

We are IntechOpen, the world's leading publisher of Open Access books Built by scientists, for scientists

6,900

Open access books available

186,000

International authors and editors

200M

Downloads

Our authors are among the

154

Countries delivered to

TOP 1%

most cited scientists

12.2%

Contributors from top 500 universities



WEB OF SCIENCE™

Selection of our books indexed in the Book Citation Index
in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?
Contact book.department@intechopen.com

Numbers displayed above are based on latest data collected.
For more information visit www.intechopen.com



Basement Tectonics and Fault Reactivation in Alberta Based on Seismic and Potential Field Data

Eneanwan Ekpo, David Eaton and Ronald Weir

Additional information is available at the end of the chapter

<http://dx.doi.org/10.5772/intechopen.72766>

Abstract

Injection-induced seismicity in Western Canada and elsewhere in North America has drawn considerable recent interest. Current models indicate that induced earthquakes occur on reactivated basement faults, which can be challenging to detect using seismic-reflection data. Here we use regional gravity and magnetic datasets, together with LITHOPROBE crustal seismic profiles, to investigate basement tectonics and crustal structure in an area of Western Canada that is prone to induced seismicity. Previously mapped basement faults that were active during the Paleozoic can be recognized on the basis of pronounced curvature, truncations and/or offsets of stratigraphic marker horizons. Within the Precambrian crystalline basement, however, brittle faults are poorly imaged by seismic data due to various factors such as the obscuring effect of multiples. Regional potential-field fabrics are critical to establish the tectonic setting of basement domains, with complementary information provided by magnetic, Bouguer and isostatic residual gravity anomalies based on 2D modelling constrained by seismic profiles. However, individual faults appear to lack diagnostic expression in regional potential-field anomaly data, since the anomalies are dominated by the effects of larger-scale crustal structures. We show evidence that large-scale basement faults can potentially be recognized on the basis of truncation and offset of distinct horizons within the Winagami Reflection Sequence (WRS), which is interpreted as a regionally-extensive mid-crustal sill complex emplaced during a Proterozoic magmatic pulse. An abundance of caution is necessary to interpret these features, due to complications arising from out-of-plane reflections at long reflection times.

Keywords: magnetics, gravity, seismic, basement reactivation, induced seismicity

1. Introduction

During the last decade, exploitation of unconventional resources, including low-permeability hydrocarbons, has been a major focus of oil and gas development in North America. One

emerging area of concern is induced seismicity, which has led to a renewed interest in faults as well as the structural architecture of Precambrian basement. Recent studies of injection-induced seismicity in parts of Western Canada [1–3] have highlighted the probable role of pre-existing basement faults in controlling the distribution of induced earthquakes. Although some basement-related faults in this region have been identified using seismic-reflection images (for example, see [4–6]), faults that may control the location of induced earthquakes are often challenging to detect using seismic-reflection images alone. Problematic cases include faults with a geometry that is unfavourable for seismic mapping in horizontally stratified rocks, such as sub horizontal thrust faults or vertical strike-slip faults, or brittle faults hosted within crystalline basement rocks that lack clear marker reflections. The latter is particularly true in the shallow crystalline basement in Western Canada, where basement structure may be difficult to discern in the presence of strong multiple reflections [7].

Modelling and interpretation of regional gravity and magnetic data can provide valuable insights for understanding crustal structure beneath sedimentary basins [8, 9] including constraints for understanding geological risk factors for induced seismicity [10]. Models derived from magnetic and gravity data, due to their non-uniqueness, are usually combined with other geological and geophysical information (e.g. seismic and well data), to provide insights into the geometry of the subsurface [9]. The Western Canada Sedimentary Basin (WCSB) is a mature hydrocarbon basin, where extensive public-domain datasets are available, including regional-scale gravity and magnetic anomaly data as well as crustal seismic profiles. To complement the potential field data, this study uses crustal seismic-reflection data from the Alberta Basement Transects (ABT) Peace River Arch Industry Seismic Experiment (PRAISE) project [11], part of Canada's LITHOPROBE program [12].

The objective of this contribution is to present new insights arising from geophysical imaging and mapping of representative basement fault structures, together with a discussion of how they may be significant as a framework for understanding induced seismicity. The LITHOPROBE seismic profiles intersect structural boundaries that are seen on the regional aeromagnetic and gravity mapping. Our interpretation approach involves mapping and identification of basement structures, followed by 2D gravity and magnetic modelling for selected features. Since the gravity and aeromagnetic data span a large geographical area they are useful to characterize large-scale trends, whereas the 2D seismic lines give detailed constraints for building a model, such as fault throw and timing. Potential field data thus give a more complete tectonic picture of the area by filling in the gaps between areas of seismic coverage, providing an opportunity to improve our understanding of the structural framework.

2. Regional geological setting

The Precambrian basement beneath Alberta was formed by amalgamation of disparate domains that were assembled by the plate-tectonic processes of subduction and collision [13–15]. The crystalline basement in Alberta can be subdivided into three broad regions

(**Figure 1**). Southern Alberta is dominated by Archean domains, bounded to the north by the Vulcan Low; central Alberta consists of the domains of the Hearne Province that surround the Snowbird Tectonic Zone (STZ); and, northern Alberta consists of the domains that surround the early Proterozoic Great Slave Lake shear zone (GSLsz). Basement domains that are the focus of this study occur between the STZ and GSLsz and have Paleoproterozoic crystallization ages (1.9–2.4 Ga).

Subdivision of the crystalline basement underlying the WCSB into tectonic domains is based on sparse drillcore samples from hydrocarbon exploration wells, coupled with potential-field interpretation [14, 15]. The drillcore samples are described by [15] in terms of location, rock type, mineralogy and crystallization age based on U-Pb geochronology. Our study area is underlain by basement rocks of the Ksituan, Chinchaga, Buffalo Head and Wabumum domains (**Figure 1**), which are composed of igneous, metaigneous and less commonly metasedimentary rocks of Paleoproterozoic age (2.4–1.9 Ga). The 1.90–1.98 Ga Ksituan domain is defined by its strong, positive magnetic expression, which is typical of calc-alkaline magmatic belts due to the presence of magnetite as an accessory mineral phase [15]. Crustal imbrication

