A FIRST LOOK AT THE ELECTRICAL RESISTIVITY STRUCTURE IN THE NECHAKO BASIN FROM MAGNETOTELLURIC STUDIES WEST OF NAZKO, B.C. (NTS 092 N, O; 093 B, C, F, G)

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ABSTRACT

The Mesozoic Nechako sedimentary basin, located within the Intermontane belt of the Canadian Cordillera in central British Columbia, is a forearc basin deposited in response to terrane amalgamation along the western edge of ancestral North America. Limited exploration of the basin to date has indicated the potential for significant oil and gas reservoirs. An important impediment to hydrocarbon exploration, however, is the inability of traditional geophysical methods to see through the thick Neogene volcanic sequence burying the basin. As the magnetotelluric method is not hampered by these volcanics, 734 combined AMT and MT sites were recorded throughout the southern Nechako Basin in the fall of 2007. The survey was designed to evaluate the technique as a tool in both hydrocarbon exploration as well as geological characterization of the basin. Preliminary analyses of these data suggest that they are sensitive to variations in the depth extent of the sedimentary basin and that there are lateral changes in the conductivity structure within the sediments. These lateral variations could be attributed to compositional differences, the presence of fluids, or changes in porosity.

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INTRODUCTION

In response to the rapid spread and destructive effects of the mountain pine beetle, a number of projects designed to assess mineral and petroleum potential have been undertaken to develop economic diversification opportunities for forestry-based communities in the affected areas of British Columbia. The potential for hydrocarbons has been noted within several interior basins of British Columbia, including the Nechako Basin. A 1994 estimate by the Geological Survey of Canada, based on very limited information, suggested that the Nechako Basin may contain as much as a trillion cubic meters of gas and a billion cubic meters of oil, although these estimates are qualified as being highly speculative (Hannigan et al. 1994).

It has been shown that the magnetotelluric (MT) method can be useful in resolving geological structures less suitable for seismic methods, such as areas that are covered by volcanic or basaltic sequences, and that it may prove to be a useful tool in the exploration of hydrocarbons (Unsworth 2005; Spratt et al. 2006; Xiao and Unsworth 2006). In the fall of 2007, 734 combined broadband and high frequency MT sites were deployed throughout the Nechako Basin (Figure 1). The primary objectives of the survey are to evaluate the technique as a tool both for oil and gas exploration and geological characterization of the Nechako Basin and to contribute to a better understanding of the potential for hydrocarbon resources in the region.

GEOLOGICAL AND GEOPHYSICAL BACKGROUND

Geology of the Nechako Basin

The Mesozoic Nechako Basin, located in the Intermontane Belt of the Canadian Cordillera, includes overlapping sedimentary sequences deposited in response to terrane amalgamation to the western edge of ancestral North America (Monger et al. 1972; Monger and Price 1979; Monger et al. 1982; Gabrielse and Yorath 1991). Regional transcurrent faulting and associated east-west extension, beginning in the Late Cretaceous, were accompanied by the extrusion of basaltic lava in Eocene and Miocence times to form a sheet that covers much of the basin at thicknesses varying

