Utility of Magnetotelluric Data in Unravelling the Stratigraphic-Structural Framework of the Nechako Basin (NTS 092N, 093C, B, G, H), British Columbia, from a Re-Analysis of 20-Year-Old Data[1]

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KEYWORDS: magnetotelluric data, electromagnetic data, Nechako Basin

INTRODUCTION

The Canadian Cordillera, where the Juan de Fuca oceanic plate is currently being subducted beneath the North American continent, is comprised of oceanic and island arc terranes accreted to the western edge of ancestral North America since the Neoproterozoic (Gabrielse and Yorath, 1991; Monger *et al*., 1972; Monger and Price, 1979; Monger *et al*., 1982). The Mesozoic Nechako Basin, located within the Intermontane Belt of the Canadian Cordillera, includes overlapping sedimentary sequences deposited in response to this terrane amalgamation. Regional transcurrent faulting and associated east-west extension, beginning in the Late Cretaceous, was accompanied by the extrusion of basaltic lava in Eocene and Miocene times that forms a variably thick sheet, averaging 100 m in thickness and possibly extending up to 1 km thick in isolated places, covering much of the basin. The main geological elements within the southern Nechako area include Miocene flood basalt, Tertiary volcanic and sedimentary rocks, Cretaceous sedimentary rocks and Jurassic sedimentary rocks (Fig. 1). Understanding the distribution and structure of these sedimentary rocks at depth is vital for assessing possible resources. An assessment of the hydrocarbon potential based on existing geological information and well data, performed by the Geological Survey of Canada in 1994, suggested that the Nechako Basin may contain as much as a trillion cubic metres of gas and a billion cubic metres of oil (Hannigan *et al*., 1994). The thick volcanic cover limits the transmission of reflection seismic waves and has made it difficult to determine the physical boundaries of the basin, impeding exploration.

Magnetotelluric (MT) data can distinguish between lithological units, as flood basalt and igneous basement rocks typically have electrical resistivity values of >1000 ohm-m, whereas sedimentary rocks are more conductive with values of 1 to 1000 ohm-m. In the 1980s, the University of Alberta recorded MT data across the Nechako Basin between 52° and 53° latitude using short period automatic MT system (SPAM) instruments that recorded data in the frequency range of 0.016 to 130 Hz (Fig. 1; Majorowicz and Gough, 1991). These data, along with other geophysical information, have been re-examined using modern analysis techniques to assess the usefulness of undertaking MT in the Nechako region and to determine specific data acquisition techniques for future MT surveys that will provide higher-resolution crustal imaging.

Initial analysis of the data collected in the 1980s (Fig. 1) revealed structure that was obtained from the phase pseudosections along a profile consisting of 26 sites. Depth estimates were based on a one-dimensional inversion of six of these sites (Majorowicz and Gough, 1991). The data revealed an anomalously conductive upper crust (10–300 ohm-m) in the eastern half of the profile and was attributed to the presence of saline water in pore spaces and fractures. The western half of the profile showed the presence of an eastward-dipping resistive feature. The resistive body has been interpreted to represent granodiorite or other crystalline rocks of the Coast Belt that extends beneath a thin layer of basalt (Gough and Majorowicz, 1992; Majorowicz and Gough, 1994; Jones and Gough, 1995; Ledo and Jones, 2001).

Since the early 1990s, considerable advancements in processing software and techniques, as well as modelling and interpretations packages, have significantly improved our abilities to analyze and interpret MT data. Many of these new techniques, including strike analysis, distortion decompositions and modern 2-D modelling inversions, have been applied to the MT data collected in the 1980s. The results of these analyses and an examination of the resolving power of MT based on borehole logs have improved our understanding of the data limitations and enhanced our knowledge of the resolution of the 2-D models in the area, particularly at crustal depths within the Nechako sedimentary basin. Our studies indicate that future MT studies can reveal substantially more shallow information related to the basin itself.

MAGNETOTELLURIC DATA ANALYSIS

The magnetotelluric (MT) method involves measuring natural variations in the Earth's electric and magnetic fields in order to provide information on the electrical conductivity structure of the subsurface (*e.g.*, Jones, 1992). The measurement of mutually perpendicular components of the electric and magnetic fields at the surface of the Earth allows us to calculate MT response curves, phase lags and ap-

