

# Evidence for Basement Fault Reactivation in Southern Alberta: An Integrated Topography and Airborne Magnetics Approach

Hernan Ugalde, Sara L. Underhay, William A. Morris, and Kristi Markham

School of Geography and Earth Sciences, McMaster University, Hamilton, Ontario, Canada

## Abstract

The influence of basement control on sedimentation through fault reactivation within the Western Canada Sedimentary Basin has been an important matter of research that lead to the Alberta Basement seismic Transects completed by Lithoprobe. However, due to the long seismic line lengths (about 40 km) and long recording times (about 16 seconds) required to acquire a seismic profile that extends into the basement, the resulting seismic data do not have the depth resolution to investigate any direct link between basement features and overlying strata. The purpose of this study is to add to the discussion on fault reactivation and basement control overlying sedimentation through the integration of topographic and airborne magnetic evidence. These datasets were interpreted jointly, and then 2.5D sections were modelled to provide some constraint on the depth to the top of the magnetic sources. Finally, the 2.5D results were integrated in 3D to show the geometry of the mapped faults. The 3D model presented here corroborates an early model for the Medicine Hat Block which comprises extensional crustal-scale ramps dipping to the west.

## Introduction

The influence of basement control on sedimentation through fault reactivation has major ramifications for oil exploration strategies within the Western Canada Sedimentary Basin that directly lead to the Alberta Basement Transects of Lithoprobe (Edwards and Brown, 1999; Hope and Eaton, 2002; Lemieux, 1999). As Ross and Eaton (1999) state the mere coincidence of structures does not provide evidence for actual displacement. Studies undertaken in the Alberta Basin have been reported as providing evidence both for and against basement reactivation (Lemieux, 1999; Ross and Eaton, 1999). While small-scale studies seem to indicate that there has been basement reactivation in the Alberta Basin, large-scale studies seem to refute this.

The purpose of this study is to add to the discussion of fault reactivation and basement control overlying structure on southern Alberta by integrating topography and airborne magnetics as evidence. The key questions being addressed are: (1) does topography reflect shallow (sedimentary) structure; and (2) if it does, is shallow structure influenced by controlling basement features?

To accomplish that, we integrate ideas about topography as it relates to the surficial and subsurface geology of the region, potential field maps and basement structure. The rationale in which we base this work is as follows:

- a) High Resolution digital elevation models (DEM) contain information on the surface trajectory of faults and the differential elevation of sedimentary layering. These can provide evidence for fault displacements;
- b) Aeromagnetic surveys over basement covered by non-magnetic sediments contain information on lithological contrasts in the basement and the morphology of the basement/cover surface;
- c) Therefore, integrating results from DEM and aeromagnetic modelling can provide direct evidence for basement reactivation.

### Four sources of data are considered:

- 1) Regional topography – 100 x 100 km topographic model produced using radar altimetry techniques (Markham, 2001).
- 2) Potential field data – aeromagnetic survey of the same 100 x 100 km region as the topographic model (Markham, 2001).
- 3) Surface geology – information based on descriptions of surficial geology as published by Beaney and Shaw (2000), Kulig (1996) and Westgate (1968).

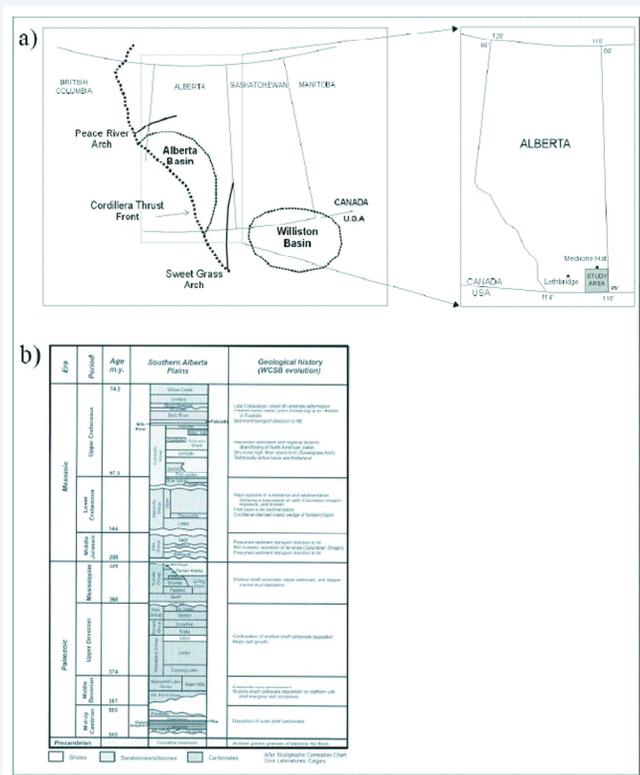


Figure 1 a). Area of study (in gray), relative to the Sweet Grass Arch, Williston Basin and the Alberta Basin. b) Stratigraphic section (adapted from Lemieux, 1999). The Phanerozoic sedimentary section overlies Precambrian crystalline basement rocks.

## Evidence for Basement Fault Reactivation...

Continued from Page 32

- 4) Basement geology of Alberta carried out using potential field and seismic data (from the LITHOPROBE study and the Geological Atlas of the Western Canada Sedimentary Basin), synthesized from studies by Burwash et al. (1994), Lemieux (1999), Lemieux et al. (2000), Pilkington et al. (2000), Ross and Eaton (1999), Ross et al. (1991) and Villeneuve et al. (1993)

Topography and magnetic data were interpreted jointly, and then 2.5D sections were modelled to provide some constrain on the depth to the top of the magnetic sources. Finally, the 2.5D results were integrated in 3D to show the geometry of the mapped faults.

