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Abstract: Two-dimensional conductivity models of the Nechako sedimentary basin have been generated from magnetotelluric data collected in southern British Columbia. The survey was designed to help understand the hydrocarbon potential of the basin and to further resolve the stratigraphy and structure beneath volcanic sequences and glacial deposits. The models show thin resistors, interpreted as basalts, that extend to depths up to 200 m, but in general are less than 50 m thick. The data identify specific conductivity signatures associated with Eocence volcaniclastic units and Cretaceous sedimenary sequences and suggest that the method can distinguish between the two, limiting the extent of hydrocarbon hosts. Complex local structure that may provide traps for oil and gas is imaged, as well as regional faulting that give insight into the tectonic history of the region. Localized conductive anomalies may indicate the presence of magma at depths of 10–12 km.

Résumé : Des modèles 2D de la conductivité dans le bassin sédimentaire de Nechako ont été produits à partir de données magnétotelluriques recueillies dans le sud de la Colombie-Britannique. Le levé a été conçu de manière à obtenir une meilleure compréhension du potentiel en hydrocarbures du bassin et à éclaircir la stratigraphie et la structure des roches sous-jacentes aux séquences volcaniques et aux dépôts glaciaires. Les modèles révèlent la présence de minces couches résistantes, assimilées à des basaltes, qui peuvent atteindre des profondeurs de 200 m, mais dont l'épaisseur ne dépasse généralement pas 50 m. Les données de conductivité révèlent des signatures particulières associées aux unités volcanoclastiques de l'Éocène et aux séquences sédimentaires du Crétacé, ce qui laisse croire que la méthode peut permettre de distinguer ces deux lithologies l'une de l'autre et ainsi de circonscrire les roches hôtes des hydrocarbures. On a obtenu une imagerie de structures locales complexes pouvant piéger du pétrole et du gaz naturel, ainsi que de failles régionales, qui nous renseignent sur l'évolution tectonique de la région. Des anomalies localisées de corps conducteurs pourraient indiquer la présence de magma à des profondeurs de 10 à 12 km.

INTRODUCTION

The Lower Jurassic to Oligocene Nechako Basin is located within the Intermontane Belt of the Canadian Cordillera and is a forearc basin that formed in response to terrane amalgamation to the western edge of the ancient North American craton (Struik and MacIntyre, 2001). Limited exploration to date has suggested that the potential for oil and gas reservoirs exists within the Cretaceous sedimentary sequences of the Nechako Basin (Hannigan et al., 1994). Understanding the distribution and structure of these units is crucial in appreciating this potential and advancing the hydrocarbon exploration of the region, however our current knowledge of the Nechako Basin is limited due to volcanic cover and glacial deposits that blanket a large portion of the region.

The magnetotelluric (MT) method is sensitive to, but not impeded by, the surface volcanic rocks and has proven to be useful in characterizing the geological structure of the subsurface in environments similar to the Nechako Basin region (e.g. Xiao and Unsworth, 2006), that are less favourable for other geological and geophysical methods (Unsworth, 2005; Spratt et al., 2007). With the aim of resolving the geology of the Nechako sedimentary basin, as well as developing an understanding for the usefulness of the method in the exploration of oil and gas, an MT survey was conducted throughout the southern Nechako Basin region in the fall of 2007 (Fig. 1). This paper describes the two-dimensional conductivity structure that characterizes the Nechako Basin.

BACKGROUND

The main geological elements present in the southern Nechako Basin area include the Neogene Chilcotin basaltic flows, Eocene volcanic and sedimentary rocks of the Endako and Ootsa Lake groups, and the Cretaceous clastic marine and fluvial sedimentary rocks that include the Skeena Group and the Taylor Creek Group (Fig. 1). Underlying the Nechako Basin are the Stikine and Quesnel volcanic arc terranes, separated by the oceanic Cache Creek Terrane (Struik and MacIntyre, 2001). Prior to the Eocene, transpressional shortening resulted in westward-directed thrusting between the Stikine and Cache Creek terranes, resulting in the strike-slip Yalakom and Fraser faults that bound the basin to the south and east (Best, 2004). Beginning in the Late Cretaceous, east-west extension associated with regional transcurrent faulting was accompanied by the extrusion of basaltic flows of the Neogene Chilcotin Group, and the Eocence volcanic groups (Price, 1994). It has been suggested that the Chilcotin Group can reach a thickness of about 200 m and averages about 100 m (e.g. Mathews, 1989); however, new studies suggest that it is comparatively thin (<50 m) across most of its extent and only thick (>100 m) in paleochannels (Andrews and Russell, 2008).

