Structural imaging in the Rocky Mountain Foothills with magnetotelluric exploration

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Summary

The magnetotelluric (MT) method has been evaluated as an exploration tool in the Rocky Mountain Foothills. The structure of the Brazeau thrust is well imaged, with underthrust, low resistivity sedimentary units in the footwall imaged to a depth of 5 km. The resistivity model shows that MT exploration can potentially complement seismic exploration in this region.

Introduction

The Rocky Mountain Foothills are the focus of ongoing hydrocarbon exploration in Western Canada. This fold and thrust belt was formed by crustal shortening in the Middle Jurassic to Eocene as terrane accretion occurred on the western margin of North America (Price, 1994; Wright et al, 1994). To date most exploration in the Rocky Mountain Foothills has used seismic exploration, as described by several case studies (Yan and Lines, 2001; Grech et al., 2003). The geological structure presents a number of challenges that include the high velocity contrasts beneath carbonate thrust sheets, and the effects of seismic anisotropy (Yan et al, 2004). The magnetotelluric method has proven to be a useful complement to seismic exploration in fold and thrust belts in other regions (Christophersen, 1991; Watts and Pince, 1998; Bedrosian et al, 2001). This paper describes the results of a pilot magnetotelluric survey that was conducted in the Foothills in 2002.

The magnetotelluric method

In the magnetotelluric (MT) method, natural electromagnetic fields are used to image the spatial variation of the Earth's resistivity structure (Vozoff, 1972). This is achieved by measurement of the time variation of magnetic and electrical fields at the Earth's surface. From the ratio of the electric and magnetic fields, the resistivity of the ground is estimated. The MT signals propagate vertically down in the Earth, and the depth of penetration decreases as frequency increases. Thus by measuring multiple frequencies, a depth sounding can be achieved. The MT method was originally developed in the 1950's, but its application was hindered by cumbersome instrumentation and inadequate interpretation methods. One particular shortcoming was that when MT data were analyzed for a 1-D Earth structure, near surface structure that produced static shifts could not be removed. In recent years, new MT systems have been developed that are light weight and with timing signals from GPS satellites, simplifying the time synchronization between instruments. As a result, it is now possible to economically collect a large volume of data which can then be interpreted with 2-D and 3-D approaches (Wannamaker et al, 1999). The extension to 2-D and 3-D has allowed the problems of static shifts to be largely overcome, since they can be estimated as additional parameters during inversion.

Previous MT studies in overthrust regions have exploited the fact that MT data are most sensitive to the depth to a low resistivity layer. Thus a thrust fault geometry with the hanging wall more resistive than the foot wall is optimal. This situation occurs when a crystalline or carbonate thrust sheet (resistivity typically ~1000 ohm-m) is emplaced above clastic sedimentary rocks (resistivity 10-100 ohm-m). Figure 1 illustrates the MT responses for a simple model. At the stations A and B the apparent resistivity equals that of the hanging wall until the frequency is low enough to detect the low resistivity footwall. Note that as the layer deepens, it is detected at a lower frequency. Watts and Pince (1998) showed that MT data could effectively image potential reservoir rocks that had been emplaced beneath a carbonate thrust sheet. Bedrosian et al. (2001) determined thrust fault geometry in Northern Tibet with MT data, since crystalline rocks were actively being placed above Quaternary sedimentary units. Do the necessary contrasts in resistivity exist in the Rocky Mountain Foothills? Figure 2(A) shows a well log that intersects the Brazeau Thrust Fault in the Southern Central Foothills. Here an electrically resistive Paleozoic thrust sheet has been emplaced above lower resistivity Mesozoic sedimentary rocks.

Magnetotelluric data acquisition and processing

To evaluate if MT data could effectively image thrust related structures in the Rocky Mountain Foothills, a pilot survey was undertaken in 2002. Magnetotelluric data were collected at the 26 locations shown in Figure 3. The profile extends from Rocky Mountain House to the Front Ranges. At each station, MT data were recorded overnight using a Phoenix Geophysics V5-2000 system. The time series data were processed to yield estimates of apparent resistivity and phase data over the frequency band 100-0.001 Hz using a variation of the robust cascade decimation scheme of Jones and Jodicke (1984). All processing used remote reference data to eliminate bias. The dimensionality and strike of the MT data were then investigated using the tensor decomposition method of McNeice and Jones, (2001). This revealed a well defined geoelectric strike of N30°W, which consistents with the regional geology strike (Figure 3). The decomposition also showed the data are relatively two-dimensional, which justifies the application of 2-D inversion to the data.The MT data were then rotated into a N60°E coordinate frame. Significant static shifts were observed at some stations near the Brazeau Thrust, and these were corrected to first order by shifting the resistivity curves to the regional average with a 1-2 km length scale.

