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ELECTROMAGNETIC IMAGES OF REGIONAL STRUCTURE IN THE SOUTHERN CANADIAN CORDILLERA

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Abstract. As part of Lithoprobe's Southern Cordilleran transect investigations, magnetotelluric (MT) soundings were made at 160 sites providing unprecedented coverage from the Rockies to the west coast. Striking lateral variation, which spatially correlates with the morphogeological belt boundaries, is apparent at periods sensing the lower crust (≈10 s). For the Rockies, MT phases are around 35^0, indicative of a moderately resistive (100's - 1000's Ω·m) North American Basement. Foreland belt phases are transitional and increase from 60^0 in the east to 70^0 in the west. Omineca and Coast belt phases are high (75^0), implying a conductive (10-30 Ω·m) lower crust, whereas Intermontane belt phases are more than 10^0 lower (equivalent to ≈150 Ω·m). The regional variation in conductivity correlates to first order with surface heat flow changes along the profile and is also correlative with coincident seismic reflection sections in some aspects.

Introduction

The Cordillera of western North America form an active laboratory for understanding continental growth by accretion, comprising an asymmetric orogen bounded by thrust faults on both sides (Monger, 1989), and modern interpretation defines a collage of distinct terranes (Coney et al., 1980; Monger et al., 1982). The Canadian Cordillera are mainly linear through their 2000 km length, in contrast to the more complex Alaskan and conterminous U.S. segments. The dominant features are five physiographic provinces (Figure 1) that form NNW-striking belts which are, in the main, fault-bounded, and their boundaries approximate major terrane boundaries.

Foreland belt (FB): mid-Proterozoic to Upper Jurassic miogeoclinal and platformal rocks, shortened and translated northeastward in the Late Jurassic onto North American basement.

Omineca belt (OB): mid-Proterozoic to mid-Paleozoic miogeoclinal rocks, intruded by Jurassic and Cretaceous plutons, metamorphosed in mid-Mesozoic to early-Tertiary to higher grade than in the bounding belts.

Intermontane belt (IB): more subdued physiographically than the two flanking belts. Upper Paleozoic to mid-Mesozoic volcanosedimentary marine sequences followed by Cretaceous and Tertiary non-marine sequences. Deformation from early Mesozoic to Neogene.

Coast belt (CB): metamorphosed late Paleozoic to Tertiary sedimentary and volcanic strata and dominant granitic rock, mainly of Cretaceous and Tertiary ages.

Insular belt: most recently accreted. Upper Cambrian to Neogene volcanic and sedimentary strata. Deformed from Paleozoic to Neogene (Monger et al., 1982).

Seismic reflection and magnetotelluric (MT) data were acquired by contractors in southern British Columbia (Figure 1) as part of Lithoprobe's Southern Cordillera transect studies. High MT data quality and station density (over 200 sites) enable qualitative interpretation from suitable displays. Static shift corrected apparent resistivities are transformed into the depth domain, from which we draw quantitative inferences. Finally, we speculate about conditions in the deep crust and correlations with seismic reflection and geothermal data.

Seismic results

The significant results from seismic reflection along the lines shown on Figure 1 (Cook et al., 1992) are depicted in cartoon form in Figure 2.

(1.) The Moho is a sharply defined boundary with only 3 km of relief over 300 km from the Purcells to the Coast Mountains. There is a major 10 km "step" beneath the Purcell Anticlinorium consistent with crustal penetration by the Slocan Lake Fault (slf). This has been confirmed by inversion of data from a recent seismic refraction survey (White et al., 1991).

(2.) Lower crustal reflections east of the Fraser River sole into a horizon thought to be the top of a thin tongue of North American Basement (NAB) that may mark a accretionary detachment since Early Jurassic.

(3.) Surface geological features correlate with reflectors tracable into the middle and lower crust. Contrary to a widely held view (e.g., Matthews and Cheadle, 1986), there is no simple division into a transparent upper crust and a reflective lower crust, even though much of the region has undergone considerable Eocene extension.

(4.) Three crustal arches, the Monashee complex, the Vernon anticline and the Nicola horst, are interpreted to have formed during Mesozoic compression and exposed during Eocene extension.