Several geophysical studies have been undertaken within the Nechako Basin region with the aim of enhancing knowledge of the geology of the basin and understanding its resource potential. Canadian Hunter Exploration Limited conducted a regional gravity survey in the 1980s that identified a gravity low in southern Nechako Basin interpreted as a Tertiary subbasin. Initial interpretation of seismic-reflection data collected by Canadian Hunter Exploration Limited revealed folded and faulted sedimentary rocks within the basin. Reanalysis of these data with modern processing techniques in the southernmost part of the Nechako Basin have resulted in a higher resolution of local structures (Hayward and Calvert, 2008). Early magnetolluric data in the frequency ranges of 0.016–130 Hz were collected by the University of Alberta in the 1980s (Majorowicz and Gough, 1991). These 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). In addition to these regional geophysical surveys, several wells were drilled throughout the southern portion of the basin between 1960 and 1986 (Fig. 1), providing detailed geological information as well as a variety of borehole logs that included natural gamma-ray spectroscopy, neutron porosity, and resistivity logs. These provide some control on the interpretation of subsurface imaging and allow constraints to be placed on the models generated from the new MT data.

MAGNETOTELLURIC THEORY AND SURVEY DESIGN

Magnetotelluric techniques

Magnetotelluric technique is a geophysical exploration method that involves measuring the natural time-varying fluctuations of mutually perpendicular electric and magnetic fields at the surface of the Earth to provide information on the electrical conductivity structure at depth (Cagniard, 1953; Wait, 1962; Jones, 1992). At low frequencies, broadband magnetotelluric (BBMT) and long period ranges, the signal is generated by interactions of solar winds with the ionosphere. At higher frequencies, audiomagnetotelluric (AMT) ranges, the signal is produced from distant lightning storms. The measurement of the orthogonal electric and magnetic fields in the time domain allows us to calculate the apparent resistivity and phase lag at various periods in the frequency domain. These are typically plotted as MT response curves for each site recorded. As the depth of penetration of these fields is directly related to their frequency (the lower the frequency, the greater the depth) and the resistivity of the material (the greater the resistivity the greater the depth), estimates of resistivity versus depth can be made beneath each site.