## Regional geology

The study area is situated on the eastern flank of the Sweet Grass Arch, a structural anticline dividing the Alberta Basin in the northwest from the Williston Basin to the southeast (Figure 1a). East and northeasterly dipping beds overlying a deep, crystalline basement characterize the thick sedimentary section (Figure 1b). The geology of the study area can be broken into three distinct units (Beaney and Shaw, 2000; Westgate, 1968):

- 1) Pleistocene glacial deposits.
- 2) Phanerozoic sedimentary rocks of the Western Canada Sedimentary Basin, which overlay older basement rocks.
- 3) Precambrian crystalline basement rocks, the continuation of Canadian Shield rocks.

The structure of these three distinct units is interdependent: structure in basement rocks may influence structure in the overlying sedimentary section, which may in turn have an effect on structure in younger glacial deposits. Each of these geological units is separated by an unconformity.

Crystalline basement rocks were formed by accretionary events that began in the Archean and ended during the Early Proterozoic (~1.8Ga). Phanerozoic cover rocks in southern Alberta range in age from Cambrian (545 Ma) to Upper Cretaceous (74.5 Ma), and are overlain by recent glacial sediments. Work by Kakreuth and McMechan (1988) suggests that about 2 km of sedimentary rocks deposited during the Mesozoic and Cenozoic have been eroded from the area since the Oligocene. If 2 km of sediments have been removed, then units beneath the recent overburden are a record of sedimentary structure and fault control as it occurred in the Cretaceous. If lineaments in topography expressed through overburden can be correlated

with structure in underlying sedimentary rocks, it might suggest recent movement along those structures. At a minimum it confirms the presence of faults or joints in the subsurface. If these lineaments can then be linked to basement structure, it furthers the argument for basement control. This was noted by Westgate (1968), who recognized surficial lineaments that could not be explained by the direction of glacial movement. These non-glacial lineaments were described from aerial photographs as being several kilometers long, and intersecting or subparallel. Westgate attributed these lineaments to represent fault or joint traces reflected through unconsolidated glacial drift.

The Alberta Basement Transects of Lithoprobe (Edwards and Brown, 1999; Hope and Eaton, 2002; Lemieux, 1999; Ross and Eaton, 1999) provided good insights into the basement structure. However, there are a number of limitations with seismic data as used to provide a direct link between basement features and overlying strata, due to the long (about 40 km) seismic line lengths and recording times (about 16 seconds) required to produce a seismic profile that extends into the basement. Vertical resolution of the Lithoprobe data is about 30 metres for thin beds and fault displacements. Therefore, neither basement nor sedimentary topographic features of 30 metres or less will produce reflector displacements; and also the structures must have a dip of less than 70 degrees to be properly resolved.



## Reservoir Characterization

Expertise in heavy oil & deep basin reservoirs

- AVO / LMR Analysis
- Neural Network Analysis
- PP & PS Registration
- Joint PP & PS Inversion
- Fracture Detection Analysis using Azimuthal AVO
- Spectral Decomposition

**Carmen Dumitrescu**

PhD Geoph., M.Sc., Manager, Reservoir Geophysics

Direct: 403-260-6588 Main: 403-237-7711

www.sensorgeo.com

Continued on Page 34

## Evidence for Basement Fault Reactivation...

Continued from Page 33

### Airborne magnetics and topography

Total field aeromagnetic data were acquired along NS lines, 150 m elevation above the ground and 400 m spacing. The data were interpolated using a minimum curvature gridding algorithm and a grid cell spacing of 80 m (Figure 2; Markham, 2001).

The most striking feature is a NW-SE trend, which has been described by a number of researchers (Leblanc and Morris, 1999; Lemieux et al., 2000; Pilkington et al., 2000; Ross and Eaton, 1999; Ross et al., 1994) as being primarily indicative of granitic basement sources, buried about 1.7 to 2.2 km under sedimentary cover rocks in the study area. In addition to this dominating fabric, a number of other magnetic textures characteristic of certain features in the study area were identified by Leblanc and Morris (1999). However, no attempts have been made to model the depth of the top of the magnetic sources before this study.

From the same airborne survey, elevation information was acquired by subtracting the radar altimeter data from the differential GPS elevation (Figure 3a; Markham, 2001). A regional topographic image of 100 x 100 km was created and used to identify surface lineaments. Lineaments were mapped semi-automatically by means of subtracting a low-passed version of topography from the raw topography (Figure 3b), and then manually by digitizing the main features (Figure 4a).

