Designing a Test Survey in the Nechako Basin, South-Central British Columbia (NTS 092N, O; 093B, C, F, G) to Determine the Usefulness of the Magnetotelluric Method in Oil and Gas Exploration

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Spratt, J., Craven, J., Shareef, S., Ferri, F. and Riddell, J. (2008): Designing a test survey in the Nechako Basin, south-central British Columbia (NTS 092N, O; 093B, C, F, G) to determine the usefulness of the magnetotelluric method in oil and gas exploration; *in* Geoscience BC Summary of Activities 2007, Geoscience BC, Report 2008-1, p. 145–150.

Introduction

In response to the rapid spread and destructive effects of the mountain pine beetle (MPB), British Columbia is facing a challenge in developing economic diversification opportunities for forestry-based communities in the interior of the province. Geoscience BC is undertaking a number of projects that will help to assess the mineral and petroleum potential in the MPB-affected area. Although only limited exploration has been carried out, the potential for hydrocarbons has been observed 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 metres of gas and a billion cubic metres of oil, although these estimates are qualified as being very speculative (Hannigan et al., 1994).

Recent examinations of 20-year-old magnetotelluric (MT) data collected from within the Nechako Basin have shown that the method can be useful in understanding the shallow structure of the subsurface beneath the basin and that additional MT data acquisition, using modern high-frequency and broadband instrumentation, may be an important tool in mapping the boundaries of the basin and the structures within it. This information will contribute to developing a better understanding of the potential for hydrocarbon resources in the region (Spratt et al., 2006). In the fall of 2007, a field campaign was designed to record more than 800 high-frequency and broadband MT sites from within the Nechako Basin. The primary objective of the survey is to evaluate the technique as a tool both for oil and gas exploration and for geological characterization of the Nechako Basin.

Keywords: *Nechako Basin, magnetotelluric, electromagnetic*

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Geological and Geophysical Background

Geology of the Nechako Basin

The Mesozoic Nechako Basin, located in the Intermontane Belt of the Canadian Cordillera, is a basin that 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 during the Eocene and Miocene to form a sheet that covers much of the basin at thicknesses varying between 5 and 200 m (Mathews, 1989; Andrews and Russell, 2007), and possibly as much as 1 km in isolated locations. The main geological elements in the southern Nechako area include Miocene basalt, Tertiary volcanic and sedimentary rocks, Cretaceous sedimentary rocks and Jurassic sedimentary rocks (Figure 1).

Geophysical Studies

Results and interpretations of magnetotelluric (MT) surveys are often both complemented and constrained by geological information and models obtained from other types of geophysical surveys. Several different studies have been carried out within the Nechako Basin in the past, and several more are being planned for the near future. Existing models or data will be used to resolve the MT inversion models, providing the most accurate interpretation for the electrical resistivity structure in the subsurface.

In the early 1980s, a regional gravity survey was carried out by Canadian Hunter that identified a gravity low in the

