Buried Proterozoic foredeep under the Western Canada Sedimentary Basin?

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ABSTRACT

Electromagnetic studies of the Precambrian basement beneath the Western Canada Sedimentary Basin in Alberta indicate a narrow linear conductivity anomaly spatially correlated with a strong positive magnetic feature, the Red Deer high. The conductor is located below sedimentary cover near the top of the crystalline basement and has limited depth extent. We propose that this anomalous feature represents graphitic metasedimentary rocks in the euxinic-flysch facies of a Proterozoic foredeep sequence. The strong magnetic anomaly results from an associated iron formation deposited on the outer ramp of the foredeep. This model explains the geophysical anomalies, has analogues on the exposed shield, and is consistent with the timing, deformation history, and known geology of the Precambrian basement.

INTRODUCTION

The collage of Precambrian terranes buried beneath the Western Canada Sedimentary Basin in Alberta is unexplored compared with the overlying Phanerozoic strata. Knowledge of the Precambrian basement is derived from analyses of drill-core samples, from interpretation of aeromagnetic and gravity data, and from extrapolation of rocks and structures exposed in the craton to the northeast (Ross et al., 1991; Villeneuve et al., 1993; Burwash et al., 1994). Where exposed, the Snowbird tectonic zone separates the Archean Hearne and Rae provinces (Hoffman, 1988) and extends under the sedimentary cover of central Alberta to the Cordillera. In Alberta, the Snowbird zone has been associated with the Thorsby low, a prominent aeromagnetic and gravity low (Figs. 1 and 2) that Ross et al. (1995) have interpreted as a crustal discontinuity. To the southeast, the Rimbey granites are interpreted as a magmatic belt formed during the closure of a small ocean between the Hearne province and the Wabamun domain (a magnetic high). Farther southeast lie the supracrustal rocks of the Lacombe domain. A narrow 500 nT magnetic anomaly (the Red Deer high) is thought to define the boundary between the Lacombe domain and the Loverna block of the Archean Hearne province.

Supported by geochronologic data from drill cores (Villeneuve et al., 1993), Ross et al. (1991, 1995) proposed a history for Alberta of oblique collision between 2.0 and 1.8 Ga. This interpretation follows Hoffman's (1988, 1989) basic theme of asymmetric accretionary orogens consisting of sedimentary prisms thrust over an Archean foreland and outboard bounding magmatic arcs. Foredeeps form in linear depressions situated between foreland fold-and-thrust belts and cratonic arches. These foreland basins migrate in front of and eventually become incorporated within the fold-and-thrust belt. Diachronous facies deposition thus distinguishes foredeep successions from underlying passive-margin and initial rift sequences. Hoffman (1987) noted that Proterozoic foredeeps differ from those in the Phanerozoic by the presence of mafic magmatism in the axial zone and the deposition of iron formations on the outer ramp.

Here we present an interpretation of electromagnetic and magnetic field data that supports the accretionary model by providing evidence for foredeep successions in the Precambrian under Alberta.

ELECTROMAGNETIC EXPERIMENT

The 1993 electromagnetic experiment involved recording the naturally occurring electric and magnetic fields in the earth. Observations were made at 38 sites along the 350 km Lithoprobe seismic reflection profile and along an auxiliary line 70 km to the south (Fig. 1). Tensor decomposition analysis (Groom and Bailey, 1989) determined that the sedimentary cover has a one-dimensional electromagnetic response and that at mid-crustal depths the response is two-dimensional, striking northeast. This strike is consistent with that inferred from the aeromagnetic anomaly fabric (Fig. 2). Strike can also be inferred from induction arrows that are representative of correlated variations between the vertical and horizontal magnetic fields (Schmucker, 1970). These ar-

