

# **High-Resolution Aeromagnetic (HRAM) Surveys: Exploration Applications from the Western Canada Sedimentary Basin -- Exploration in Highly Deformed Terrains Using Fixed-Wing Aircraft and Helicopter-Mounted Systems\***

By  
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## **Abstract**

Typical high-resolution aeromagnetic (HRAM) data in the fold belt region of the Western Canada Sedimentary Basin (WCSB), acquired with fixed-wing aircrafts flying 125 meters above the ground, imaged deformed lithological units, allowing the recognition of key geological structures within the detached sedimentary section.

We also illustrate that an important contribution of HRAM surveys is the detection of reactivated basement faults, which either enhance the reservoir potential of rocks or result in the compartmentalization of certain hydrocarbon traps.

The quality of fixed-wing surveys might deteriorate in areas with rugged topography. Helicopter-mounted system has the advantage of increased resolution as well as the ability to perform draped surveys over rugged terrains.

## **General Statement**

The application of aeromagnetic data to hydrocarbon exploration has moved from primarily mapping basement structures and lithologies to imaging and mapping structures within the sedimentary section. High-resolution aeromagnetic (HRAM) surveys are now relatively inexpensive tools for 3-D mapping of faults and fracture systems propagating through hydrocarbon-bearing sedimentary levels.

Advances in data acquisition techniques (enhancements in magnetometers, compensation software/hardware for suppressing airplane noise, positioning utilizing GPS systems, pre-planned drape surveys, gradiometers measuring horizontal and vertical total magnetic intensity gradients, etc.), as well as data processing and displaying procedures (such as micro-leveling), have significantly improved data quality and resolution, providing levels of detail that are compatible to those derived from seismic, well, and surface geological data.

Current industry standards view "high-resolution" aeromagnetic data as fixed-wing surveys with flight-line spacing of 400-800m and tie-lines every 1200-2400m, and with mean flight clearance of 100-125m.

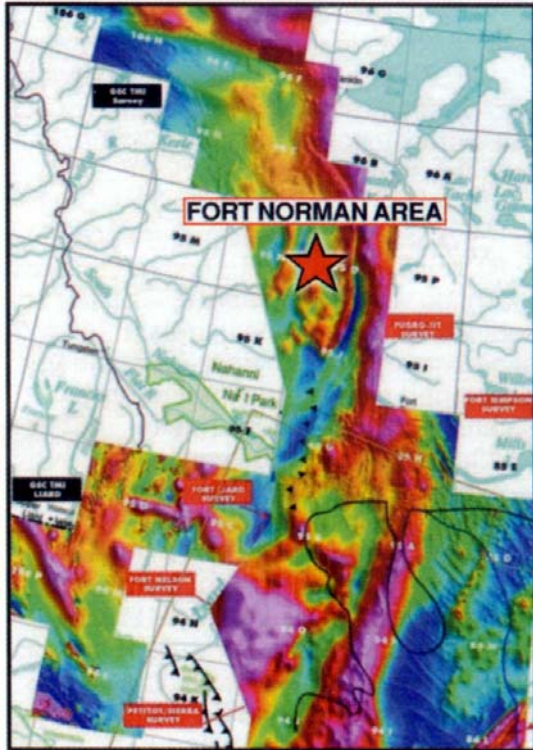
The Canadian petroleum industry has been receptive to the introduction of HRAM data as a tool for exploration. Consequently, a large volume of HRAM data has been collected over both mature and frontier portions of the Western Canada Sedimentary Basin (WCSB), including part of the highly deformed Canadian Fold Belt.

### **HRAM Data In Western Canada**

A portion of HRAM data collected in the WCSB is shown in Figure 1. The imagery represents an amalgamation of several different speculative HRAM surveys that were collected over the past decade by industry vendors and the Geological Survey of Canada (GSC).

The area contains approximately one million line-kilometers of HRAM data (representing about a third of the total data collected in the entire basin), covering parts of the WCSB and Mackenzie Corridor. We focus first on the Canadian Fold Belt region because:

- The geological structures that will be shown are clearly detached from the basement, and thus illustrate that HRAM data can image sedimentary structures.
- Fold belt regions are usually characterized by extremely complex structures that are difficult (and extremely expensive) to image with seismic data.
- The collection of HRAM data is done in a non-invasive manner and therefore can be collected in environmentally sensitive areas.
- The rugged topographic relief of fold belts allows us to demonstrate the ability of the new surveys to overcome the effects of topography on the magnetic signature of structures.
- Fold belt regions appear to represent a significant portion of the remaining uncharted areas for frontier oil and gas exploration.