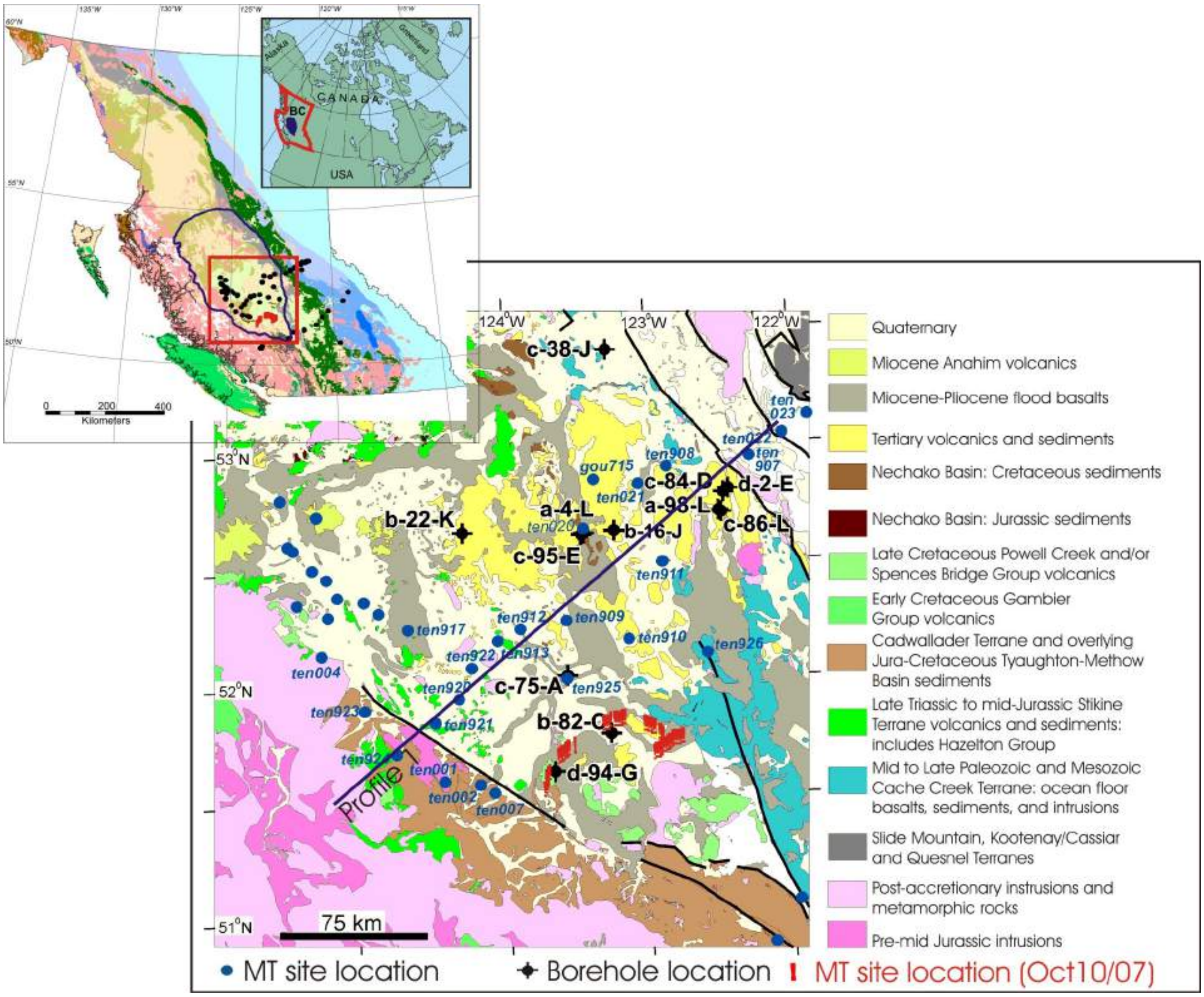

Figure 1. Location and geology of the Nechako Basin, showing the locations of the boreholes, old MT sites and the newly acquired MT sites. The blue outline on the location map in the upper left shows the outline and extent of the Nechako Basin. The blue line labelled 'Profile 1' is the surface trace of the two-dimensional model shown in Figure 3.

southern Nechako Basin. In early 2000s, Bemex Consulting International confirmed this anomaly with ground gravity and magnetic data collected in the southern tip of the basin (Figure 2). In addition to these regional surveys, several boreholes were drilled throughout the southern portion of the basin between 1960 and 1986 (Figure 1), 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.

More than 100 rock samples have been sent to the Geological Survey of Canada's 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.

Finally, new seismic information will soon be available. Seven long-term teleseismic stations have recently been deployed within the Nechako Basin as part of a joint project involving the Geological Survey of Canada–Pacific (GSC), the BC Ministry of Mines, Energy and Petroleum Resources, and the University of Manitoba. In addition, Geoscience BC is acquiring Vibroseis® data and the GSC is planning to acquire explosive-source seismic reflection data in 2007–2008. These projects have been designed to account for the surface volcanic layers and will be an insightful addition to the magnetotelluric interpretations.