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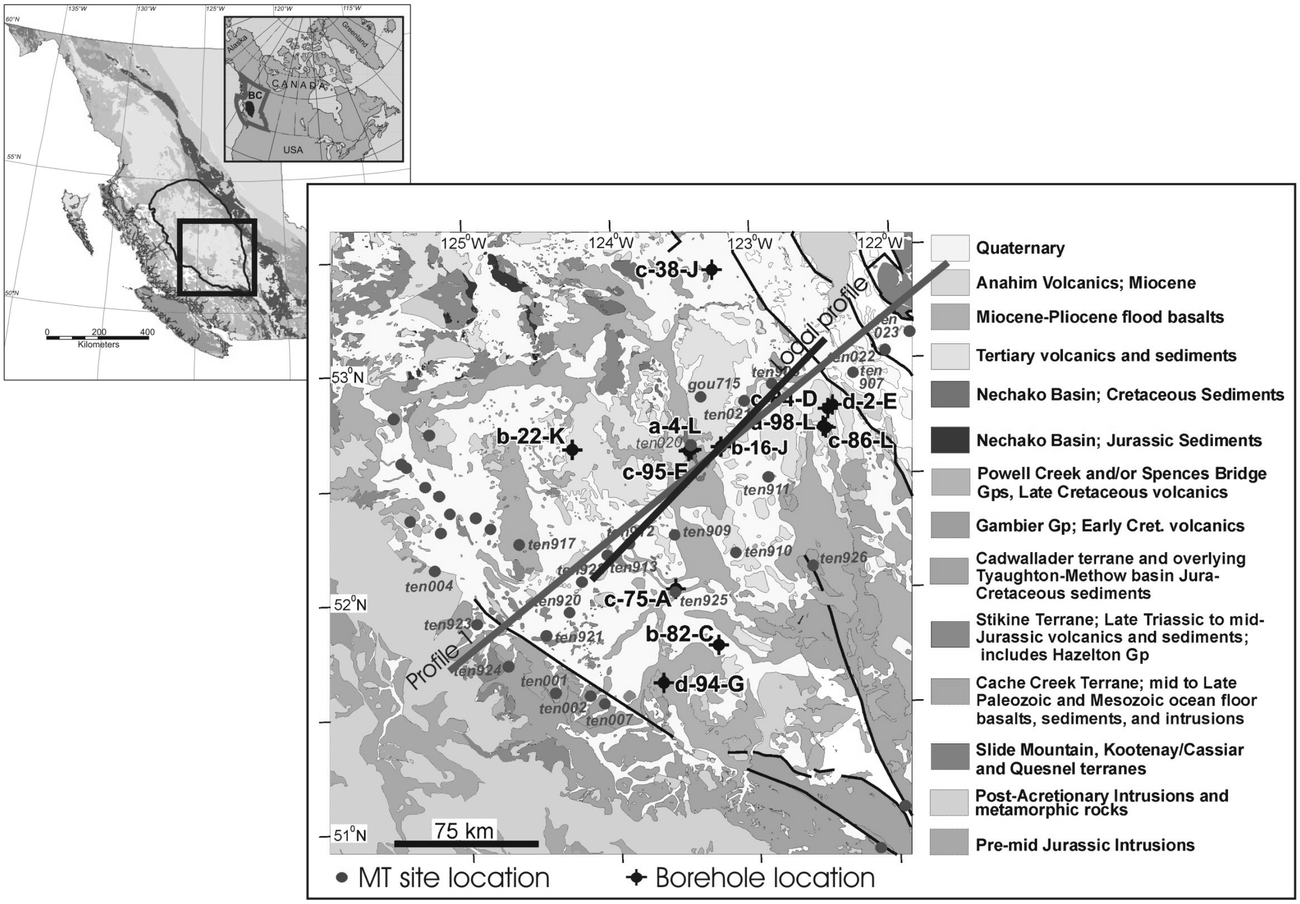

Figure 1. Geology of the Nechako region. The blue dots show the location of magnetotelluric sites recorded in the 1980s. The red and blue lines indicate the orientation of two-dimensional MT models generated for these data. The black dots indicate the location of borehole wells. *Modified from* Ferri and Riddell (2006).

parent resistivities at various frequencies for each site recorded. Since the depth of investigation of these fields is directly related to the frequency of the measurement and the resistivity of the material, estimates of the phase and apparent resistivities provide a rough guide to the true spatial variation of resistivity beneath each site. For example, if apparent resistivities rise as the frequency drops, that is an indication that the true resistivity is increasing with depth. To arrive at a more realistic depth image of the subsurface resistivity distribution, a model must be generated with synthetic or calculated responses that match the measured data within measurement error. The choice of an algorithm to calculate the synthetic data is strongly dependent on the complexity of the subsurface resistivity distribution. In turn, the complexity of the resistivity distribution is a function of a number of factors, including lithological variations, structural fabrics, rock porosity and salinity of groundwater within pore spaces. It is common in geological situations to have predominantly two-dimensional distributions (*i.e.,* the electrical conductivity is invariant in one direction, the strike direction) and therefore most of the modelling algorithms in use today assume a two-dimensional structure.

Because orthogonal components of the electric and magnetic fields are measured, four response curves can be formulated to define the four elements of the 2 by 2 MT tensor. The tensor contains the information to discern the complexity of the Earth's electrical distribution. In a two-dimensional Earth, two of the elements are zero and two are not. The two non-zero elements are referred to as the Transverse Electric (TE) and Transverse Magnetic (TM) modes of electromagnetic (EM) field propagation. The four components of the tensor are non-zero in three-dimensional environments. The two modes of electromagnetic field propagation demonstrate equivalent phase lags when the structure is one-dimensional or layered. Mathematical decomposition analysis on the tensor data is typically undertaken to determine if it is appropriate to use two-dimensional modelling algorithms and to assign the preferred geo-electric strike direction for the sites along a profile (Groom and Bailey, 1989). The results of decompositions also provide the TE and TM-mode response curves that most accurately reflect the two-dimensional structure. Two-dimensional modelling of these data will then determine the most reasonable resistivity structure of the subsurface beneath a profile. The analysis begins by re-examining the data, using modern tensor decompositions, to determine if two-dimensional algorithms are appropriate.

Decomposition Analysis

Single-site and multisite Groom-Bailey (1989) decompositions, using the method of McNeice and Jones (2001), were applied to the MT sites along the profile and showed much of the data to be one-dimensional as maximum phase differences between the two modes were below 10°, particularly at frequencies above 1 s (Fig. 2). For the few sites with a strong two-dimensionality, and that exhibited larger phase differences, the preferred geo-electric strike angle was determined to be –35° degrees, *i.e.*, north-northwest, approximately parallel to the geologically mapped strike of the belts. The models generated in the McNeice-Jones decomposition analysis show that the data fit well within 3.5%, equivalent to a 2° error floor in phase. This geo-electric strike angle is consistent throughout the dataset and appears to correlate well with structures revealed in the gravity data (Fig. 3) indicating that the strike is likely to be dominated by regional large-scale two-dimensional structures.