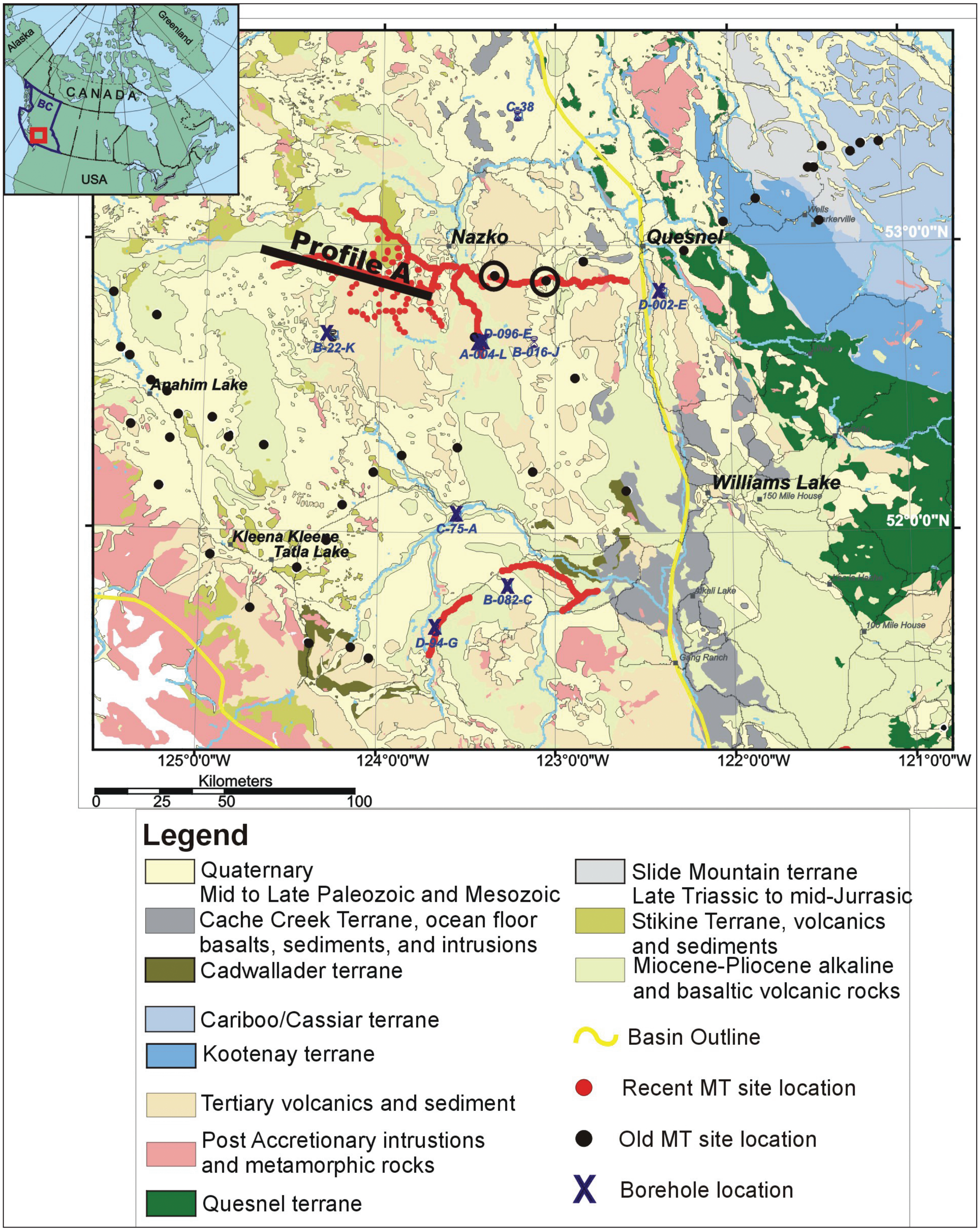

Figure 1: Map showing the location and geology of the Nechako Basin along with the locations of the boreholes, old MT sites, and the newly acquired MT sites. The black line shows the trace of profile A, and the black circles indicate the locations of sites ten 24, eo61, ten 21, and eo5 shown in Figure 3.

between 3 and 200 m (Mathews 1989; Andrews and Russell 2007). The main geological elements in the southern Nechako area include Miocene basalt, Tertiary volcanic and sedimentary rocks, and Cretaceous and Jurassic sedimentary rocks (Figure 1).

Geophysical Studies

The MT survey parameters, such as site locations, data ranges, and site spacing, were strongly influenced by early geophysical studies, such as gravity, magnetic, and resistivity measurements in borehole logs. In the early 1980s, a regional gravity survey was carried out by Canadian Hunter Exploration Limited that identified a gravity low in southern Nechako Basin. In the early 2000s, Bemex Consulting International confirmed this anomaly with ground gravity and magnetic data collected in the southern tip of the basin. In addition to these regional surveys, several boreholes were drilled throughout the southern portion of the basin between 1960 and 1986 (Figure1), providing detailed geological information as well as a variety of borehole logs that included natural gamma-ray spectroscopy, neutron porosity, and resistivity.

Due to absorption and reflection effects, the presence of the surface basaltic flows and Tertiary volcanic rocks covering most of the region has, to date, prevented uniform and consistent seismic-energy penetration and complicated the magnetic interpretations. However, re-analysis with modern processing techniques of these data from the southernmost part of the Nechako Basin is yielding a better resolution of local structures (Hayward and Calvert 2007). New seismic information will soon be available from 7 long-term teleseismic stations deployed in the Nechako Basin as part of a joint project between the Geological Survey of Canada (Pacific), the BC Ministry of Mines, Energy and Petroleum Resources, and the University of Manitoba. Additionally, Geoscience BC is planning a Vibroseis® survey, and Natural Resources Canada an explosive-source seismic reflection investigation, which will both coincide closely with the MT survey locations. Information from these geophysical data will both complement and constrain the results and interpretations of the magnetotelluric survey.