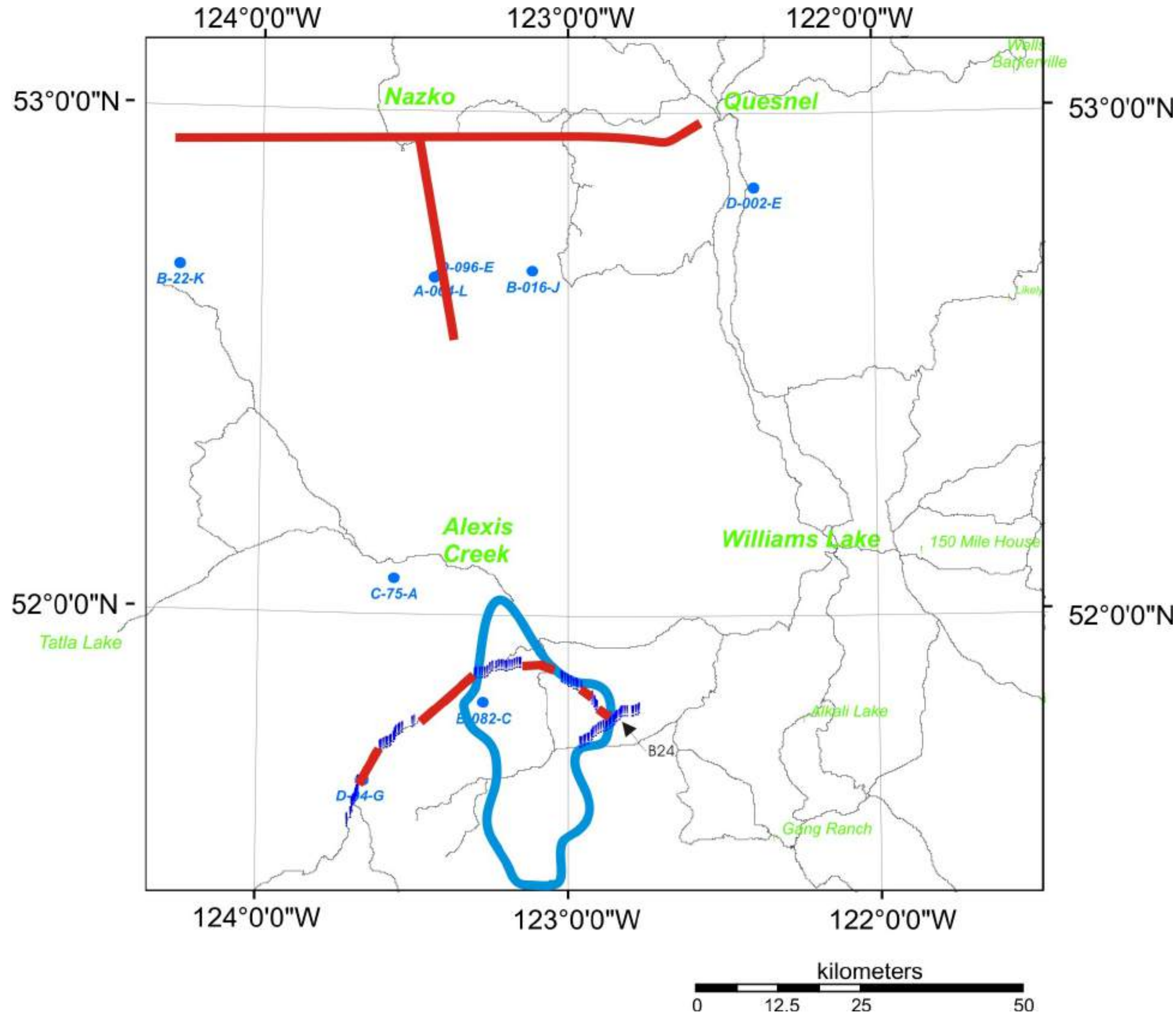

Figure 2. Locations of the MT profiles (thick orange lines) along which data is expected to be collected by the end of November 2007. The blue exclamation points show the locations of the sites collected to date, and the light blue line marks the outline of the observed gravity low. The light blue circles show borehole names and locations.