Preliminary Borehole Comparisons

Several boreholes have been drilled within the southern Nechako Basin region since the 1960s and resistivity well log data were acquired for some of them (Fig. 4). Most MT sites are too far away from the wells to be useful in comparing measured and modelled responses; however, well log a-4-L is located close to MT site ten020 and can be used for this comparison. Synthetic apparent resistivity and phase curves were calculated using the Geotools MT interpretation package from long normal and deep induction logs measured at well a-4-L (Fig. 5a). From these synthetic curves, as well as measured curves from the data recorded at site ten020, one-dimensional models were generated (Fig. 5b). The 1-D models for both sets of curves, synthetic (from the borehole data) and measured (at the MT site), are generally quite similar with just two major differences: 1) the starting resistivity value is nearly one order of magnitude higher in the MT data compared to the synthetic well data; and 2) the different resistivity layers appear to be downshifted, that is, that the boundaries between the layers occur at deeper depths in the 1-D model for the MT site. Contrary to the assumptions made by Majorowicz and Gough (1991) — that there was little static-shift effect on the data — these differences indicate that there is most

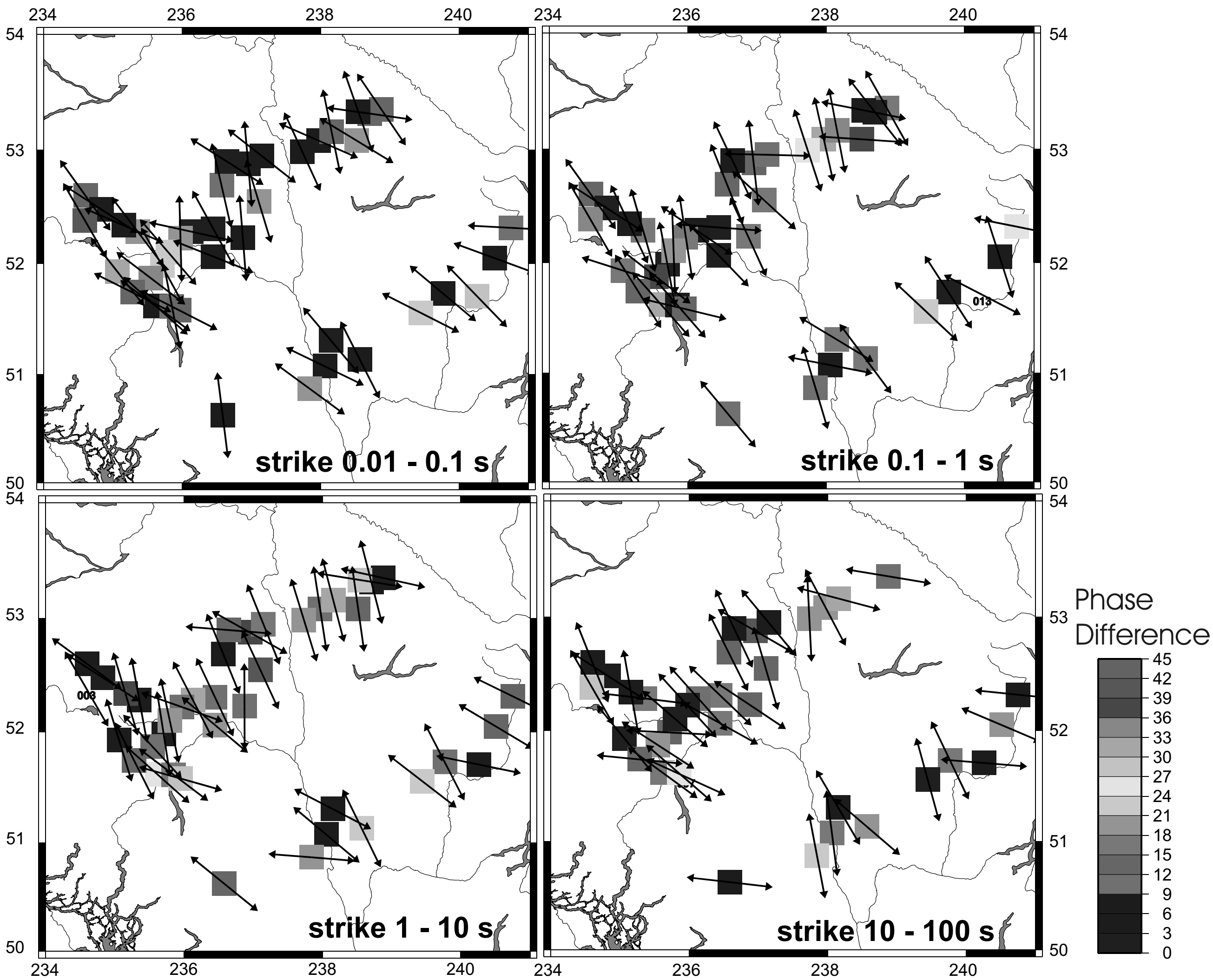

Figure 2. Maps showing the geo-electric strike directions determined from Groom and Bailey (1989) galvanic decomposition models for each site at four different period bands between 0.01 and 100 s. The colours represent the maximum phase difference between the Transverse Electric (TE) and Transverse Magnetic (TM) modes. Each band samples progressively deeper into the crust and represents the best-fit two-dimensional strike of the electrical units in the subsurface. Small phase differences are indicative of one-dimensional or layered geometries in the subsurface.