More than 100 rock samples have been sent to John Katsube's Geological Survey of Canada petrophysical laboratory in Ottawa for measurement of the resistivities and porosities of key lithological units in the Nechako Basin. The intent of this analysis is to provide information on the primary electrical conduction mechanisms and level of electrical anisotropy of the different units. These, along with the resistivities from existing well logs, will place constraints on the conductivity models generated and make it possible to account for distortion due to anisotropy and static shift effects.

MT method and previous studies

The magnetotelluric (MT) method provides information on the electrical conductivity of the subsurface of the Earth by measuring the natural time-varying electric and magnetic fields at its surface (Cagniard 1953; Wait 1962; Jones 1992). At low frequencies, the signal is generated by interaction of solar winds with the ionosphere. At high frequencies, the signal is produced from distant lightning storms. The phase lags and apparent resistivities (MT response curves) can be calculated from the measured fields at various frequencies for each site recorded. The depth of penetration of these fields is dependent on frequency (lower frequencies penetrate more deeply) and the conductivity of the material (deeper penetration with lower conductivity), and therefore depth estimates can be made from the response curves beneath each site (Kearey and Brooks 1991). The frequency range recorded is therefore dependent on the target depth of interest. AMT (audio magnetotellurics) sensors measure data in the highest frequencies (10 000 to 5 Hz), where MT sensors measure lower frequencies (380 to 0.001 Hz).

As MT data are sensitive to changes in the resistivity of materials, the method can distinguish between some lithological units. For example, basalt and igneous basement rocks typically have electrical resistivity values of more than 1000 ohm-m, whereas sedimentary rocks are more conductive, with values of 1 to 1000 ohm-m. Aside from lithology, other factors are known to affect the overall conductivity of a specific unit in the crust. The presence of saline fluids, changes in porosity, and the presence of graphite films and interconnected metallic ores are all factors that can substantially increase the conductivities of rocks (Haak and Hutton 1986; Jones 1992). Because the method is sensitive to, but not impeded by, the surface volcanic rocks and can detect variations within the different units, it should prove useful in locating the boundaries of the Nechako Basin and defining the structure within. In addition to lithology, the MT method may be able to provide some estimate of bulk properties, such as porosity (Unsworth 2005; Xiao and Unsworth 2006). Measured resistivity and salinity can be used to estimate porosity through Archie's law.

Early magnetolluric data, in the frequency ranges of 0.016 to 130 Hz, were collected by the University of Alberta in the 1980s (Majorwicz and Gough 1991). These data showed that the data were successful in penetrating the surficial basalts and revealed a conductive upper crust that was interpreted as saline water in pore spaces and fractures (Jones and Gough 1995). Since then, instrumentation improvements, as well as the development of signal processing algorithms and advancements in 2- and 3-dimensional modelling inversion programs, have significantly improved the ability of the MT method to image subsurface structures.

DATA ANALYSIS

Acquisition and Processing

The data were recorded during the fall of 2007 using MTU-5A systems manufactured by Geosystems Canada of Toronto. In general, 3 teams each deployed 6 sites per day, where 2 of the sites were telluric only, 2 of the sites were 5-channel AMT sites, and the remaining 2 sites were 5-channel MT sites. The tight station spacing of 500 m and the generally layered subsurface conditions mean that the magnetic field recordings (AMT or MT) at the different sites could be used with the telluric channels at all sites (Figure 2). The end result was that a total of 734 combined AMT and MT sites were recorded throughout the region (Figure 1).