Magnetotelluric 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 (E) and magnetic (H) fields at its surface (Cagniard, 1953; Wait, 1962; Jones, 1992). The measurement of these mutually perpendicular electric and magnetic fields allows the calculation of phase lags and apparent resistivities at various frequencies, known as MT response curves, for each MT site recorded. Since the depth of penetration (or skin depth) of these fields is dependent on frequency (lower frequencies penetrate deeper) and the conductivity of the material (the lower the conductivity, the greater the depth), estimates of depth can be made from the response curves beneath each site (Kearey and Brooks, 1991).

As magnetotelluric (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 >1000 ohm-m, whereas sedimentary rocks are more conductive, with values of 1–1000 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). As 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 the early 1980s, the University of Alberta recorded MT data across the Nechako Basin between 52° and 53°N using short-period automatic MT system (SPAM) instruments that recorded data in the frequency range 0.016–130 Hz (Figure 1; Majorowicz and Gough, 1991). Initial analysis of these data revealed an anomalously conductive upper crust (10–300 ohm-m) in the eastern half of the northeast-southwest profile that 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 extend beneath a thin layer of basalt (Gough and Majorowicz, 1992; Majorowicz and Gough, 1994; Jones and Gough, 1995; Ledo and Jones, 2001).

Modern processing software and techniques, as well as modelling and interpretation packages, were applied to these original MT sites (Spratt et al., 2006). The new analysis included detailed strike analysis, distortion decomposition and two-dimensional modelling inversions. Using these advanced methods, it was shown that the MT data were capable of penetrating the Cenozoic volcanic rocks and imaging the shallow features of the Nechako Basin (Figure 3).

Magnetotelluric Data Acquisition

Design of the Survey

Borehole resistivity measurements were analyzed to assess the frequency range, expected resolution and site spacing that would be most appropriate for defining the structure of the Nechako Basin and for oil and gas exploration. Synthetic MT response curves were calculated from existing borehole resistivity measurements for three different frequency bands: broadband (BBMT, 10 000–0.01 Hz), magnetotelluric (MT, 380–0.01 Hz) and audiomagnetotelluric (AMT, 10 000–5 Hz). One-dimensional Occam inversion models were then generated from these synthetic curves for each band at each well. These 1-D models indicate that the AMT frequency set produced the best models at most depths, showing a shallow and highly resistive layer. In some cases, the MT range appears to be necessary for imaging slightly deeper structure. From these results, it was decided that the most accurate basin structure could be imaged using a combination of AMT and MT data acquisition.

In order to accurately compare results and interpretations, the magnetotelluric profiles were originally designed to coincide as much as possible with those outlined in the proposed Geoscience BC Vibroseis® seismic-reflection survey to be undertaken in the region. The MT profiles have been altered due to accessibility. Figure 2 shows the current intended MT profiles in the southern Nechako Basin, with the southern lines running through a region of lower gravity anomalies. The total length of the profiles is approximately 355 km. Data were initially collected with a mix of daytime and night-time acquisition periods by three independent crews. The AMT data were collected at each site for 1 hour during the daytime, with a productivity of 6–8 sites/day per crew. At the end of each day, sufficient equipment was left in the field to record AMT and MT data overnight. The overnight data were significantly better than the daytime data due to the generally stronger source field at night (Garcia and Jones, 2002) and the longer recording time. It was