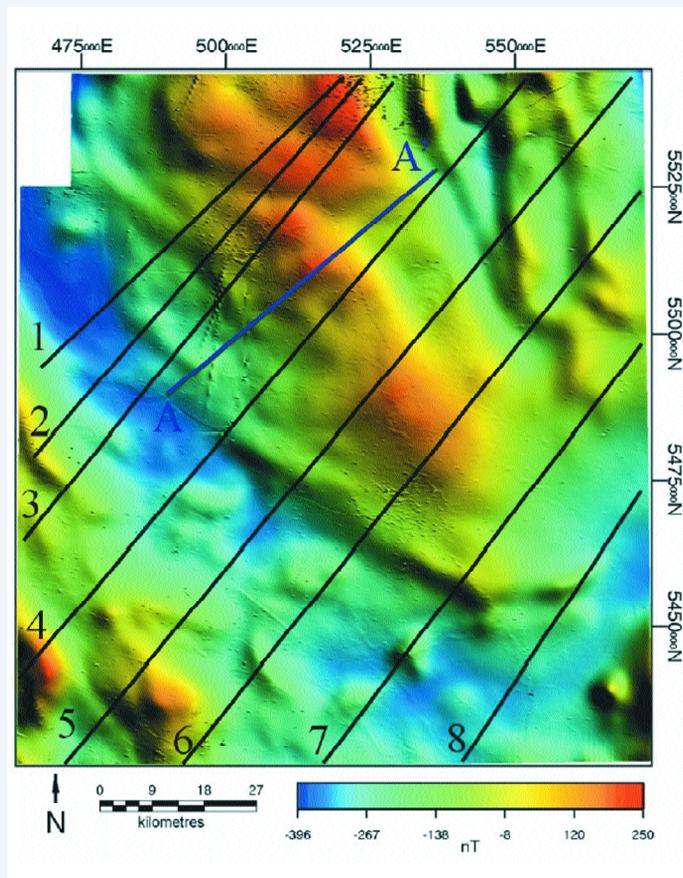


Figure 2. Total magnetic field (TMI) image. The 2.5D modeled sections are shown in black, and numbered 1-8. Section AA' for base model is shown in blue. The linear features around 500000E, 5510000N have been identified as Eocene intrusive dikes; small "bumps" are largely culturally-sourced well-heads. The circular feature at 530000E, 5550000N is the Eagle Butte impact structure.

Both datasets were integrated as a shaded relief image (Figure 4b). This image shows a strong correlation between the magnetic data (colour) and the topography (relief).

### Modelling results

Figure 5 shows a model across the centre of the main magnetic anomaly (section AA', see Figure 2 for location) of two different situations that resemble what is observed here: the first one shows uplifted basement with a thick sedimentary package on top. The model fits the data in great detail (Figure 5a). The second model shows a uniform sedimentary package above an

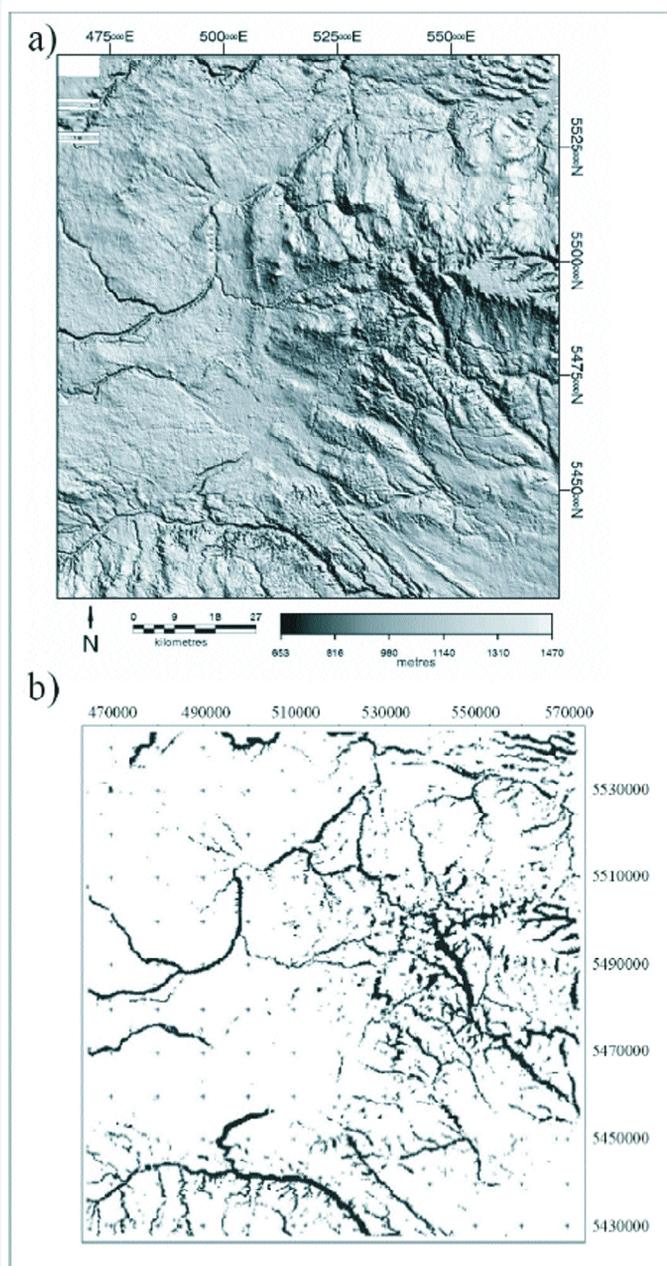


Figure 3 a). Topography over the area of study. The dataset was obtained from the same airborne magnetic survey shown in Figure 2, by subtracting the aircraft radar altimeter from the differential GPS altimeter; b) Lineaments mapped from topography. They were obtained by subtracting low-passed topography from the original topography of a).