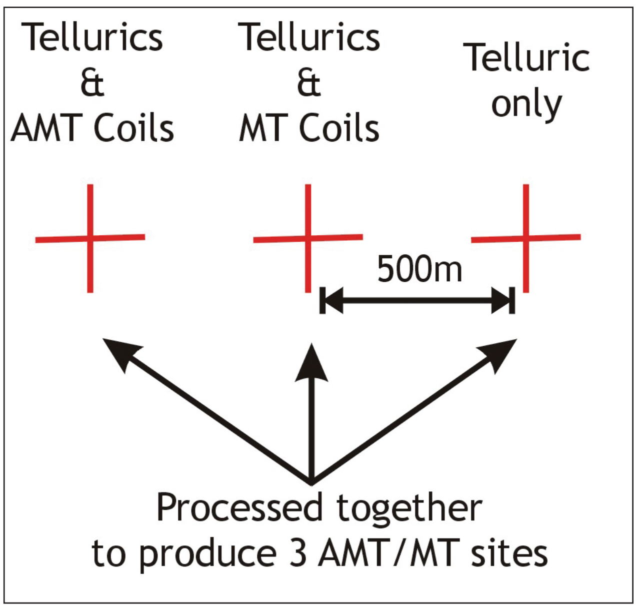

Figure 2: Illustration of the site deployment and processing scheme developed to maximize the data quality and frequency range at each site.

The data were processed by Geosystems Canada using robust remote reference techniques as implemented by the Phoenix Geophysics software package Mt2000. Figure 3 shows examples of response curves generated both for sites collected nearly 20 years ago as part of the Lithoprobe project (Figures 3a and 3c) and for sites collected in the fall of 2007 (Figures 3b and 3d). The response curves for the new sites show significant improvement in data quality over a much larger period range extending from 0.00001 to 1000 s. This, along with tighter station spacing, will provide better resolution at shallow depths and will allow deeper structures to be modeled.

Decomposition Analysis

Single site and multi-site Groom-Bailey decompositions were applied to each of the MT sites along profile A in Figure 1 in order to determine the most accurate geoelectric strike direction and analyze the data for distortion effects (Groom and Bailey 1989). Figure 4 illustrates the results of single site strike analysis for each decade period band recorded at each site along the profile. The direction of the arrows shows the preferred geoelectric strike direction with a 90° ambiguity, and the colour scale represents the maximum phase difference between the 2 modes.

Nearly all the sites along the profile show a maximum phase difference that is less than 10°, at periods below 0.1 s, indicating that the data are independent of the strike angle. The maximum phase splits, where the data are most dependent on the 2-dimensional strike direction, are observed between 0.1 and 10 s. The westernmost sites along the profile consistently indicate a preferred geoelectric strike angle of approximately 5° between 0.1 and 10 s, whereas the eastern half of the profile prefers an angle of 30° to 35°. Special analysis and model appraisals will need to be undertaken to account for this change in strike angle when generating 2-dimensional models of the profile.

DATA MODELING AND PRELIMINARY RESULTS

Validity of 1-D models

Pseudosections of the observed phase values with increasing periods in both the XY and YX modes were generated along profile A (Figure 5). Where the phases of the 2 modes are the same, the data are independent of the geoelectric strike angle and are considered 1-dimensional. The red line in Figure 5 illustrates the maximum period to which the phases are similar, below which the data are either 2- or 3-dimensional. The 1-dimensional models generated are therefore only accurate to periods of 0.1 to 1 s at most of the sites along profile A. Schmucker's c-function analysis was applied to each site, providing a depth estimate at these periods by calculating the depth to maximum eddy current flow (Schmucker 1973). These indicate that the 1-dimensional models should accurately represent the conductivity structure of the subsurface to depths of 1000 to 2500 m.

1-D Models

One-dimensional layered earth resistivity Occam models were generated for each site along profile A using the WinGLink MT interpretation software package. These