**Figure 1. HRAM data collected over the northern portion of the Western Canada Sedimentary Basin. The HRAM surveys were collected with 800m flight-line spacing and mean elevation of 125m above ground. The red star indicates the location of the Fort Norman data set.**

### **HRAM Mapping -- Fort Norman Area, Northwest Territories**

In 1998 the GSC began to collect a series of non-exclusive HRAM surveys along the Mackenzie Corridor. HRAM data was collected at 800m flight-line spacing and mean elevation of 125m above ground. One such survey was collected over the Fort Norman area, along a partially exposed portion of the Mackenzie Mountains thrust belt (Figure 2). In this area, the structural style of the fold belt is further complicated by the presence of a major northeast-trending tectonic element known as the Gambill Shear Zone (GSZ).

Figure 2a illustrates that in the subsurface the Gambill Diapir acted as a transfer zone, linking the GSZ with the Norman Wells Thrust (MacLean and Cook, 1999). Geological mapping (Figure 2b) and the digital elevation model (Figure 2c) show that the structural features associated with these tectonic elements are only partially exposed at the surface. However, the HRAM data (Figure 2d) clearly demonstrate that the transfer zone reflects the presence of a complex shear element that exhibits basement-involved, right-lateral faulting, which resulted in a complex pattern of surface and near-surface anticlines. In addition, one can notice that the overall magnetic intensities do not reflect the rugged topography found in this region.

The block diagram shown in Figure 3 illustrates that the GSZ consists of high-angle wrench faults and a series of tight salt core anticlines that developed and wrapped around a structural high to the north. Strike-slip reactivation of northeast-trending basement faults may have triggered the development of salt diapir structures along this fault zone during Laramide deformation.