Continued on Page 35

## Evidence for Basement Fault Reactivation...

Continued from Page 34

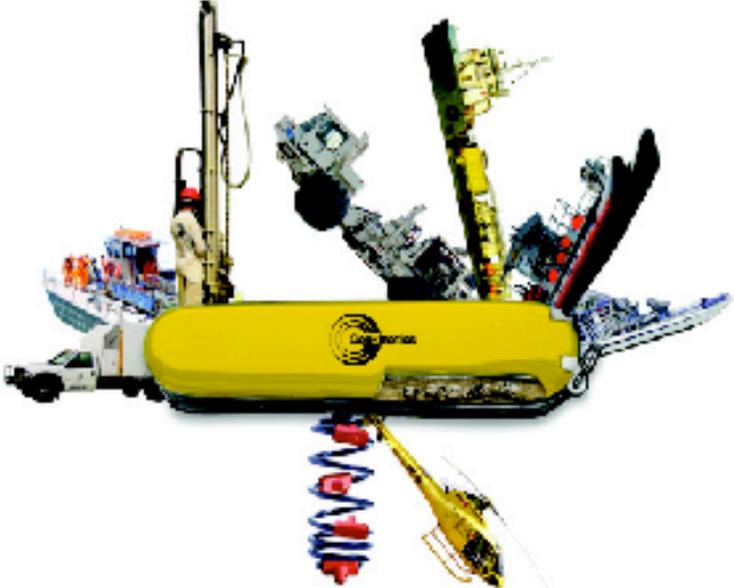
eroded basement. The assumption of no basement uplift leads to a poor fit (Figure 5b). This simple model comparison provides direct evidence in support of basement reactivation

Using the same reasoning, we subsequently computed 2.5D magnetic models on 8 NW-SE sub-parallel profiles; each profile is perpendicular to the trend of the proposed fault structures (profiles 1-8 on Figure 2). As in the test model (Figure 5a), the sedimentary package overlaying the crystalline basement was treated as one uniform unit with no magnetic susceptibility ( $k=0.0$  SI). That is, the magnetic sources were entirely attributed to the crystalline basement (Archean granitic gneisses of the Medicine Hat Block). Lateral variations in magnetization along the profiles were interpreted as lateral magnetization variations within the basement (Figure 6). The contact locations of the basement blocks were estimated from the gradient of the TMI profiles and also from the structural mapping done on the TMI map (Figure 4a). The purpose of these models was to determine the structure of the basement on a regional scale; therefore high-frequency anomalies which might be attributed to minor topographic variations of the sediment-basement interface, or localised near surface magnetic property variations within the sedimentary sequence were not modelled. Any of these structures that correlate with surficial topographic features implies a reactivation of an older structure.

Finally we computed a 3D model that integrates the eight 2.5D sections in 3D. A 3D solid model of all the geological formations was constructed using Voronoi diagrams (Calcagno et al., 2006). Starting from a generated set of points issued from the data, this method computed a partition of space according to the nearest neighbour. The constructed solids are topologically closed and share common boundaries. Since the construction of the solid is automatic, the proposed solution allows iteration of the interpretation and model-construction process until the model is deemed satisfactory. The 3D geological model (Figure 7) shows the geometry of the sediments and the mapped structures. The modeled faults show a consistent plunge to the east, which fits the regional basement structure, as observed by Burwash et al. (1994) and Lemieux et al. (2000).

## Discussion and Conclusions

The lineaments identified from the TMI exhibit good correlation with the topographic image (see figure 4a for location). In particular, the one identified as Medicine Lodge Coulee (MLC), running northwest-southeast has both a topographic signal and a magnetic signature, as does the northeast-southwest trending lineament crossing the MLC (located south of the Seven Persons Creek, thus named SPC). The SPC lineament shows a subtle topographic signature. Another topographic lineament running sub-parallel to this feature is visible to the south (about 10 km



**TOUGH DATA-ACQUISITION MISSION?  
WE HAVE THE TOOLS TO HANDLE IT.**

The more extreme the environment, the more you need Geokinetics. Because our highly capable crews have earned their world-class reputation by adapting to the toughest challenges and fielding an impressive array of data-acquisition tools.

They have planted geophones, transported drills and deployed telemetry units in some of the planet's most hostile environments:

from Indonesia's steamy jungles to Colombia's treacherous mountains to Bangladesh's precarious transition zones. The tougher the challenge, the greater their satisfaction.

Which is why more and more results-oriented energy companies depend on Geokinetics. We deliver the decision-critical intelligence it takes to cut the cost of every barrel of oil you discover.

INGENUITY. EXPANDING. WORLDWIDE. [WWW.GEOKINETICS.COM](http://WWW.GEOKINETICS.COM)



Continued on Page 36

## Evidence for Basement Fault Reactivation...

Continued from Page 35

south of the SPC, with similar orientation and shape). This lineament (D on Figure 4a) runs sub-parallel to the preglacial divide and also has a distinct relationship with topography (an approximate 1 km wide, 40 m deep feature). Note also that the river channels are generally oriented either northwest-southeast or northeast-southwest. As expected due to the different properties being mapped, not all the lineaments identified from the magnetic data are associated with a topographic feature, nor do all the topographic lineaments have a magnetic signature.

