Seismic reflections and electrical conductivity: A case of Holmes's curious dog?

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''Is there any other point to which you wish to draw my attention?''
''To the curious incident of the dog in the night time.''
''The dog did nothing in the night time.''
''That was the curious incident,'' remarked Sherlock Holmes.—Arthur Conan Doyle

ABSTRACT

In the Purcell anticlinorium of the Canadian Cordillera, prominent upper-crustal seismic reflectors and areas of high electrical conductivity coincide over a wide area. Reflective layers traceable to outcrop and to a drill hole are caused mostly by impedance contrasts between Proterozoic gabbroic sills and metasedimentary rocks. Layers with high electrical conductivity are zones enriched in magnetic sulfide (probably pyrrhotite) within the sedimentary rocks. Attempts to interpret reflectivity and high conductivity in terms of a single geologic process, although tempting and certainly satisfying by appealing to Occam's razor, must be done with care. We speculate that some explanations for crustal reflectors and conductors may be unrealistic and propose an alternative paradigm of interlayered sills and (meta)sedimentary rocks rich in high-conductivity minerals to explain both.

INTRODUCTION

Application of collocated seismic reflection profiles and deep-probing electrical conductivity techniques to regional studies of crustal structure have provided a database within which correlations of prominent reflections with zones of high conductivity are common (e.g., Jones, 1987, 1992). The causes of both reflectivity and enhanced conductivity are usually ambiguous; thus, interpreters have adopted Occam's razor and logically assumed that this apparent spatial coincidence can be used as a boundary condition for interpretation, with crustal structures considered to have both high acoustic impedance contrasts with surrounding material as well as high electrical conductivity. However, rarely, if ever, are highly reflective and conductive layers traceable to outcrop or sampled in drill holes.

In the Kapuskasing structural zone of northern Ontario, for example, geophysical and geologic data are consistent with uplifted mid- to lower crustal rocks that may be analogous to material in the deep crust elsewhere where high-reflectivity and high-conductivity materials are present. Although the Kapuskasing rocks are quite reflective (e.g., Geis et al., 1990), they have very low electrical conductivity compared to present-day lower crust. This may be because (1) fluids could have been present when these rocks were at depth (and thus could have caused high electrical conductivity) but were expelled during uplift (Woods and Allard, 1986), or (2) graphite films could have been connected under pressure (lower crust) but were separated during uplift such that electrical current is no longer easily transmitted (Mareschal et al., 1992). Surface electromagnetic surveys have been interpreted to show enhanced conductivity, albeit weakly, by more than an order of magnitude, from a background value of $<0.000\,025$ S/m (resistivity $> 40\,000$ Ω·m) to ~0.0002–0.001 S/m (resistivity = 1000–5000 Ω·m), and this change can be correlated with a sequence of bright reflections (Jones et al., 1994). Whether the association between reflectivity and conductivity is due to the same geologic process cannot be corroborated without drilling and may be an artifact of resolution of surface data.

In the southern Canadian Cordillera, observations of regional electrical characteristics of the crust since the mid-1960s have established the presence of a prominent lower-crustal conductor (e.g., Caner et al., 1971; Gough, 1986; Jones et al., 1992). Its cause, however, remains elusive. Recent models in which high lower-crustal temperatures and high conductivity are related to prominent seismic reflectivity have these deep layers associated with fluids expelled during metamorphic reactions (e.g., Lewis et al., 1992; Marquis et al., 1994).

In the Purcell anticlinorium of the southern Canadian Cordillera, zones with high electrical conductivity are traceable to the shallow crust where they coincide with prominent, regionally extensive reflectors. Following established practice, it is tempting to explain these observations by a common geologic process; however, without direct ties to known features, it is not possible to evaluate such correlations. In this paper, we present data that allow detailed correlations of both electrically conductive zones and reflectors to stratigraphy in a drill hole and in outcrop.

