Preliminary Images of the Conductivity Structure of the Nechako Basin, South-Central British Columbia (NTS 092N, O, 093B, C, F, G) from the Magnetotelluric Method

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Spratt, J.E. and Craven, J.A. (2009): Preliminary images of the conductivity structure of the Nechako Basin, south-central British Columbia (NTS 092N, O, 093B, C, F, G) from magnetotelluric methods; *in* Geoscience BC Summary of Activities 2008, Geoscience BC, Report 2009-1, p. 175–182.

Introduction

The rapid spread and destructive effects of the mountain pine beetle (MPB) in areas of British Columbia have prompted the need to develop economic diversification opportunities for the interior of the province. As a result, Geoscience BC has initiated a number of projects with the aim of assessing the mineral and petroleum potential of the affected region. Limited exploration to date has indicated some potential for oil and gas reservoirs within the interior basins of central BC, including the Nechako sedimentary basin (Hannigan et al., 1994; Hamblin, 2008). In order to gain a better understanding of the potential for hydrocarbon resources in the region, a magnetotelluric survey, designed to evaluate the usefulness of the method in oil and gas exploration and to characterize the conductivity structure of the Nechako Basin, was conducted in the fall of 2007 (Spratt et al., 2008; Spratt and Craven, 2008; Figure 1).

The Nechako Basin is an Upper Cretaceous to Oligocene sedimentary basin located in the Intermontane Belt of the Canadian Cordillera (Figure 1). The basin formed in response to terrane amalgamation to the western edge of ancestral North America, and consists of overlapping sedimentary sequences (Monger et al., 1972; Monger and Price, 1979; Monger et al., 1982; Gabrielse and Yorath, 1991). Underlying the Nechako sedimentary rocks are the Stikine and Quesnel volcanic arc terranes, separated by the oceanic Cache Creek Terrane (Struik and MacIntyre, 2001). Transpressional tectonic processes were dominant until the Eocene, with westward-directed thrusting between the Stikine and Cache Creek terranes prior to 165 Ma (Best, 2004). Regional transcurrent faulting and associated east-west extension, beginning in the Late Cretaceous, were accompanied by the extrusion of basaltic lava in Eocene and Miocene times.

Basaltic flows of the Neogene Chilcotin Group, volcanic rocks of the Eocene Endako and Ootsa Lake groups, and Pleistocene glacial deposits cover a large portion of the Nechako Basin, complicating the interpretation of modern subsurface imaging methods. As a result, much of the stratigraphy and structure of the underlying sedimentary rocks remains uncertain. It has been suggested that the Chilcotin Group can reach a thickness of ~200 m and averages ~100 m (e.g., Mathews, 1989); however, new studies suggest that it is comparatively thin (<50 m) across most of its distribution and only thick (>100 m) in paleochannels (Andrews and Russell, 2008). 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 has complicated the magnetic interpretations. It has been shown that the magnetotelluric (MT) method can be useful in resolving geological structures that are less favourable for characterization by seismic methods (Unsworth, 2005; Spratt et al., 2007). As the method is sensitive to but not impeded by the surface volcanic rocks and can detect variations within the different units, it can be useful in locating the boundaries of the Nechako Basin and defining its internal structure.

Methodology

The magnetotelluric (MT) method measures the natural time-varying electrical and magnetic fields at the surface of the Earth to provide information on the electrical conductivity of its subsurface (Cagniard, 1953; Wait, 1962; Jones, 1992). Signal for MT is generated from interactions between solar winds and the ionosphere at low frequencies, and from distant lightning storms at higher frequencies. The MT response curves (phase lags and apparent resistivities) are calculated from the measured fields at various frequencies for each site recorded. As lower frequencies penetrate deeper through resistive materials, an estimate of conductivity variation with depth can be made from the response curves beneath each site.

Where the Earth is electrically two-dimensional (2-D), the conductivity varies laterally along a profile and with depth.

