zone: Implications for the distribution of fluids

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ABSTRACT

Long-period magnetotelluric data have been used to image the deep electrical structure of the Cascadia subduction zone in British Columbia, Canada. Zones of elevated electrical conductivity were found in both the forearc and backarc regions and are interpreted as a consequence of the fluid release from subducting slab. A shallow zone of high conductivity beneath Vancouver Island is likely due to fluids that are trapped above the subducting plate. East of this structure is a conductive (~0.03 S/m) forearc mantle wedge that also exhibits low seismic velocities and may be serpentinized. A free fluid phase is required to account for this enhanced conductivity. Elevated conductivities are observed in the upper mantle throughout the backarc (~0.01 S/m) and strongly support the hypothesis of a shallow, convecting asthenosphere. This enhanced upper mantle conductivity can be explained by either hydrogen ion diffusion in olivine minerals, or by a few percent partial melting (<4%).

Keywords: Cascadia subduction zone, magnetotelluric surveys, fluids, electrical conductivity, asthenosphere.

INTRODUCTION

Subduction zones are an important part of the global plate tectonic system because they transport large amounts of water into the Earth's interior, which is then released at depth by compaction and metamorphic reactions (Peacock, 1990). The upward flux of these fluids may profoundly change the physical properties of the overlying crust and mantle, and the resulting change in rheology can influence the deformation pattern (Hyndman et al., 2005). Geophysical observations provide important constraints on the fluid distribution within subduction zones. The Cascadia subduction zone (British Columbia, Canada) is one of the best-studied examples on Earth. At this location, the forearc of the Juan de Fuca plate subduction is characterized by enhanced seismic reflectivity and low seismic velocity (Green et al., 1986; Calvert, 2004), and by high electrical conductivity (Kurtz et al., 1990). These properties can be explained with a combination of free fluids or other hydration processes (Christensen, 2004; Nicholson et al., 2005).

Many backarc regions are also characterized by elevated electrical conductivity in the mid-crust. With higher temperatures in the backarc, this observation has generally been attributed to partial melting (Brasse et al., 2002). Previous studies in the Cascadia subduction zone have also revealed enhanced electrical conductivities in the backarc of this subduction zone (Gough, 1986; Ledo and Jones, 2001). The depth extent of this conductive zone has remained unresolved because previous magnetotelluric (MT) data were restricted to short periods that failed to sample the lower crust or upper mantle. Although several studies have suggested the presence of a shallow asthenosphere (Gough, 1986; Clowes et al., 1995), there are few direct constraints on upper mantle structure in this region.

To address these questions, long-period MT data were collected across the Canadian Cascadia subduction zone in 2003 to image the lower crust and upper mantle for the first time.

MT DATA COLLECTION AND ANALYSIS

Variations in the Earth's natural electromagnetic field were measured at 32 locations (Fig. 1). The data were processed to give estimates of MT and magnetic (tipper) transfer functions over the period 1–20,000 s. Analysis of MT data requires that the dimensionality of the data set is understood and determines if a two-dimensional (2-D) analysis is valid. This study