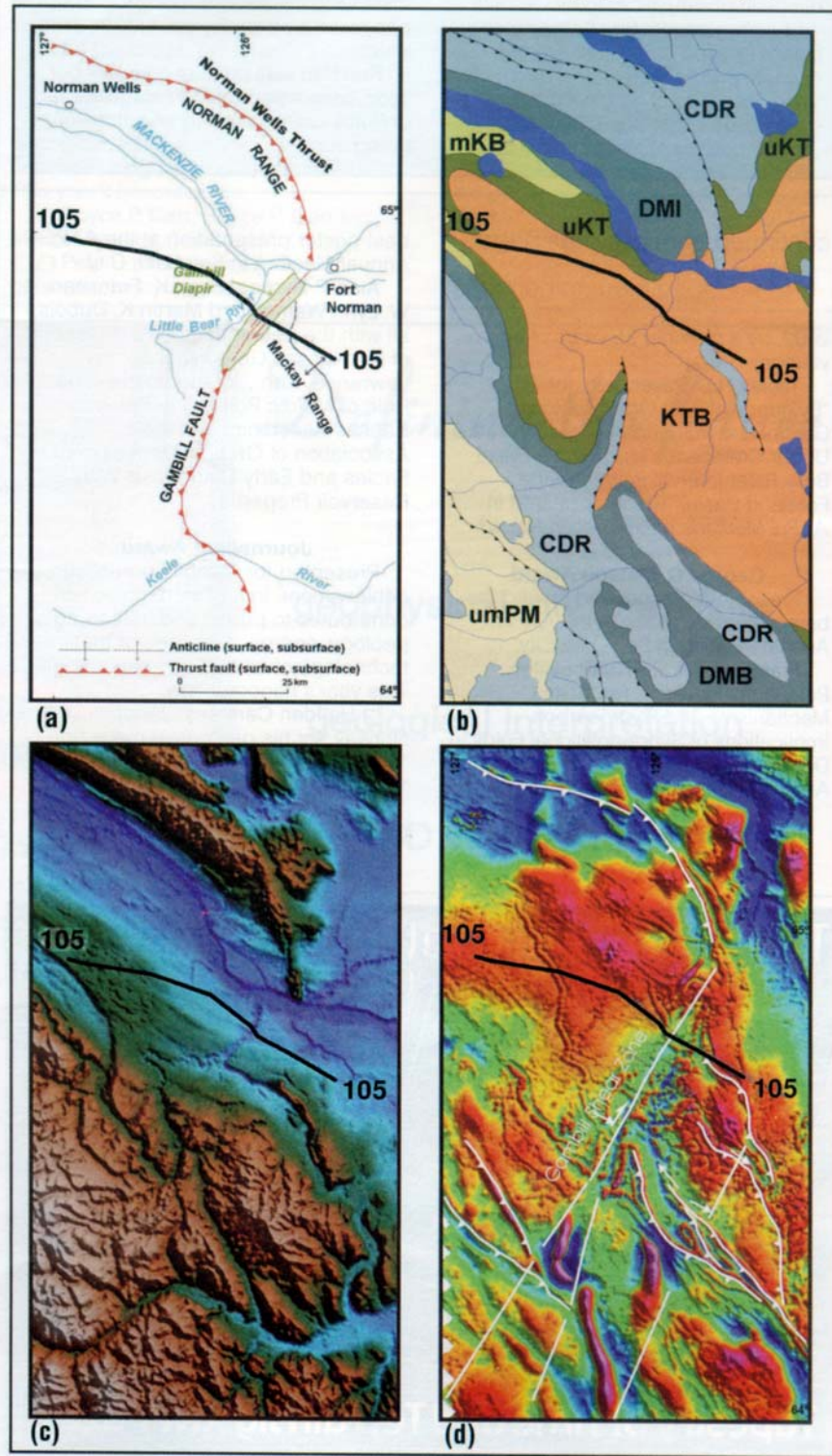
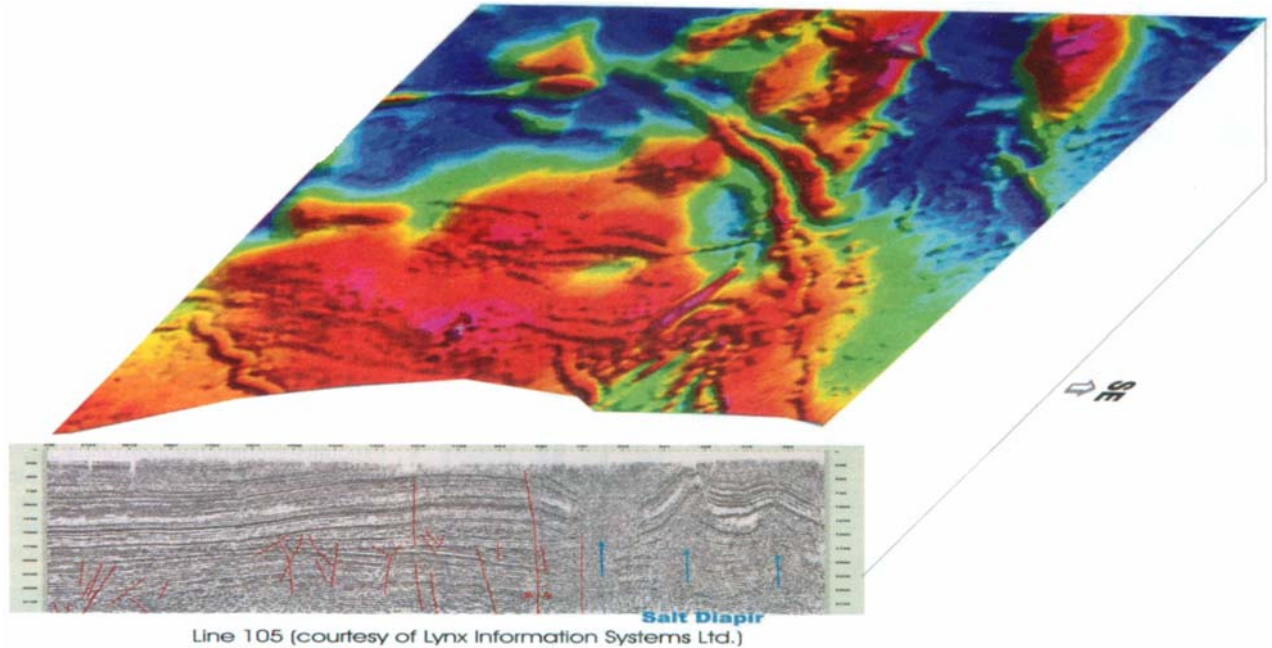


Figure 2. Interpretation of the Gambill Shear Zone in the Fort Norman area. (a) Simplified tectonic map of the Fort Norman area (from MacLean and Cook, 1999) (b) Surface geological map (Wheeler and McFeely, 1991). (c) Geological Survey of Canada (GSC) digital elevation model (DEM) derived from GSC HRAM survey. (d) GSC HRAM imagery with major tectonic elements. Note that the majority of magnetic anomalies show no correlation with topography. The location of seismic line 105 is displayed in the imagery.