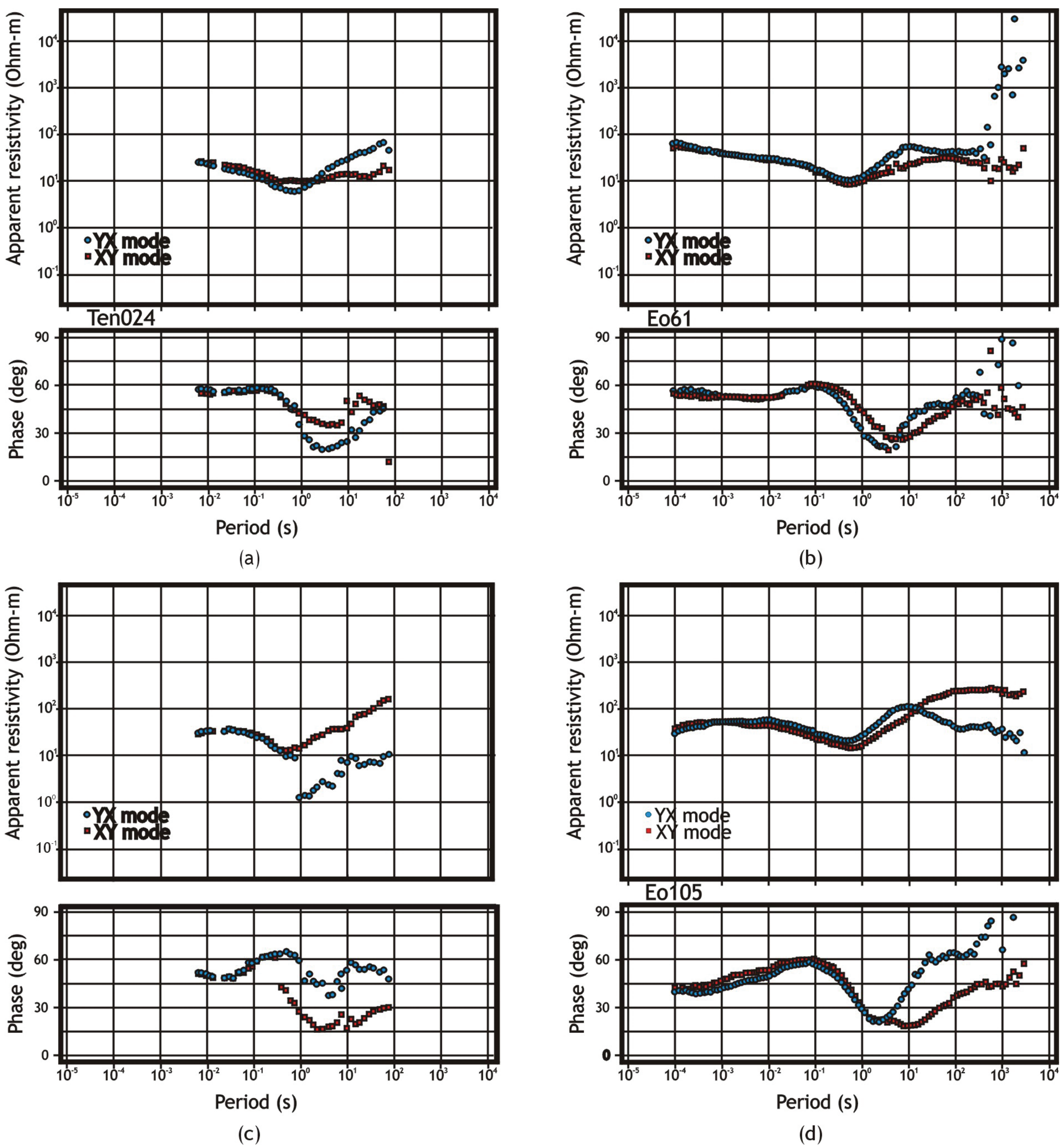

Figure 3: Examples of the improved data quality between the old Lithoprobe sites and the recent data acquisition in the Nechako Basin. The locations of the sites are shown in Figure 1, where (a) lithoprobe site ten24 and (b) Nechako site eo61 have the same position and (c) lithoprobe site ten21 and (d) Nechako site eo5 have the same position.

models are shown in Figure 6, where the warm colours illustrate conductive regions and the cold colours reveal more resistive material. For some sites, there appears to be a very thin (approximately 100 to 200 m) resistive layer (greater than 1000 ohm-m) near the surface that thickens towards the east. This most likely represents the surficial volcanic rocks, as the geology strip at the top of Figure 6 shows more volcanic cover in the eastern half of the profile. The data are not sensitive to the extremely shallow structures and may not reveal a volcanic cover that is less than 50 m thick. Nearly all of the sites reveal a significant decrease in resistivity (from 10 to 100 ohm-m to more than 1000 ohm-m) at depths ranging between 1000 and 3000 m, shown by the black line in Figure 6. These depths are consistent with those of the Nechako Basin, suggesting that the data are imaging the base of the sediments and penetrating into the deeper basement units.