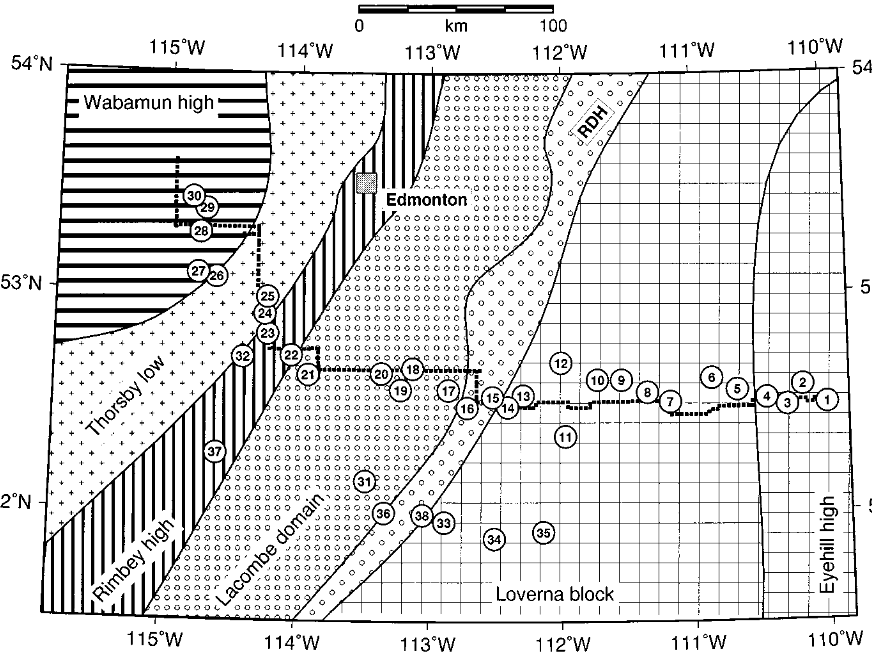

Figure 1. Tectonic map of Alberta (modified from Ross et al., 1991) indicating major features inferred in Precambrian basement as interpreted from potential field data and drill results. Numbered circles indicate electromagnetic measurement sites. Dotted line indicates seismic reflection profile. RDH is Red Deer high.

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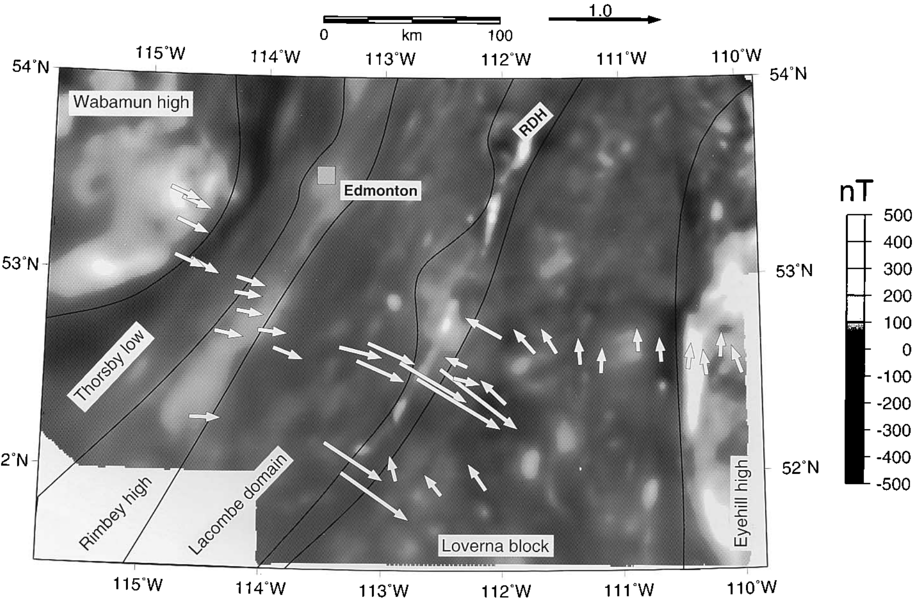

Figure 2. In-phase induction arrows for magnetic field variations at period of 320 s plotted over aeromagnetic anomaly map. Arrows project from site location and point toward northeast-striking current concentrations just east of RDH. Above map, unit-length induction arrow shown for scale.

rows point toward current concentrations and in Alberta indicate a major conductor striking northeast near the center of the profile (Fig. 2). The largest arrow has an unusually large amplitude of 0.92 at a period of 300 s. Small-amplitude arrows (sites 13, 14, and 33) locate the axis of the conductor, and the induction arrows at most other sites point toward this region. This current channel is the dominant feature of our data.