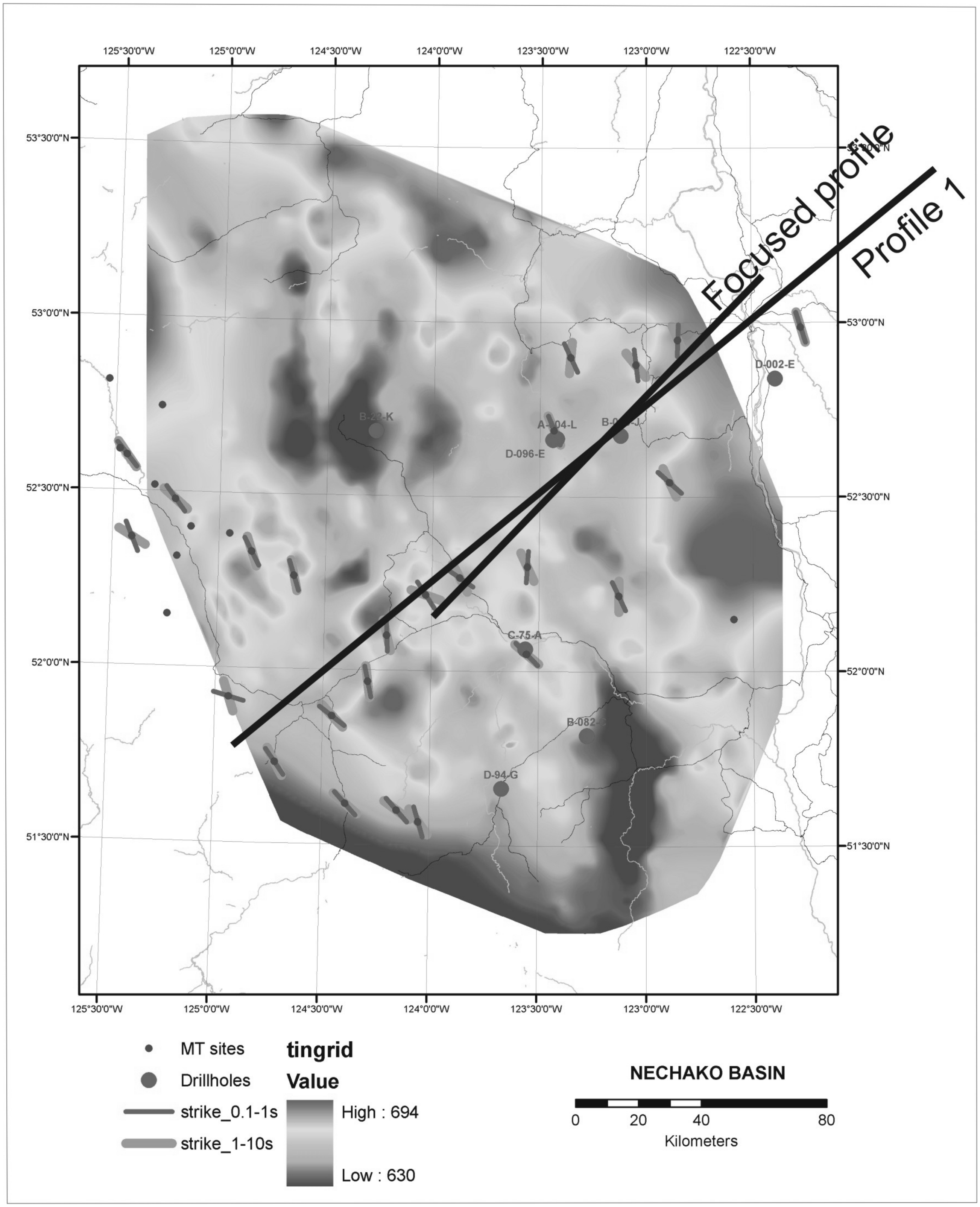

Figure 3. Bouguer gravity for the Nechako region and strike directions obtained using multifrequency McNeice-Jones decompositions for period bands 0.1 to 1 s and 1 to 10 s. The black lines mark the profile traces of the MT models. *Modified from* Ferri and Riddell (2006).

likely a significant effect of static shift on the measured MT data and these effects need to be accounted for in further models. The similarities suggest that the MT data is capable of imaging the shallow conductivity layers observed in the well. The differences indicate that there is a need for additional measures to be taken in future MT data acquisition in this region in order to get an accurate depth estimate for these layers. For example, the model obtained from the data (Fig. 5b) is entirely featureless at depths shallower than 100 m, suggesting that the frequency bandwidth utilized by the SPAM system (up to 130 Hz) is insufficient to explore at shallow depths. High-frequency audio-magnetotelluric (AMT) soundings up to 10 000 Hz would help to constrain the resistivity structure at shallow depths and other methods, such as time-domain electromagnetic, borehole resistivity logs or electrical rock property measurements performed in a laboratory, could be used to correct for this static-shift effect.

DATA MODELLING

Two-dimensional models along Profile 1 (Fig. 1) were determined for the decomposition-corrected MT responses at a geo-electric strike angle of –35° of both the Transverse Magnetic (TM) and Transverse Electric (TE) modes, as well as the TE mode only. Since the nature of MT models is non-unique, careful steps need to be undertaken to ensure that the model generated is the best representation of the structure of the Earth. A trade-off is required between the smoothness of the model between cells, the tau value (τ), and the fit of the model to the data, the RMS (root mean squared) misfit value. Inverse modelling using Rodi and Mackie's (2001) code, as implemented in Geosystem's WinGlink software package, was run for 100 iterations for models with varying smoothness parameters (τ). Higher values of τ increase the smoothness and therefore the fidelity of the model, but degrade the fit of the model as represented by the RMS. From the L-curve trading-off fit (RMS) against τ, the best trade-off was determined to be at $\tau = 3$ (Fig. 6). In order to account for static-shift effects, the data were inverted to preferentially fit the phase data, with high error floors (25%) set for the apparent resistivities. The data were also inverted with error floors for both the phase and apparent resistivities equivalent to 2° (as determined acceptable from the distortion analysis) and after 100 iterations, a static-shift correction was applied to the model parameters. The structures of the different models and the associated conductivity values were very similar and the final model generated achieves an RMS misfit of 2.4. Pseudosections allow a visual comparison between the calculated forward response of the apparent resistivities and phases, and the original data (Fig. 7). These show that there is a reasonable fit at most sites along the profile, particularly at shallow depths.

