INTRA-SEDIMENTARY MAGNETIZATION OF THE HINES CREEK FAULT (N. ALBERTA) BY VERTICAL FLUID FLOW AND EXOTIC GEOCHEMISTRY

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Published in slightly different form in The Leading Edge, January, 1998, pp. 89-92.

SUMMARY

A seismic line crossing the Hines Creek Fault with magnetic depth solutions plotted in time as an overlay shows a remarkable correspondence between the position of intra-sedimentary magnetic depth solutions and the position of the seismically imaged fault trace. This one-to-one correlation clearly demonstrates that the region immediately around the fault plane is magnetized.

We propose a model involving vertical flow of fluids along fractures and faults to explain the observed magnetization along fault planes detected by High Resolution AeroMagnetic (HRAM) surveys. This model involves the transport of iron in oxidized waters flowing along vertical fractures near basement and the precipitation of exotic iron-bearing minerals during ascent of the water as it undergoes redox reactions within the fracture system.

INTRODUCTIONS AND HYPOTHESIS

New HRAM surveys have been or are being flown during 1994-1997 over the majority of the Western Canada Sedimentary Basin south of 610 and Canadian portions of the Williston Basin. This case history covers a portion of the Peace River Arch (Twp 78-87, Rge 1-3 W6) and demonstrates one approach to interpreting these new data.

Since the mid 1980's evidence has been accumulating that intra-sedimentary fault planes are sometimes magnetized sufficiently to detect from airborne surveys (e.g., Jain, 1986), but unarguable evidence has been very sparse in the literature. Our recent work (e.g., Ebner et al., 1995; Peirce et al., in press) has convinced us that fluid flow along fractures and fault planes is the underlying cause of such magnetization.

OBSERVATIONS

1. Regional hydrodynamic studies of the Alberta Basin show that there is widespread potential for vertical migration of fluids (Rakhit et al., 1996). For the most part, however, this is unrealized because of the presence of laterally extensive low vertical permeability strata such as shales and evaporites.

2. Fractures and faults provide one of the few mechanisms to move fluids across regional scale, laterally continuous barriers to vertical migration.

3. Where fractures or faults permit vertical fluid migration, fluids and rocks of contrasting redox potentials co-mingle and conditions for the deposition of magnetic minerals may exist. Precipitation of magnetic minerals by redox reactions is enhanced by the presence of sulfur and hydrocarbons in the rock-fluid system.

Figure 1. (top) Authigenic pyrrhotite seen in polished thin section in sample taken from 75 m depth, drill hole ATH 94-01, Lac Minerals. The image length is 4 mm. Pyrrhotite locally makes up 1-5% of the calcareous shales of the Waterways Formation (Mid. - Upper Devonian) in NE Alberta. The presence of authigenic pyrrhotite is interpreted to indicate highly reducing conditions associated with bacterial sulfate reduction (BSR) in upflow zones.

Figure 2. (bottom) Native sulfur crystals line a vertical fracture in bituminous laminites of the Methy (Winnipegosis) Formation, NE Alberta (sample from 291.8 m depth, drill hole ATH 94-03, Lac Minerals). Native sulfur records fracture controlled inflow of saline brines and reduction of sulfate.

4. Studies of Paleozoic cores in NE Alberta have shown that there has been vertical migration of sulfate rich waters in the presence of hydrocarbons from the oxidizing environment of the Devonian Elk Point Group into overlying reduced calcareous shales of the Devonian Beaverhill Lake Group. This fluid migration has caused the low temperature formation of exotic mineral species such as pyrrhotite and pentlandite in the Beaverhill Lake Group (Figure 1) and native sulfur in bituminous laminites of the Methy Formation (Figure 2) in NE Alberta.

5. Detailed magnetic depth analyses done on a profile by profile basis detect vertically oriented patterns of depth solutions which can be correlated over several flight lines for distances of kilometers (Jain, 1986; Peirce et al., in press). In some cases these vertical alignments of depth solutions have been correlated to seismically defined faults.