SEISMIC REFLECTION DATA

Over 1000 km of seismic reflection data recorded in the Purcell anticlinorium have been processed with listening times appropriate for reflections from the lower crust and upper mantle (Cook et al., 1988; Cook and Van der Velden, 1995; Fig. 1). Some data were recorded during petroleum exploration activities and have been reprocessed to extend record times (Cook and Van der Velden, 1995), whereas others were recorded specifically to address crustal-scale problems (Cook et al., 1988). Reflections in this area have several causes, but the most prominent are apparently from Proterozoic (ca. 1468 Ma) gabbroic sills in the middle and lower parts of the Belt-Purcell Aldridge (Prichard in the United States) Formation (Cook and Van der Velden, 1995). The reflections outline extensive structures that can be followed from the U.S. border to at least lat 50°30'N. and from the Rocky Mountain trench (Fig. 1) to the west side of the anticlinorium (Cook and Van der Velden, 1995).

ELECTRICAL CONDUCTIVITY

Studies of electrical conductivity of the crust in the southern Canadian Cordillera have delineated a number of conductive structures. Two of the most prominent are the regional Cordilleran conductor in the lower crust west of the Purcell anticlinorium (e.g., Caner et al., 1971; Gough, 1986; Jones et al., 1992) and a shallow conductor in the anticlinorium (Keller et al., 1990; J. Gupta and A. Jones, unpublished). The deep regional conductor has been interpreted in a variety of ways, and some recent models combine interpretations of high conductivity, elevated temperature, and high reflectivity. Prominent reflectors appear to coincide spatially with zones of high conductivity and high temperature, and these observations have been assumed by some to be caused by the same geologic phenomenon.