To convert the frequency domain MT data into a geoelectric model, a two-dimensional (2-D) approach was used. This utilized the 2-D inversion algorithm of Rodi and Mackie (2001) which determines the smoothest resistivity model that is consistent with the measured MT data. This approach is suitable for MT data since it reflects the diffusive nature with which MT signals travel in the Earth. A wide range of inversion parameters were used, to check that the final model was well defined. The model shown in Figure 4 was obtained by inverting both transverse electric (TE) and transverse magnetic (TM) modes, which are the result of electric current flow along and across strike, respectively. The MT data are fit to a root-mean-square error of 1.48, which indicates an acceptable fit.

Model interpretation

The resistivity model in Figure 4 is overlain with a simple structural interpretation for the Southern Central Foothills modified from the Nordegg Area Cross Section (Lagenberg and Kubll, 2002). The thick, low resistivity, sedimentary sequence of the Alberta basin is obvious at offsets of 40-65 km (A). The high resistivity (crystalline) basement dips gently west, in agreement with Lagenberg and Kubll (2002). Figure 2(B) shows a comparison of the MT derived resistivity models with a neighbouring well log. Note that the lowest resistivity values are observed in the Cretaceous units (Wapiabi formation) owing to the high salinity pore fluids. The resistivity derived from MT data is smoother than that measured from the well log. This arises from the smoothing imposed in the inversion process, and reflects the fact that MT measurements use long wavelengths that average short wavelength variations in resistivity.

The low resistivity Cretaceous units can be traced westward as they shallow through the triangle zone, and then dip west to form the footwall of the Brazeau Thrust. At this location the hanging wall comprises more resistive Paleozoic rocks. The dip of the Brazeau thrust inferred from the MT data is around 30 degrees which agrees with the dip reported by Lagenberg and Kubll (2002). The footwall rocks exhibit a low resistivity (<10 ohm-m) to a depth of 3 km. Further west the resistivity increases (B) before decreasing again (C). The low resistivity feature (C) imaged by the MT data is also observed in well logs (Figure 2(A)).

To determine if the higher resistivity gap (B) is a real feature, a synthetic inversion study was undertaken. Synthetic MT data were computed for the two resistivity models shown in Figure 5. These models contain the key features observed in the real model (Figure 4). Random noise and synthetic static shifts were added to the data, which were then inverted with same paramters as used for the field data. The resulting models shown in Figure 5 show that the gap (B) is required by the data, and not a result of the station distribution.

Interpretation and Discussion

Resistivity values in this region are dominantly controlled by the porosity and chemistry of the pore fluids. Thus if the regions A-B-C are all the same geological formation, then the resistive zone B must reflect a decrease in fluid content compared to the same formation to the east and west (C). This decrease could be the result of a porosity decrease resulting from increased compaction with greater depth, or perhaps reflects the fact that the saline fluids have escaped, or been expelled through fractures formed during thrusting. Alternatively, the resistive zone might represent a different, more resistive lithology due to the emplacement of another thrust sheet of Paleozoic material. The low resistivity region C is inferred to be Cretaceous strata from drilling (well 100051303712w500). This is the deepest zone of low resistivity observed in the model. The formation resistivity is around 10 ohm.m, and formation fluid resistivity is inferred to be in the range 0.2-0.25 ohm.m (Block, 2001). Archie's Law predicts a water saturation in the range 22-28% (Archie, 1942).

Conclusion

This study shows that MT can contribute to structural imaging in the Rocky Mountain Foothills. While MT cannot image detailed structure in the same way as seismic reflection, it provides important structural information as a reconnaissance tool. In addition, it can reveal details of hydrogeological structure. In imaging thrust faults, MT works best where high resistivity units overlay low resistivity units. This contrast usually corresponds to high seismic velocity over low velocity, a scenario that can cause problems for seismic methods. MT exploration also has the advantage of not requiring signal generation and has a relatively low environmental impact.

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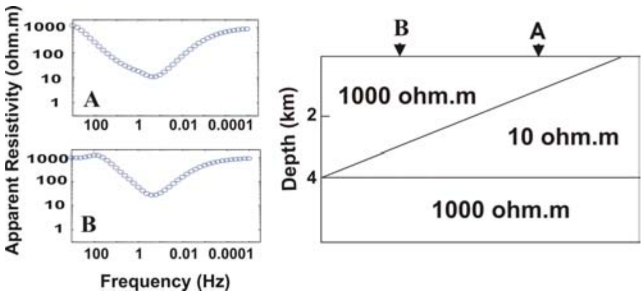

Figure 1: Synthetic model illustrating how MT data can detect a conductive layer. At both stations, the decrease in apparent resistivity is due to the underthrust layer.