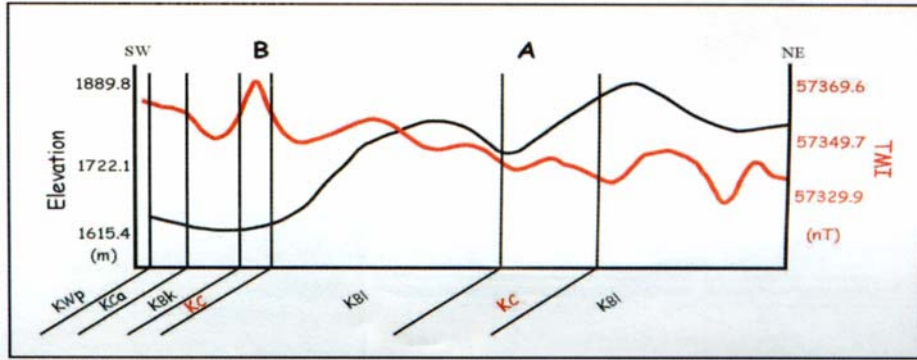


**Figure 3. Block diagram showing GSC residual HRAM and seismic line 105 (courtesy of Lynx Information Systems Ltd.) with interpretation of major structures. Red lines represent faults; Blue arrows indicate salt diapir structures and salt-cored anticlines.**

### **Magneto-Stratigraphy In the Coleman Area**

Our experience in fold belt regions shows that HRAM data collected at sufficient resolution and flown at low altitude can resolve magnetic signatures that are associated with structures found within the sedimentary section. Studies have shown that HRAM data can image the internal geometry of folded strata, given that they detect minute variations in the magnetic response of near-surface deformed rock units.

For example, an HRAM TMI (total magnetic intensity) profile nearby the Coleman gas field in the southern Canadian Fold Belt reveals that lithostratigraphic units produce magnetic "highs" and "lows" (Figure 4). In this case, the diagram illustrates that the Crowsnest Formation (volcanic sediments) is associated with a magnetic high, suggesting that it contains minerals with relatively higher magnetic susceptibilities than the surrounding rocks of the Blackstone Formation and Blairmore Group. Consequently, this formation forms a "magnetic marker bed" that may reveal the size and shape of folds at a consistent stratigraphic level.



**Figure 4.** Magneto-stratigraphic profile in the Coleman field area. The Crowsnest Formation is associated with a magnetic high and can be regarded as a "marker bed," allowing geologists to map structures based on magnetic response. KWp Wapiabi Formation; KCa Cardium Formation; KBk Blackstone Formation; KC Crowsnest Formation; KBl Blairmore Group. A and B illustrate that TMI profile values may or may not mimic topography.

### Helicopter-Mounted Systems

There are benefits of using helicopter-mounted systems to acquire HRAM data. These surveys are normally collected with 50- to 100-meter flight-line spacing by a sensor hanging from a helicopter at a mean altitude of 30 meters (Figure 5).

The helicopter-mounted system has the advantage of increased resolution as well as the ability to perform draped surveys over rugged terrains -- however, the tight flight-line spacing requires that these surveys be flown over site-specific areas, such as existing fields or prospective regions.



**Figure 5.** Helicopter-mounted HRAM system. The magnetic platform is suspended at an altitude of 30 meters, enabling the sensor to drape topography in rugged terrain and thus minimize the effect of topographic relief in the magnetic data.

## **Geological Mapping: Coleman Gas Field**

In this example, the helicopter-mounted system was flown over the Coleman gas field in the WCSB's southern foothills, approximately 150 kilometers south of Calgary (Figure 6). The Coleman Field produces gas from fractured carbonates along the leading edge of thrust sheets that are detached from the shallow structures outcropping at the surface. The field is also located within a major structural discontinuity known as the Vulcan Low.