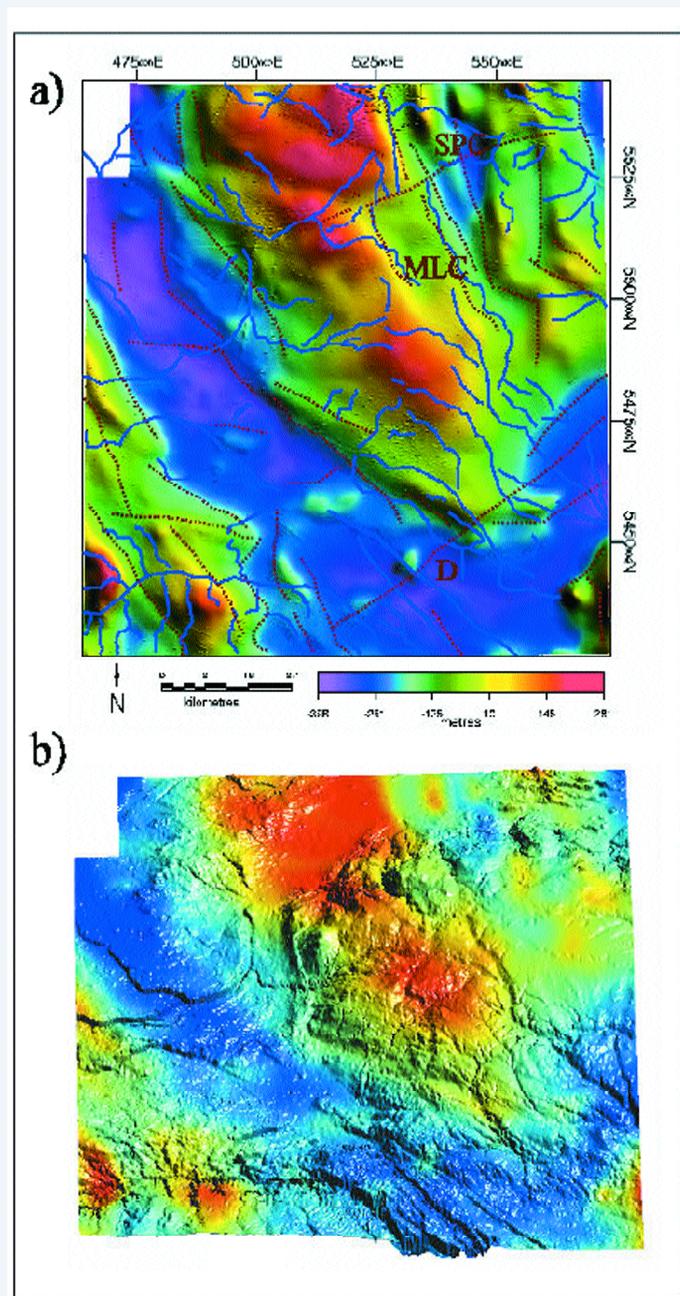


Figure 4 a). Total magnetic field (TMI) image, with structures mapped from topography (blue) and TMI (brown). Due to the thick sedimentary cover, the structures mapped by TMI are deep basement structures. Any correlation between both sets represents a reactivated basement structure. MLC is Medicine Lodge Coulee lineament; SPC is Seven Persons Creek lineament; D is Divide lineament (see text for details); b) 3D image of TMI (colour) draped over topography, to show the correlation between both datasets, and thus the reactivation of basement structures.

However, one of the most important features, the MLC lineament, was seen by both the 2.5D and 3D models.

All topographic features result from a wide range of environmental processes acting on different spatial and time scales. The more surficial ones, rivers, tend to flow along a path of least resistance. In the absence of fault influence the flat lying sedimentary strata of the study should produce dendritic drainage patterns as seen in the channel tributaries. The large river systems (Milk River, Four Mile Coulee, Etzikom Coulee) run through deep, wide canyons (up to 5 km wide, 200 m deep). Many parts of these channels are oriented northwest-southeast and make up the topographic lineaments that correlate with the dominant magnetic fabric. The spatial extent of these channels and their orientation suggest that they might be controlled by subsurface faults.

The alignment of dominant surficial features (defined by topography) with basement fabric (defined by magnetics) in southern Alberta seems to support the evidence from Lemieux (1999) for basement control in the area, although the main length of the Southern Alberta Lithoprobe Transect (SALT) lines on that study are located west of the area of this study. Using seismic and potential field data (Lemieux et al., 2000) propose a crustal