The apparent resistivity and phase curves corresponding to electric current flowing perpendicular to strike (open circles in Fig. 3) are remarkably uniform in shape at all sites, and the apparent resistivity increases gradually to the west. In contrast, curves corresponding to current flowing along strike (solid circles in Fig. 3) vary markedly along the profile. Although quantitative interpretation requires numerical inversion, the above observations suggest narrow, electrically isolated conductors that strike northeast. The strongest response in

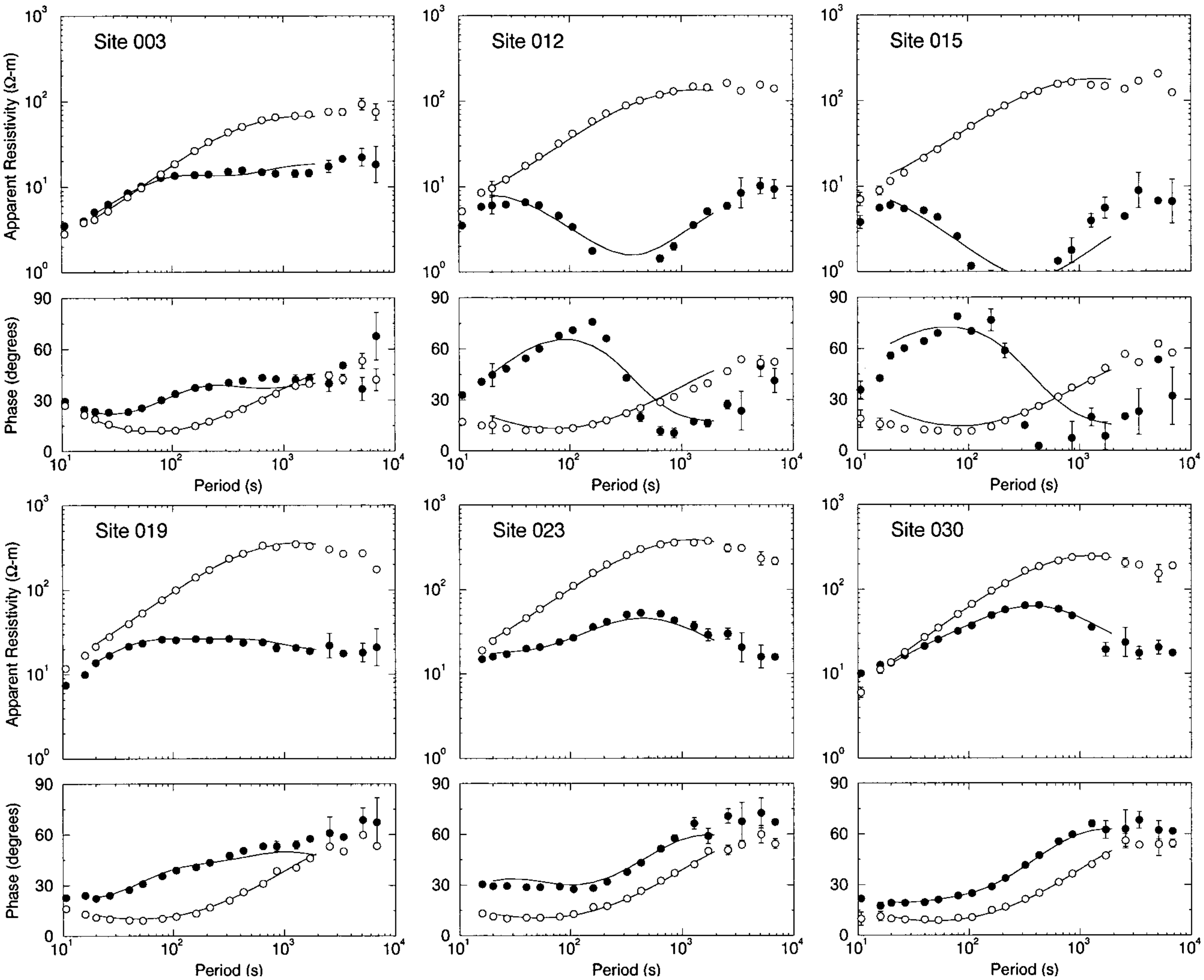

Figure 3. Montage of apparent resistivity and phase data from six sites along electromagnetic profile (strike coordinate system of N45°E/N45°W). Solid lines show response of model in Figure 4. Misfit near site 15 can be reduced by relaxing smoothing constraints imposed by inversion method.

the data occurs just east of the Red Deer high magnetic anomaly.