APPROACH

Our approach is to interpret every profile from HRAM surveys using detailed Werner and 2D Euler depth analysis using MagprobeTM software in batch mode. Vertical alignments of depth solutions are common within both the sedimentary section and within the basement when the parameters are set appropriately. We interpret these vertical alignments of depth solutions as faults or fractures. The same analyses also provide estimates to the top of magnetic basement. We use filtered versions of the gridded magnetic data to help us correlate faults between flight lines, and the resulting product is a structural grain map. We usually produce one intra-sedimentary structural grain map and one basement structural grain map. On the basement map we also combine the available deep well control with magnetic depth estimates to produce contours of the depth to crystalline (magnetic) basement, which is usually (but not always) the same as the Precambrian surface. The final basement map has more detail than can be made from the well control alone, and the contouring reflects the structural grain derived from the faults seen on the depth profiles. This approach has proved effective at finding basement-related structural leads which have later been confirmed by seismic methods.

EXAMPLE

In the Hines Creek case history at least five areas of structural closure are highlighted in a 33 Twp area. The shapes and sizes of these closures are quite different from those based on well control alone, and they can be related to the regional structural grain of faults and fractures.

A seismic line crossing the Hines Creek Fault provided a clear example of a large basement offset with an overlying intra-sedimentary fault extending up into the Cretaceous section. Magnetically, this portion of the Hines Creek Fault system is very clearly seen on high frequency filtered versions of the magnetic data. On a profile basis there is no clear separation between the anomaly caused by the basement offset and anomalous effects caused by intra-sedimentary magnetization. However, on the MagprobeTM section there is a intra-basement set of depth solutions and a distinctly separate set of depth solutions (with vertical dips) related to the fault at depths 400 m above basement. When the depth solutions are plotted in seismic travel time as an overlay on the seismic section (Figure 3) there is a very close correspondence (+/- 150 m) between the position of the depth solutions and the seismic image of the fault offset.

This remarkable correspondence between the seismic and magnetic images of the fault is, in our opinion, the "smoking gun" piece of evidence that demonstrates inarguably that some fault planes are magnetized. Our experience to date suggests that perhaps only 25% of the seismically visible faults can be detected magnetically using this approach. However, we also see numerous fractures magnetically which are not detected seismically, presumably because there is no significant offset on the fracture. More direct comparisons between seismic and magnetics are needed to refine this initial estimate.