Keywords: *Nechako Basin, hydrocarbon exploration, magnetotelluric, electromagnetic, conductivity structure*

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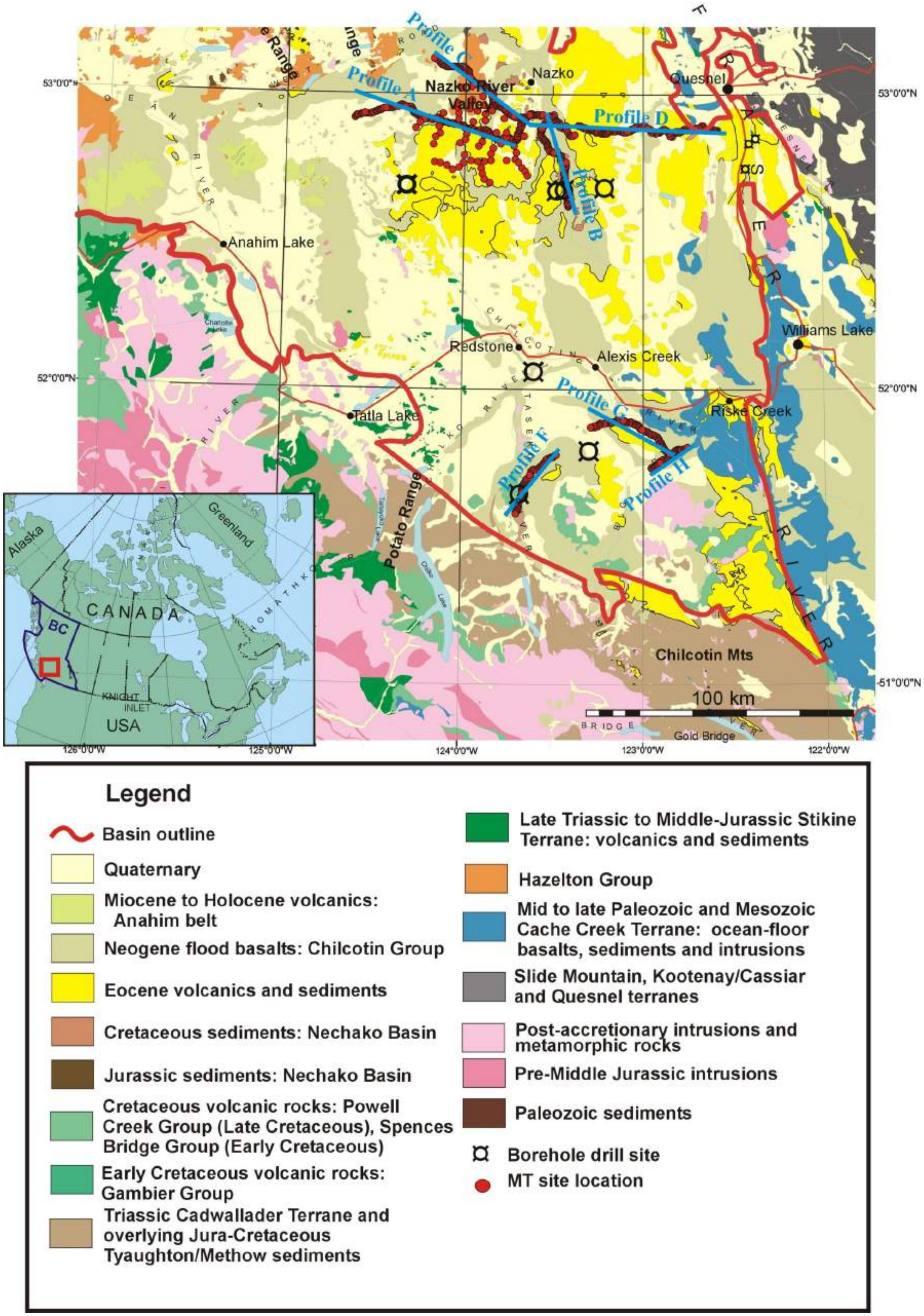

Figure 1. Regional geology of the study area (Riddell, 2006), showing the location of the magnetotelluric stations and the borehole wells.

In this case, apparent resistivities and phases differ along strike compared to those in the perpendicular direction, and some form of directionality analysis is required to determine the preferred geoelectric strike direction. The transverse-electric (TE) mode refers to the along-strike direction and the transverse-magnetic (TM) mode is perpendicular to strike.