INVERTED MODEL

The electromagnetic data expressed in the strike coordinate system were inverted using the philosophy of Smith and Booker (1991) and Wu et al. (1993) to derive a two-dimensional model. Because band-limited, noisy data allow for nonunique models, this approach involves the pragmatic decision to find the smoothest model having a response that fits the data. Therefore, the minimum root mean square (RMS) misfit between the data and model response was sought, and then the model was smoothed until the misfit increased substantially. As the smooth end member of the class of conductivity models that fit the measured data to within the estimated variances, our final model (Fig. 4) should contain only the minimum conductivity structure required by the data.

Model responses are plotted in Figure 3 to indicate the superior fit (RMS misfit = <2.0) to the data from all the stations along the profile. The only region of misfit is over the large conductor near site 15 and results from the smoothing constraints preventing extreme (i.e., "rougher") models and from subtle three-dimensional characteristics of the conductor.

In the preferred model, conductive Phanerozoic sedimentary rocks extend to a depth of 2 to 3 km. The conductance (depth-integrated conductivity) of these rocks is well resolved and is directly comparable to conductance estimates derived from industry borehole logs. The crust under the sedimentary rocks is basically resistive, and yet the lower crust is quite reflective of seismic energy. Although several isolated conductors do occur within the upper and middle crust, the primary features are the two strongly conductive bodies beneath the sedimentary section near sites 15 and 16. The width of these conductors is less than the station spacing of ~10 km. The bodies are abnormally conductive (>10 S/m) and laterally isolated. Additionally, the (imbricated?) bodies may dip to the southeast, are close to the base of the overlying Phanerozoic sedimentary rocks, and have limited (<5 km) vertical extent. These anomalies do not appear to be imaged by the seismic reflection data, possibly because of multiple contamination. However, they are on the flank of a basement high with some 180 m of vertical relief.

Of the other conductive anomalies, two (beneath sites 17 to 20 and 8 to 11) coincide with seismically defined "culmination" zones in the central part of the transect. A northwest-dipping conductive anomaly (beneath sites 28 to 30) is coincident with a change in reflection depth of the Moho from 14 to 11.4 s. These minor conductors may be off-line, are at least 20 times less conductive than the conductors near the Red Deer high, and probably require additional electromagnetic data to be reliably imaged. Thus, for geologic interpretation, we focus on the conductors near the Red Deer high (sites 12–15).

TECTONIC INTERPRETATION

The extremely high conductivities of the anomalies near the Red Deer high limit the choice of plausible electrical conduction mechanisms. Ionic conduction by pore fluids is unlikely to be a realistic mechanism because the conductivities require unrealistically high porosities and it is difficult to conceive a trapping mechanism that could spatially confine fluids to such elongated and possibly dipping channels. Electronic conduction within the rock matrix, the other possible mechanism, would imply a Proterozoic age for the conductive rocks.

We propose that the conductive and magnetic anomalies are part of a foredeep succession comprising graphitic-sulfitic shale sequences and outer-ramp Superior-type iron formations as documented by Hoffman (1987) in exposed 2.0–1.8 Ga foredeeps across Laurentia. This interpretation explains the location of the anomalies near the western margin of the Hearne province. It is also consistent with the observation that the electromagnetic anomaly and the Red Deer

Figure 4. a: Red Deer magnetic anomaly correlated with the conductors near site 15. b: Two-dimensional conductivity model to depth of 50 km along entire profile. Seismic reflection line drawing is also shown. Structures are considered to extend out of plane of page and strike northeast. Red indicates zones that are most conductive. Conductive Phanerozoic sedimentary rocks form thin veneer (2–3 km thick). c: Enlargement of conductivity model near Red Deer high.

magnetic anomaly are nearly coincident, narrow, linear, and of >200 km lateral extent. Moreover, it provides a plausible mechanism for unusually high conductivities.

Carbonaceous rocks may be graphitized by metamorphism above 400 °C if provided additional strain energy through deformation (Ross and Bustin, 1990). Graphitization is irreversible and thus is unaffected by later metamorphism and deformation. The Lacombe domain is at least greenschist facies, and the overall seismic signature of the orogen is that of compression (Ross et al., 1995).