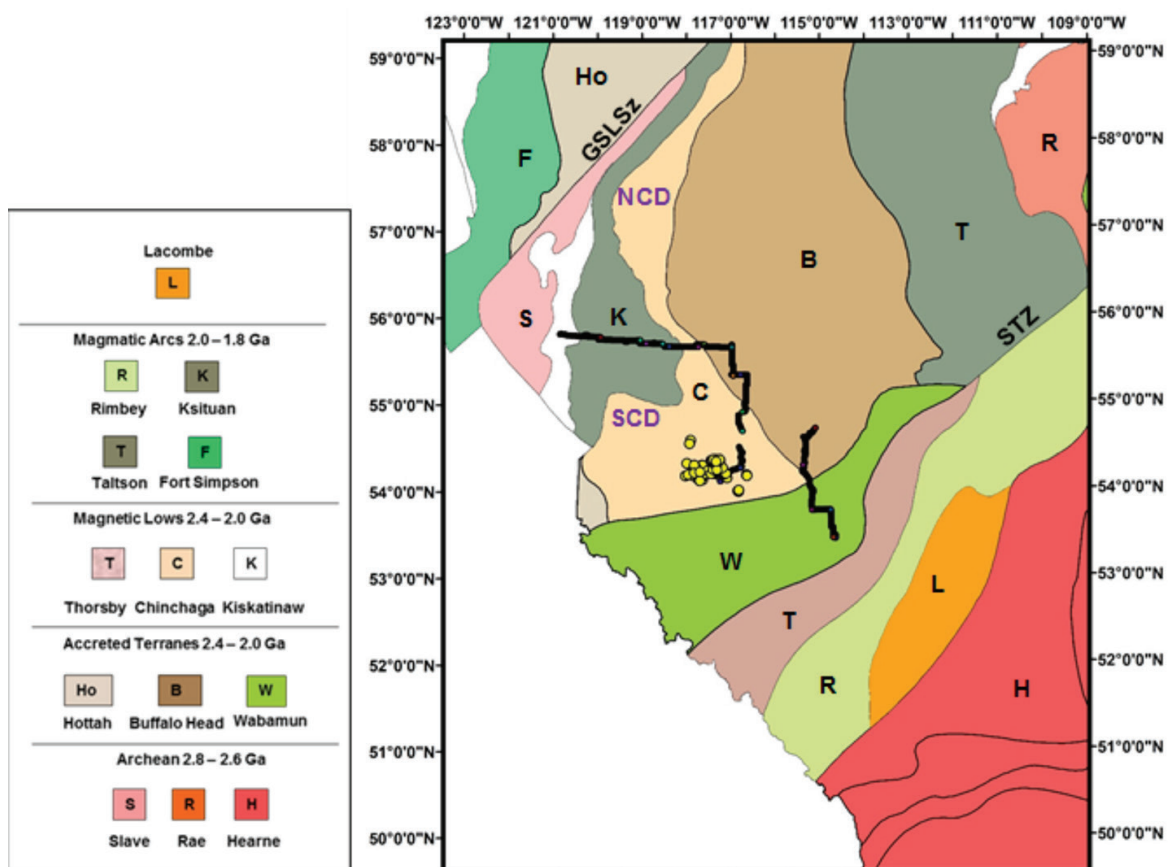


Figure 1. Location map showing tectonic domains of the Precambrian basement from [15]. Black lines show LITHOPROBE seismic profiles from the ABT-PRAISE transect. Yellow dots show seismicity from within the region 54–56°N, 116–118°W, from January 2014 to January 2017 ($M_w \geq 2.5$). Abbreviations and generalized ages of basement domain names are indicated in the legend. In addition, GSLsz denotes Great Slave Lake shear zone, STZ denotes Snowbird Tectonic Zone, SCD and NCD denotes southern and northern Chinchaga domain.

and pervasive ductile deformation of the Ksituan domain is evident from well-developed seismic-reflection fabrics, in the form of panels of dipping reflections in the upper and middle crust [4]. To the east, the slightly older (2.0–2.32 Ga) Buffalo Head Terrane is characterized by sinuous aeromagnetic patterns and discrete subdomains, composed of metaplutonic and subordinate felsic metavolcanic rocks [14]. The eastern edge of the Buffalo Head is defined by the Kimiwan anomaly, a linear magnetic high ~250 km in length. The origin of this magnetic anomaly has been interpreted as either a decapitated calc-alkaline pluton, or a broad zone of hydrothermal alteration and enhanced susceptibility above a crustal-scale extensional fault [9]. The former interpretation is more consistent with oxygen isotope signature of basement samples [16].

To the south, the Chinchaga domain overlaps in age with the Buffalo Head Terrane and is delineated by a negative magnetic anomaly pattern that reflects the absence of calc-alkaline granitic rocks. As discussed below, we distinguish between the northern and southern Chinchaga domains based on potential-field evidence. The southern Chinchaga domain is of particular interest as it underlies the Kaybob-Duvernay region where induced seismicity is concentrated. Finally, the Wabamun domain is interpreted as a structurally bound wedge-shaped block that is enclosed by strands of the Snowbird Tectonic Zone (STZ; [14]), possibly analogous (in terms of structural style) to Archean crustal-scale lozenges formed by annealed mylonites where the STZ is exposed at the surface [17].

Throughout the study area, dipping reflection fabrics observed on LITHOPROBE profiles in the upper and middle crust are cross-cut by the Winagami Reflection Sequence (WRS), a set of prominent, sub-horizontal reflections with an estimated areal extent of ~120,000 km² [18]. These reflections are interpreted as sheet-like mafic intrusions that record a ca. 1.8 Ga magmatic event. At several locations, the reflections can be followed around perpendicular bends in survey lines with no change in apparent dip, confirming that the reflectors are approximately horizontal [18]. As illustrated in **Figure 2**, at some locations individual reflections appear to be truncated and offset, suggestive of post-intrusive fault displacement [9].

Sedimentary units in this part of the WCSB are broadly divisible into three major stratigraphic successions that were deposited in three distinct phases [19]. From Cambrian to mid-Devonian time this region was situated near a passive margin, with non-deposition in the emergent Peace River Arch over a large region in the northern part of this study area [4]. During the Devonian, extensive carbonate shelf complexes formed, locally capped by linear reef chains, isolated reefs or reef complexes [20]. It has been suggested that sedimentation patterns, including abrupt facies changes, the development of fracture porosity and the orientation of reef trends or clastic strandlines, may have been influenced by small topographic features on the basement surface [21] that were transferred up section through a process of tectonic inheritance [20]. During the next major phase, the topographic expression of the Peace River Arch reversed to form the Peace River Embayment. Within the embayment, the formation of a network of satellite grabens caused localized subsidence during the Carboniferous, followed by more widespread subsidence during Permian and Triassic time [22]. The final major depositional phase was characterized by enhanced Mesozoic subsidence within a foreland basin in front of advancing Laramide thrust sheets [23].