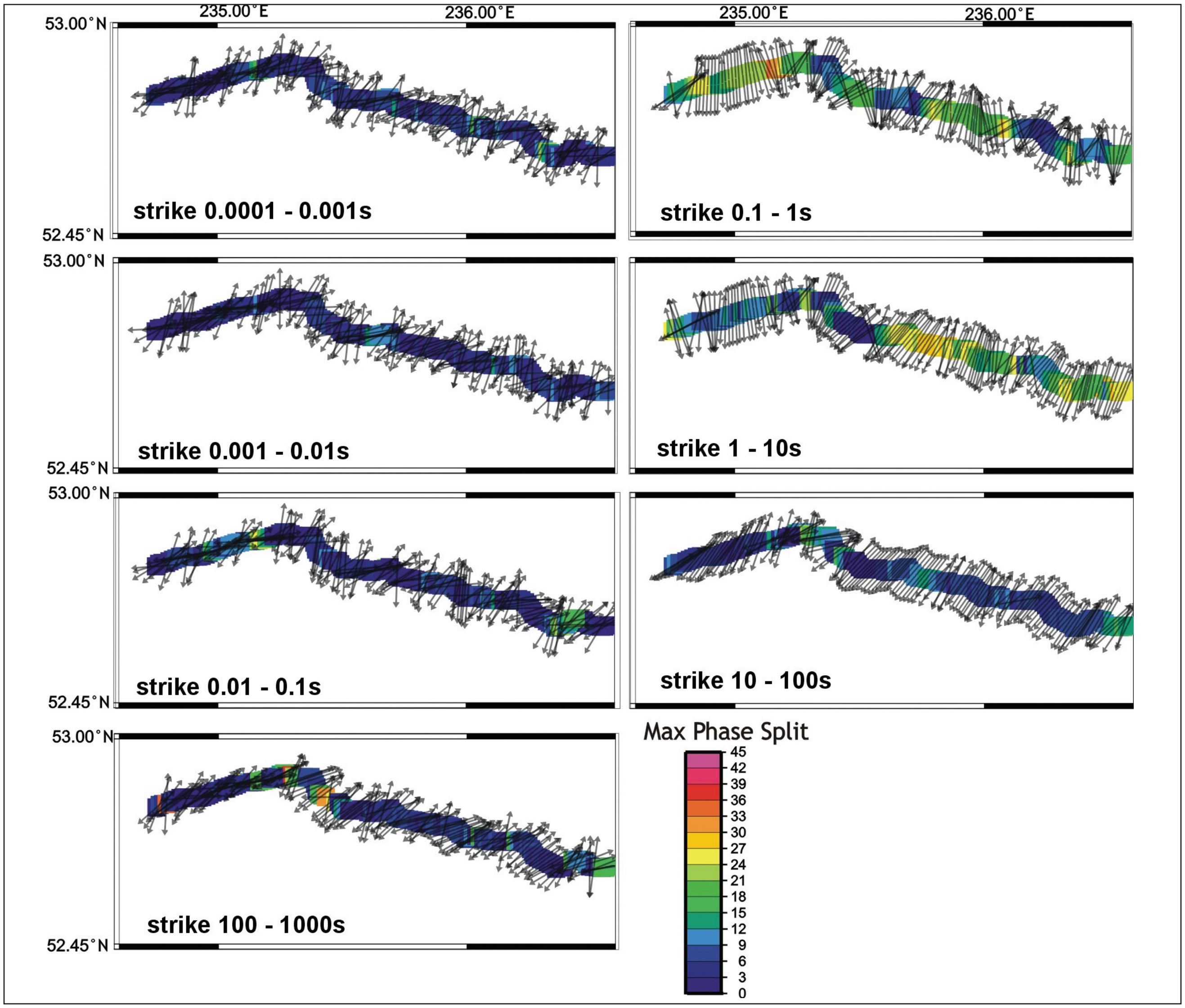

Figure 4: Map illustrating the preferred geoelectric strike angle for each site along Profile A for each decade period band. The colour shows the maximum phase split between the 2 modes.

The 1-dimensional models were stitched together with a smoothing parameter applied, resulting in Figure 7. The colour scale is the same as that used in Figure 6. The black line illustrates the variations in the depth of the boundary between the upper sediments and the lower basement rocks along the profile. Additionally there are lateral variations in the conductivity structures within the sediments that could be attributed to compositional changes, the presence of fluids, or changes in the effective porosity of the material. These variations appear to correlate with results from a regional gravity survey, seen at the top of Figure 7, that was collected by Canadian Hunter in the 1980s.