As an arc-continent collision zone overlapping in time with magmatic activity in central Alberta, the Wopmay orogen (Hoffman, 1980; King, 1986) may serve as a surface analogue of the buried Rimbey-Lacombe-Hearne tectonic zone. The Wopmay orogen evolved on the active western margin of the Slave province and exposes one of the best-studied Early Proterozoic foredeeps. Although an electromagnetic study by Camfield et al. (1989) crossed the orogen south of the exposed foredeep (Recluse Group), the thick graphitic Fontano Formation shale may be the source of the conductive anomaly detected, but unidentified, by Camfield et al. (1989).

DISCUSSION

The EM experiment in the Western Canada Sedimentary Basin has revealed several conductivity anomalies in the Precambrian basement, mostly situated above a highly reflective, yet resistive, lower crust. The conductive bodies are laterally disconnected in a style similar to that of the Trans-Hudson orogen (Jones et al., 1993). Two conductors are spatially associated with seismic "culminations," although the interpretation of these features relies on additional electromagnetic data to establish their extent and correlation with other geophysical and tectonic features. The Snowbird tectonic zone does not appear to be strongly conductive.

The most prominent electrical conductors are spatially associated with an enigmatic magnetic anomaly and have no clear seismic response. The conductive anomaly is interpreted to delineate the euxinic-flysch phase of an Early Proterozoic foredeep sequence, whereas the magnetic anomaly arises from an outer-ramp iron formation. This information adds into the geotectonic interpretation of the accretion of cratonic fragments under southern Alberta.

Early Proterozoic foredeeps provide a consistent explanation for several upper-crustal "orogenic" conductors including several of those identified by Korja and Hjelt (1993) in the Svecofennian shield. Because other major conductors are associated with circumcratonic, Early Proterozoic collisional zones, the foredeep interpretation may be more widely applicable.

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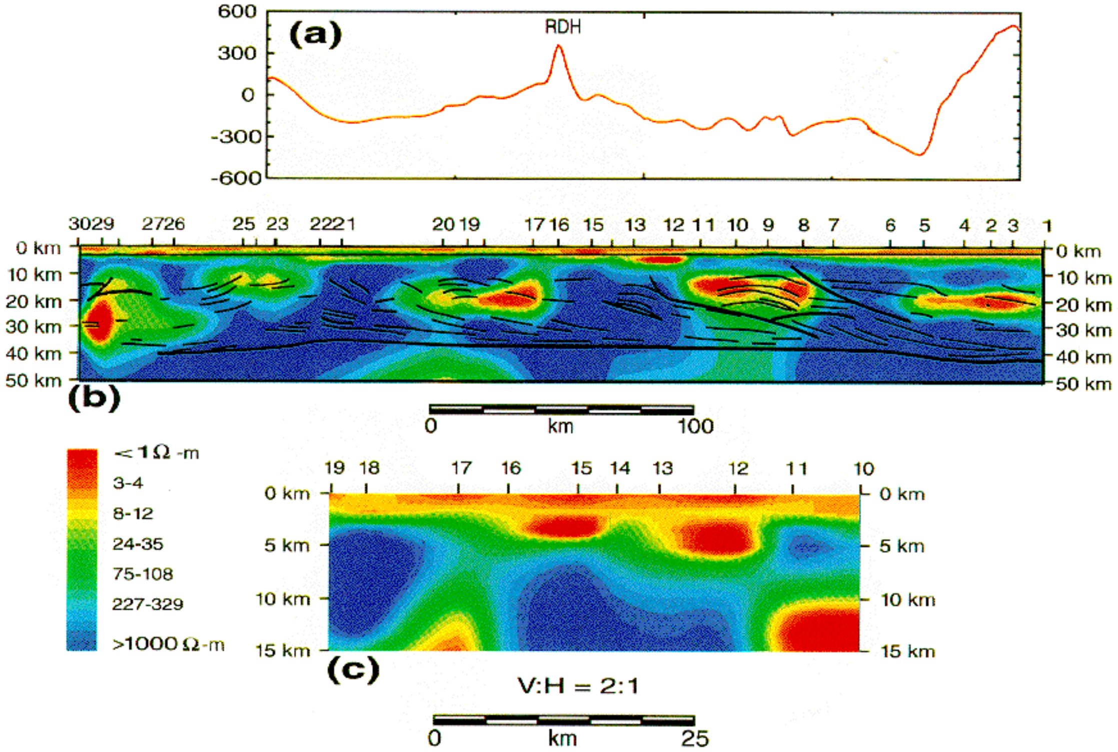
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