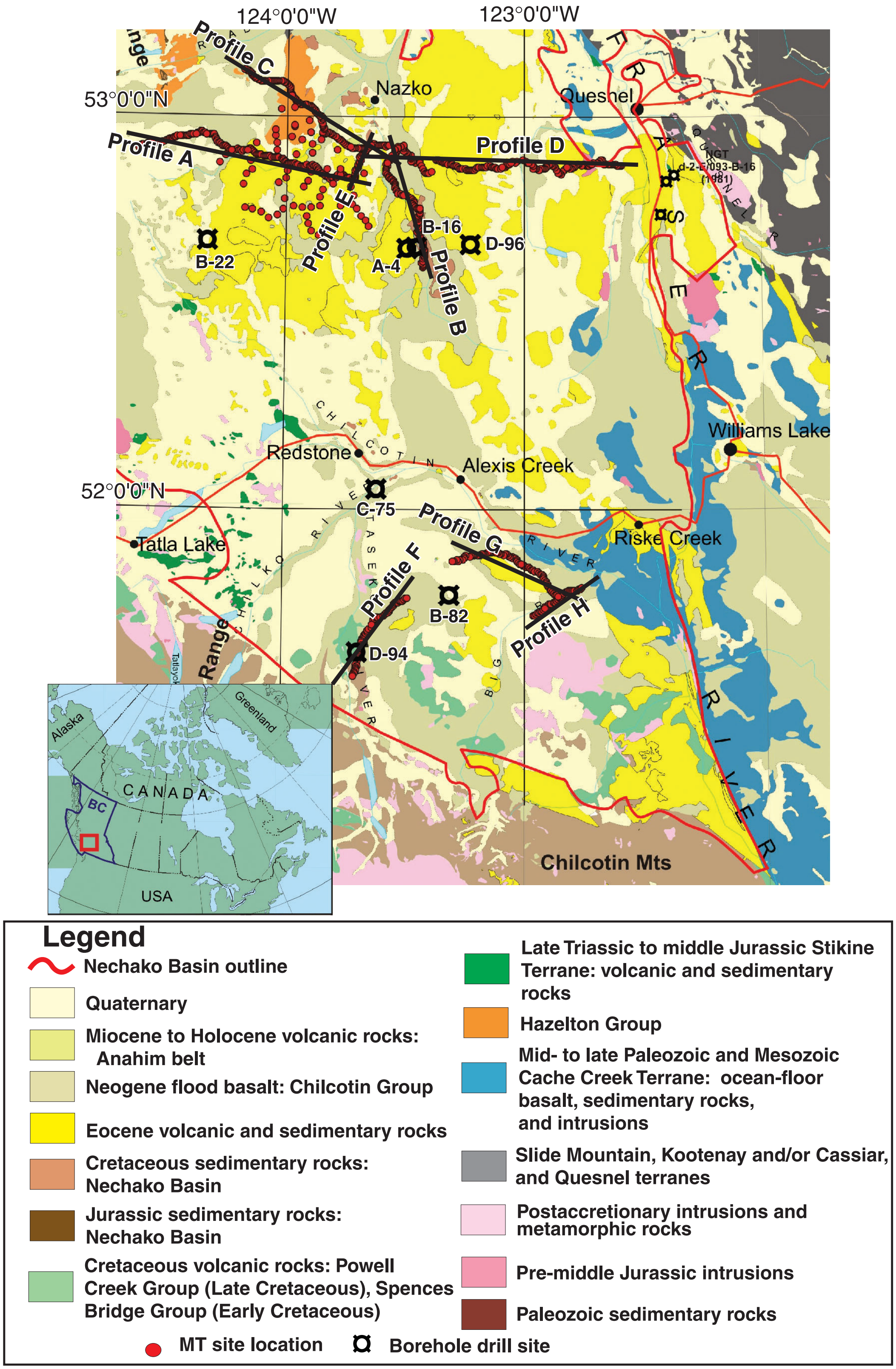

Figure 1. Regional geology map of the study area illustrating the location of the MT sites, drilled boreholes, and two-dimensional profile traces. Map taken from Riddell (2006).

The MT response curves are represented in a 2 x 2 MT impedance tensor that contains information on the dimensionality of the Earth beneath each site. In a one-dimensional layered Earth, where the conductivity structure is laterally uniform, two of the tensor elements are zero, and the other two, referred to as the transverse electric (TE) and transverse magnetic (TM) modes of electromagnetic (EM) field propagation, are equal. In a two-dimensional Earth, where the conductivity varies laterally along a profile and with depth, two of the elements are zero, however the TM mode (parallel to geoelectric strike) and TE mode (perpendicular to strike) are different (d'Erceville and Kunetz, 1962; Rankin, 1962). In this case analysis of directionality by mathematical decomposition is typically applied to the tensor data to determine the preferred geoelectric strike direction consistent with the data (Groom and Bailey, 1989). In a three-dimensional Earth, the four components of the tensor are nonzero and a two-dimensional model would not accurately represent the data. Three-dimensional modelling of the data set is then required.

Data

In the fall of 2007, combined high-frequency audiomagnetotelluric and broadband magnetotelluric data were collected at 734 sites through the southern Nechako Basin region at a site spacing of 200 m (Fig. 1). Apparent resistivity and phase response curves were generated for each site using robust remote reference codes as implemeted by Pheonix Geophysics Ltd. processing software. In general, the data quality is excellent with smooth curves and low error bars that extend over seven period decade bands in the range of 0.00001–1000 s (Fig. 2). The data set has been subdivided into eight separate profiles, A through H, for analysis and modelling.

Decompositions

Single-site and multisite Groom-Bailey decompositions were applied to the MT data along each of the profiles in order to statistically determine the preferred geoelectric strike direction and to analyze the data for effects of galvanic distortions and three-dimensionality (Groom and Bailey, 1989; McNeice and Jones, 2001). Nearly all of the sites show a maximum phase difference between the two modes of less than 10° at periods below 0.1 s. This indicates that at high frequencies (shallow depths) the data are independent of the geoelectric strike angle and can be considered to be one-dimensional. Maximum phase splits are observed between 0.1 s and 100 s, where small changes in the strike angle will most affect the data and associated errors. The geoelectric strike angle may be controlled regionally, for example large-scale faulting, or locally by oriented grains. Ideally, one particular strike angle, yielding acceptable misfits for all frequencies at all sites along a profile, can be used to generate a two-dimensional model of the data; however, where the geoelectric strike angle varies along profile or with depth, additional modelling may be required to test the robustness of the features revealed and to minimize the misfit value. At some sites along certain profiles an acceptable misfit cannot be obtained at particular frequencies for any strike angle, suggesting three-dimensional distortion of the data.