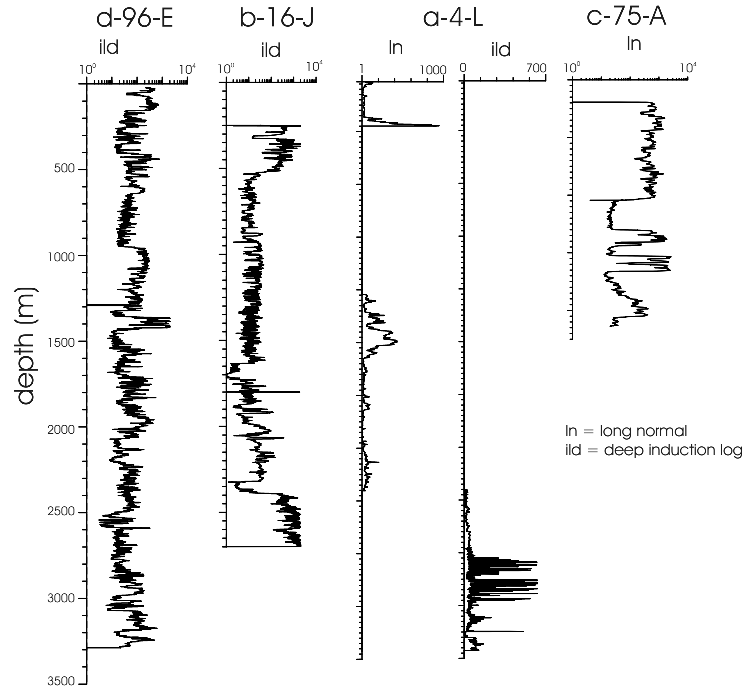

Figure 4. Resistivity data measured at four of the wells in the southern Nechako region.

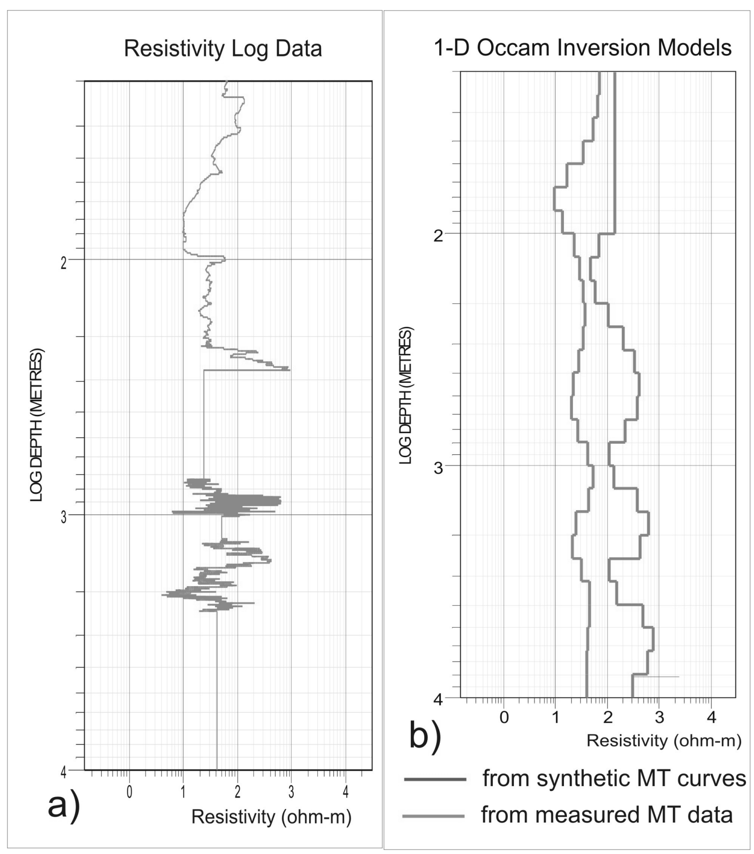

Figure 5. a) Resistivity log data recorded at well a-4-L re-plotted in log domain; b) one-dimensional models of synthetic data from borehole log a-4-L and magnetotelluric (MT) site ten020 at the same location.

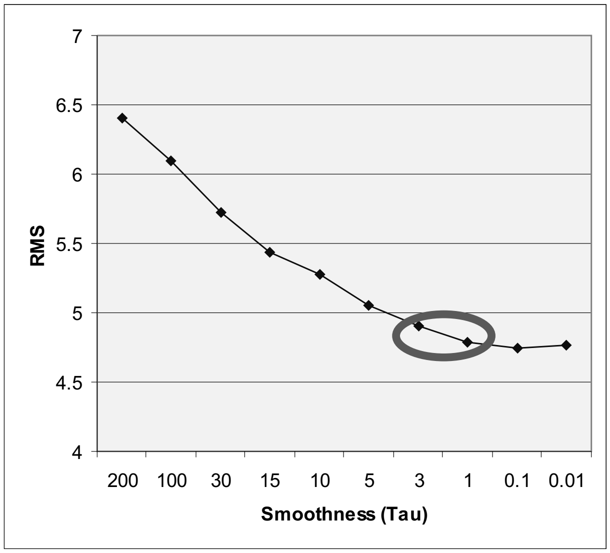

Figure 6. Trade-off plot shows the relationship between the root mean squared (RMS) misfit value and the smoothness modelling parameter, tau (τ). The red circle shows the region where the model has the highest τ (smoothest model) and the best fit (smallest RMS).