Previous EM results

Geomagnetic studies during the early 1960s (see Law and Riddihough, 1971) found low vertical to horizontal magnetic field ratios in western and central southern British Columbia compared to further east. Caner and Cannon (1965) showed this to be a general feature of the North American Cordillera and ascribed it, together with the high heat flow and low P_n upper mantle observed, to a rise in mantle isotherms, as suggested by White and Savage (1965). The region of Kootenay Lake (Figure 1) was found to be the eastern boundary of this zone, thought to be due to lateral variation in the mantle (Caner and Cannon, 1965). Subsequent MT data were more consistent with a low resistivity (10±5 Ω·m) lower crustal layer west of Kootenay Lake beginning at a depth of 15±5 km, thickness 20-40 km, whereas to the east the whole crust was modeled as resistive (>1000 Ω·m, Caner et al., 1969).

A large-scale magnetometer array study in 1980 (Gough et al., 1982) confirmed both the two-dimensional (2D) nature of the gross conductivity structure and the exis-

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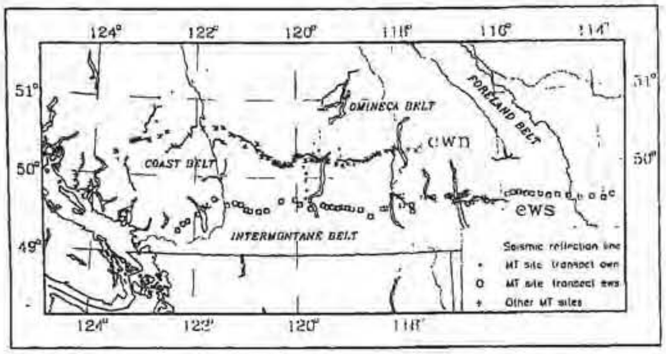

Fig. 1 Locations at which seismic and MT measurements were made in southern British Columbia. MT date interpreted in this paper came from the two east-west transects labeled *ews* and *ewn*. Kootenay Lake lies directly below the label *ewn*.

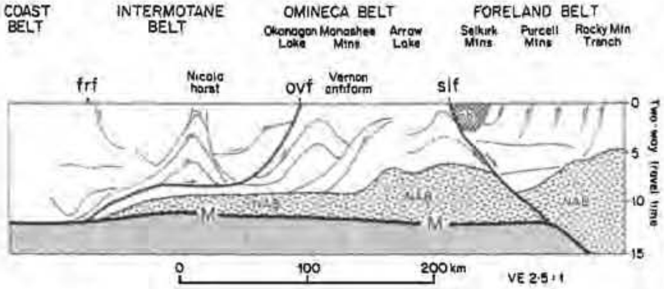

Fig. 2 Cartoon of the seismic interpretation from Cook et al.(1992). NAB: North American Basement; M: Moho; frf: Fraser River fault; ovf: Okanagan Valley fault; slf: Slocan Lake fault.

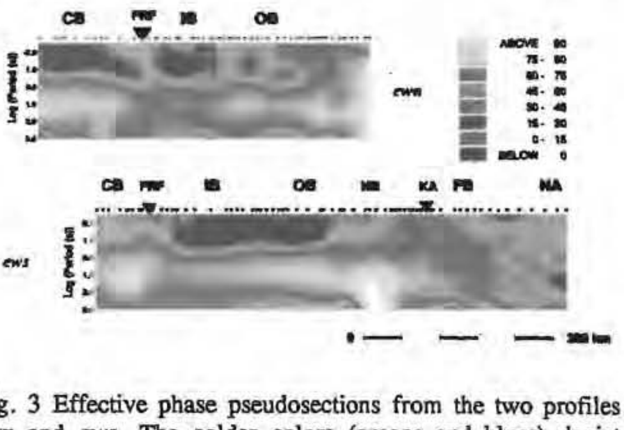

Fig. 3 Effective phase pseudosections from the two profiles *ewn* and *ews*. The colder colors (greens and blues) depict phases less than 45°(resistive structures), whereas the hotter colors (reds and yellows) depict phases greater than 45°(conductive structures). CB: Coast belt; IB: Intermontane belt; OB: Omineca belt; FB: Foreland belt; FRF: Fraser River fault; NB. Nelson batholith; KA: Kootenay Arc.