3. Geophysical data

In the 1990s, the Canadian LITHOPROBE program acquired a series of long 2D seismic-reflection transects as part of the Alberta Basement Transects program, with the objective of identifying structures present in the sedimentary basin and deeper levels of the crust [11]. The data were acquired using vibroseis sources and recorded to 18 s two-way time (TWT). In the case of the ABT-PRAISE program, acquisition parameters included a 25-m receiver group interval, 480 channels and unusually long offsets (>6 km) that are conducive to attenuation of multiple reverberations [4]. A representative 2D migrated data example is shown in **Figure 2**, where the approximate depth in the crystalline basement is calculated assuming an average P-wave velocity of 6 km/s.

Terrestrial gravity data used in this study were compiled on a 1 km grid by the Canadian Geodetic Survey and made available through the Geoscience Data Repository for Geophysical Data. Although the grid is sampled at 1 km, the raw data were acquired using an irregular distribution of stations with an average inter-station spacing of >5 km. Despite dense sampling along LITHOPROBE profiles [9], anomaly wavelengths that can be resolved without aliasing (based on the Nyquist criterion) are thus greater than 10 km. A Bouguer gravity anomaly map of Western Canada derived from this dataset contains a conspicuous gravity low (~ -200 mGal) associated with the isostatic root coincident with areas of high elevations in the Rocky Mountains (**Figure 3a**). This anomaly obscures most of the basement domains that are of interest in this study. One exception is the Snowbird Tectonic Zone (STZ), which is almost perpendicular to the deformation front and forms the southern boundary of basement domains in our study area. The isostatic residual gravity anomaly map (see [24]) is plotted in **Figure 3b**. By removing most of the gravitational effects of the isostatic root, the isostatic anomaly map reveals a distinct basement fabric parallel to the STZ that is truncated by orogen-parallel anomalies. A residual positive isostatic anomaly with an amplitude of ~ 25 mGal

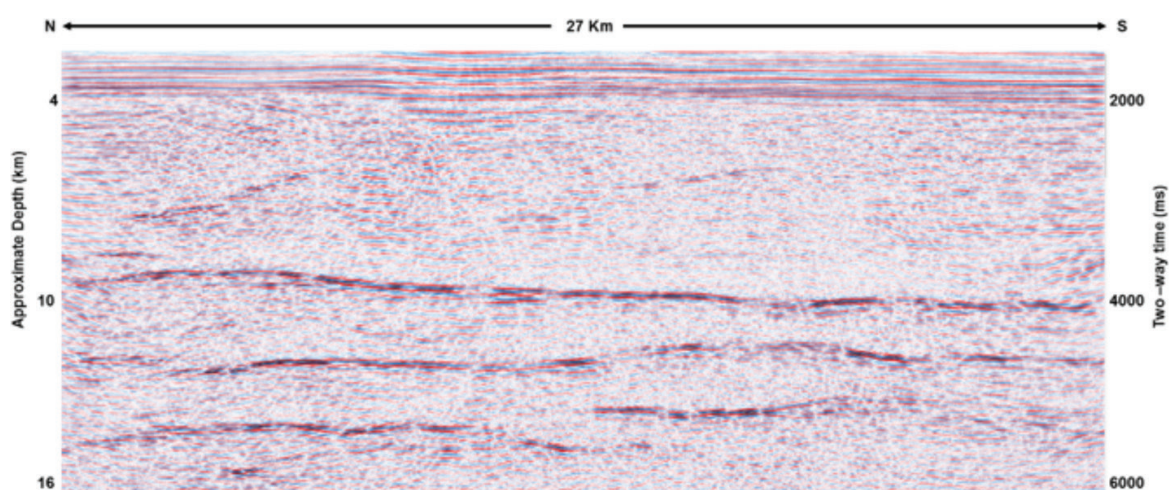


Figure 2. Representative seismic expression of the Winagami Reflection Sequence (WRS) from LITHOPROBE deep seismic profiles. The WRS is comprised of subparallel high-amplitude reflections that form an anastomosing fan that converges toward the southeast [18]. The location of this section is marked in **Figure 4**.

is caused by flexural support of the Rocky Mountain front ranges, which is not accounted for by the isostatic correction [2].

An enlargement of the isostatic gravity map for our study area is shown in **Figure 4a**. The area is characterized by positive anomalies with ovoid shape and peak amplitudes of ~10 mGal,