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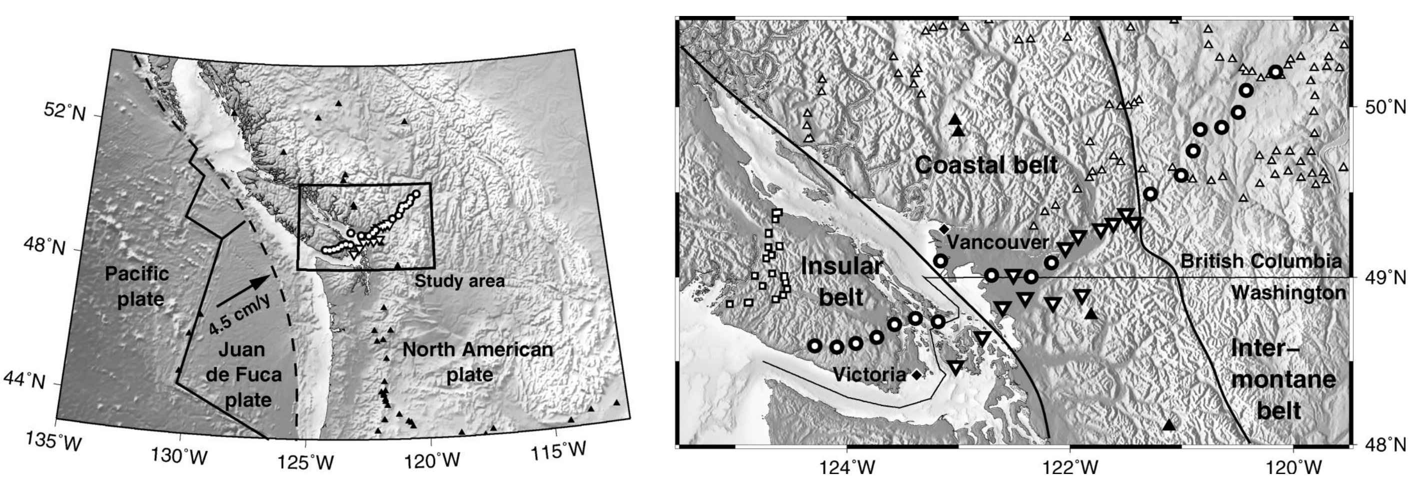

Figure 1. Location of magnetotelluric (MT) sites in northern Cascadia subduction zone. Large symbols denote University of Alberta–POLARIS deployment in 2003 (circles represent LIMS instruments, inverted triangles, NIMS instruments). Small symbols show locations of previous LITHOPROBE MT stations from Kurtz et al. (1990) (squares) and Ledo and Jones (2001) (triangles). Solid triangles mark volcanoes.