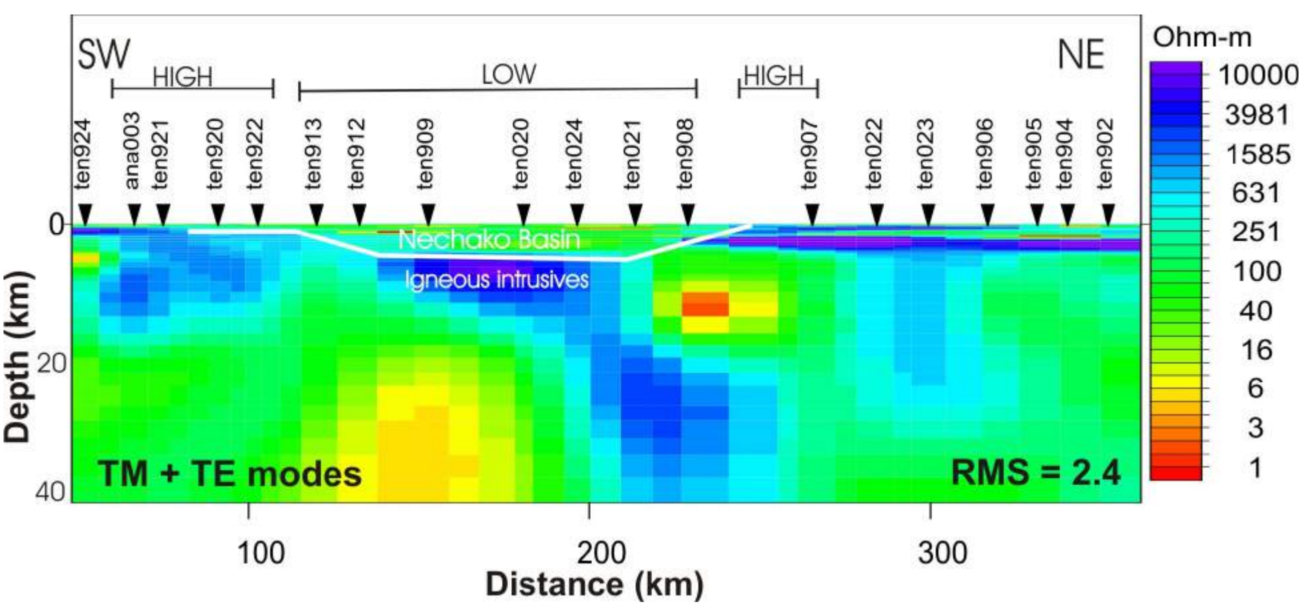

Figure 3. Two-dimensional conductivity model from 20-year-old MT data that were re-analyzed using modern techniques. The red and blue colours represent conductive and resistive regions, respectively. The white line (from Spratt et al., 2006) marks the interpreted boundary of the Nechako Basin.

therefore decided to switch to entirely overnight recordings. In such a scheme, the crews deploy equipment at 6 sites/day. After completion of the fall field campaign, a total of 880 combined AMT sites and BBMT sites are expected to be collected along these profiles.

Data Acquisition

The data are recorded using MTU-5A systems from Phoenix Geophysics Limited. A standard site layout is composed of five electrodes, either lead-lead-chloride porous pots or steel rods, to measure the electric fields in two perpendicular directions, and three separate coils to measure the magnetic fields in the horizontal and vertical directions (Figure 4). Currently, each of three separate teams installs 6 sites/day and leaves them to record overnight. Two of the six sites are telluric only, meaning that only the two telluric or electric field channels are deployed. Two of the sites are five-channel AMT sites, meaning that the telluric and AMT magnetic fields are measured. The remaining two sites are five-channel MT sites, meaning that the telluric and MT magnetic fields are recorded. The relatively 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 can be used with the telluric channels at all sites. The end result is that each crew is deploying six combined AMT and MT sites per day.

To date, more than 100 sites have been collected along the southernmost profiles (Figure 2). The data quality in general is very good, with combined AMT and BBMT sites yielding apparent-resistivity and phase response curves over a span of seven period decades (i.e., orders of magnitude; Figure 5a). The response curves at site B24 show a resistive layer (100 ohm-m to 0.005 s) above a slightly more conductive layer (~10 ohm-m); with increasing period, the response curves suggest the presence of a third bottom layer that is strongly two-dimensional, as indicated by the phase split between the two curves. An approximate depth estimate for the boundary between the second and third layers, using the skin depth equation, is 890 m. Although considerable analysis and depth modelling still need to be completed, this site shows a good indication that the method is imaging the resistive upper volcanic rocks, the more conductive sediment rocks, and a more complex deeper structure below.

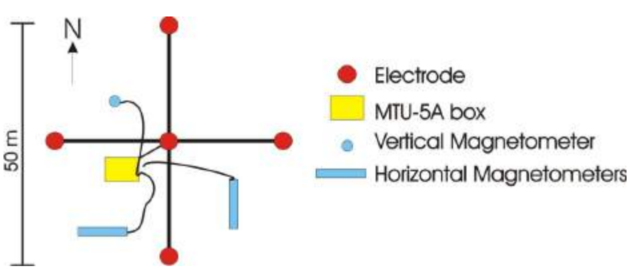

Figure 4. Plan view of a typical layout for an MT site.