The MT method is sensitive to contrasts in the resistivity of juxtaposed materials and can therefore distinguish between some lithological units. Basalt and igneous rocks, for example, commonly have electrical resistivity values >1000 ohm-m (Ù-m), whereas sedimentary rocks are less resistive, with values ranging between 1 and 1000 Ù-m. In the crust, other factors that can greatly influence the overall conductivity of a specific unit include the presence of saline fluids, changes in porosity and the presence of graphite films or interconnected metallic ores (Haak and Hutton, 1986; Jones, 1992). In addition to defining structure, the MT method may be able to provide some estimate of bulk properties, such as porosity and percent salinity, that may give direct evidence for the presence of hydrocarbons (Unsworth, 2005).

Data and Analysis

Combined high-frequency audio-magnetotelluric (AMT) and broadband (BBMT) data were collected at a total of 734 sites through the southern part of the Nechako Basin in the fall of 2007 (Figure 1). The data were acquired by Geosystem Canada using MTU-5A recording instruments manufactured by Phoenix Geophysics Ltd. of Toronto. The data were processed by Geosystem using robust remote reference techniques resulting, in general, in excellent data quality covering a period range of nearly seven decades (0.0001–1000 seconds). The dataset was divided into eight separate profiles for subsequent data analysis and 2-D modelling (Figure 1).

Single-site and multisite Groom-Bailey decompositions were applied to each of the MT sites along profiles A, B, C, D and F, in order to determine the most accurate geoelectric strike direction and to analyze the data for distortion effects (Groom and Bailey, 1989; McNeice and Jones, 2001). Figure 2 illustrates the results of single-site strike analysis for each decade period band recorded at each site along the profiles. Nearly all of the sites show a maximum phase difference between the two modes of less than 10 at periods below 0.1 second (s), indicating that the data are independent of the geoelectric strike angle and can be considered 1-D. The maximum phase splits are observed between 0.1 and 10 s, where small changes in the selected strike angle will most affect the data and associated errors.

Profiles A and C are similar, with strikes of 5–10 at the westernmost edge of the profiles changing to a strike of ~35 towards the east. Profile B shows only moderate phase splits at only a few sites, suggesting that the majority of the data are 1-D. Profile D shows much stronger phase splits, with a preferred strike angle of ~32 for most sites to periods of 100 s; however, the misfit values for the decomposed data, even when no constraints were placed on the data, were significantly high. This is a strong indication of 3-D distortion effects, so 2-D models may not accurately represent the data. Results along profile F indicate strong phase differences at periods greater than 1 s with a fairly consistent strike angle of 22–28 . In general, there is a roughly northeast to southwest trend observed in the variations in the geoelectric strike angle. These changes may have resulted from different tectonic pulses, where the stress directions are preserved in the conductivity structure.

Data Modelling and Preliminary Results

One-Dimensional Models

One-dimensional models have been generated for all of the MT sites within the Nechako Basin. Layered Earth models were derived from Occam inversions using the WingLink^{TM} interpretation software package. Dimensionality and depth analysis indicate that, in general, the data can be considered 1-D up to periods between 0.1 and 1 s, corresponding to depths below 1000–2500 m. Figure 3 shows the results of the 1-D models for varying depth slices in the MT survey region. In general, among the northern set of sites, there appears to be a northeast to southwest trend in conductivity structure, consistent with the results from the decomposition analysis. However, more complex structure is revealed in the southern set of sites, and additional dimensionality analysis is necessary. At 50 m depth, the blue region at the westernmost extent of the survey area most likely represents the resistive volcanic cover. Consistent with the results from Andrews and Russell (2008), the limited lateral extent of this resistor suggests that the volcanic cover is either thinner than 50 m or not as widespread as initially presumed. There is a change in conductivity from ~200 to >700 Ù-m in the eastern half of the survey area between depths of 1000 and 2000 m. This likely represents the change from conductive sedimentary rocks to the underlying resistive basement units; however, this change is not observed through the entire region, indicating that the sedimentary packages are thicker towards the eastern edge of the Nechako Basin. An anomalously conductive zone (<15 Ù-m) is observed in the centre of the MT survey region at a depth of 500 m, along profile D, within the sedimentary units and appears to dip towards the east. These dramatic changes may be related to salinity of groundwater or changes in porosity.