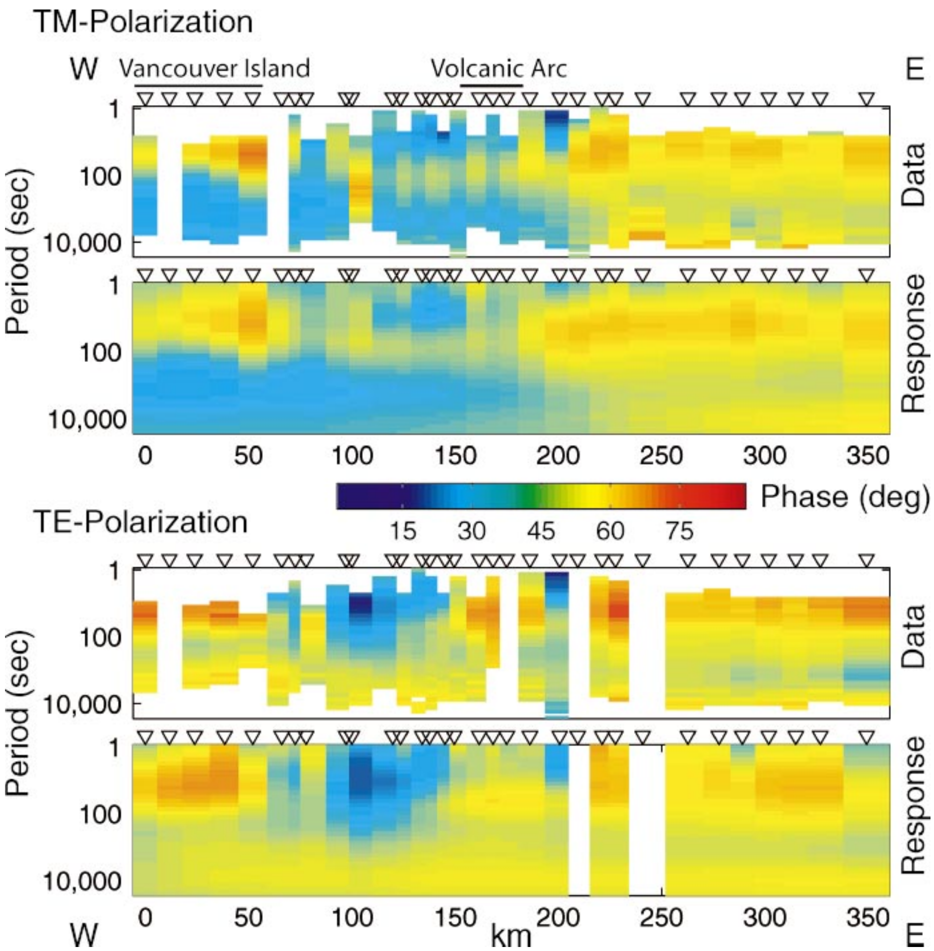

Figure 2. Pseudosections of measured magnetotelluric phase angles and model responses for both polarization modes with currents flowing across (TM) and along (TE) geological strike. Note that phases >45° generally indicate high conductivity values.

used the technique of Caldwell et al. (2004), and analysis of induction vectors (Figs. DR1, and DR2 in the Data Repository[1]). Signals with relatively short periods (<100 s) are sensitive to shallow structure and the seawater. At longer periods, both analyses indicate that N30°W is a well-determined strike direction for lower crustal and upper mantle structure.

Pseudosections of rotated impedance phases show that high conductivities (indicated by phase angles >45°) are found beneath Vancouver Island and east of the volcanic arc (Fig. 2). To further interpret the data, period must be converted to depth. This was achieved by use of a combination of 2-D forward modeling and automated inversion with the algorithm of Rodi and Mackie (2001) applied to the MT apparent resistivities and phases, and projected induction vectors. Note that electrical resistivity is the reciprocal of the conductivity. Static shift coefficients were estimated by the algorithm for the transverse electric (TE) mode. The conductive ocean west of Vancouver Island was included as a fixed structure and the resulting inversion model is shown in Figure 3. The predicted responses (Fig. 2) are in good agreement with the measured data with a root-mean-square misfit of 1.59.

[1]GSA Data Repository item 2006008, Figures DR1–DR3, is available online at www.geosociety.org/pubs/ft2006.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

INTERPRETATION

Vancouver Island Conductor

A conductor is observed beneath Vancouver Island at a depth of ~20 km (E in Fig. 3). This is similar to the feature reported by Kurtz et al. (1990), and corresponds to the dipping conductor resolved in Oregon by Wannamaker et al. (1989). This conductor is coincident with a 5–8-km-thick zone of seismic reflectivity and low shear wave velocity, the so-called E layer. The original interpretation was that these anomalies represent the top of the subducting Juan de Fuca plate (Green et al., 1986). It has also been suggested that the bottom of this layer coincides with the top of the oceanic plate (Nedimovic et al., 2003), or that it represents a region of sheared, imbricated crustal rocks above the subducted plate (Calvert, 2004). A low-velocity zone imaged in teleseismic data may coincide with the E reflector and mark the top of the subducting plate (Nicholson et al., 2005). Because only five MT stations were deployed on Vancouver Island in 2003, the position of this conductor cannot be resolved more precisely than by Kurtz et al. (1990). However, because of the correlation of seismic and MT results, interconnected fluids released from the slab are likely responsible for the anomalous observations (Hyndman and Shearer, 1989).

Lower Mainland Conductor

Farther east, a shallow conductor is associated with the sedimentary sequence of the Fraser River delta (100–140 km along profile). In this region, a deeper conductor (A in Fig. 3) is present at 40–60 km depth. To determine if A is an artifact, a constrained inversion was used. The conductor was removed from the model and the inversion restarted with the edited region forced to be more resistive (0.001–0.01 S/m). The inversion was unable to regain the same statistical fit, indicating that feature A is required by the data (Fig. DR3; see footnote 1). A separate analysis of either the northern (British Columbia) or the southern (Washington) MT sites of this area in the inversion gave comparable results.