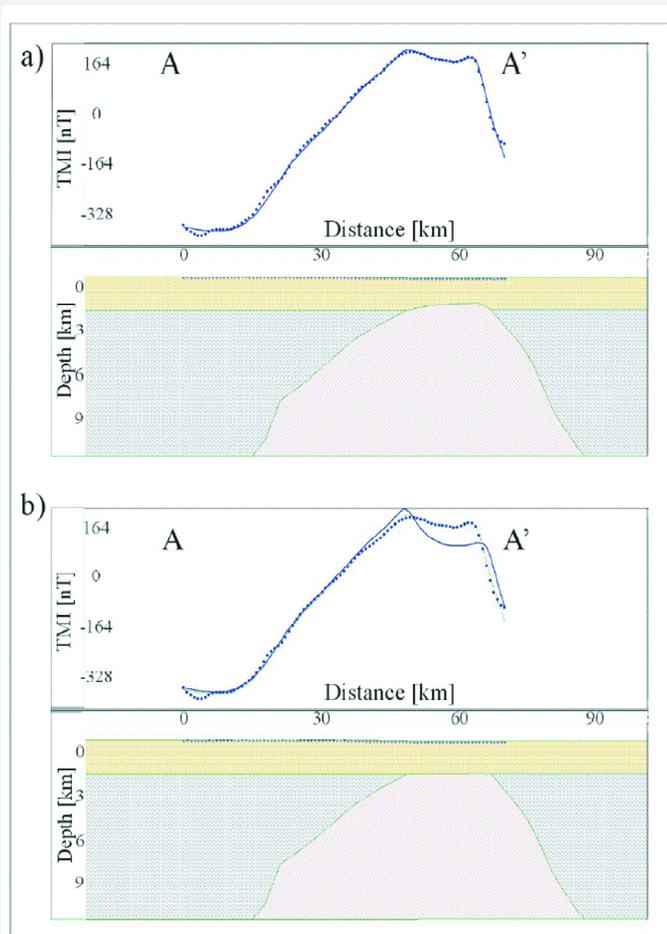


Figure 5. Basic 2.5D model over section AA' (see Figure 2 for location). A) Model representation of a basement uplifted block, the model fits the observed data in great detail; b) Model representation of no basement uplift block. This time the fit between the model and the observed data is very poor.

Continued on Page 37

Evidence for Basement Fault Reactivation...

Continued from Page 36

structural model for the Medicine Hat Block which comprises extensional crustal-scale ramps dipping to the west, which corroborate the main results of this work (Figure 7) and the regional basement structure by Burwash et al., 1994 (Figure 8).

Further control (well logs, petrophysical control, stratigraphic records or detailed seismic data) is needed to unequivocally relate the lineaments observed in topography with magnetic lineaments and faults in sedimentary strata. However, the current 3D model presents sufficient evidence for the relationship between surficial features with basement structures. **R**

References

Beaney, C. L., and J. Shaw, 2000, *The subglacial geomorphology of southeast Alberta: evidence for subglacial meltwater erosion*: Canadian Journal of Earth Sciences, v. 37, p. 51-61.

Burwash, R. A., C. R. McGregor, and J. Wilson, 1994, *Precambrian basement beneath the Western Canada Sedimentary Basin*, in G. D. Mossop, and I. Shetsen, eds., Geological Atlas of the Western Canada Sedimentary Basin: Calgary, Canadian Society of Petroleum Geologists, p. 49-56.

Calcagno, P., G. Courrioux, A. Guillen, D. J. Fitzgerald, and P. McNerney, 2006, *How 3D implicit geometric modelling helps to understand geology: the 3D-Geomodeller methodology*, XIth International Congress, Society for Mathematical Geology, Liege, Belgium.

Edwards, D., and R. J. Brown, 1999, *Understanding the influence of Precambrian crystalline basement on Upper Devonian carbonates in central Alberta from a geophysical perspective*: Bulletin of Canadian Petroleum Geology, v. 47, p. 412-438.

Hope, J., and D. W. Eaton, 2002, *Crustal structure beneath the Western Canada Sedimentary Basin: constraints from gravity and magnetic modelling*: Canadian Journal of Earth Sciences, v. 39, p. 291-312.

Kakreuth, W., and M. McMechan, 1988, *Burial history and thermal maturity, Rocky Mountain Front Ranges, Foothills and Foreland, east-central British Columbia and adjacent Alberta, Canada*: AAPG Bulletin, v. 72, p. 1395-1410.

Kulig, J. J., 1996, *The glaciation of the Cypress Hills of Alberta and Saskatchewan and its regional implications*: Quaternary International, v. 32, p. 53-77.

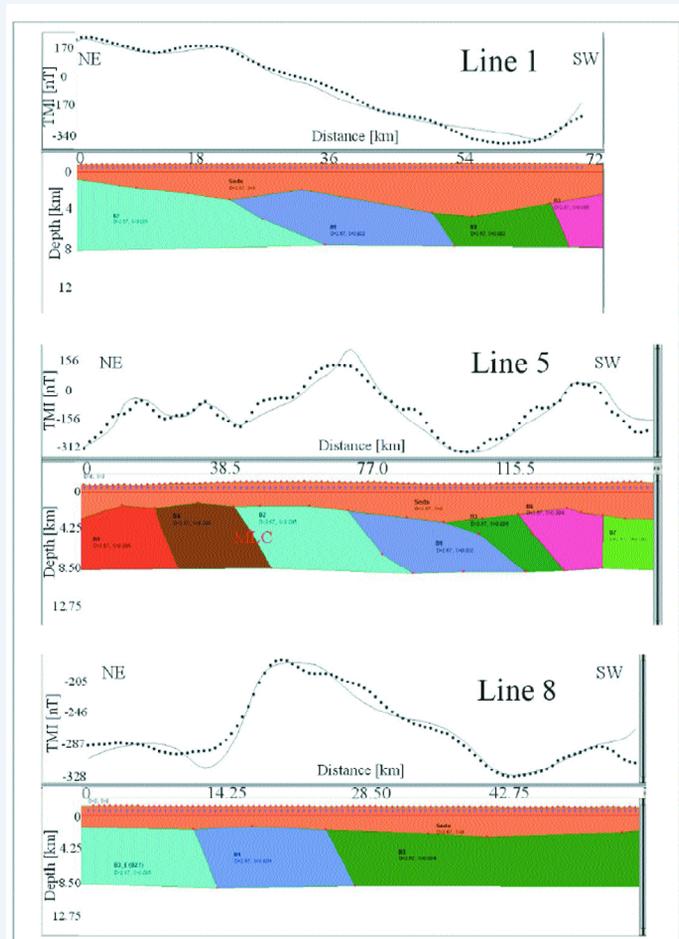


Figure 6. Three 2.5D sections (out of the eight sections modeled). Lines 1 (top), 5 (middle) and 8 (bottom) are shown. See Figure 2 for location. All the models were based on the basic idea of Figure 5: a thick sedimentary sequence with no magnetic susceptibility ( $k=0.0$  SI), and a magnetic crystalline basement with lateral variations of magnetic susceptibility. The contact between each block is a fault and was located based on gradients of TMI along the profile, and structures mapped on the TMI map (Figure 4a). Note that the vertical and horizontal scales are not exactly equal on all the sections. MLC is the Medicine Lodge Culee lineament identified on Figure 4a.