Main Model Features

The model shows distinct variations in the conductivity structure along the profile and reveals a moderately conductive layer (40 ohm-m) that varies in depth up to ~5 km (Fig. 8). There is a good correlation between the gravity lows, which are assumed to represent sedimentary sequences, and the high conductivity layer (<100 ohm-m) where it thickens between sites 922 and 908 in the 2-D model along Profile 1 (Fig. 8). Where the MT model shows resistive structure near the surface at both ends of the profile, there are gravity highs that have been interpreted to represent volcanic basement. This indicates consistency between the two datasets and suggests that the MT data are capable of distinguishing the different lithological units at depth and defining the boundary of the Nechako Basin.

Model Focused on Shallow Basin Structure

A new model was generated for the eastern edge of the Nechako Basin using the high-frequency data only (1–130 Hz) in order to determine how sensitive the data are to the shallow structures in this region. This model shows significant conductivity changes at shallow depths along the profile (Fig. 9). A comparison of calculated modelled responses to the observed data is shown in Figure 10. To the southwest, there is a conductive (~100 ohm-m) region

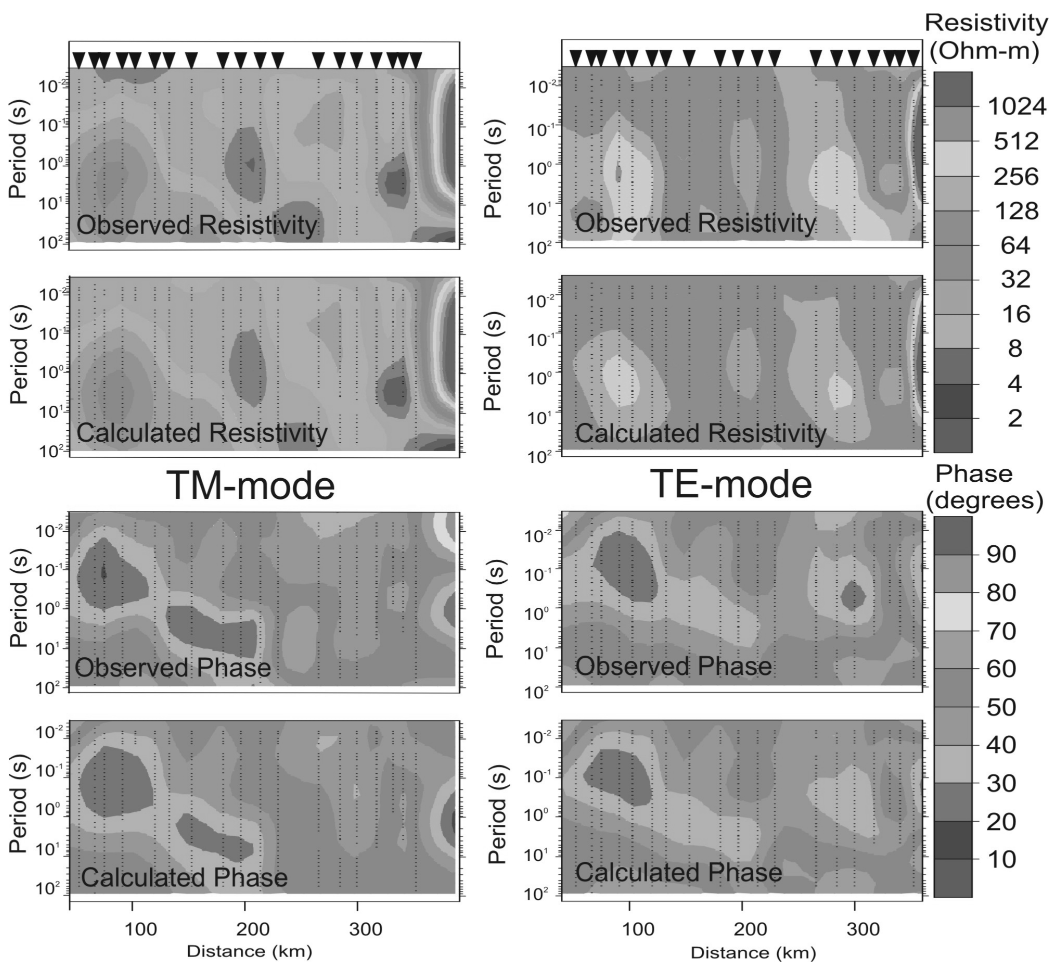

Figure 7. Plots of the measured data and the model forward responses of the apparent resistivities and phases for both Transverse Magnetic (TM) and Transverse Electric (TE) modes of the two-dimensional model shown in Figure 8.

overlying resistive (>1000 ohm-m) material; Majorowicz and Gough (1991) interpreted this to represent sedimentary rocks in Nechako Basin overlying granitic intrusions. To the northeast, the conductive region becomes resistive across the boundary between the Nechako Basin and the Cache Creek Terrane (Fig. 1, 9). The model also shows two very conductive features (<10 ohm-m) that correlate with the surface-mapped Tertiary volcanic and sedimentary rocks (Fig. 1).