Two-Dimensional Modelling

Two-dimensional models have been generated along profiles A, B, C, D and F using the WingLink interpretation

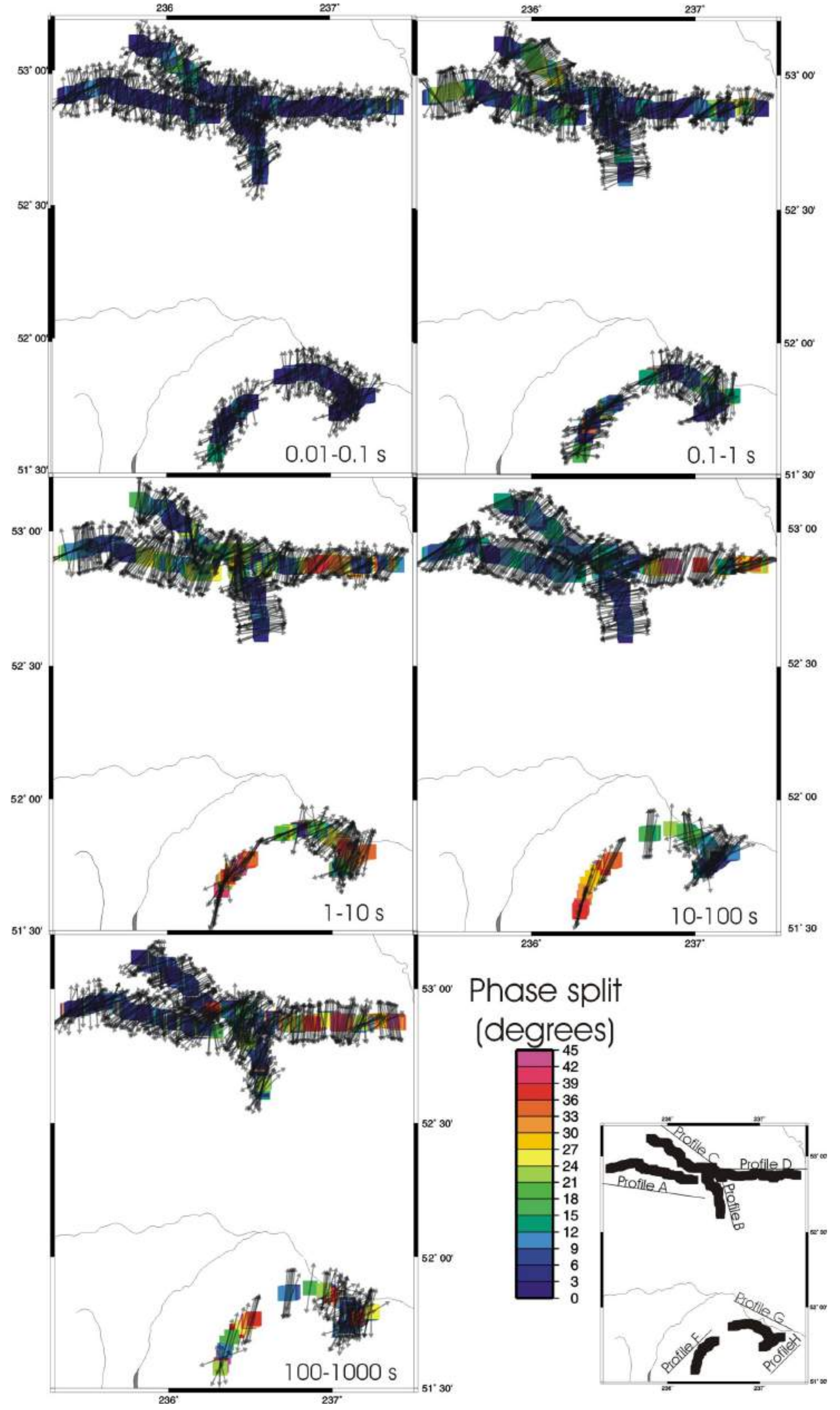

Figure 2. Preferred geoelectric strike angle at each decade period band recorded for each of the MT sites within in the Nechako Basin. The colours illustrate the maximum phase difference between the TM and TE modes, where the warmer colours represent a higher phase split.