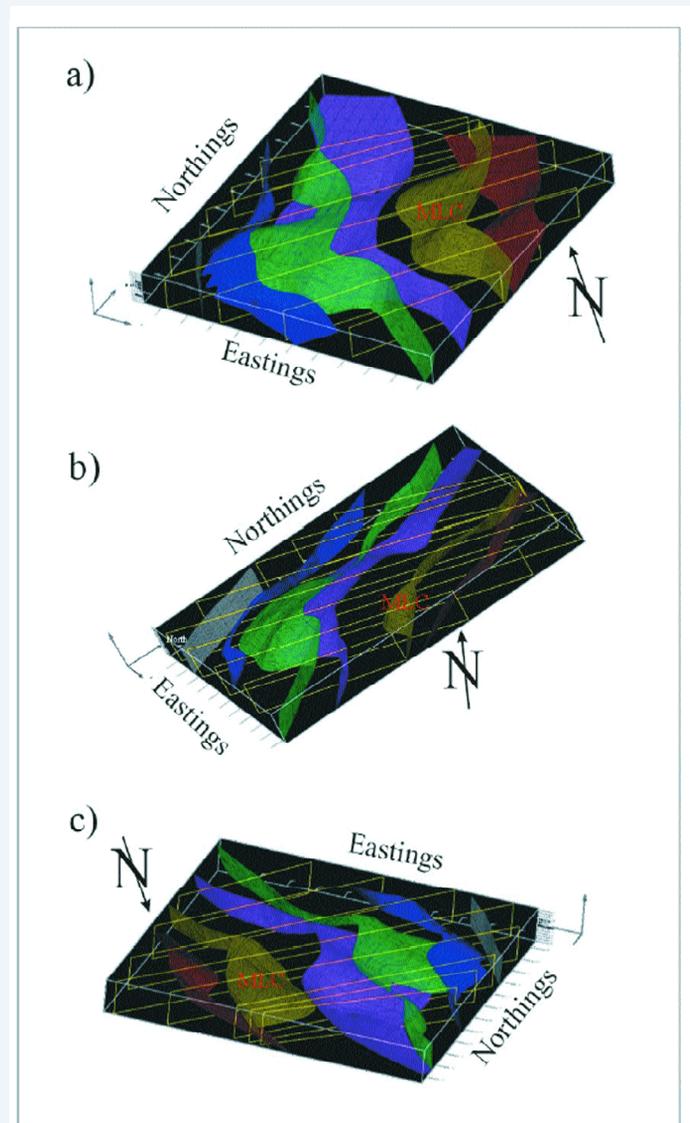


Figure 7. Three views of the 3D model computed from the eight 2.5D sections in 3D-Geomodeller. Only the 3D expression of the faults (contacts between different basement blocks) is shown for simplicity. The location of the eight sections is shown for reference and orientation. a) View from the top; b) view from the top, tilted to facilitate the appreciation of the dip of the structures; c) reversed view from south to North. MLC is the 3D expression of the Medicine Lodge Culee lineament identified on Figures 4a and 6.

Continued on Page 38

## Evidence for Basement Fault Reactivation...

Continued from Page 37

Leblanc, G. E., and W. A. Morris, 1999, *Aeromagnetism of southern Alberta within areas of hydrocarbon accumulation*: Bulletin of Canadian Petroleum Geology, v. 47, p. 439-454.

Lemieux, S., 1999, *Seismic reflection expression and tectonic significance of Late Cretaceous extensional faulting of the Western Canada Sedimentary Basin in southern Alberta*: Bulletin of Canadian Petroleum Geology, v. 47, p. 375-390.

Lemieux, S., G. M. Ross, and F. A. Cook, 2000, *Crustal geometry and tectonic evolution of the Archean crystalline basement beneath the southern Alberta plains, from new seismic reflection and potential field studies*: Canadian Journal of Earth Sciences, v. 37, p. 1473-1491.

Markham, K., 2001, *Methods for producing digital terrain elevation models: analysis, comparison and integration with geophysical data.*: MSc thesis, McMaster University, Hamilton, 158 p.

Pilkington, M., W. F. Miles, G. M. Ross, and W. Roest, 2000, *Potential field signatures of buried Precambrian basement in the Western Canada Sedimentary Basin*: Canadian Journal of Earth Sciences, v. 37, p. 1453-1471.

Ross, G. M., and D. W. Eaton, 1999, *Basement reactivation in the Alberta Basin: Observational constraints and mechanical rationale*: Bulletin of Canadian Petroleum Geology, v. 47, p. 391-411.

Ross, G. M., J. Mariano, and R. Dumont, 1994, *Was Eocene magmatism widespread in the subsurface of southern Alberta? Evidence from new aeromagnetic anomaly data, Lithoprobe Alberta Basement Transects*, p. 240-249.