The results of decomposition analysis along profiles A, C, and E indicate consistent preference for a geoelectric strike angle of about 35° (Fig. 3). Profile B shows only

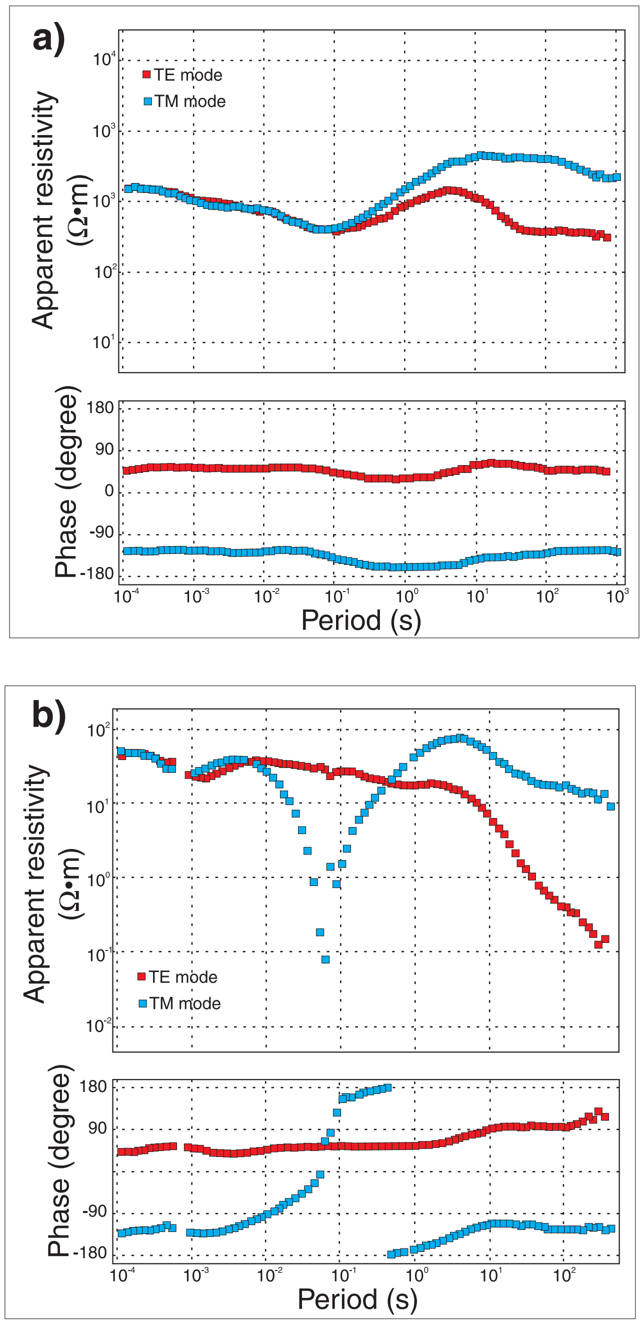

Figure 2. Examples of apparent resistivity and phase curves of MT data recalculated at 34° **a)** located midway along profile A, shows the general data quality obtained for most sites in the survey, whereas **b)** shows an example of the sever distortion at the east end of profile D.

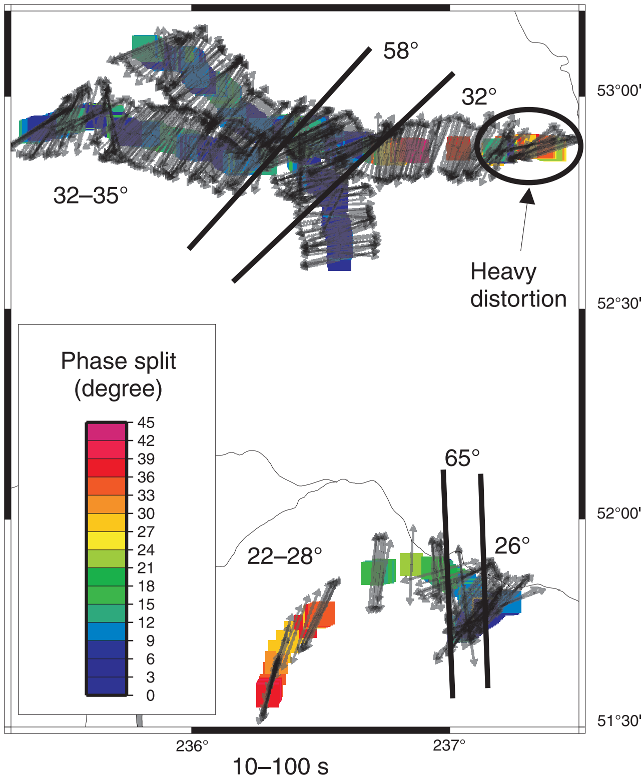

Figure 3. Preferred geoelectric strike direction for the 10–100s period band, at each site. The colour scale represents the maximum phase split between the TE- and TM-modes.

moderate phase splits at only a few sites, suggesting that the majority of the data are one-dimensional. The sites that indicate weak two-dimensionality show a preferred strike angle of 76°. Profile D shows much stronger phase splits, with a preferred strike angle of about 32° for most sites, and about 58° for the westernmost sites, to periods of 100 s. The misfit values for the decomposed data at many sites along profile D, even when no constraints were placed on the data, were significantly high. This is a strong indication of three-dimensional distortion effects and two-dimensional models may not accurately represent the data.