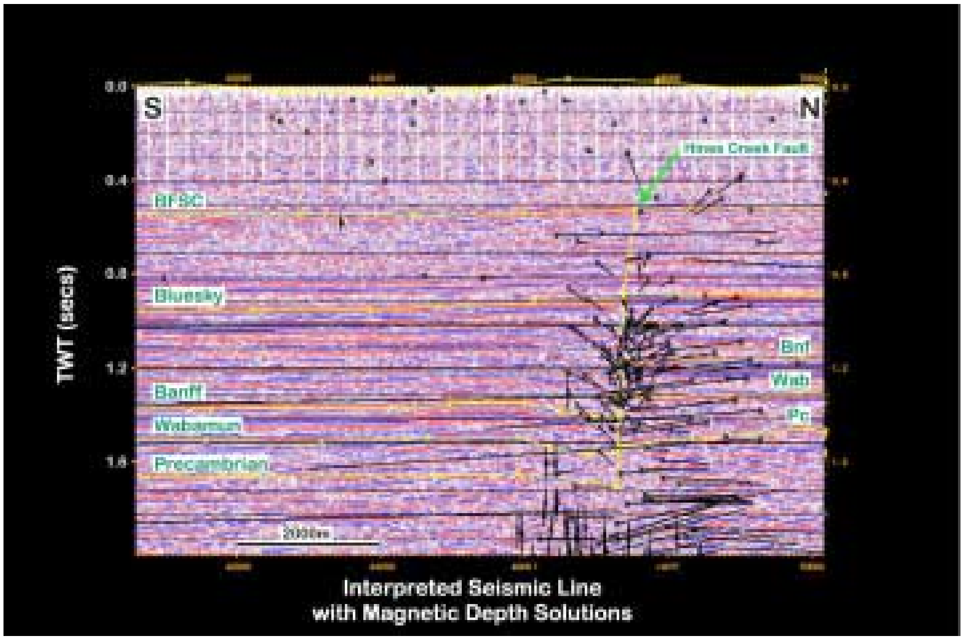

Figure 3. Seismic line crossing the Hines Creek Fault. North is to the right. This 48 fold line was shot with dynamite in 1973 and reprocessed in 1997. This migrated section is displayed in time. Imperial Oil Resources Ltd. kindly provided the seismic line and Seiscraft Processing Inc. reprocessed it. The interpreted horizons shown are the Base Fish Scales (Upper Cret.), Bluesky (Lower Cret.), Banff (Miss.), Wabamun (Upper Dev.), and Precambrian displayed. Werner and Euler magnetic depth solutions from an aeromagnetic line are plotted in seismic travel time as an overlay. The aeromagnetic line was flown in 1996 in modified drape mode at 120 m ground clearance using real time three dimensional DGPS. It runs north-south and its position is about 100 m west of the seismic line. Note how closely the magnetic depth solutions plot to the seismically imaged fault plane.

GEOCHEMICAL MODEL

Rocks of the Alberta Basin are representative of deposition under a variety of redox conditions. These range from the highly oxidizing conditions prevailing during deposition of evaporites to the highly reducing conditions during deposition of anoxic marine shales. Burial and generation of hydrocarbons introduces another reduced component into the basin. Sulfur is a convenient indicator of redox conditions because of its multiple valence states (-2 to +6) and its participation in redox reactions at virtually all temperatures.

This geochemical model below is based on evidence from NE Alberta, about 400 km east of the Hines Creek Fault. We believe that the processes described in the geochemical model are general and are applicable in any hydrocarbon-rich basin.

A simplified geochemical model for redox relations amongst iron and sulfur aqueous and mineral species has been calculated. The variable "logf(O2)" is the logarithm of oxygen fugacity (similar to partial pressure, but corrected for non-ideal behavior of O2 gas) and is a geochemical representation of the redox state of the system under consideration. Thus, greater (less negative) values of logf(O2) indicate more oxidized conditions. For example, surface water in equilibrium with atmospheric oxygen has a logf(O2) value =~ -3.6. By comparison, pyrrhotite forms only at oxygen fugacities below -60.

The phase diagram shows that the redox state of a rock can be estimated by its mineralogy. For example, a red bed-evaporite system with abundant hematite and anhydrite represents a more oxidized environment than a marine evaporite containing pyrite and anhydrite. Pyrrhotite is the most reduced iron bearing mineral in this system.

Its occurrence within the calcareous shales of the Waterways Formation is unusual and is explained by bacterial sulfate reduction (BSR) in the presence of hydrocarbons. Because the stability field for pyrrhotite lies below the lower limit of calcite stability we know that this example of pyrrhotite formation is not a bulk rock process. Similarly, the presence of native sulfur in fractures within the Methy and Waterways Formations indicates that fractures are the preferred site for deposition of exotic minerals by redox processes induced by vertical flow of waters of contrasting redox state. Stratigraphic and redox relations in NE Alberta are schematically illustrated in Figure 4.

At temperatures greater than approximately 1200C BSR is no longer important and the sulfate reduction reaction proceeds spontaneously through thermochemical sulfate reduction (TSR) (Goldhaber and Orr, 1995). This process is responsible for the generation of large volumes of H2S in deep reservoirs. We suggest that TSR is likely to occur in deeper fractures if sulfate and hydrocarbons come in contact through vertical movement of fluids. For reasons similar to those outlined for NE Alberta, we hypothesize that deeper seated redox reactions are likely to occur in fractures and result in deposition of iron-bearing minerals with a wide range of susceptibilities. Thus redox-controlled fracture mineralization of iron-bearing species may be an explanation for intra-sedimentary magnetization associated with regions of reactivated basement faulting.