Ross, G. M., R. R. Parrish, M. E. Villeneuve, and S. A. Bowring, 1991, *Geophysics and geochronology of the crystalline basement of the Alberta Basin, Western Canada*: Canadian Journal of Earth Sciences, v. 28, p. 512-522.

Villeneuve, M. E., G. M. Ross, R. J. Theriault, W. F. Miles, R. R. Parrish, and J. Broome, 1993, *Tectonic subdivisions and U-Pb geochronology of the crystalline basement of the Alberta Basin, western Canada*: Geological Survey of Canada Bulletin, v. 447, p. 86.

Westgate, J. A., 1968, *Surficial geology of the Foremost-Cypress Hills area, Alberta*, Research Council of Alberta.

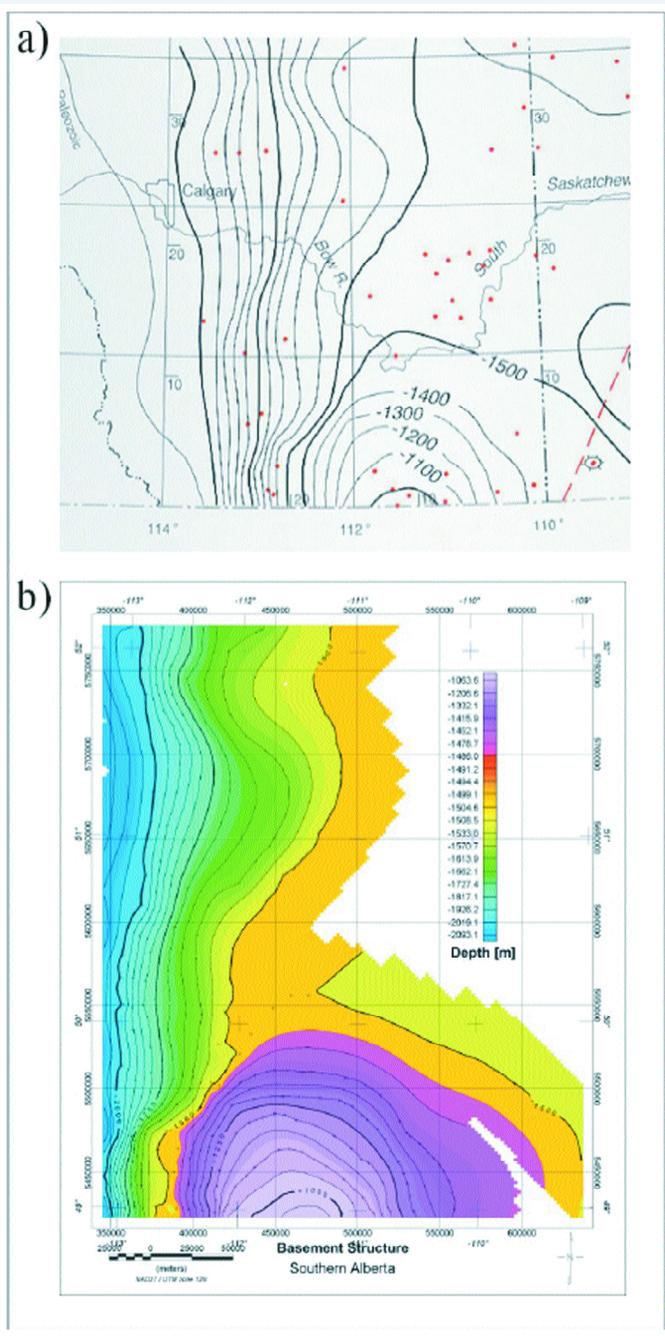


Figure 8. Regional basement structure in Southern Alberta. a) The original depth to basement map, as published by Burvash et al. (1994); b) The above map, digitized, interpolated by minimum curvature and displayed in colour. This information was incorporated in the 3D model as an extra constraint.



**Hernan Ugalde** received a B.Sc. (1994) and M.Sc. (1997) in geophysics from the Universidad de Chile, in Santiago, and Ph.D. (2006) from University of Toronto. He worked for Paterson, Grant, and Watson Limited, Santiago, in 1997–2001, and as a consultant for their main office in Toronto (2001-). Ugalde is now a Postdoc in applied geophysics at McMaster University in Hamilton, Ontario. His research interests are in exploration geophysics, including potential fields, borehole geophysics and integrated 3D modelling. He is a member of SEG, AGU, and CGU.



**Sara L. Underhay** is on the third year of her B.Sc. (Honours) program in Geoscience at McMaster University in Hamilton, Ontario. Her research interests are exploration geophysics and 3D modeling.



**William A. Morris**, B.Sc. (Leeds) and Ph.D. (Open University). He is a Professor at the School of Geography and Earth Sciences, McMaster University, Hamilton, Ontario since 1990. With over 30 years of experience on Exploration Geophysics, Bill's main areas of interest are potential field modeling and image analysis, application of paleomagnetic, rock magnetic and other geophysical techniques to general geological mapping and 3D interpretation. He is a member of SEG, AGU, CGU, EEGS, GAC, KEGS.



**Kristi Markham** completed her B.Sc. (Honours) in Geology (1999) and M.Sc. (2001) at McMaster University in Hamilton, Canada. Her Master's research focused on the use of ancillary geophysical data to develop topographic maps to be used in conjunction with geophysical data processing and map interpretation. As a Ph.D. candidate at McMaster University she worked with remotely sensed data to assist in geophysical studies.