One possible interpretation is that the

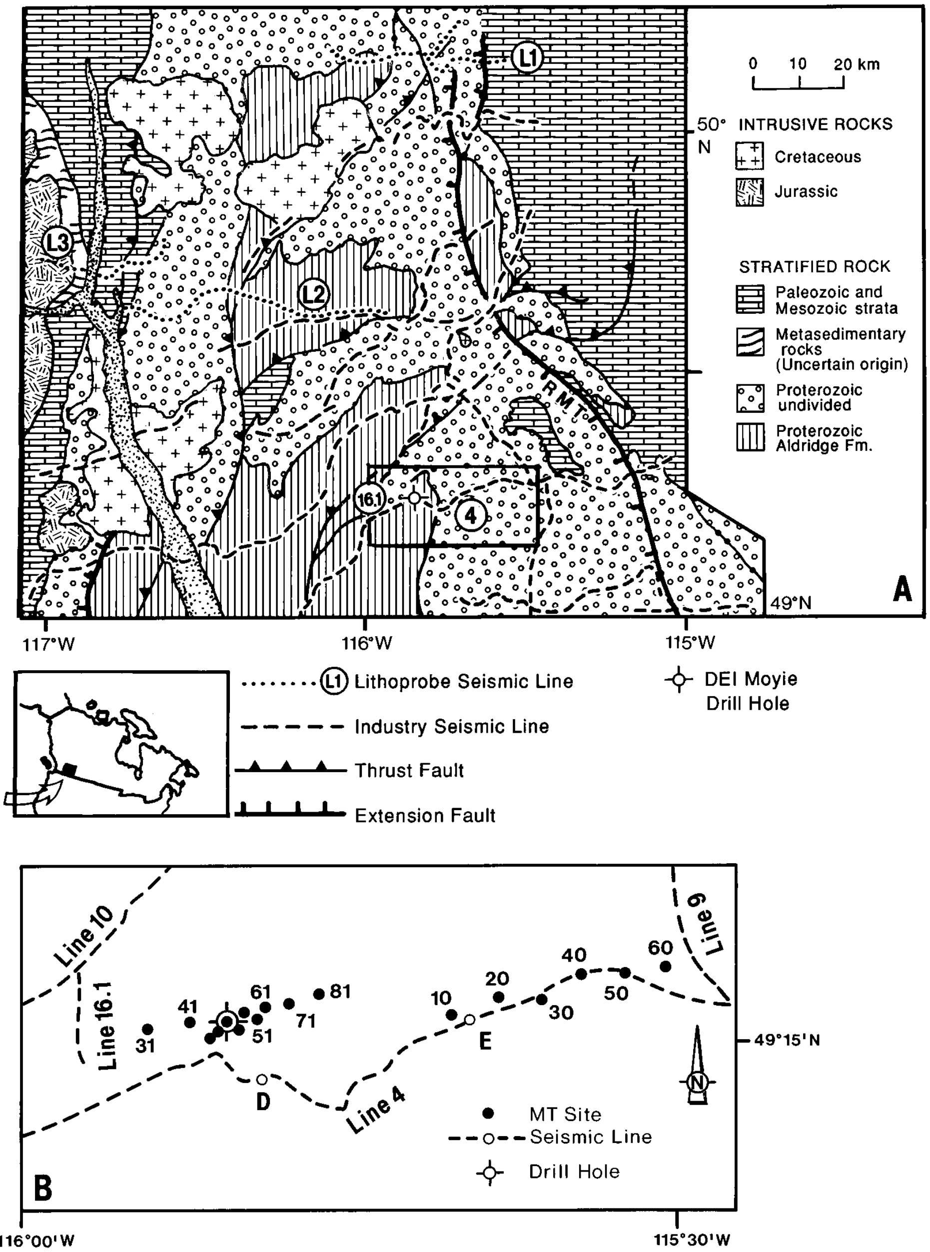


Figure 1. A: Geologic map of southeastern British Columbia (modified from Cook and Van der Velden, 1995). Dotted and dashed lines are locations of seismic profiles. RMT is Rocky Mountain Trench. B: Detail of area around DEI Moyie #1 well with seismic line locations (dashed lines) and magnetotelluric sites (solid circles).

deep crustal layers represent fluids expelled during high-temperature metamorphic reactions, that these fluids provide high acoustic impedance contrasts with the surrounding rock, and that they are interconnected to allow electrical current to be conducted easily (Hyndman and Shearer, 1989; Marquis et al., 1994). As the regional conductor and reflective layers are in the deep crust, it is not possible to test this idea with detailed correlations to either outcrop or drill holes.

However, in southeastern British Columbia, rocks with high conductivity are traced to within a few hundred metres of the surface and appear to coincide spatially with prominent reflectors. A model for the electrical data from all sites along the line (Fig. 1B) has a zone of high electrical conductivity at ~3 km depth near the Moyie drill hole (J. Gupta and A. Jones, unpublished). A high-resolution image (Fig. 2B) of the conductivity structure around the well was obtained by reanalyzing and modeling the data from the westernmost 11 sites (31 to 81) by using decomposition methods (Groom et al., 1993). In this model, the local geoelectric strike of N50°W for data in the range 1–100 Hz compares to the regional strike of N30°W for the Purcell anticlinorium (J. Gupta and A. Jones, unpublished).

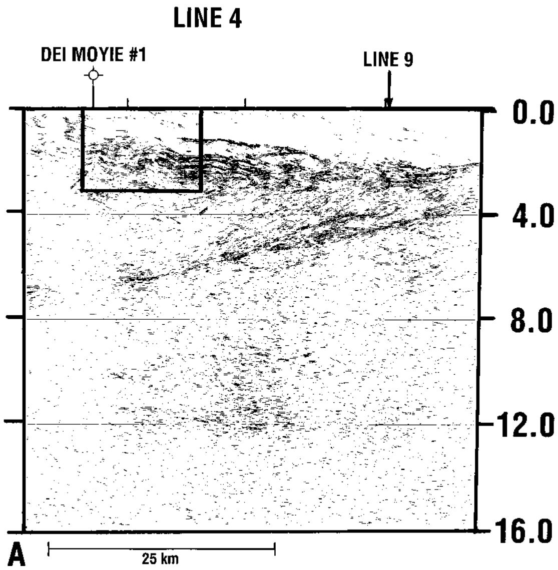
DRILL HOLE AND SURFACE PROJECTIONS

The DEI Moyie #1 drill hole was spudded near the axis of the Moyie anticline in southern British Columbia and is located near both seismic profiles (e.g., line 4, Figs. 2, 3) and magnetotelluric stations (Figs. 1, 2B). Reflections along the profile correlate with outcrops of Proterozoic diabase sills that intruded quartzite of the middle and lower Aldridge Formation and with sills that were penetrated by the drill hole between ~500 and 3477 m depth (Fig. 3). The most prominent reflectivity is caused by contrasts between sills and surrounding metasedimentary rocks (primarily quartzite) of the Aldridge Formation (Fig. 4).