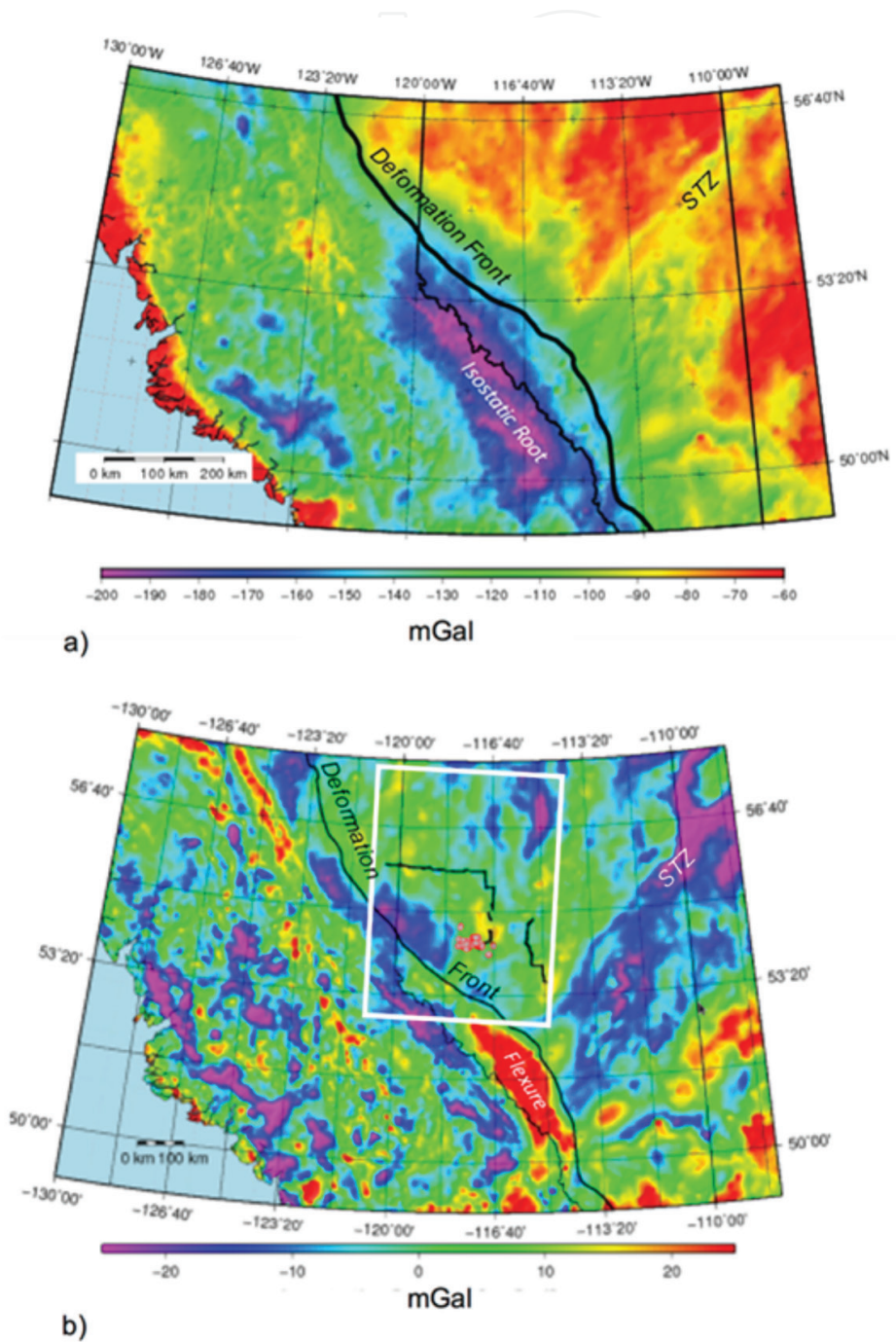


Figure 3. (a) Bouguer gravity anomaly map of Western Canada, showing a -200 mGal anomaly associated with the isostatic root beneath high elevations in the Rocky Mountains as well as a linear anomaly along the Snowbird Tectonic Zone (STZ). (b) Isostatic gravity anomaly map, highlighting a positive residual associated with lithospheric flexural support for high topography [2]. Black lines show ABT-PRAISE transect and white box shows area of **Figure 4**.

which produce overall weak NE–SW fabric wavelengths in the ranges of 25–50 km. The only basement tectonic domain boundary that is clearly expressed in this map is the boundary between the southern Chinchaga domain, characterized by positive isostatic gravity residual, and the Wabamun domain which has a weakly negative character.

The aeromagnetic dataset used in this study is a 200-m residual total-field intensity grid obtained from the national aeromagnetic database (Geoscience Data Repository for Geophysical Data). This grid was compiled from different vintages of survey data, including public-domain and industry surveys flown over several decades [9]. **Figure 4b** shows an aeromagnetic anomaly map of the study area derived from this dataset. In contrast to the gravity anomaly map (**Figure 4a**), basement domain boundaries are prominently expressed in the aeromagnetic map. This is expected, since at a regional scale, the shape and intensity of the magnetic anomalies is primarily controlled by the magnetic susceptibility of the basement domains [15]. Apart from the loss of short-wavelength content toward the southwest due to thickening of the sediment cover, short-wavelength basement topography is muted by the high flexural strength of the lithosphere [21] and thus has a relatively minor influence on the magnetic anomalies.

There are a number of prominent magnetic features in **Figure 4b**. The Ksituan domain (K) is characterized by elongate positive magnetic anomalies with wavelengths ~5–10 km that converge northwards toward the GSLsz, located in the northwest corner of the map. An abrupt rectilinear high-gradient zone separates the Ksituan domain from the southern Chinchaga

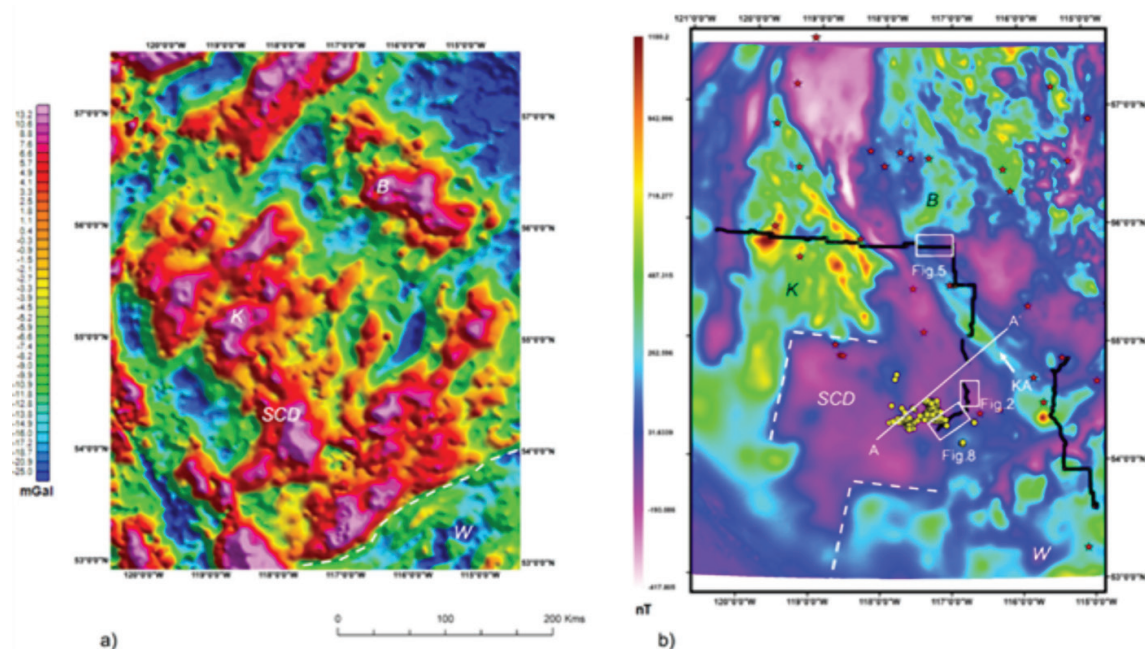


Figure 4. (a) Enlargement of isostatic residual gravity anomaly map within the area outlined in **Figure 3**. K, B, W and SCD denote Ksituan, Buffalo Head, Wabamun and Southern Chinchaga Domain, respectively. Dashed line indicates boundary between SCD and W, which may be a northern splay of the Snowbird Tectonic Zone. (b) Aeromagnetic anomaly map of the same area. Red stars show locations of basement drillcore and yellow circles show seismicity from **Figure 1**. SCD is bounded to the north and south by similar rectilinear edges, as shown by the dashed white lines. Short-wavelength features of magnetic anomalies diminish to the southwest due to increasing basement depth.