The southern profiles, F, G, and H, indicate strong phase differences at periods greater than 1 s with a fairly consistent strike angle of 22–28°, except for a few sites along both profiles G and H that show a preference for a geoelectrical strike angle of 65° at longer periods (greater depths). The abrupt changes in strike direction may represent different tectonic pulses, where the stress directions are preserved in the conductivity structure.

The data from along each profile have been recalculated at the geoelectric strike angle obtained from decomposition analysis to provide the transverse electric- and transverse magnetic-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. Where more than one angle was appropriate for different sections of a profile, either along profile or with depth, the data were recalculated at both angles and modelled separately in order to assess the differences in the resulting conductivity structure imaged.

DATA MODELLING AND INTERPRETATIONS

Two-dimensional models have been generated using the WinGlink™ interpretation software package, for profiles A through H from the distortion-corrected data recalculated at the preferred geoelectric strike angle. Over 200 iterations were executed for each profile and included data in the period range of 0.0001–1000 s, from the transverse electric-mode, the transverse magnetic-mode, and the vertical field transfer function. In general, the model misfits are fairly good with RMS (root mean squared) values less than 3, however certain models do not fit the data well, particularly those for profile D. This is attributed to three-dimensionality of the data, implied from the decomposition analysis.

As transverse magnetic solutions are nonunique in nature, several models were generated for each of the profiles using various combinations of modelling parameters (adjusting the smoothing parameters, mesh sizes, and regularization models) in order to observe their effects on the conductivity features revealed. The full profile two-dimensional models shown here used a smoothing value (τ) of 7 and error floors of 7% for apparent resistivity and 2º for phase. In an attempt to refine the structure at key areas along certain profiles, additional models were generated using data from selected sites at higher frequencies. These result in focused models that include fewer data from fewer sites using a finer mesh, and have a better overall fit to the data.

In general, the two-dimensional transverse magnetic models generated along each of the profiles reveal three distinct horizontal units that characterize the conductivity structure of the Nechako Basin: a near-surface resistor (>500 Ω•m), a shallow conductive layer (<100 Ω•m), and a deeper resistive unit (>300 Ω•m).

The near-surface resistive layer ranges in depth from 0 to 200 m (Fig. 4a). This layer correlates well with the surface mapped Chilcotin Group basalts, thickens toward the western end of profiles A and C, and is consistently thick along profile H. The Canadian Hunter Exploration Ltd. resistivity logs recorded in boreholes B-022 and B-016 show values associated with the basalts to be greater than 1000 Ω•m, further suggesting that the surface resistor is representing the Miocene Chilcotin Group. The regional extent of this resistive layer is limited compared to the mapped surface exposure of the basalts. As the data recorded are not sensitive to the uppermost 50 m, this suggests that either the Chilcotin Group basalts are not as widespread as initially presumed, or are regionally thinner than about 50 m.

The shallow conductive layer, the base of which ranges in depth from 0 to 4000 m, can be divided into two separate units with different conductivity characteristics. This is best illustrated along profile B (Fig. 4b), where the southern half of the profile is mapped as Cretaceous sedimentary rocks and the northernmost part of the profile as Eocene volcaniclastic rocks. Below the Cretaceous sedimentary rocks the layer is moderately conductive (10–100 Ω•m) and is laterally highly variable. Geological constraints from borehole A-04 show this conductivity signature to represent the Cretaceous Skeena Group sedimentary rocks to 2500 m depth. A similar signature is observed along profile F, where borehole D-94 suggests that the conductivity signature is associated with the Cretaceous Taylor Creek sedimentary rocks (Fig. 4c). The strong lateral variations could be due to structural complexities, variations in lithology or porosity, or may represent electrical anisotropy resulting from the presence of thin layers of shale.

Toward the north end of profile B, below the mapped Eocene volcaniclastic rocks, the shallow conductive layer is laterally more consistent, and has resistivity values less than 4 Ω•m (Fig. 4b). Although there are few constraints from