The uppermost reflections along line 4 project to the surface along line 16.1 where sills and metasedimentary rocks of the lower and middle Aldridge Formation are exposed. In outcrop, the strata drilled between 500 and 2500 m (Fig. 4) are primarily stained (iron oxide) quartzites. In the subsurface, these metasedimentary rocks include thin (metre-scale) stringers with high concentrations of magnetic sulfides (primarily pyrrhotite) that correlate to zones of extremely high electrical conductivity (hundreds of siemens per metre) and that are very much more conductive than the sills (~0 S/m; Fig. 4). Thus, the zones of high conductivity and high reflectivity are caused by different geologic features.

DISCUSSION

Sedimentary rocks throughout much of the DEI Moyie #1 drill hole are quartzites that contain disseminated sulfides. In many cases, the sulfides are nonmagnetic (pyrite) and may not contribute significantly to the high-conductivity zones even though they compose 10%–20% of the material. Furthermore, not all of the thin (1–5 m) high-conductivity zones are represented by an increase in magnetic material in the well samples, perhaps because the sample interval (3 m) is insufficient to discern thin zones and because contamination from rocks above is common. However, examination of samples from the drill hole establishes that all, or nearly all, of the zones that do have large quantities of magnetic material are zones of high electrical conductivity. In some cases, magnetic zones correlate with unconsolidated, low-density, low-velocity sands with a high percentage of oxidized material (e.g., ~600 and 1800 m; Fig. 4). It is tempting to attribute sulfide oxidation in



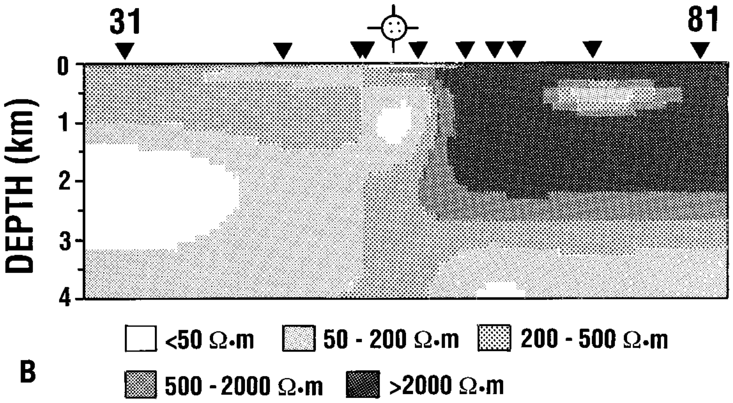


Figure 2. A: Seismic reflection data from part of line 4 near location of DEI Moyie #1 drill hole. Note arched reflections near drill hole. Outlined area is enlarged in Figure 3. B: Model of magnetotelluric data near Duncan Moyie drill hole. Inverted triangles indicate MT station locations, and numbers 31 and 81 are station numbers. Decomposition of regional impedances at 14 frequencies in 1–100 Hz range, and for both modes of induction (e.g., Jones, 1992), was inverted by using Smith and Booker's (1991) RRI algorithm. Resulting model fits data with an average misfit of 1.72. Note that near-surface conducting zone only exists in vicinity of drill hole and is electrically discontinuous from slightly deeper zones to east and west.

this section to fluid flow either through fractures or poorly consolidated sediments. However, high-conductivity zones between 1000 and 1500 m are not low density (Fig. 4), and a similar explanation for their oxidation level is not as obvious.