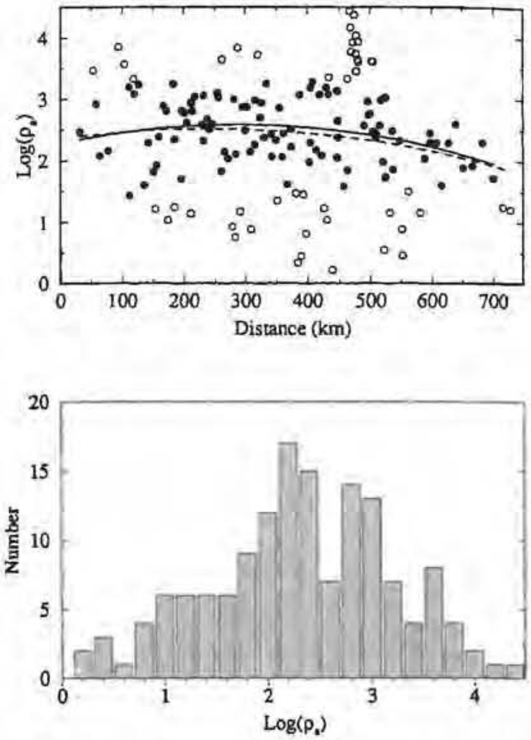

Fig. 4 E-pol apparent resistivities at 10 s from all sites along profiles *ewn* and *ews*. *Upper panel:* Variation with distance east of 124^0 longitude. Solid circles are within one standard error of the mean, whereas open circles are outside one standard error. Solid line is a quadratic regression to the solid circles; Dashed line is a quadratic regression to all the data. *Lower panel:* Histogram of the data.

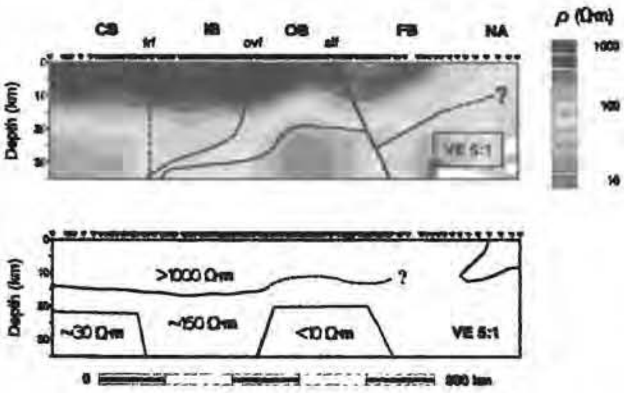

Fig. 5 *Upper panel:* Neblett-Bostick depth sections from the E-pol phases and shifted apparent resistivies from all sites along both profiles, *ewn* and *ews*. The significant seismic horizons of Fig. 2 are shown for comparison. *Lower panel:* Cartoon of the regional electrical structure.

tence of the high conductivity zone, named the Canadian Cordilleran Regional (CCR) conductor (Gough 1986), beneath much of the region. An array in northwestern U.S. mapped the continuation of the CCR conductor into Washington, where it abuts against resistive blocks associated with the Columbia Embayment and the Blue Mountains (Gough et al., 1989), znd it was concluded that the CCR conductor is mainly at lower crustal depths.

MT phase images

Phases considered here are those of the "effective impedance" (Berdichevsky and Dmitriev, 1976) given by the square root of the determinant of the MT impedance tensor. Such phases are little affected by galvanic 3D distortion caused by near-surface inhomogeneities. MT phase is 45^0 for a uniform zone; phases greater than 45^0 indicate a zone of higher conductivity than the zone above it whereas phases less than 45^0 indicate the converse.

Figure 3 shows phase pseudosections from the two east-west profiles *ews* (east-west south) and *ewn* (east-west north) separatedby 70-100 km along strike.

(1) At periods greater than 0.1 s the two profiles have similar phase values on a gross scale.

(2) There are five main "blocks" of phases at periods where the fields are sampling the lower crust, i.e., $\approx$10 s.