Would a high conductivity feature be expected here? Teleseismic receiver function data (Nicholson et al., 2005) and LITHOPROBE seismic refraction data (Clowes et al., 1995) indicate that there is a weak Moho velocity contrast in this region, consistent with low seismic velocities in the upper mantle. In interpreting a similar observation from the southern Cascadia subduction zone, Bostock et al. (2002) proposed that this velocity reduction was the result of serpentinization of the forearc mantle wedge due to fluids released from the subducting slab. However, Christensen (2004) reported that lizardite, the form of serpentinite with a pronounced low seismic velocity, is not stable at upper mantle pressures and temperatures. Serpentinite in the mantle wedge is likely to be present as antigorite, which has seismic properties closer to other lower crustal and upper mantle materials. Thus, other explanations may be required to account for the reduced seismic velocity in the mantle wedge.

It was once believed that serpentinite had an elevated electrical conductivity as a result of possible high magnetite content (Stesky and Brace, 1973). However, recent studies have reported a low conductivity of 0.001 S/m for dry serpentinite at forearc mantle temperatures (Bruhn et al., 2004). One possibility is that free aqueous fluids are present in the mantle wedge. Assuming that the fluid had the same conductivity as seawater, then Archie's Law (1942) with an exponent of 1.5 requires a fluid fraction of 5% to give a bulk conductivity of 0.03 S/m. The upper bound of Hashin and Shtrikman (1962) requires a fraction of 1%–