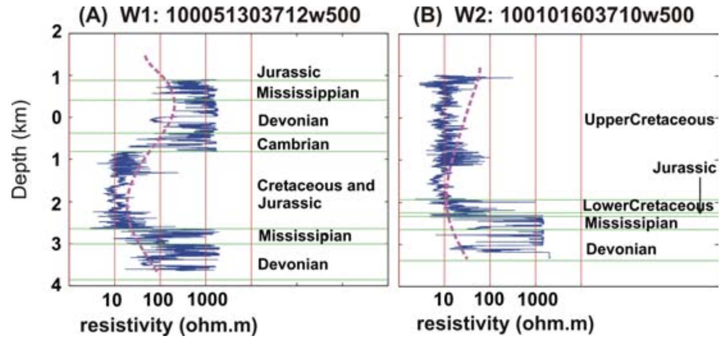

Figure 2: Comparison of resistivity logs (solid lines) and the MT derived resistivity model (dashed lines) at the two well locations shown in Figure 3. Depth is relative to sea level.

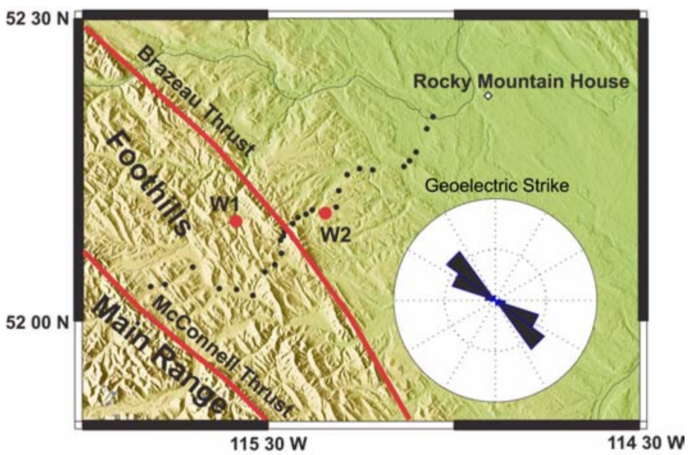

Figure 3: Location map of the MT stations in Rocky Mountain Foothills (squares). The rose diagram shows the strike direction determined from the MT data, which agrees with the regional geology. Black dots denote locations of MT sites. Red dots denote well locations.

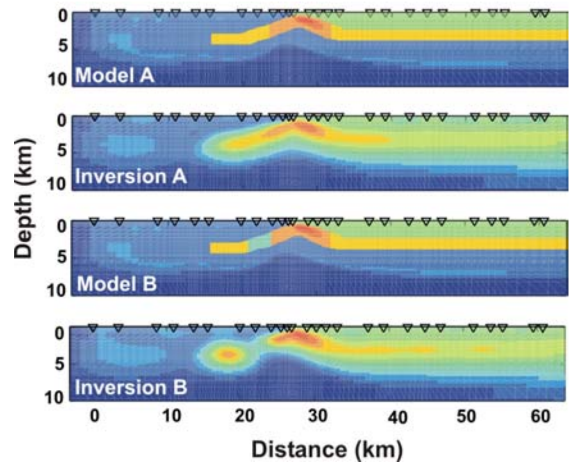

Figure 5: Synthetic inversion study used to test sensitivity of data to the underthrust layer. Synthetic data were computed for both models A and B. The resistive break (B) in Figure 4 is clearly required by the data. Resistivity scale is the same as in Figure 4.

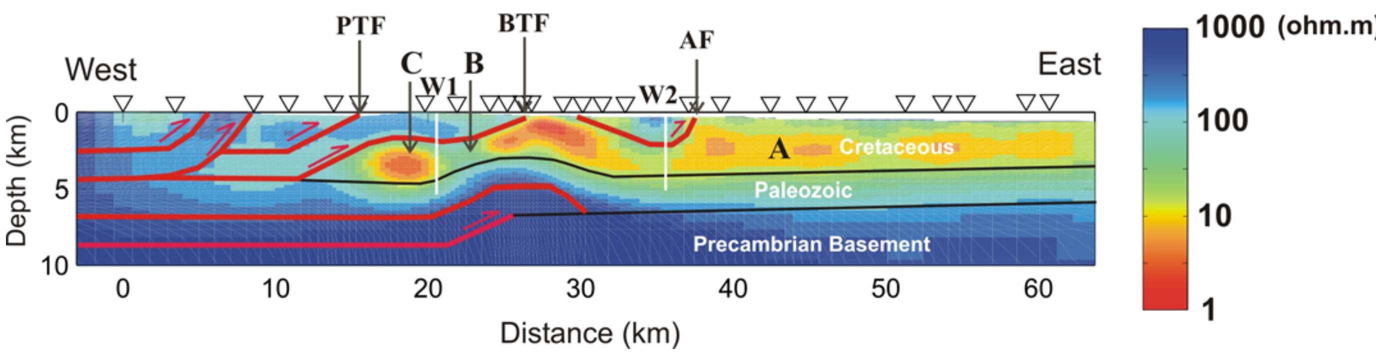

Figure 4 Electrical resistivity model obtained by inversion of the MT data. The structural interpretation is modified from Lagenberg and Kubll (2002); Triangles denote MT stations; PTF=Pineneedle Thrust Fault; BTF=Brazeau Thrust Fault; AF=Ancona Fault; W1=well:100051303712w500; W2=well: 100101603710w500.