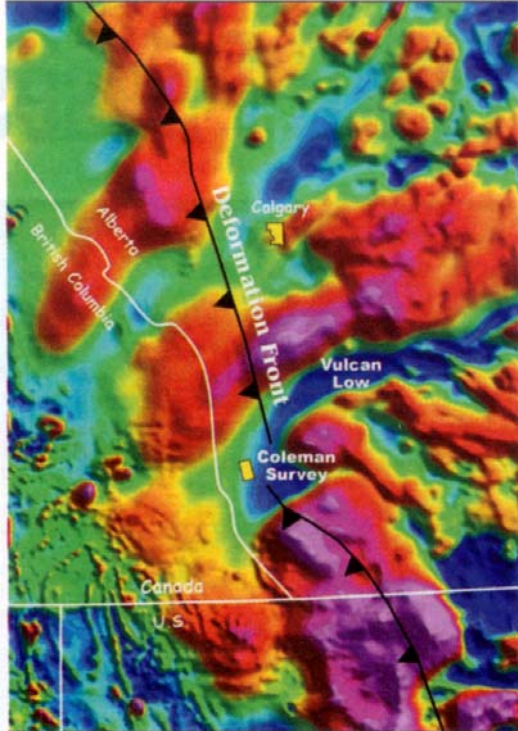
The survey's objective was to identify faults that, due to their slight offsets, could not be seen on seismic data but still compartmentalized the reservoir. Figure 7 shows some of the datasets used in the interpretation of the Coleman survey. These include HRAM imagery, digital elevation model (DEM) data, and surface geological information derived from published geology maps.

The Figure 7 imagery illustrates that the helicopter-mounted system produces a "smooth" magnetic image that is generally not affected by the strong topographic relief present in the Coleman area. The strongest anomalies visible in the HRAM data arise from contrasts in the magnetic susceptibility of outcropping units. These anomalies act as stratigraphic markers, outlining near-surface geological structures found in the survey area.

The internal geometry of anticlines and synclines is characterized by the presence of several elongated and asymmetrical "magnetic ridges," which reveal the attitude of inclined bedrock strata and outlines the location of folds and plunging noses. The HRAM imagery also illustrates that several magnetic markers are cut and offset by linear features, which are believed to represent fault systems.

We postulate that the major northeast-trending magnetic feature (A-A'), which corresponds to the field's southern boundary, reflects late reactivation of a major fault or zone of weakness in the basement. This feature is coincident with a prominent gravity and magnetic low in the basement referred to as the Vulcan Low (see Figure 6), and as such, has been coined the Vulcan Low Fault Zone (VLFZ).

On the other hand, the northwest-trending features (B-B') appear to reflect shallow "tear faults" and do not correlate with deep-seated basement structures. These faults seem to strongly affect the internal geometry of the producing field. It is interesting to note that the latter fault system appears to manifest subtle topographic expressions that can be detected on the DEM imagery, suggesting recent motion along these faults.



**Figure 6. Regional setting of the Coleman gas field, in the southern foothills of the Canadian Rocky Mountains. The regional GSC magnetic data illustrate that the Coleman area is situated over the Vulcan Low basement structure.**

## Conclusions

Because HRAM surveys are strongly influenced by near-surface structures, they are particularly useful in areas where the reservoir targets are located within the upper thrust sheets, where there is significant correlation between surface and subsurface structures. We have concluded that HRAM data also can detect the presence of reactivated basement faults as well as "tear faults." The recognition of these faults is crucial in exploration, because they can either enhance the reservoir potential of rock units or raise concern about the presence of structural compartments within a targeted fold.

The quality of HRAM surveys in rugged areas, however, may deteriorate due to strong topographic effects, which are very difficult to remove with current processing techniques. The best way to overcome this problem is to collect data with helicopter-mounted systems. Although significantly more expensive, these systems are flown while draping the landscape, and as such, minimize the effect of topography.

Since the 1999 acquisition of the HRAM data over the Coleman Field, several similar surveys have been collected over developed and undeveloped gas fields in the Canadian Fold Belt region. In all cases, the helicopter-mounted systems proved very useful to map near-surface geological structures, which are nearly impossible to image with conventional fixed-wing surveys due to strong topographic effects during data collection.