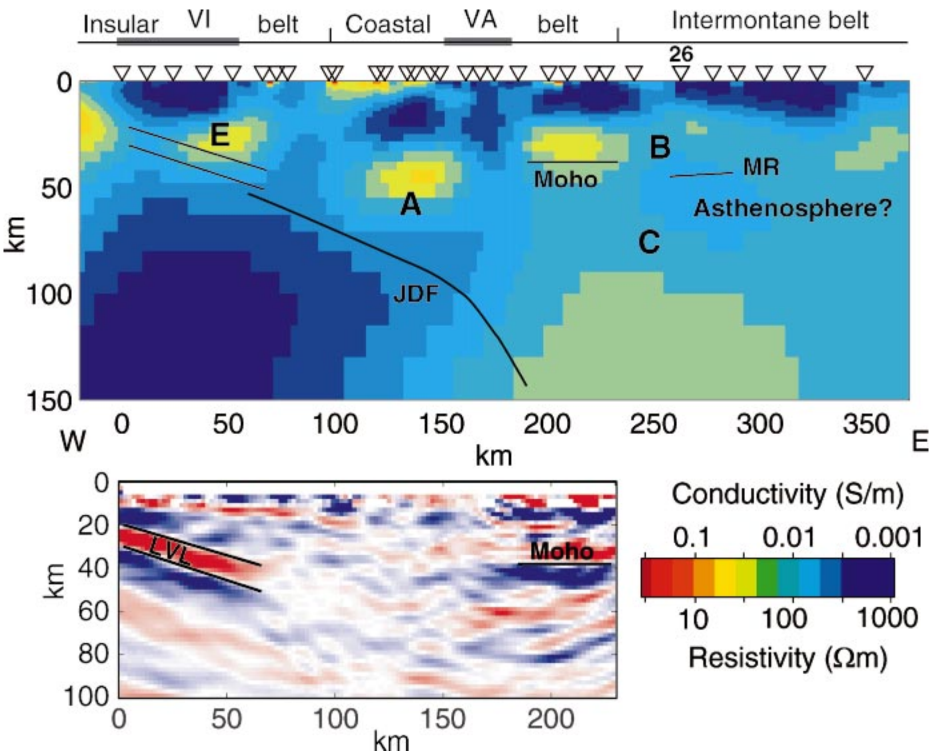

Figure 3. Top: Conductivity model for Cascadia subduction zone obtained from joint inversion of magnetotelluric impedance and magnetic tipper data. Bottom: Relative seismic S-wave velocities from receiver function analysis of Nicholson et al. (2005). High conductivity beneath backarc crust hints at shallow asthenosphere, in accordance with observed seismic wide-angle reflection, supposed to mark base of lithosphere (MR—mantle reflection; Clowes et al., 1995). JDF—top of subducted Juan de Fuca plate, as sketched in Clowes et al. (1995); VA—volcanic arc; VI—Vancouver Island; LVL—Low-velocity layer. Resolution of structures A and C is investigated in Figure DR2 (see footnote 1).

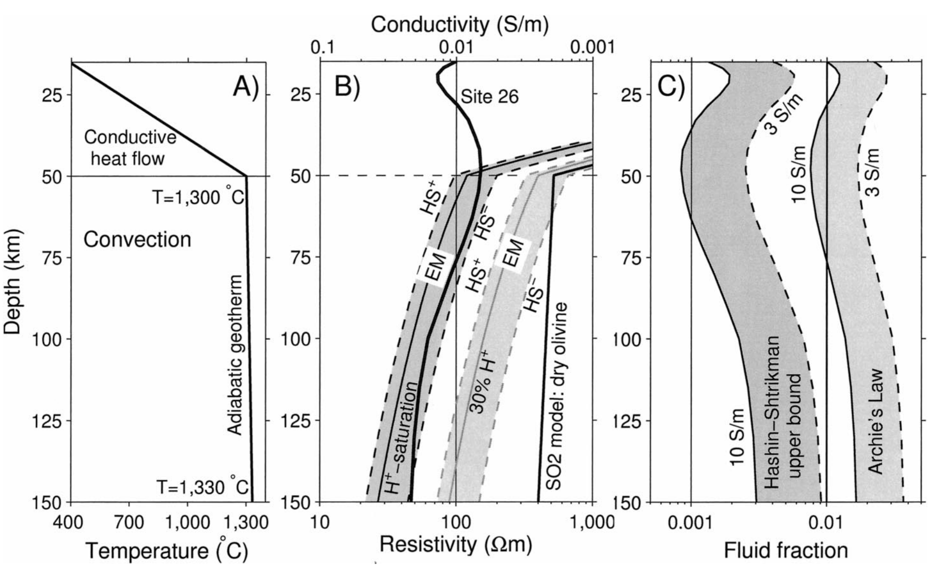

Figure 4. Possible explanations of elevated backarc mantle conductivities by either hydrogen diffusion through olivine minerals or by interconnected conductive fluid phase. A: Simplified geotherm used to calculate expected conductivities based on H^+ diffusion for 100% and 30% hydrogen-saturated olivine, shown in B, together with modeled conductivities below site 26 (see Fig. 3). $HS^{\pm}$ mark upper and lower Hashin-Shtrikman bounds, used to convert highly anisotropic conductivities of wet olivine to isotropic values. EM—effective media theory (Shankland and Duba, 1990). Also shown is SO_2 model for dry olivine from Constable et al. (1992). C: Fluid fractions reproducing modeled conductivities, assuming two-phase medium with resistive host (0.001 S/m) and fluid conductivity of 3 and 10 S/m, using upper Hashin-Shtrikman bound for ideal connectivity and Archie's Law with exponent 1.5 for conservative estimate.

2%. It has also been proposed that the material in the wedge is a stack of imbricated crustal units (Clowes et al., 1995). In this case, fluids would still be required to account for the high conductivity because it exceeds estimates for dry crustal rocks at moderate forearc temperatures. A low-velocity forearc wedge is present along much of the Cascadia subduction zone (Brocher et al., 2003).