domain, which is characterized by muted, longer-wavelength negative magnetic anomalies. A “conjugate” rectilinear boundary, geometrically identical to the northern rectilinear boundary, marks the southern edge of the Chinchaga magnetic low. The Kimiwan anomaly (KA) is a NW-trending positive magnetic anomaly that merges with the arcuate western margin of the Buffalo Head high (B). Unlike other parts of the WCSB [9, 24], there is remarkably little correlation between the anomaly fabrics evident in the gravity and magnetic maps. The Kaybob-Duvernay region, where a high-concentration of induced seismicity exists, is underlain by basement rocks of the southern Chinchaga domain. Although the epicentral distribution in **Figure 4b** reveals a diffuse cloud that is elongate in an east-west direction, the location uncertainty for individual events is ~20 km. In contrast, recent studies that feature high-resolution epicentre locations [2] and well-resolved focal mechanisms [3] indicate that individual fault planes are approximately vertical with a likely north-south strike direction. Thus, local potential-field anomaly fabrics in this region with a roughly north-south trend may be of particular relevance for understanding induced seismicity.

4. Modelling and interpretation

The first example that we consider is the Tangent fault, a Carboniferous normal fault that bounds a half-graben within the Peace River Embayment [4]. This fault has not generated any induced seismicity, but it provides a useful template for interpretation of the geophysical expression of other faults. **Figure 5** shows a LITHOPROBE profile across the Tangent fault, which is characterized by a clearly defined down-to-the-east displacement of the top of the Precambrian basement. After correlating stratigraphic picks using a well tie, it is evident that overlying Paleozoic marker reflections (Wabamun, Banff, Debolt) exhibit a folded (or draped) character across the Tangent fault. This deformation style is consistent with a case study by [6],

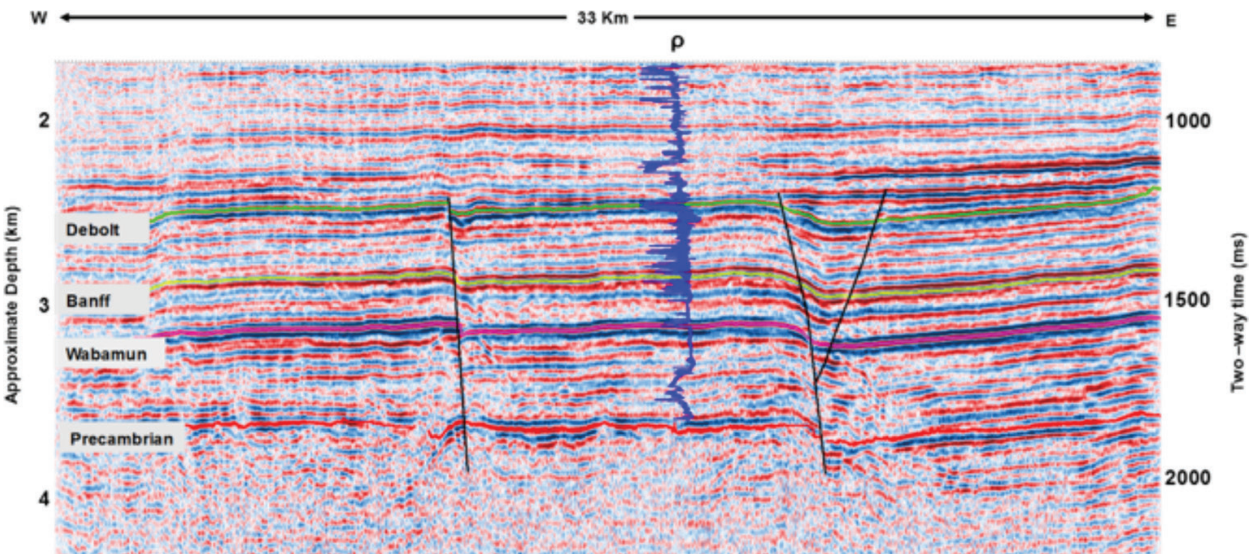


Figure 5. Seismic profile across the Tangent fault as well as a smaller fault to the west, showing the density well log used to obtain a stratigraphic tie. This section was used to build the 2D model in **Figure 6**.

who argued that curvature attributes derived from seismic data are well suited to identify subtle faults in the Kaybob-Duvernay region. In addition to the main Tangent fault, an antithetic fault and a smaller fault are visible in the profile.

Figure 6 shows a simple gravity model for the Tangent fault, based on geometrical constraints derived from the seismic profile (**Figure 5**). The 2D gravity modelling method is based on the computed gravitational response of polygonal prisms of uniform density [25]. The model comprises three lithostratigraphic successions: Carboniferous-Mississippian (Debolt and Banff), Devonian (Wabamum) and Precambrian (Top of the crystalline basement). An average density was used from the available density log in the area as a constraint. The density of each layer is indicated on the profile. A good fit between observed and modelled gravity was achieved; however, the faults in this profile have a very small gravitational response. While this may reflect the coarse sampling of the raw gravity data, it demonstrates that the public-domain gravity data are primarily useful for regional interpretations, rather than investigation of small-scale structures such as individual faults. This can be observed with the gravity anomaly profile replicating the topmost layer of the crystalline basement.