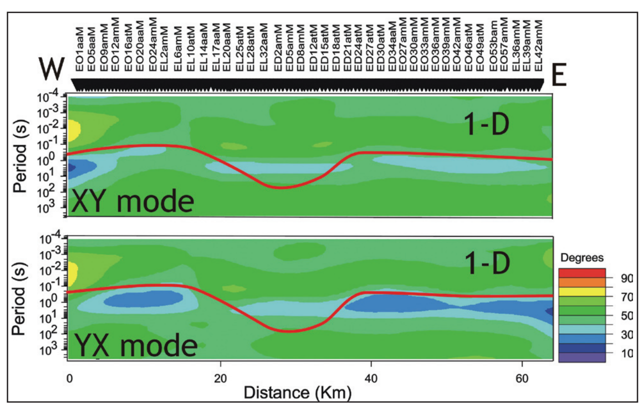

Figure 5: Pseudosections of the phase values in the XY and YX directions along Profile A. The red line marks the maximum period to which the data can be considered 1-dimensional.

Although a limited number of samples have been analyzed for percent effective porosity and electrical conductivity in the horizontal direction only, preliminary results show a direct correlation between the resistivity and porosity of certain rock units (Figure 8). This indicates that the

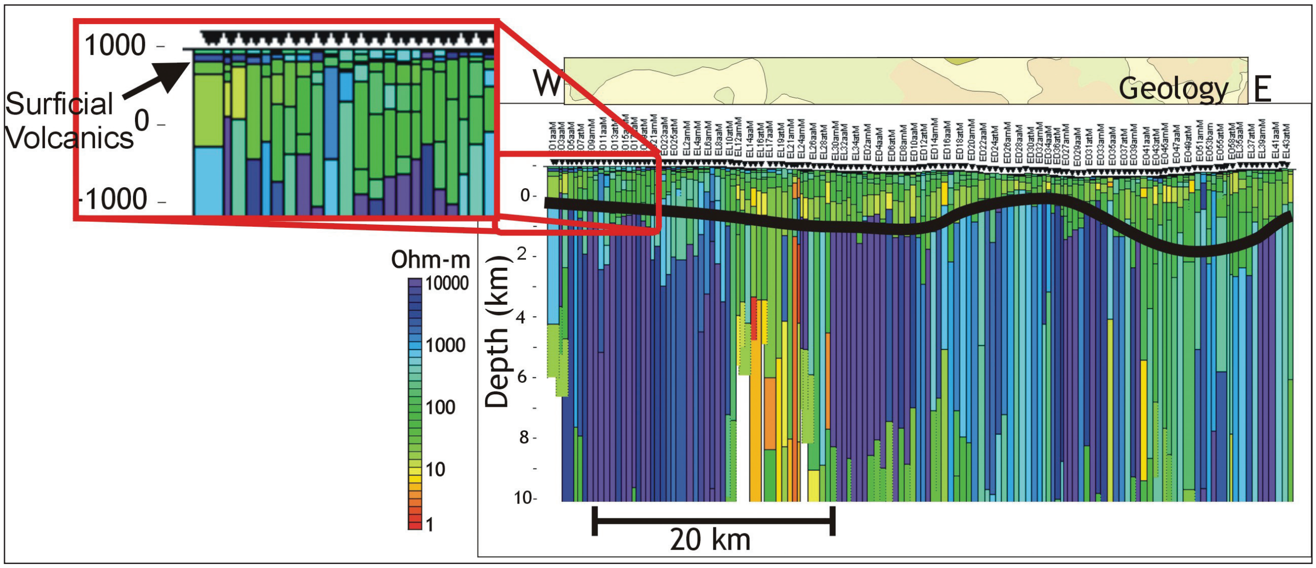

Figure 6: One-dimensional models generated for each site along profile A. The warm colours illustrate regions of high conductivity, and the cool colours indicate resistive regions. The thick black line marks the boundary between the sedimentary sequences and the underlying crystalline rocks. The local geology along the profile is shown in a strip above the cross-section.