Conclusions

The magnetotelluric method has proven to be useful in imaging lithographic structures of varying conductivities (e.g., distinguishing sedimentary units from volcanic and crystalline basement rocks). A magnetotelluric survey has been designed to assess the capabilities of the MT method in the exploration for hydrocarbons in the Nechako sedimentary basin and evaluate the extent to which the structure of the basin can be defined. Analysis of borehole resistivity

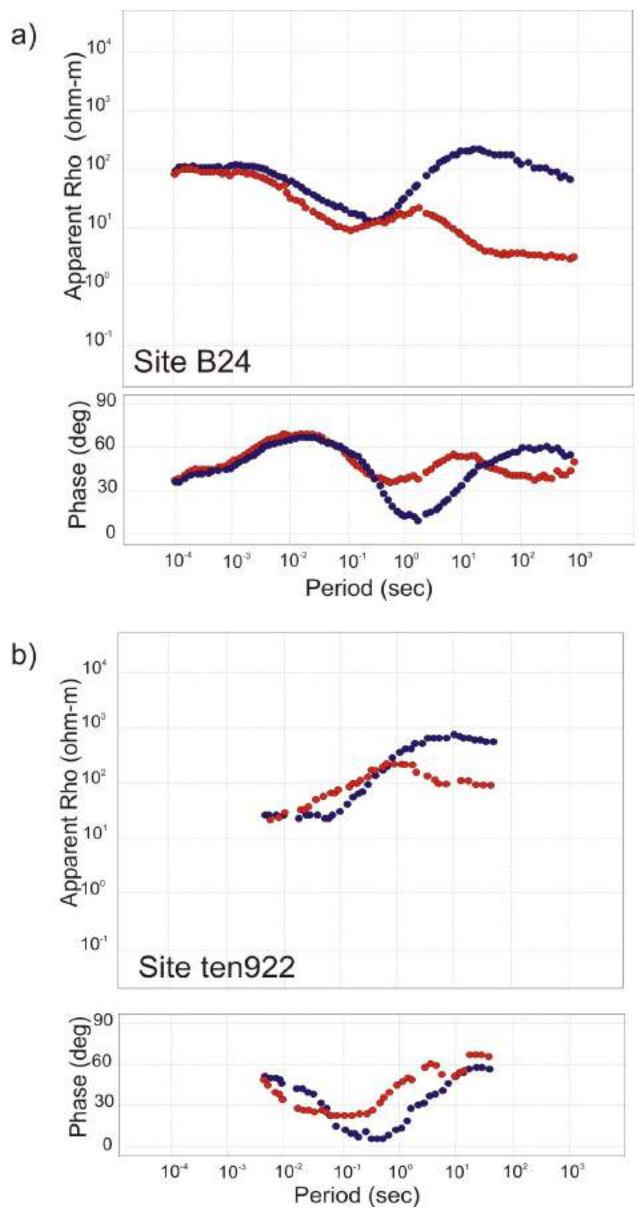

Figure 5. Examples of the apparent-resistivity and phase-versus-period response curves: **a)** data collected recently at a combined MT-AMT overnight site, and **b)** data quality at one of the 20-year-old sites. The quality of the data at the newer site is very good through seven decades, including the AMT dead band. The blue and red dots show the transverse magnetic and transverse electric modes, the difference in the curves indicating a difference in the north-south direction compared to the east-west direction.

data from the region has provided guidelines for data acquisition parameters, such as the most appropriate frequency ranges to record and site spacing. The planned survey consists of more than 800 AMT and BBMT sites that will be collected from within the Nechako Basin. Data acquisition began in mid-September, and initial results show excellent data quality. It is expected that all data will have been collected by the end of November 2007, after which detailed analysis, modelling and interpretations will be undertaken.

Acknowledgments

Financial support for this work comes from the Geological Survey of Canada, Geoscience BC and the BC Ministry of Energy Mines and Petroleum Resources. The authors wish to thank D. Snyder and P. Keating for their reviews, insightful comments and constructive suggestions.

Geological Survey of Canada contribution 20070349.

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