MT data collected during the Electromagnetic Sounding of the Lithosphere and Asthenosphere Beneath the Juan de Fuca Plate (EMSLAB) experiment in Oregon showed an anomaly of similar conductivity as structure A at a slightly shallower depth in the lower crust, interpreted by Wannamaker et al. (1989) as a zone of upward-migrating fluids released from the slab. More recent analyses confirm that the EMSLAB data also require elevated forearc mantle conductivities beneath the continental crust (Vanyan et al., 2002).

Shallow Asthenosphere

The Cascade volcanic arc is not associated with a shallow conductivity anomaly in Figure 3, but exhibits a pronounced lateral change in lower crustal and upper mantle structure. East of the volcanic arc, the upper mantle conductivity (C in Fig. 3) is an order of magnitude higher than in the oceanic lithosphere to the west. Imaging beneath a conductor requires care, so a sensitivity analysis was performed, which showed that an upper mantle conductivity of ~0.01 S/m is required by the MT data (Fig. DR3; see footnote 1). This result supports the idea that the asthenosphere is present at shallow depths. Asthenospheric convection is also required to explain high heat flow data (~75 mW/m^2) in the backarc and isostatically balanced high elevations in conjunction with a thin crust (Hyndman et al., 2005). Although it has been suggested that circulation in the asthenospheric wedge is driven by traction and cooling along the top of the plate, Currie et al. (2004) showed that a uniformly high heat flow requires small-scale convection cells with relatively high flow rates. The driving source for this flow was inferred by Dixon et al. (2004) to be a viscosity reduction caused by water released from the subducting slab.

Laboratory measurements suggest that water in hot mantle materials can enhance the electrical conductivity in two ways: hydrogen ions diffusing through olivine, carrying electric current (Mackwell and Kohlstedt, 1990); and water reducing the melting temperature and increasing the amount of partial melt (Ulmer, 2001). These two scenarios are quantified in Figure 4. Conductivities resulting from H^+ ion diffusion in olivine were calculated by use of diffusivity and solubility data (Bai and Kohlstedt, 1992), following Lizarralde et al. (1995). This calculation depends strongly on temperature because the diffusivities are thermally activated and governed by an Arrhenius Law. A simplified geotherm was used with a shallow asthenosphere as required by heat flow data (Fig. 4A; Currie et al., 2004). The results are shown in Figure 4B and indicate that olivine minerals that are 50%–100% saturated with H^+ ions can explain the enhanced upper mantle conductivity in the backarc. However, this mode of conduction is not universally accepted.

In the alternative scenario, can the conductivities be explained on the basis of partial melting? Conductivities of melt phases are typically found in the range 1–10 S/m at temperatures of 1200–1400 °C (Tyburczy and Waff, 1983). Melt fractions required to explain observed conductivities in the upper mantle were computed for a two-phase medium with a resistive host (0.001 S/m) and a conductive fluid (3 and 10 S/m). Use of the upper bound of Hashin and Shtrikman (1962) for complete connectivity gives a minimum fluid fraction estimate of <1% (Fig. 4C). Archie's Law (1942) with exponent 1.5 provides a conservative estimate (Hyndman and Shearer, 1989) and yields fluid fractions of <4%.

A high degree of interconnectivity of the fluid phase implies that the mineral matrix is permeable, and the presence of free fluids at depth requires a sustained fluid supply. Upward migration of melt is controlled by the supply rate from slab-induced melting (Hyndman and Shearer, 1989), and solidification of the partial melt at the base of the crust might lead to accumulation of larger amounts of water that could explain the observed lower-crustal conductivities (B in Fig. 3) observed in the backarc.

In conclusion, the conductivity anomalies described in this study appear to be related to the release of aqueous fluids from the subducting slab. An aqueous fluid content of 1%–5% for seawater salinity is required to explain the observed conductivity in the forearc region. The conductivity enhancement in the backarc can be explained by hydrogen diffusion in olivine minerals at high temperatures (>1200 °C), interconnected partial melts, or both. These observations provide strong support for the idea that backarc regions have a shallow convecting asthenosphere.

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