CONCLUSIONS

The seismic and magnetic evidence demonstrate that part of one fault in the Hines Creek Fault system is magnetized within the sedimentary section and the basement over a lateral distance of 12 km. We believe that the sedimentary magnetization is caused by exotic geochemical reactions involving iron, sulfur compounds and hydrocarbons. These reactions can precipitate magnetic minerals under favorable redox conditions. Bacterial catalysis may enhance the formation of unexpected mineralogy such as authigenic pyrrhotite at shallow depths.

ACKNOWLEDGEMENTS

We would like to acknowledge John Gorveatt of Varidata Surveys Ltd. for helping in locating the example seismic line, Zig Doborzinski of Imperial Oil Resources Ltd. for providing the seismic line, and Joan Likuski of Seiscraft Processing Inc. for reprocessing the seismic line.

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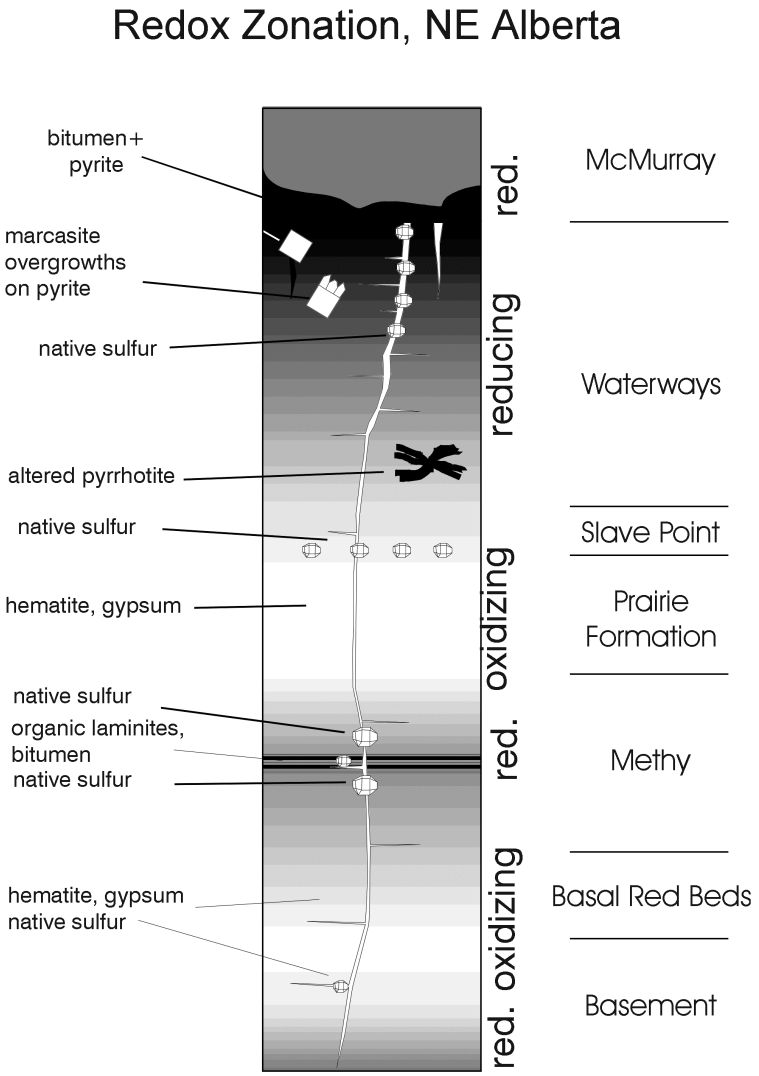

Figure 4. Schematic model of redox stratigraphy of NE Alberta. There are two oxidized-reduced successions.

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