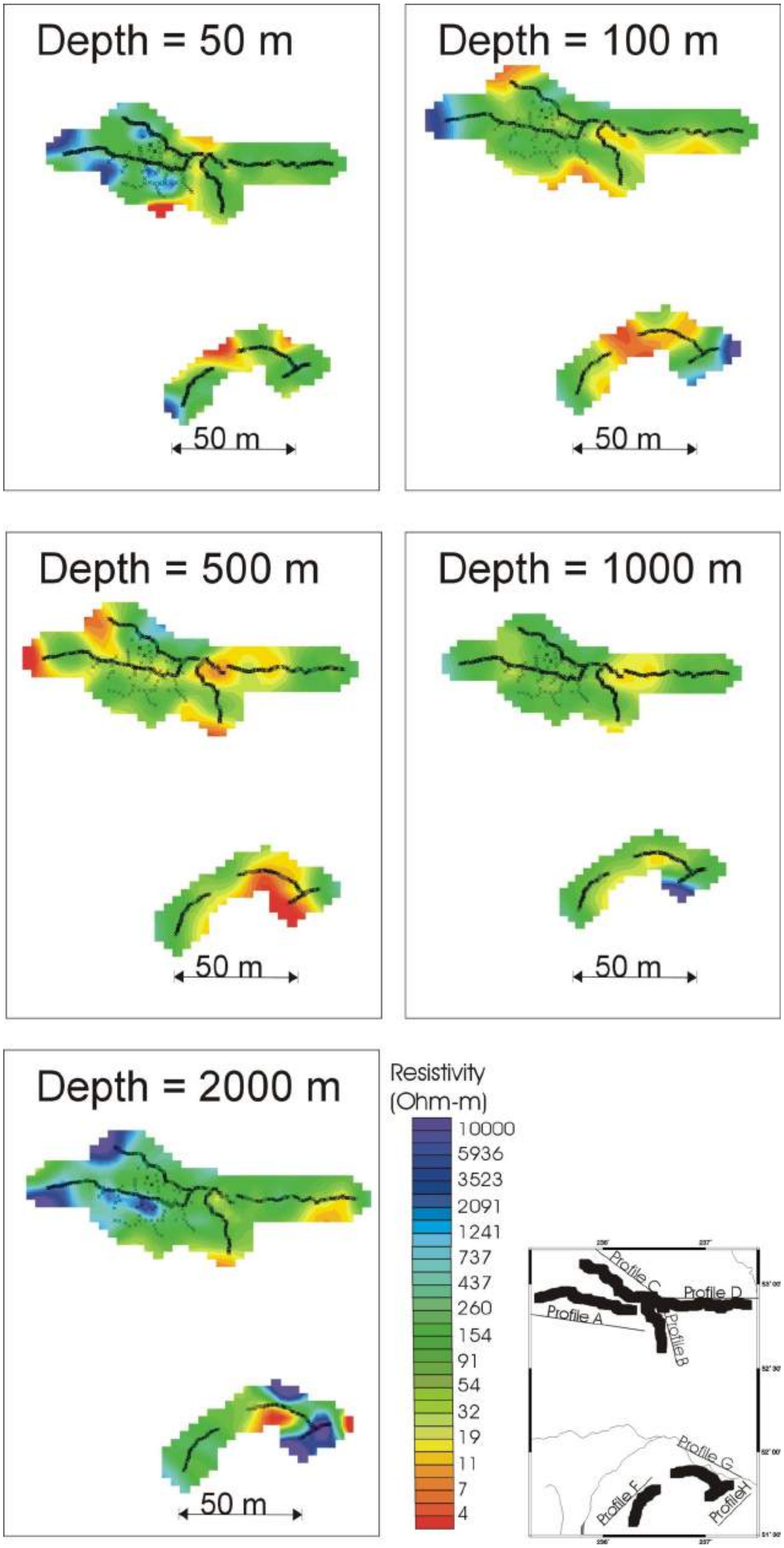

Figure 3. Results of one-dimensional modelling of all MT sites within the Nechako Basin at various depths within the Earth. The warm colours represent areas of high conductivity and the cooler colours represent resistive regions.