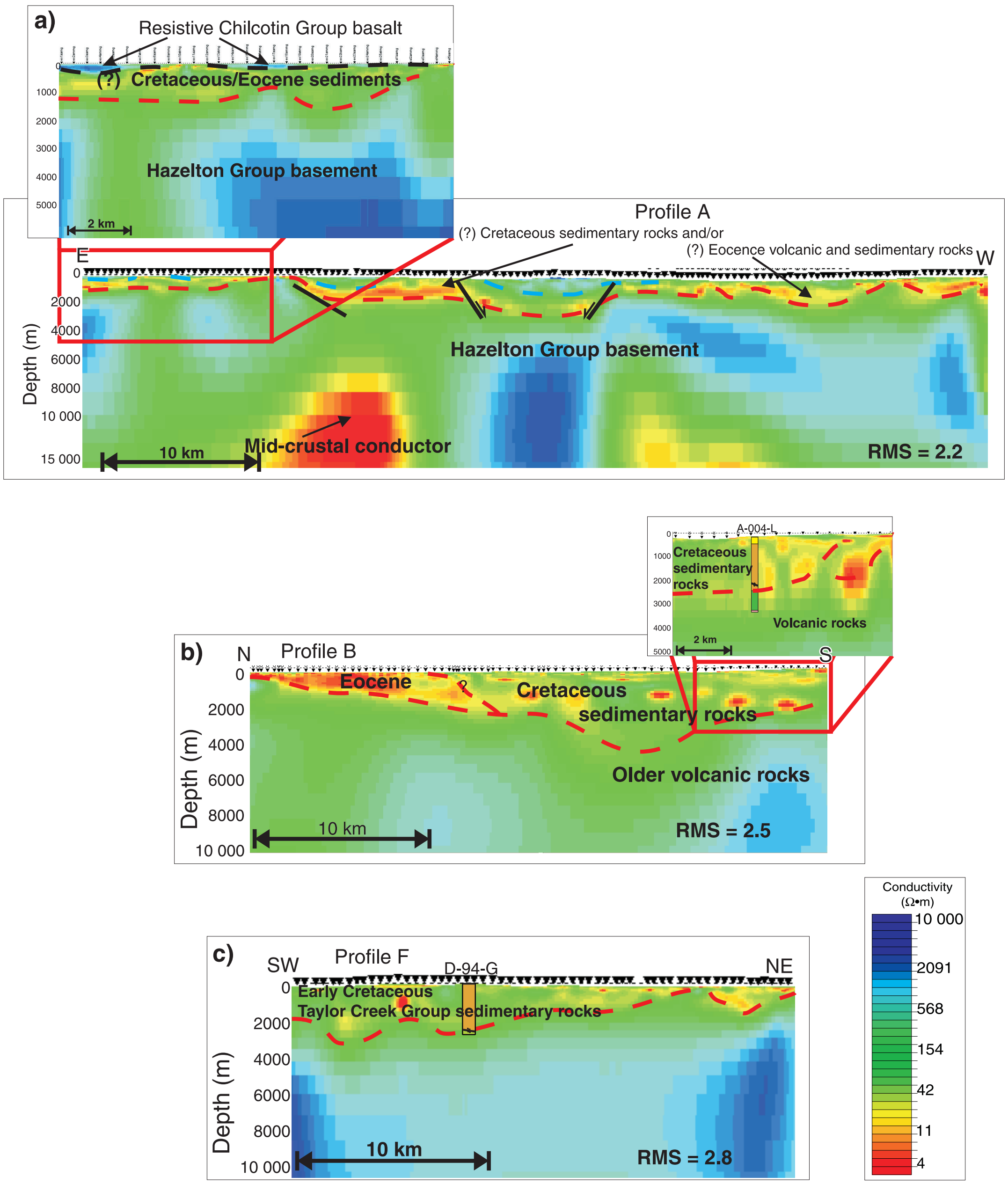

Figure 4. Two-dimensional conductivity models and interpretations for **a)** profile A, **b)** profile B, **c)** profile F, **d)** profile C, **e)** profile E, **f)** profile D, and **g)** profile G. The red dashed line illustrates the interpreted base of the Nechako Basin and the black lines represent fault lines. Stratigraphic columns have been *modified from* Ferri and Riddell (2006).

boreholes for this unit, it is observed along most of the profiles (A, B, C, D, G, and H) and regionally correlates with the surface-mapped Eocene groups. Causes for these low resistivity values include continuous sheets of shale, graphite, or sulphides, or the presence of saline fluids; however, neither graphite or sulphides have been observed in drillcore or surface samples.

The deeper resistive unit correlates with older volcanic units, either Cretaceous volcanic rocks or older island-arc terranes. The boundary between this unit and the shallow conductive layer is, therefore, interpreted as the base of the Nechako Basin. Along much of profile C, the conductive layer is not present and this resistive unit extends toward the surface (Fig. 4d). This correlates spatially with the mapped exposure of the volcanic-arc assemblages of the Hazelton Group of the Stikine Terrane.