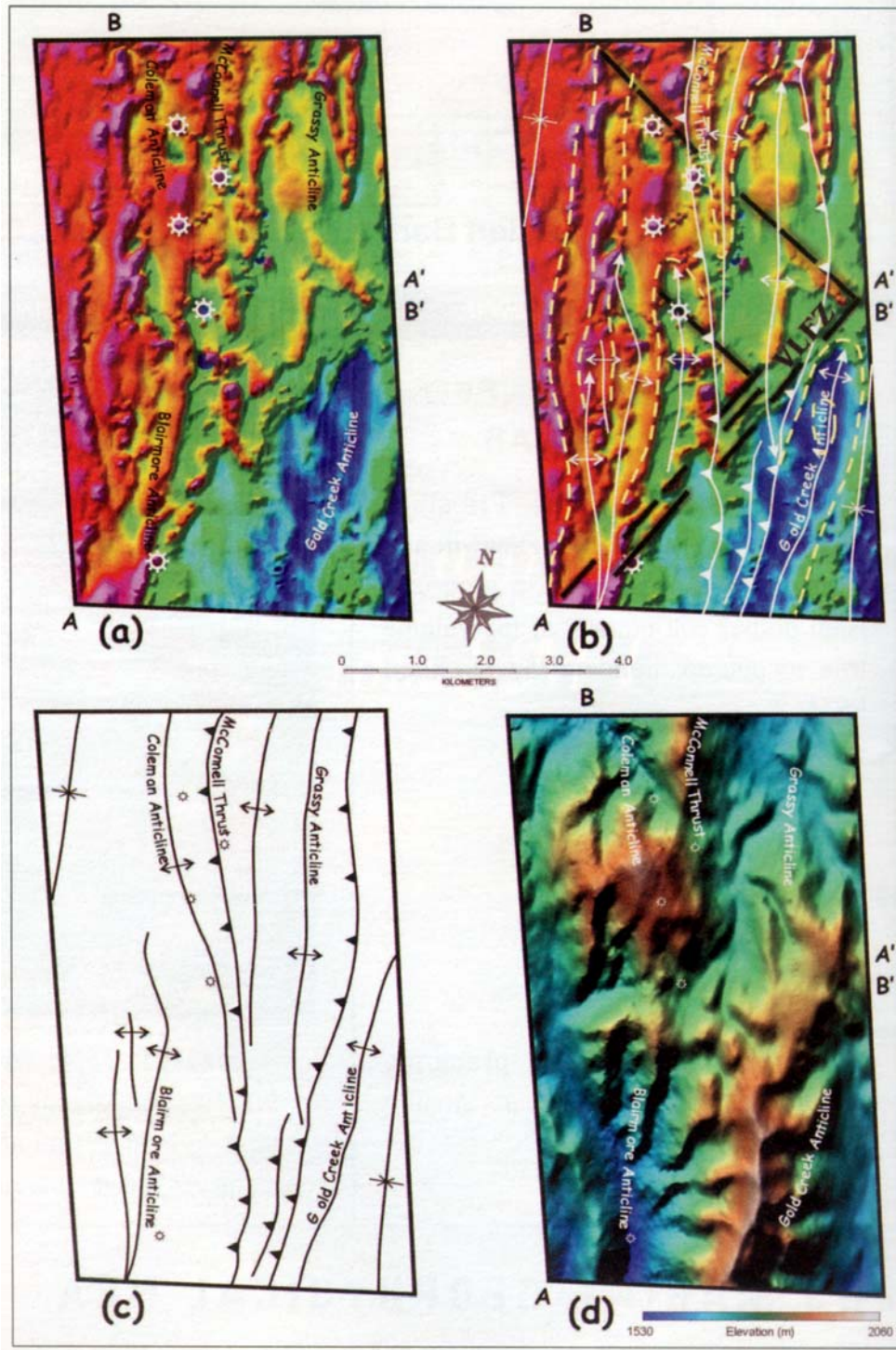


Figure 7. Interpretation of the HRAM survey over the Coleman area, showing: (a) HRAM imagery over the Coleman Field area; (b) Geological interpretation of the Coleman survey data; (c) Main structural features compiled from published GSC geology maps; (d) Digital elevation model (DEM) derived from the HRAM survey. The interpretation reveals that several magnetic marker beds can be used to outline folds and fracture patterns within the survey area. Basement (A-A') and near-surface (B-B') fault systems can be detected in the data. Comparison of the HRAM and DEM reveals that most of the magnetic features are not related to topography. VLFZ Vulcan Low Fault Zone.

The main contribution of helicopter-borne HRAM data to exploration and development activities is the detection of reactivated basement faults and detached "tear faults" that have not previously been recognized through conventional surface and subsurface mapping techniques. It must be emphasized that these surveys only improve the recognition of near-surface structures within the first kilometer below the surface. Unfortunately, they do not provide significantly more information regarding deep-seated structures, which can be detected with less expensive conventional fixed-wing HRAM surveys.

### **References**

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