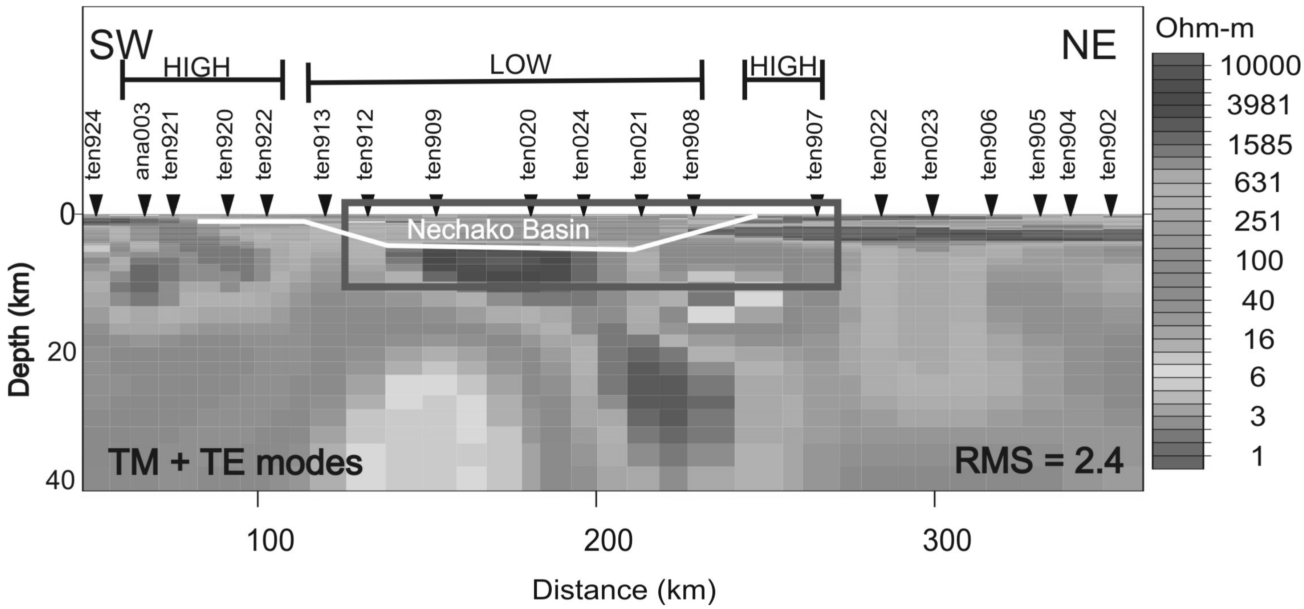

Figure 8. Two-dimensional resistivity model obtained from MT data across the Nechako Basin. The model was generated using both Transverse Electric (TE) and Transverse Magnetic (TM) mode distortion-decomposed apparent resistivity and phase data, and a root mean squared (RMS) misfit of 2.4 was achieved. The red box indicates the region of localized modelling shown in Figure 9. The black bars above the model illustrate the regions of high and low gravity data, as seen in Figure 3.

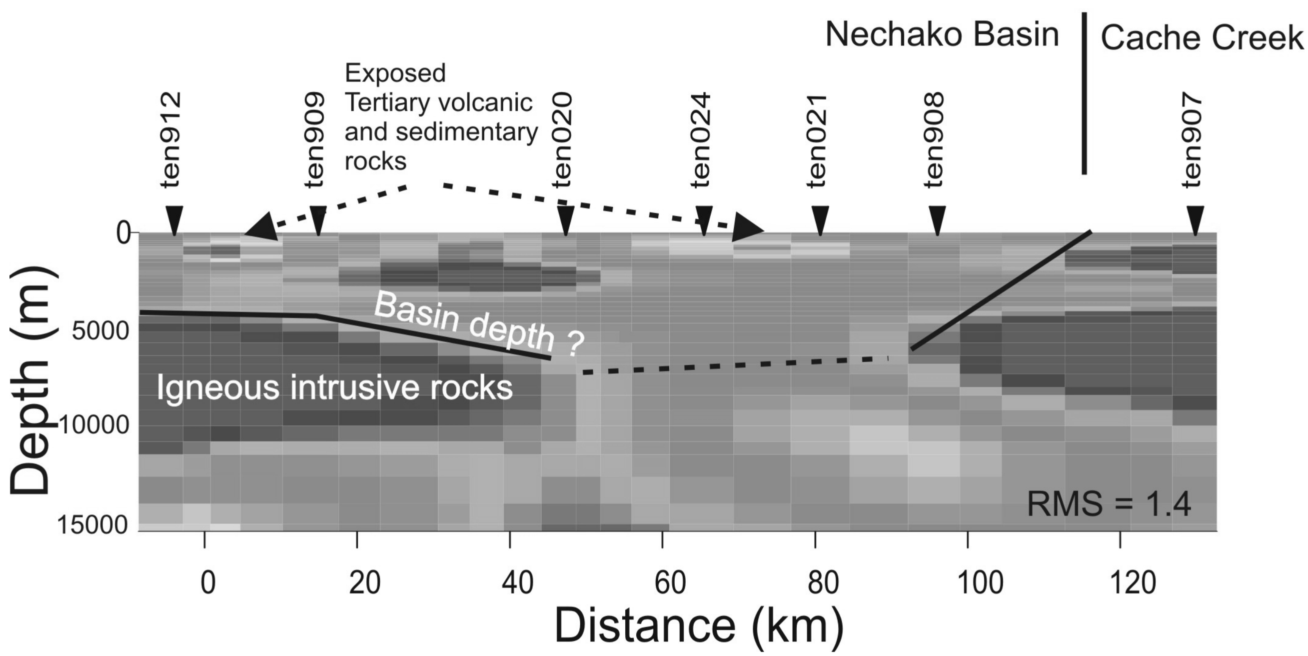

Figure 9. A two-dimensional model focusing on the shallow structures crossing the eastern boundary of the Nechako Basin. The model was generated using high-frequency data (1–130 Hz) for both the Transverse Electric (TE) and Transverse Magnetic (TM) modes and a root mean squared (RMS) misfit of 1.4 was achieved.