In addition to the three conductivity layers, several major structural features are imaged along the profiles. Breaks in the continuity of the upper conductor are observed along many of the profiles (Fig. 4a, f, g) that may represent normal

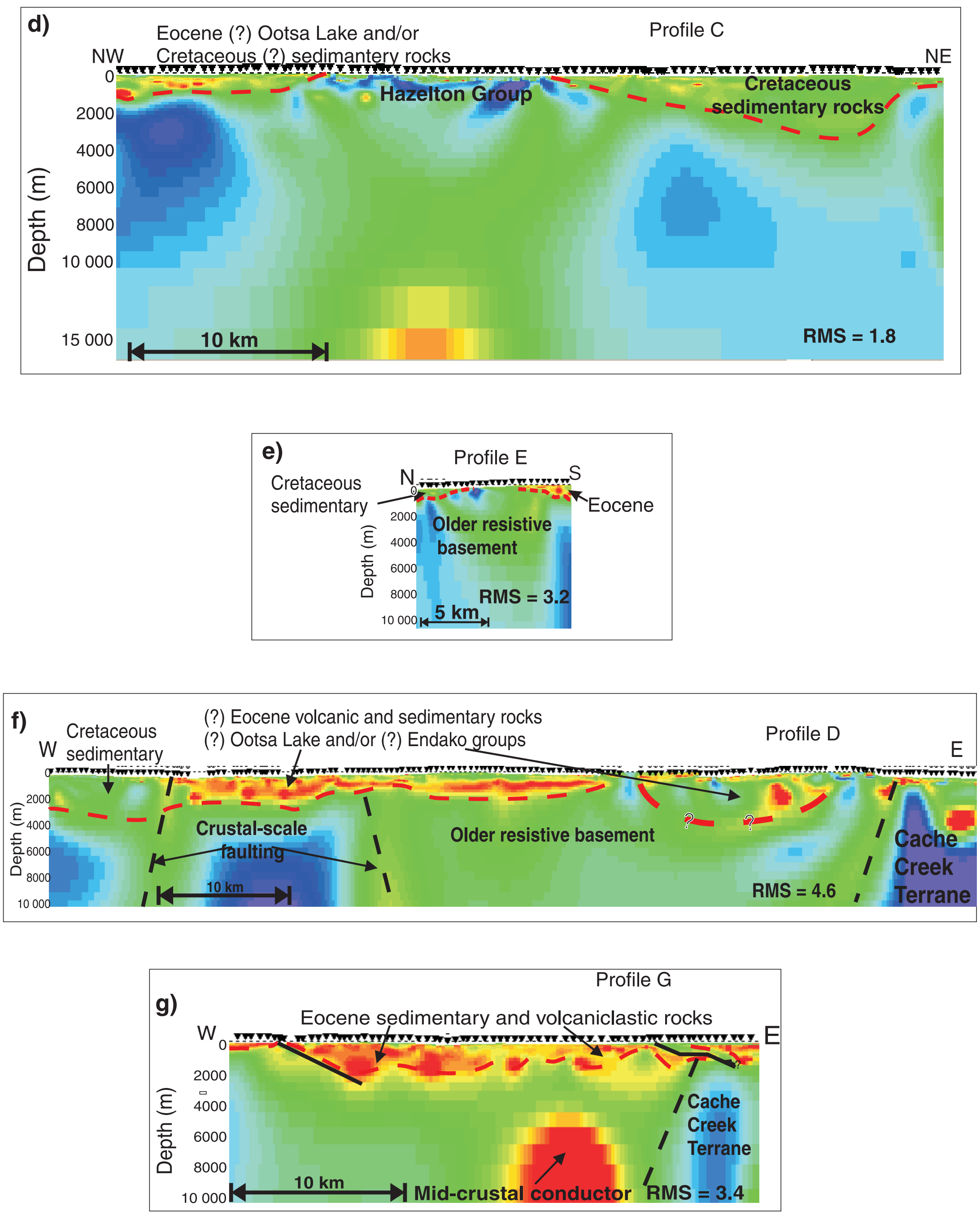

Figure 4. continued.

faulting that juxtapose resistive material from deeper regions against the conductive sedimentary rocks. Along profiles D and G, subvertical crustal scale features are observed that likely represent major faults (Fig. 4f, g). These correlate with the location of sites that have a higher preferred geoelectric strike angle, indicating that the faults are locally influencing current flow. The easternmost crustal-scale 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, separating the Stikine from the Cache Creek terranes.

The models generated for profiles A and G both reveal a region of anomalously high conductivities (<4 Ω•m) at mid-crustal depths (Fig. 4a, g). Due to the relationship between conductivity and the skin depth, the electric and magnetic fields are attenuated in this conductor and its depth extent cannot be ascertained. Data from the regional Canadian Hunter Exploration Ltd. survey reveal areas of low gravity that correlate well with the location of the mid-crustal conductors. One possible interpretation for enhanced conductivity and low density in the crust is the presence of fluids, either partial melt or metamorphic saline water. The authors' preferred interpretation is the presence of rising magma at depths of 10–12 km in the crust. Recent seismic activity in the vicinity of the mid-crustal conductor along profile A, west of the Nazco cone (the easternmost expression of the Anahim hot spot) has been interpreted to result from magma that is intruding deep within the Earth's crust (Fig. 5; Hickson (2008)). Electrical conductivity is highly sensitive to partial melt, where less than 1% melt can significantly increase the conductivity value (Partzsch et al., 2000).