software package (Figure 4). More than 100 iterations were executed and included data from the TE mode, the TM mode and the vertical field transfer function, in the period between 0.0001 and 1000 s. All of the models reveal a decrease in conductivity at depths ranging from 1000 to 3000 m, corresponding to approximate depth estimates for the thickness of the Nechako sedimentary packages. This indicates that the MT data are sensitive to the base of the Nechako Basin and can delineate its structural boundaries.

In addition, along-profile variations in the conductivity structure are revealed. Feature A (Figure 4b, d) is an anomalously conductive region (>10 Ù-m) that lies within the sedimentary units. This feature is observed at the northern end of profile B and along the west-central part of profile D, consistent with the northeast to southwest trend observed in the strike analysis. Causes for significantly high conductivity may include the presence of saline fluids, graphite sheets or sulphides, or may result from a significant increase in the relative porosity of the sedimentary rocks. Feature B is an anomalously resistive unit located at shallow depths along profile C (Figure 4c). This feature correlates spatially with the mapped exposure of the volcanic-arc assemblages of the Hazelton Group of the Stikine

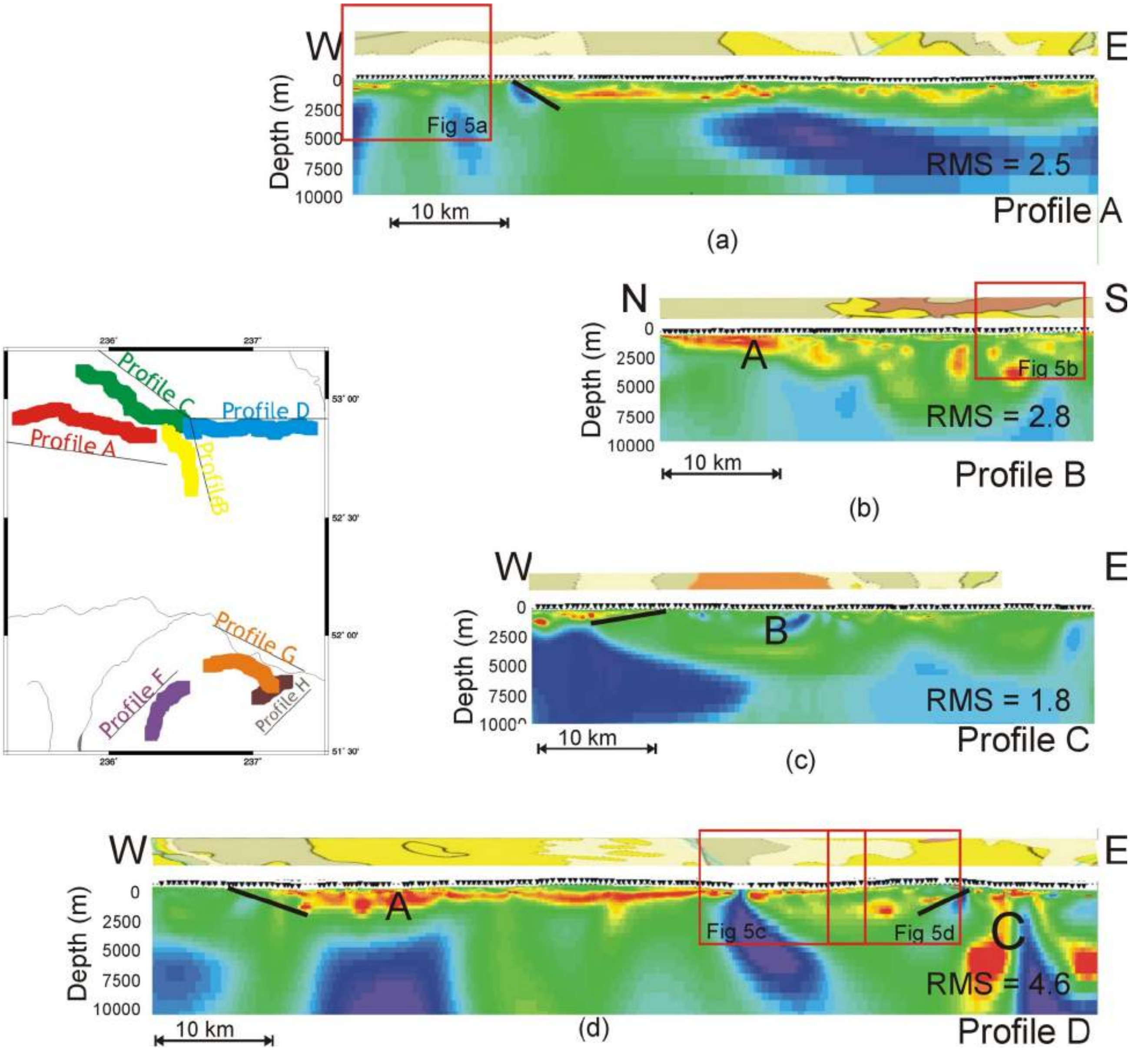

Figure 4. Cross-sections illustrating the two-dimensional models generated along profiles A, B, C and D. The local geology is shown above each profile and the different units are described in the legend for Figure 1. The red squares mark the sections where detailed focused inversions have been generated and shown in Figure 5. The black lines illustrate structural boundaries in the lateral continuity of the shallow conductive layer.

Terrane. Additional modelling is required to constrain the structural nature of this feature. The easternmost extent of profile D illustrates major structure at mid-crustal depths, labelled as feature C. These structures may be related to the lateral fault-bounded eastern extent of the Nechako Basin, and may be an indication for north-northwest-striking subvertical splays of the Fraser fault. Several breaks in the continuity of the upper conductor are observed along many of the profiles (Figure 4a, c, d). These may represent faulting that juxtaposes resistive material from deeper regions against the conductive sedimentary rocks.