NA: Phases from stations in the Rockies and Albertan foothills (the eastern part of profile *ews*) are below 45^0 with decreasing values to the east.

FB: Stations in the Foreland belt have transitional phases from 60^0 to 70^0 with higher values to the west.

OB: Omineca belt phases are generally around 75^0.

IB: Phases in the Intermontane belt are 60-65^0.

CB: Coast belt phases generally exceed 75^0.

(3) There is an abrupt lateral change in phase at 10 s near the Fraser River fault (frf). Jones et al. (1992) show that the EM data support a crustal extent for the fault.

(4) Phases for stations on the Nelson Batholith (NB) exceed 90^0, which results from highly complex 3D induction effects due to the batholith (Jones et al., 1988).

Niblett-Bostick Depth Sections

To determine the resistivity-depth variation, one needs to estimate undistorted regional levels of the apparent resistivity (ρ_a) curves. These levels are affected by static shifts (Jones, 1988) and conductivity variations in the uppermost crust. These latter variations are important for the complete MT study, but are effectively "noise" on the regional scale and must be removed. Over an earth which can be modeled as 2D over a 1D substratum, the theoretical E-polarization (E-pol) mode (electric fields parallel to strike) ρ_a model curves from all sites have the same long period asymptote. In contrast, the B-pol (electric fields perpendicular to strike) ρ_a curves at long periods are parallel but displaced from each other. Thus, it is the E-pol ρ_a data which must be curve-shifted prior to transformation or 1D modeling. A first-order technique for correcting the MT data involves fitting the apparent resistivities at a given period from all sites to a parametric function; the curves are then shifted in log-domain to match the functional value for that location.

Figure 4 shows the E-pol apparent resistivities from all 135 sites on the two profiles at 10 s period as a function of distance east of 124^0 longitude (upper panel) and in histogram form (lower panel) (10 s was chosen to give penetration through the upper crust). The mean $\log_{10}(\rho_a)$ is 2.4 $\pm$0.9 (s.d.). At distances of 460-490 km ρ_a is upward-biased by the Nelson batholith. There is obviously a regional variation, with lower ρ_a values at each end.

The phase pseudosections suggest using a low-order polynomial to represent the lateral variation in lower crustal resistivity. The dashed and full lines are quadratic polynomial fits to all the data and the filled symbols respectively (Figure 4). Clearly the outliers cause little bias to the regression. The E-pol curves were shifted such that the apparent resistivities at 10 s matched those of the polynomial, and both profiles were merged into a single east-west transect. The E-pol phases and shifted apparent resistivities were Niblett-Bostick transformed (Jones, 1983) into the depth section shown in Figure 5 (upper panel). Also shown are the major boundaries defined by the seismic reflection survey (Figure 2). The image in Figure 5 should be interpreted with caution; the Niblett-Bostick transform gives a good *qualitative result*, but can be quantitatively poor. However, previous analyses gave a resistivity-depth model west of Slocan Lake fault which is in agreement with Figure 5 (Jones et al., 1988). A highly resistive upper crust (>1000 Ω·m) to 9 km overlies a moderately resistive middle crust ($\approx$150 Ω·m) to 19 km, below which is a conductive lower crust (5 Ω·m). Also, two-dimensional inversion of data from around the Fraser River fault (frf) gave a model which is also in agreement with Figure 5 (Jones et al., 1992). A conductive lower crust to the west of the fault is juxtaposed against a more resistive lower crust to the east.

These corroborations give us confidence that the resistivity image of Figure 5 is valid in its gross features, which are depicted in cartoon form in the lower panel (Figure 5).

Upper crust: Here the curve shifting has smoothed out much structure. The lower resistivities which dip to the west at the eastern end of the profile may represent sediments underthrust beneath the Rockies.

Middle crust: In the color scale used, yellow-green denotes 300 Ω·m, which is transitional between resistive upper crust and conductive lower crust for a typical continental region (e.g., Jones 1987, Figure 2). This contour, with its shallowest levels beneath the Omineca belt, correlates with heat flow (Lewis et al., 1991) and is in harmony with results from MT transects along strike further northwest (Gough and Majorowicz, 1992). Given the global correlation between the cessation of crustal earthquakes and the top of the zone of enhanced crustal conductivity, this 300 Ω·m contour may approximate the depth to the brittle-ductile,or frictional/quasi-plastic (Sibson, 1982), transition in the middle crust.