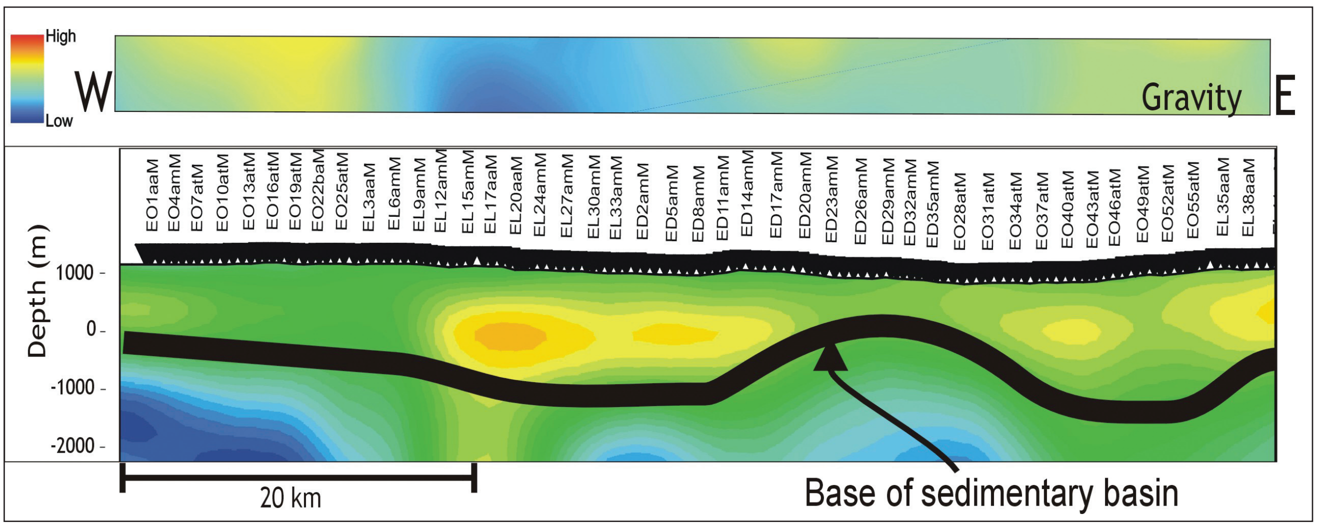

Figure 7: Smoothed, stitched one-dimensional models along profile A. Gravity results along the profile are shown in a strip above the cross-section; the blues show gravity lows, and the reds, high anomalies.

MT method is sensitive to porosity changes in the sedimentary units and suggests a cause for the link between areas of low density observed in the gravity data and areas of low resistivity in the MT data.

DISCUSSION AND CONCLUSIONS

Magnetotelluric data, in the AMT and MT frequency ranges, were collected at 734 sites within the Nechako Basin. Strike analyses of 134 sites show changes in the preferred geoelectric strike angle along the 70-km-long profile. These changes suggest that localized structure is influencing the strike direction at periods between 0.1 and 10 s. The different strike angles may represent different tectonic pulses, resulting in compressional faulting that causes a juxtaposition of conductive sediments and resistive basement rocks.

Initial results of 1-dimensional modelling of the data reveal in some areas a shallow resistive layer that is interpreted as the surficial volcanic rocks. The data also show a significant decrease in the apparent resistivity values at depths, which corresponds to the approximate boundary between the sedimentary basin and the underlying basement rocks. These results indicate that the MT method is sensitive to thicker regions of volcanic cover and that it is able to penetrate these volcanics and image the deeper structure. A cross-section of the stitched 1-dimensional MT models

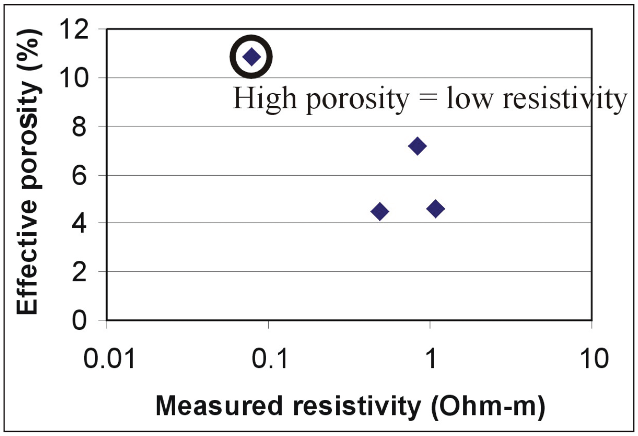

Figure 8: Results of petrophysical analysis of several rock samples, showing the relationship between porosity and resistivity.

indicates variations in the depth of this boundary from east to west. Additionally, at shallow depths within the sedimentary basin, changes in the conductivity values of up to 1 order of magnitude are observed. This suggests lateral changes in the physical properties of the basin that could be attributed to compositional difference or the presence of fluids. However, preliminary results of laboratory tests on rock samples, along with a correlation between high conductivity and low gravity, suggest that these changes may be related to changes in the effective porosity of the material.

Future work on this data will include 2-dimensional modeling and model appraisals of the presented profile, 3-dimensional modeling of the northernmost sites, and integrated modeling and interpretations of various geophysical data sets, including new seismic and gravity information.

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