Preliminary 2-D modelling has been initiated along profile F (not shown). Although additional testing is required to assess the validity of the model, there is a general deepening of the resistive lower layer from northeast to southwest. This is consistent with interpretation of the seismic data, which suggests a thickening of the Cretaceous sedimentary rocks towards the southwest (Hayward and Calvert, 2008).

Profiles A, B, and D were divided into shorter segments, and each segment was modelled separately to obtain higher resolution of the shallow structure beneath the profile and to generate a model that reasonably fits all the data. This is achieved by allowing a denser mesh and by reducing weighted averaging between sites by fitting the model to a smaller dataset. These focused inversions enable the resolution of enhanced detail, such as imaging the surficial volcanic rocks where they are thicker than ~50 m (Figure 5a), and reveal specific structure that imposes constraints on the lateral continuity of the conductive sedimentary rocks (Figure 5b, d). In addition, they allow for a comparison between the models and geological observations in the boreholes (Figure 5b). They also result in models that have a better fit to the data, reducing inaccurate modelling effects (Figure 5c).

Conclusions and Future Work

Continued analysis of magnetotelluric data collected throughout the Nechako Basin has, to date, yielded one-dimensional models for the entire dataset and two-dimensional conductivity models along four of the seven major profiles. A conductivity contrast between the surface volcanic rocks, the Nechako sedimentary rocks and the underlying basement rocks is observed, indicating that the method is capable of imaging the structure of the basin. The two-dimensional models image the surface volcanic rocks in isolated locations, suggest-