In contrast to the sedimentary rocks, the igneous sills have very low amounts of sulfides and correspondingly low conductivity (Fig. 4). Conversely, sills have seismic velocities of ~6.4–6.6 km/s and densities of ~3000 kg/m^3, whereas the quartzite velocities are typically ~5.4–5.8 km/s with densities near 2700 kg/m^3(Fig. 4). The contrasts between these rocks produce reflection coefficients that are commonly about ±0.10–0.15 (Fig. 4), and this results in good reflections. However, at some levels, near 600 and 2500 m, for example, densities and velocities of the sedimentary rocks are lower, and the reflection coefficients between these rocks and the sills can be as high as ±0.2–0.4 (Fig. 4); these results provide an explanation for the prominent reflectivity in the anticlinorium.

The detailed correlation of the high-conductivity layers to sulfide-rich zones in the Aldridge metasedimentary rocks implies that, unless this scale (metres to tens of metres) of observation is attained, it may not be possible to use electrical conductivity together with seismic reflectivity to provide boundary conditions for interpreting the physical properties and tectonic significance of deep crustal layering. In the Purcell anticlinorium, highly conductive layers do not correlate with sills, which in turn are responsible for most of the reflectivity. Hence, reflective and highly conductive layers of the deep crust, although appearing to correlate spatially, may in detail be seen to arise from different geologic features.

Previous interpretations of coincident reflectivity and enhanced conductivity in terms of a single cause have led to a paradigm involving fluids within the deep crust (e.g., Jones, 1987; Hyndman and Shearer, 1989). The Moyie hole data, although establishing that this simple and convenient explanation is invalid for the observed reflectivity and enhanced conductivity within the upper crust of the Purcell anticlinorium, serve as a caution that there may be no need to interpret a single cause for both. Experiments need to be performed that can directly address such coincident geophysical features. As an example, the interpretation of the Vancouver Island "E-reflector" and enhanced conductivity (Green et al., 1987) in terms of fluids within porous sediments trapped beneath an impermeable zone (Jones, 1987; Hyndman, 1988) was partly supported by subsequent shear-wave studies (Cassidy and Ellis, 1993), but theoretical modeling studies (Calvert and Clowes, 1990) suggested that the compressional-wave impedances require contributions from lithologic contrasts to account for the high ratios of the individual reflectors (to 0.2).

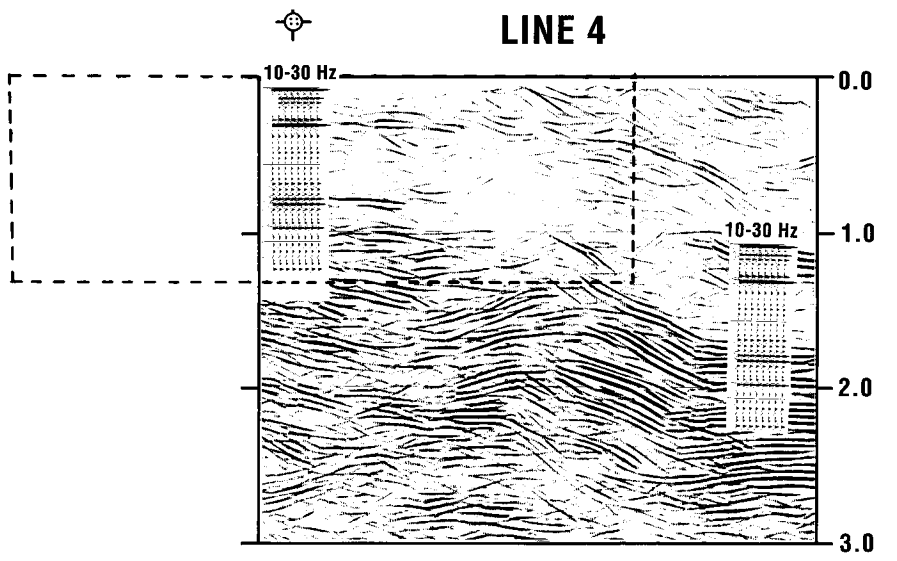


Figure 3. Enlargement of part of reflection line 4 near DEI Moyie #1 drill hole and synthetic seismic trace correlated to data. Synthetic trace is correlated at well location as well as at position ~8 km to east along a downdip projection of reflections. Dashed outline represents area covered by MT model in Figure 2B.