The well-documented basement faulting illustrated above provides an interpretative template for basement faults in the Kaybob-Duvernay region. **Figure 7** shows a 1.7–2.4 s time

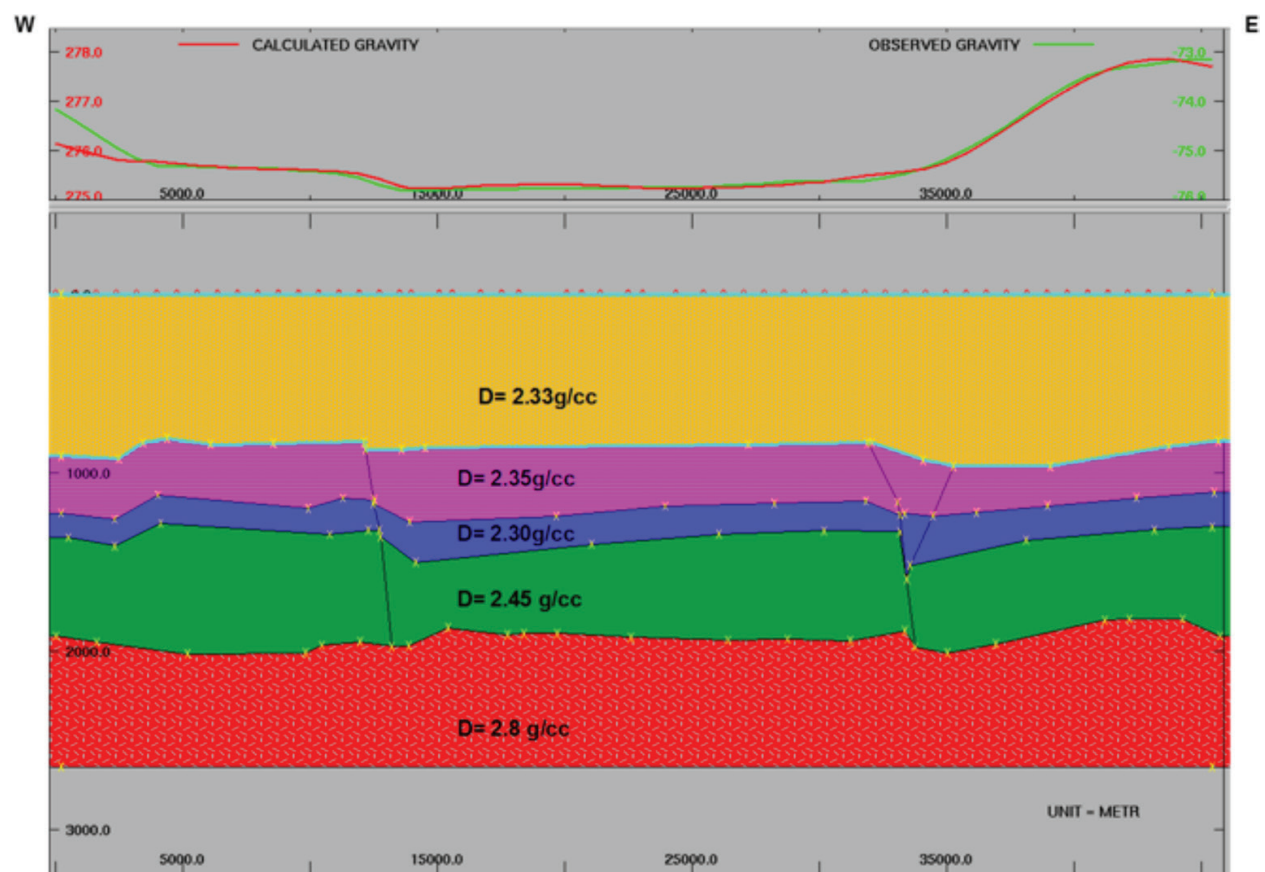


Figure 6. 2D gravity model across the Tangent fault as well as a smaller fault to the east. Layer boundaries are defined based on seismic profile data (**Figure 5**). These faults appear to have a subtle gravity response.

window of data from the ABT-PRAISE transect in this region, which is prone to induced seismicity. The profile is plotted with a vertical exaggeration of $\sim 8:1$. There are several interpreted basement faults in this profile, as marked by the black lines. These faults are interpreted based on observed reflection discontinuities. These features share some characteristics with the Tangent fault, including similar, albeit lower amplitude, expression of folding/drape within the sedimentary layers. One of the inferred basement faults is in close proximity to the edge of the Bigstone Leduc reef, while another inferred fault appears to correlate with a positive topographic feature that coincides with a downlap reflection termination (Z-marker) in the Upper Devonian Ireton formation [26]. Due to the effects of contamination by multiple reverberations below the top of basement at ~ 2100 ms, it is not clear if these interpreted faults merge at depth in the crystalline basement.

Figure 8 shows the same seismic profile as in **Figure 7b**, but for a larger time window of 1.5–6.25 s, plotted with a vertical exaggeration of ~ 1.4 . This profile contains strong but discontinuous WRS reflections, with a gentle southwest apparent dip within an approximate depth extent of 11–16 km (based on an assumed average basement velocity of 6.0 km/s). Individual WRS reflection show apparent truncations as they approach a listric corridor where these mid-crustal reflections are absent. This pattern of disrupted WRS reflections resembles a similar disrupted pattern described by [9] for a crustal seismic profile across the Kimiwan Anomaly. Based on this reflection geometry, a crustal-scale reverse fault is tentatively interpreted that extends to the top of crystalline basement, at a point where faulting is seen in **Figure 7**. The