One explanation for increased seismic reflectivity and electrical conductivity in the middle crust is the presence of an impermeable zone beneath which fluids are trapped (Jones, 1987). This model has been questioned for "old" regions on petrological grounds (Yardley, 1986), but for geologically "young" regions, such as the Cordillera which have been accreted to North America since the early Jurassic, metamorphic fluid retention times of the order of 100 Ma may be reasonable (Bailey, 1990). An alternative source of free fluids at these depths could be deep-probing meteoric fluids (Nesbitt and Muehlenbachs, 1991).

Lower crust: The resistivity of the lower crust varies significantly with <10 Ω·m beneath the Omineca belt, $\approx$150 Ω·m beneath the Intermontane belt, and 30 Ω·m beneath the Coast belt. Beneath the eastern end of profile, i.e., for cratonic North American basement, the lower crustal resistivity is greater than 200 Ω·m.

Relatively abrupt changes in lower crustal resistivity at the locations of the Slocan Lake (slf) and Fraser River (frf) faults have previously been noted in Jones et al. (1988, 1992). Inversion of recent seismic refraction data shows a marked change in seismic velocity, by 0.3 km/s, near the Slocan Lake fault, with higher velocity to the west (6.5 km/s) (White et al., 1991). At depths greater than 22 km beneath the Valhalla complex, near the eastern boundary of the Omineca belt just west of the Slocan Lake fault, there appears to be a good correlation between a zone devoid of seismic reflections, an MT high conductivity zone, and modeled elevated crustal temperatures (Jones et al., 1988; Lewis et al., 1991). The latter two observations suggest that the lower crust in this region may be partially molten (Lewis et al., 1991), but this may be at variance with the observed velocity structure.

Beneath the western Omineca belt and most of the Intermontane belt (at least as far west as the Okanagan Valley) the lowermost crust is now thought to be cratonic North American basement (Ghosh, 1991), although more highly metamorphosed and deformed than its counterpart east of the Slocan Lake fault. A thin "tongue" of such rocks would be unresolvable in these MT data. What is clear is that the exotic lower crusts of the overlying allochthonous terranes have much lower resistivities than the lower crust to the east of the Slocan Lake fault.

Our interpretation is that this variation is mainly due to varying porosity and/or salinity of the fluid, and that there are additional conductivity enhancements due to partial melt beneath the Garibaldi volcanic belt (in the Coast belt) and beneath the eastern part of the Omineca belt. The mantle upflow proposed by Gough (1986) may now be located beneath the Omineca Belt, on the basis of both MT and geothermal evidence.

Conclusions

We have shown that the CCR conductor is not homogeneous laterally. The resistivity-depth pattern that we have obtained spatially correlates in its lower crustal part with the surface morphogeological belts. Such a correlation is difficult to reconcile with "thin-skinned" tectonic models of the region.

There has been much discussion of the cause of enhanced lower crustal reflectivity, and it has been recognized by many that no one cause is likely, nor should be sought, but that it is very much dependent on "local" factors. Non-seismic information can aid in discriminating between competing hypotheses, and MT results have been offered as useful in this regard (e.g., Gough, 1986; Jones, 1987). It is apparent from this study, however, that there is not always a perfect correlation between seismic and MT results.

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References

Bailey, R.C., Trapping of acqueous fluids in the deep crust, *Geophys. Res. Lett.*, *17*, 1129-1132, 1990.

Berdichevsky, M.N. and Dmitriev, V.I., Basic principles of interpretation of magnetotelluric sounding curves, in *Geoelectric and Geothermal Studies*, edited by A. Ádám, KAPG Geophysical Monograph, Akadémiai Kiadó, 165-221, 1976.

Caner, B. and Cannon, W.H., Geomagetic depth-sounding and correlation with other geophysical data in western North America, *Nature*, *207*, 927-929, 1965.

Caner, B. et al., A large-scale magnetotelluric survey in western Canada, *Can. J. Earth Sci.*, *6*, 1245-1261, 1969.