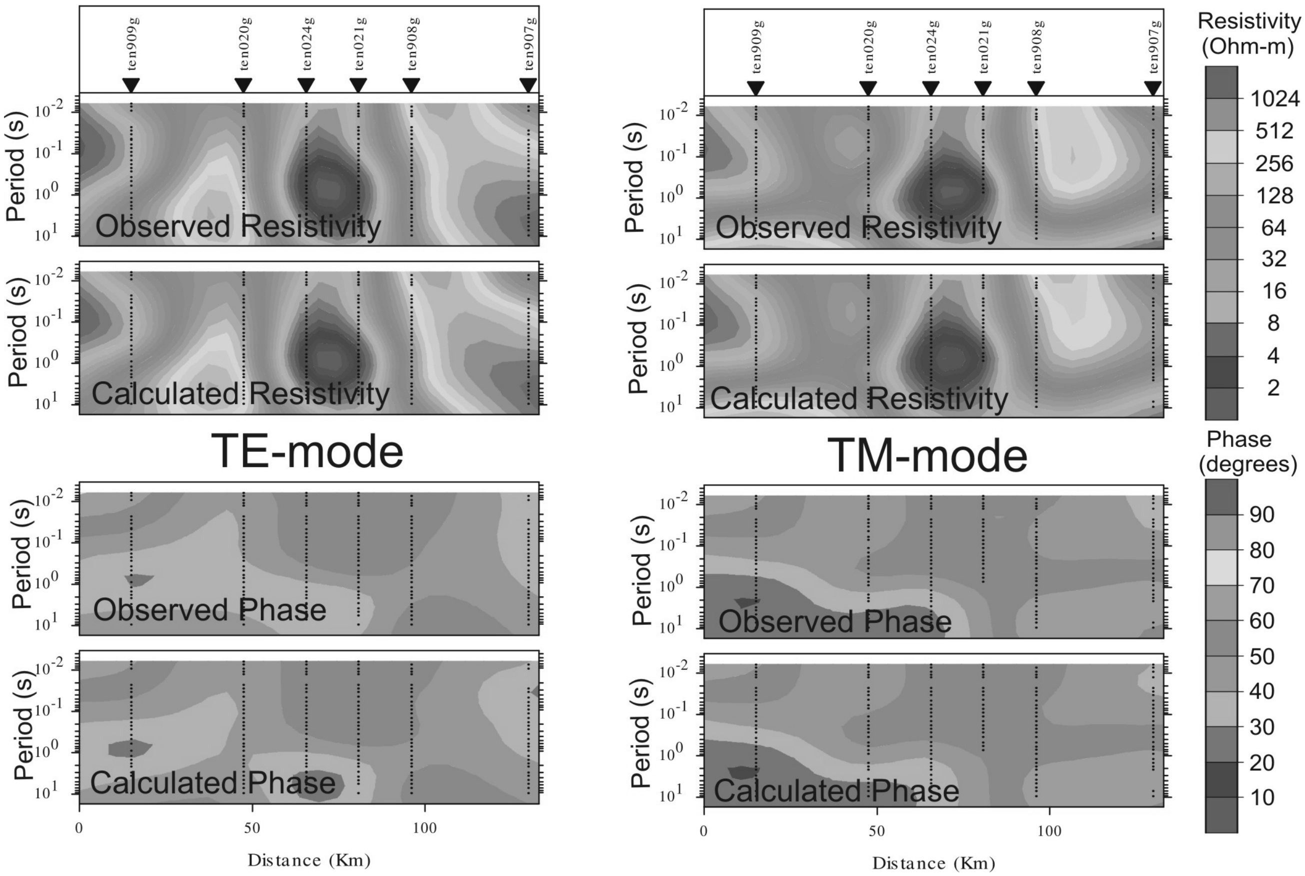

Figure 10. Plots of the observed data and the data calculated from the model forward responses of the apparent resistivities and phases for both Transverse Magnetic (TM) and Transverse Electric (TE) modes of the two-dimensional model shown in Figure 9.

Hypothesis testing of these shallow conductors was undertaken by replacing the high conductivity values with a higher resistivity value (~200 ohm-m, similar to the surrounding values) and running a forward response. The RMS values increased dramatically (from 1.4 to 8.2) and a comparison of the calculated versus measured pseudosections of both the TM and TE modes, in both the apparent resistivities and phases, showed distinct differences. This indicates that the shallow conductive structures are required by the measured data and are not artifacts of the inversion algorithm and that, although currently sparse, the MT data is capable of discerning shallow structure within the Nechako basin. The SPAM MT systems used for acquisition of the measured data recorded a maximum frequency of 130 Hz (0.007 s). Modern audio-magnetotelluric (AMT) instruments can reliably acquire data to 10 000 Hz (0.0001 s). With a dense site spacing, additional AMT and broadband MT data acquisition would be useful in determining the shallow structure within the Nechako Basin and would allow the basin boundaries to be clearly identified.

CONCLUSIONS

Magnetotelluric data collected two decades ago are capable of penetrating the Cenozoic volcanic rocks and imaging the shallow features of the Nechako Basin. The two-dimensional models show a good correlation between along-strike conductivity variations and mapped geological units as well as observed gravity anomalies. A comparison with measured borehole resistivities allows us to quantify static-shift effects and indicates the need to account for these effects in the interpretation of the existing data. Additional MT data acquisition using modern high frequency (AMT) and broadband instrumentation would be a highly cost-effective method to determine the thicknesses and boundaries of the Nechako basin. This information is key for advancing our understanding of the region's resource potential.

ACKNOWLEDGMENTS

Helpful reviews by R. Stevens and C. Lowe are gratefully acknowledged. Borehole data was provided by J. Mwenifumbo of the Geological Survey of Canada. The project has received financial support from Geoscience BC and the BC Ministry of Energy, Mines and Petroleum Resources.

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