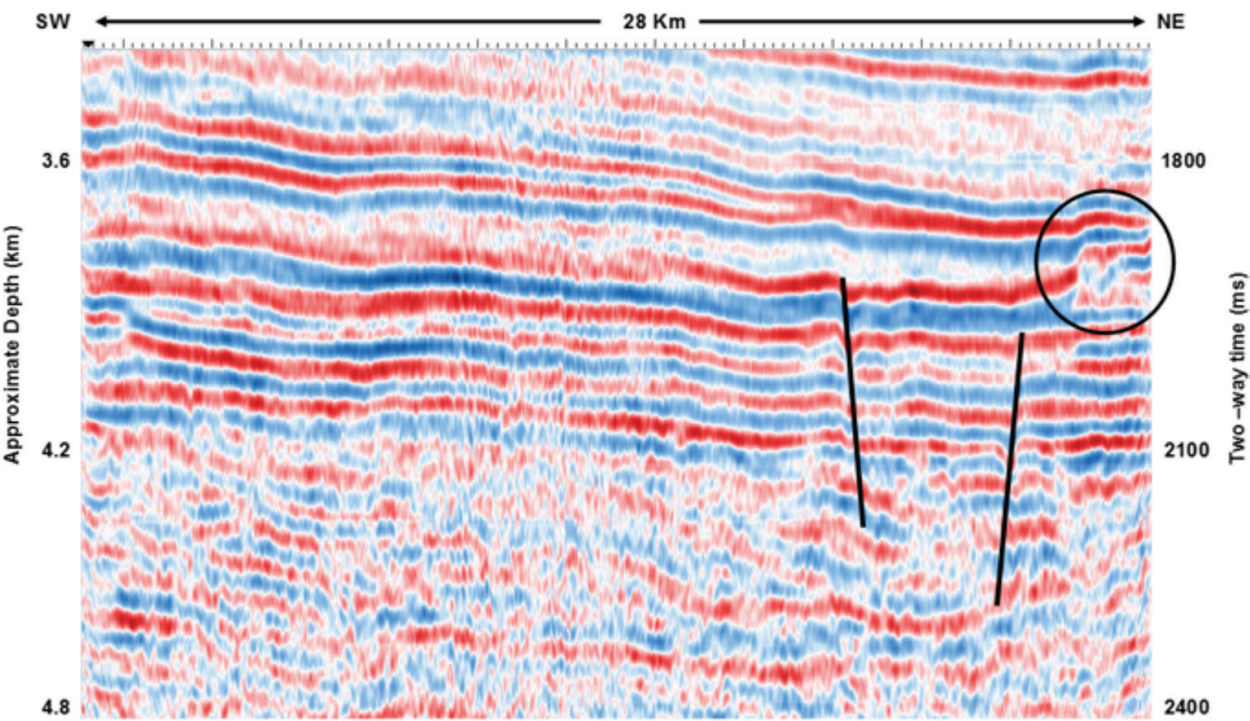


Figure 7. LITHOPROBE seismic profile showing sedimentary layers (vertical exaggeration $\sim 8:1$) from the Kaybob-Duvernay region, where induced seismicity has occurred. Several basement faults are evident, as indicated by the black lines. Circle highlights a Leduc reef (Bigstone). Previous workers have suggested that basement faulting may have been influenced the locations of Leduc reefs [7, 20].

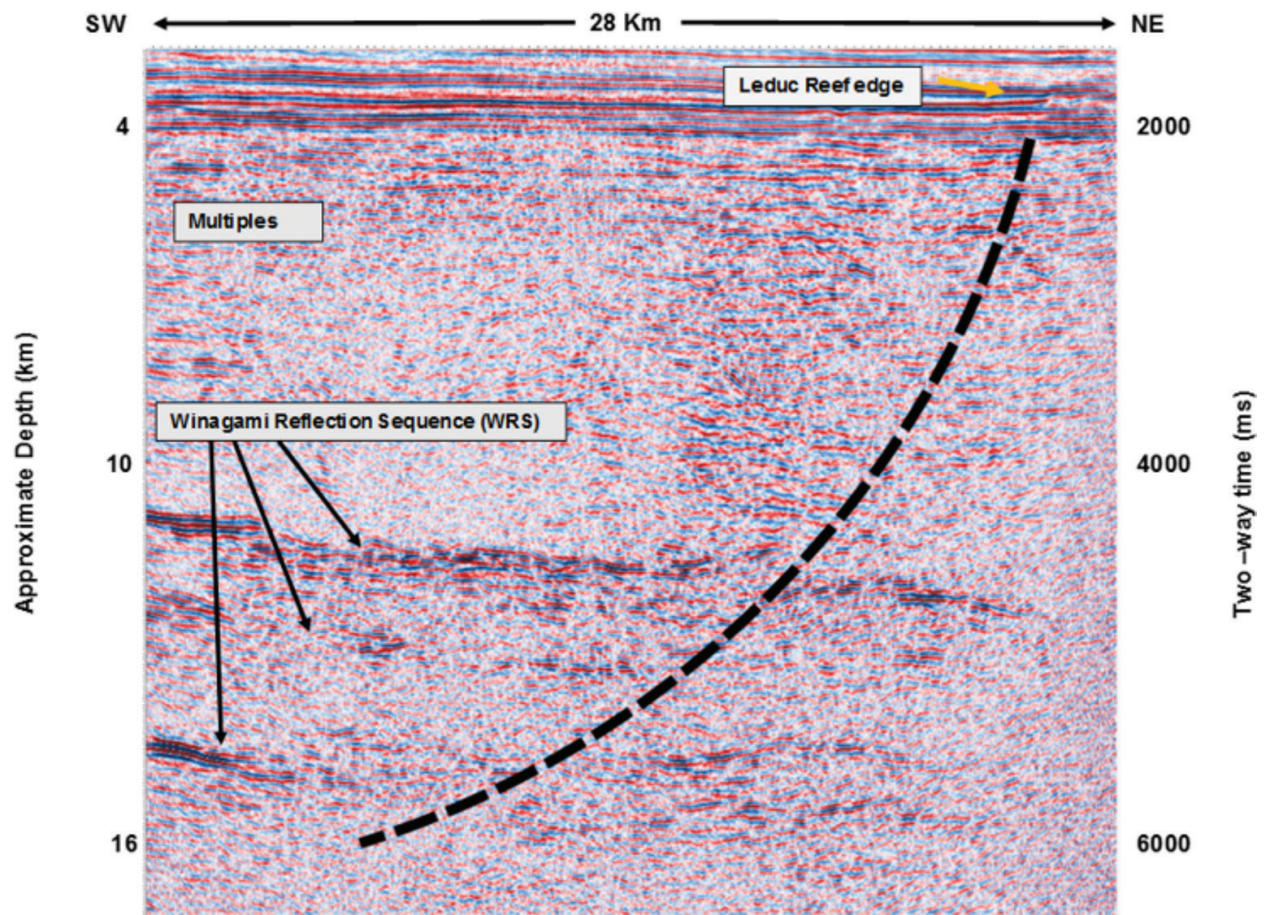


Figure 8. LITHOPROBE seismic data from the same spatial location as in **Figure 6**, showing crustal-scale structure of Winagami Reflection Sequence (WRS). Disruption of the WRS reflections is interpreted here as evidence for post-intrusion basement faulting.

apparent fault offsets of Paleozoic reflections are considerably smaller in amplitude than the apparent offset evident in the middle crust. The interpreted crustal geometry in **Figure 8** was used to develop a gravity and magnetic model (**Figure 9**), with layer parameters in **Table 1**.