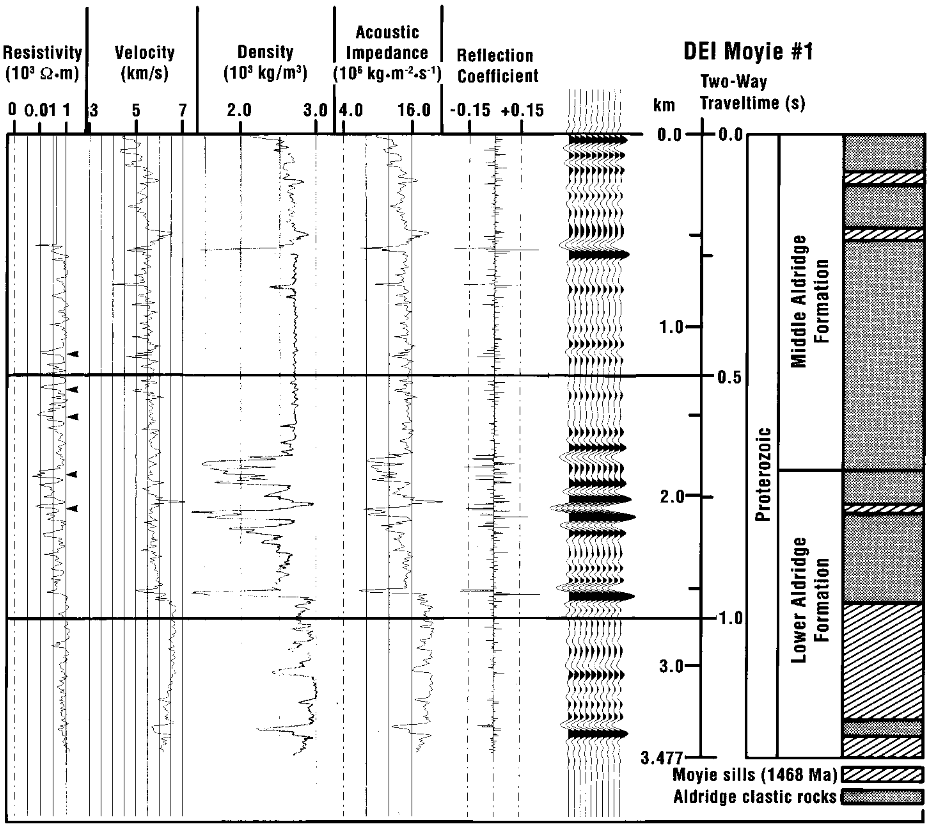


Figure 4. Logs of resistivity, velocity, density, acoustic impedance (velocity times density), and reflection coefficient and synthetic seismic trace (reflection coefficient convolved with 5–10–30–45 Hz pulse) from DEI Moyie #1 drill hole. Arrowheads indicate zones with resistivity <10 Ω·m; only one of these (lowest) is close to a sill. All others are within Aldridge clastic rocks. Note also zones of very low, and somewhat enigmatic, density near 600, 1800, 2100, and 2500 m.

CONCLUSIONS

In the Purcell anticlinorium of western Canada, seismic reflectivity is mostly caused by the acoustic impedance contrasts between Proterozoic Aldridge metasedimentary rocks and the Moyie sills that intrude them. In contrast, high electrical conductivity is caused by the presence of magnetic sulfides within the metasedimentary rocks. In some sediment layers with low density and high oxidation levels, these effects coincide; in others, they do not. Because these characteristics appear to correlate spatially in a regional context, it would be tempting to use both as necessary boundary conditions for interpreting the layers. However, as they do not always correlate in detailed in situ observations, such an interpretation might well be incorrect. As with Holmes's dog (Doyle, 1930; p. 347), that the seismic and electrical methods do not always give us information about the same horizons is just as significant and as useful a boundary condition as if they did.

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