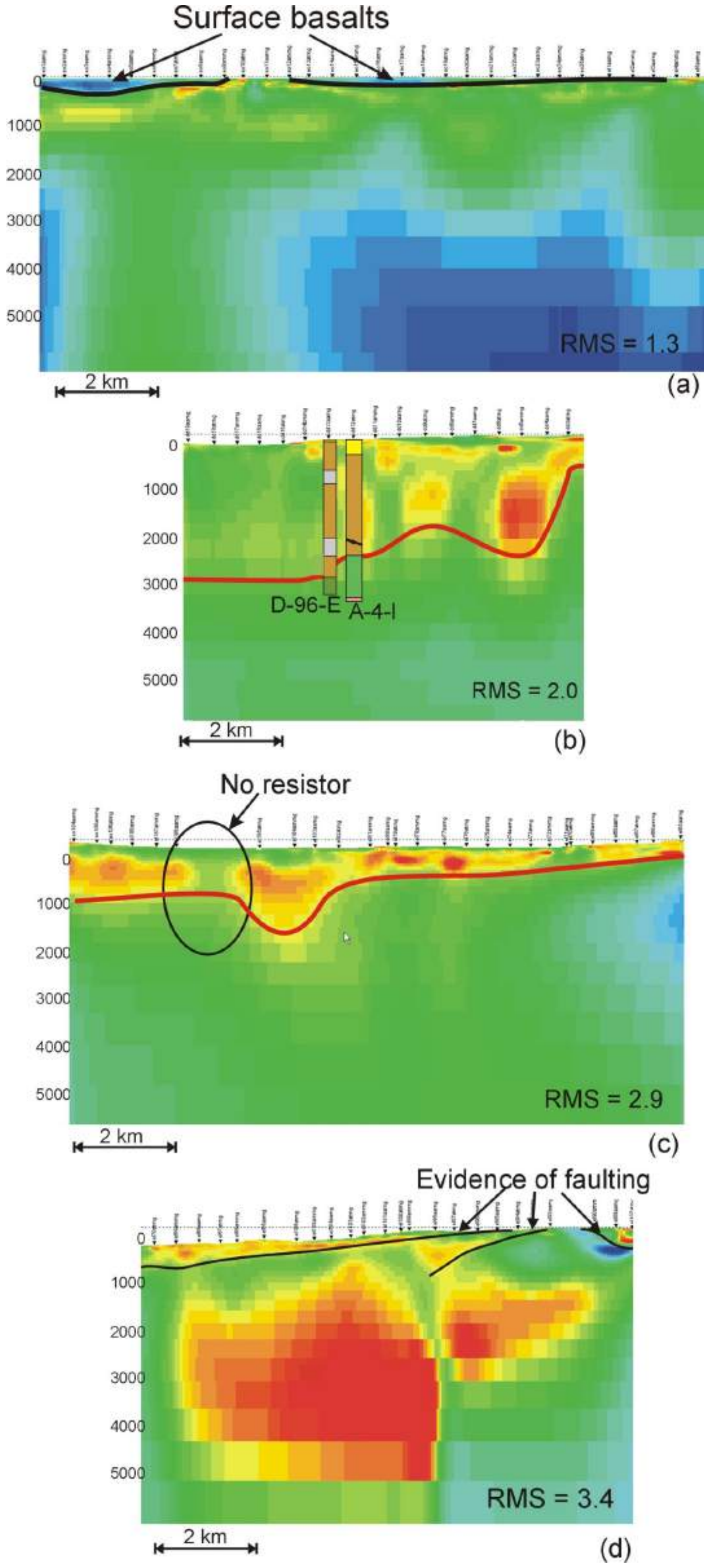

Figure 5. Examples of the detail obtained with focused two-dimensional inversions along sections of the main profiles. The red line marks the boundary between the conductive upper unit and a more resistive underlying layer, which is interpreted as the base of the Nechako sedimentary rocks. The black line indicates the base of the surface basalts. Wells d-96-A and a-4-L (*from* Ferri and Riddell, 2006) are shown in (b).

ing that they are either too thin to be detected using audiomagnetotelluric methods or they are not as widespread as initially thought. The thickness of the sedimentary packages varies greatly along the different profiles, and structural constraints are placed on the lateral continuity of the conductive sedimentary rocks. Along-strike variations in conductivity within the sedimentary packages are observed, suggesting changes in mineralogy, porosity or salinity. Characterizing these changes will be important in assessing the potential for oil and gas within the region.

Acknowledgments

The authors are grateful to the Geological Survey of Canada, Geoscience BC and the BC Ministry of Energy, Mines and Petroleum Resources for providing financial support for this research. They also thank M. Pilkington for proving insightful comments and a constructive review of this paper.

Geological Survey of Canada contribution 20080463.

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