CONCLUSIONS

The two-dimensional models generated from magnetotelluric data collected within southern British Columbia reveal the conductivity structure of the Nechako sedimentary basin. A near-surface resistive layer is interpreted as the Chilcotin Group basalts and its limited extent suggests that the basalts are typically less than 50 m thick. The Cretaceous sedimentary units are characterized by moderate conductivities that are laterally highly variable, where higher, more uniform, conductivity values appear to be associated with the Eocene volcaniclastic groups. This suggests that the MT data are capable of discerning between the two lithologies, and may therefore be useful in targeting units that have a higher potential for oil and gas reservoirs. The base of the Nechako Basin is marked by an increase in resistivity associated with the deeper, underlying volcanic units. The data also image folding and faulting of the Nechako Basin sedimentary rocks, structural features that may provide an environment for trapping hydrocarbons.

The MT data provide information on the stratigraphy and structure of the Nechako Basin that may help in identifying oil and gas resevoirs, but also give insight into the deeper structure and the tectonic setting of the basin. For example, several crustal-scale faults are observed that appear to locally control the geoelectric strike directions. These are evidence of major tectonic events related to the transpressional shortening between the Stikine and Cache Creek terranes. Finally, the models reveal two mid-crustal conductors that correlate with low-gravity anomalies interpreted as rising magma.

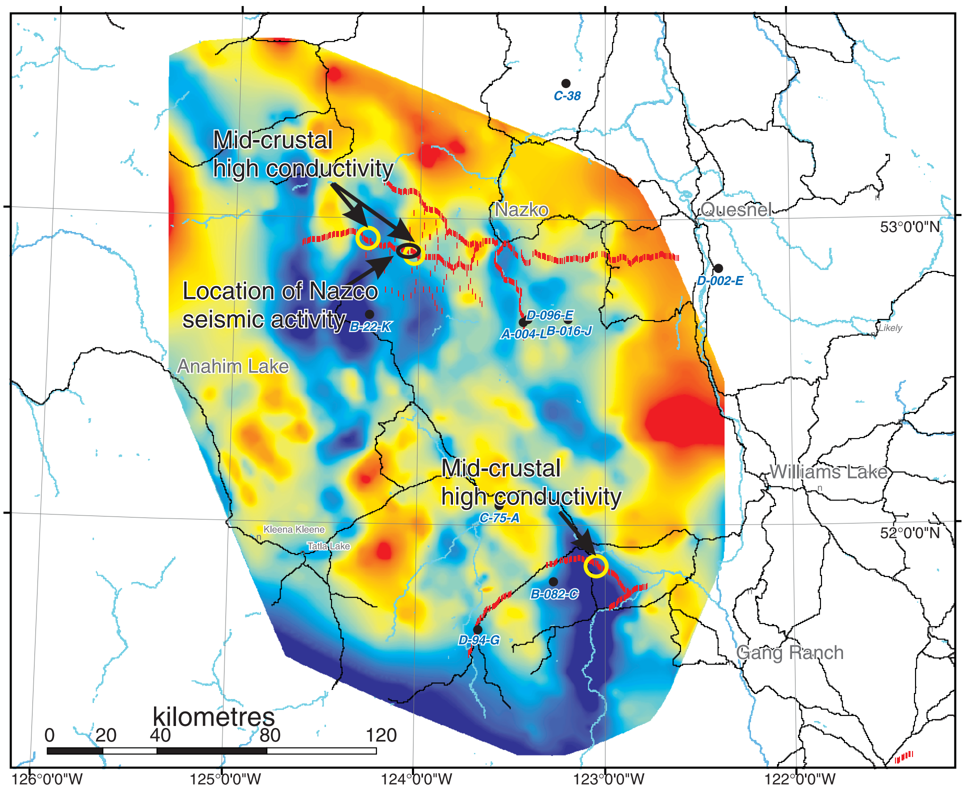

Figure 5. Map of the regional gravity data collected by Canadian Hunter Exploration Ltd., illustrating the location of the mid-crustal high conductivities and the recent seismic activity. The red dots show the MT site locations and the black dots, show the location of the drilled boreholes.

FUTURE WORK

Data integration with other geophysical methods will provide more constraints on the interpretations of the conductivity models. New seismic data may determine whether or not lateral variations are related to structural changes and gravity results may give evidence for porostity or fluid salinity changes. Petrophysical analysis of samples collected from various rock units should provide information on electrical anistropy and may identify the specific cause for enhanced conductivity associated with the Eocene volcanic groups.

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