Coney, P.J., Jones, D.L. and Monger, J.W.H., Cordilleran suspect terranes, *Nature*, *288*, 329-333, 1980.

Cook, F.A. et al., Lithoprobe crustal reflection cross section of the southern Canadian cordillera I: Foreland Thrust and Fold belt to Fraser River Fault, *Tectonics*, *11*, 12-35, 1992.

Ghosh, D.K., *Nd and Sr isotopic constraints on the timing of obduction of Quesnellia onto the western edge of North America*, Publication from the LITHOPROBE Cordilleran Transect Workshop held in Calgary on 16th - 17th March, in Workshop Proceedings pp. 113-127, 1991.

Gough, D.I., Mantle upflow tectonics in the Canadian Cordillera, *J. Geophys. Res.*, *91*, 1909-1919, 1986.

Gough, D.I. et al., Conductive structures in southern Canada: a regional magnetometer array study, *Can. J. Earth Sci.*, *19*, 1680-1690, 1982.

Gough, D.I. et al., Conductive structures and tectonics beneath the EMSLAB land array, *J. Geophys. Res.*, *94*, 14,099-14,110, 1989.

Gough, D.I. and Majorowicz, J.A., Magnetotelluric soundings, structure and fluids in the southwest Canadian Cordillera, *Can. J. Earth Sci.*, *July*, , 1992.

Jones, A.G., On the equivalence of the "Niblett" and "Bostick" transformations in the magnetotelluric method, *J. Geophys.*, *53*, 72-73, 1983.

Jones, A.G., MT and reflection: an essential combination, *Geophys. J.R. Astron. Soc.*, *89*, 7-18, 1987.

Jones, A.G., Static shift of magnetotelluric data and its removal in a sedimentary basin environment, *Geophysics*, *53*, 967-978, 1988.

Jones, A.G. et al., Magnetotelluric observations along the LITHOPROBE southeastern Canadian Cordilleran transect, *Geophys. Res. Lett.*, *15*, 677-680, 1988.

Jones, A.G. et al., Electromagnetic constraints on strike-slip fault geometry – the Fraser River fault system, *Geology*, *20*, 561-564, 1992.

Law, L.K. and Riddihough, R.P., A geographical relation between geomagnetic variation anomalies and tectonics, *Can. J. Earth Sci.*, *8*, 1094-1106, 1971.

Lewis, T.J., Bentkowski, W.H. and Hyndman, R.D., Crustal temperatures near the Lithoprobe Southern Cordilleran transect, *Can. J. Earth Sci.*, in press, 1991.

Matthews, D.H. and Cheadle, M.J., Deep reflections from the Caledonides and Variscides west of Britain and comparison with the Himalayas, in *Reflection Seismology: A Global Perspective*, edited by M. Barazongi and L. Brown, Amer. Geophys. Union, Geodynamics Series, **13**, 5-19, 1986.

Monger, J.W.H., Overview of Cordilleran geology, in *Western Canada Sedimentary Basin: A Case History*, edited by B.D. Ricketts, Can. Soc. Petrol. Geol., 9-32, 1989.

Monger, J.W.H., Price, R. and Templeman-Kluit, D., Tectonic accretion of two major metamorphic and plutonic welts in the Canadian Cordillera, *Geology*, *10*, 70-75, 1982.

Nesbitt, B.E. and Muehlenbachs, K., Stable isotopic constraints on the nature of the syntectonic fluid regime of the Canadian Cordillera, *Geophys. Res. Lett.*, *18*, 963-966, 1991.

Sibson, R.H., Fault zone models, heat flow, and the depth distribution of earthquakes in the continental crust of the United States, *Bull. Seism. Soc. Am.*, *72*, 151-163, 1982.

White, W.R.H. and Savage, J.C., A seismic refraction and gravity study of the Earth's crust in British Columbia, *Bull. Seism. Soc. Amer.*, *55*, 463-486, 1965.

White, D. et al., Crustal structure of the Canadian eastern cordillera from seismic refraction, *EOS*, *72*, 297, 1991.

Yardley, B.W.D., Is there water in the deep continental crust? , *Nature*, *323*, 111, 1986.

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