Like the gravity modelling, the magnetic modelling was performed using a 2D algorithm based on uniformly magnetized polygonal prisms. Only induced magnetization was considered, based on local parameters for the geomagnetic field. The 2D gravity and magnetic modelling depicted in **Figure 8** shows that a good fit can be achieved between measured and observed potential-field profiles, using polygon vertices derived from the seismic interpretation. Following [9], no regional-residual separation was applied to permit assessment of the influence of features at various crustal levels. The dominant wavelength of the anomalies (>20 km) implies that the depth of features that give rise to the anomalies is considerably deeper than the top of the crystalline basement (~4 km). In this model, the sedimentary package overlaying the crystalline basement (light brown) was treated as one uniform unit with no magnetic susceptibility ($k = 0$ SI). Hence, the magnetic sources were attributed only to the crystalline basement. The model showed the structure of the basement on a regional scale. Hence, high-frequency anomalies were not modelled. This example also demonstrates

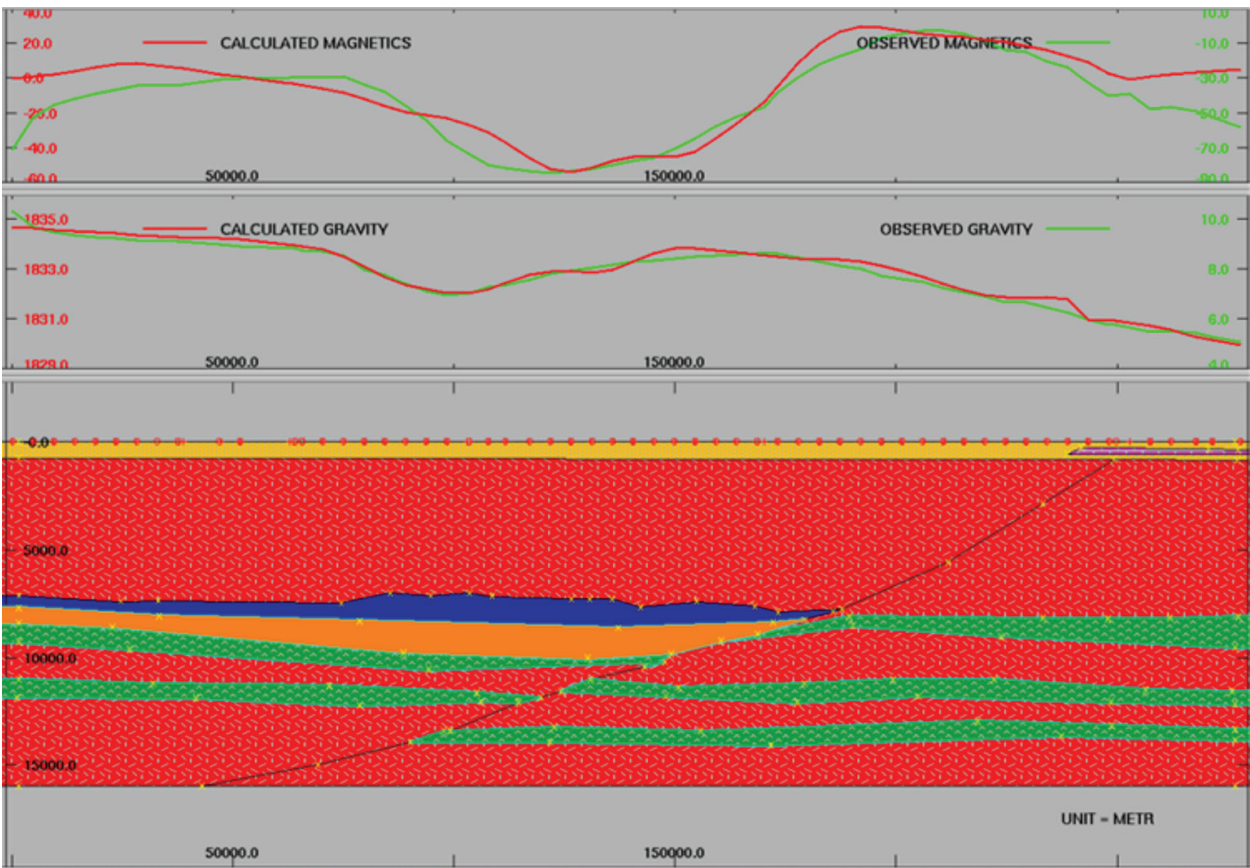


Figure 9. Gravity and magnetic model constructed based on seismic data in **Figures 6** and **7**. Layer densities and magnetic susceptibilities are given in **Table 1**. Total magnetic field parameters used for the 2D magnetic modelling: inclination 68.80°N, declination 2°N and magnitude 49,738 nT.

Modelled layers	Density (g/cc)	Magnetic susceptibility (SI)
Sedimentary package	2.17	0
Leduc reef (pink)	2.08	0.00017
WRS (blue)	2.64	0.02
Basement (brown)	2.82	-0.027
WRS (green)	2.64	0.063
Basement (red)	2.79	0.05

Table 1. Density and magnetic susceptibility values for **Figure 9**.

that the seismic structural interpretation is consistent with the observed gravity and magnetic anomalies.

A final modelling example is presented in **Figure 10**. Here, magnetic and gravity profiles are extracted from the total-intensity aeromagnetic and isostatic gravity anomaly grids, along profile A-A' (**Figure 4**). This profile cross-cuts the Kimiwan Anomaly as well as a north-south

trending positive magnetic anomaly within the southern Chinchaga domain. The Kimiwan Anomaly has a positive magnetic signature (**Figure 4**) about 40 km in width with a northwest orientation. In the isostatic gravity map, this feature is difficult to map. The observed magnetic profile was extracted from the total field intensity magnetic map by getting a profile perpendicular to the two features of interest. Since no seismic constraint is available along this profile, the purpose of this simple forward model is to examine the applicability of the alteration-zone model for the Kimiwan Anomaly [9] to the north-south trending magnetic anomaly from the southern Chinchaga domain. The data was fitted with the anomalous regions situated in the middle crust (**Figure 10**). The observed gravity profile is included for reference. It is not modelled, as the gravity anomaly has a different and non-orthogonal strike direction from the magnetic anomaly so the 2D modelling assumptions would be violated. This example shows that the north-south trending Chinchaga magnetic anomaly, near the region of induced seismicity, can be fit using an anomalous region in the middle crust with susceptibility, depth extent and geometry that is similar to (albeit with a narrower than) the alteration-zone model for the Kimiwan Anomaly [9].

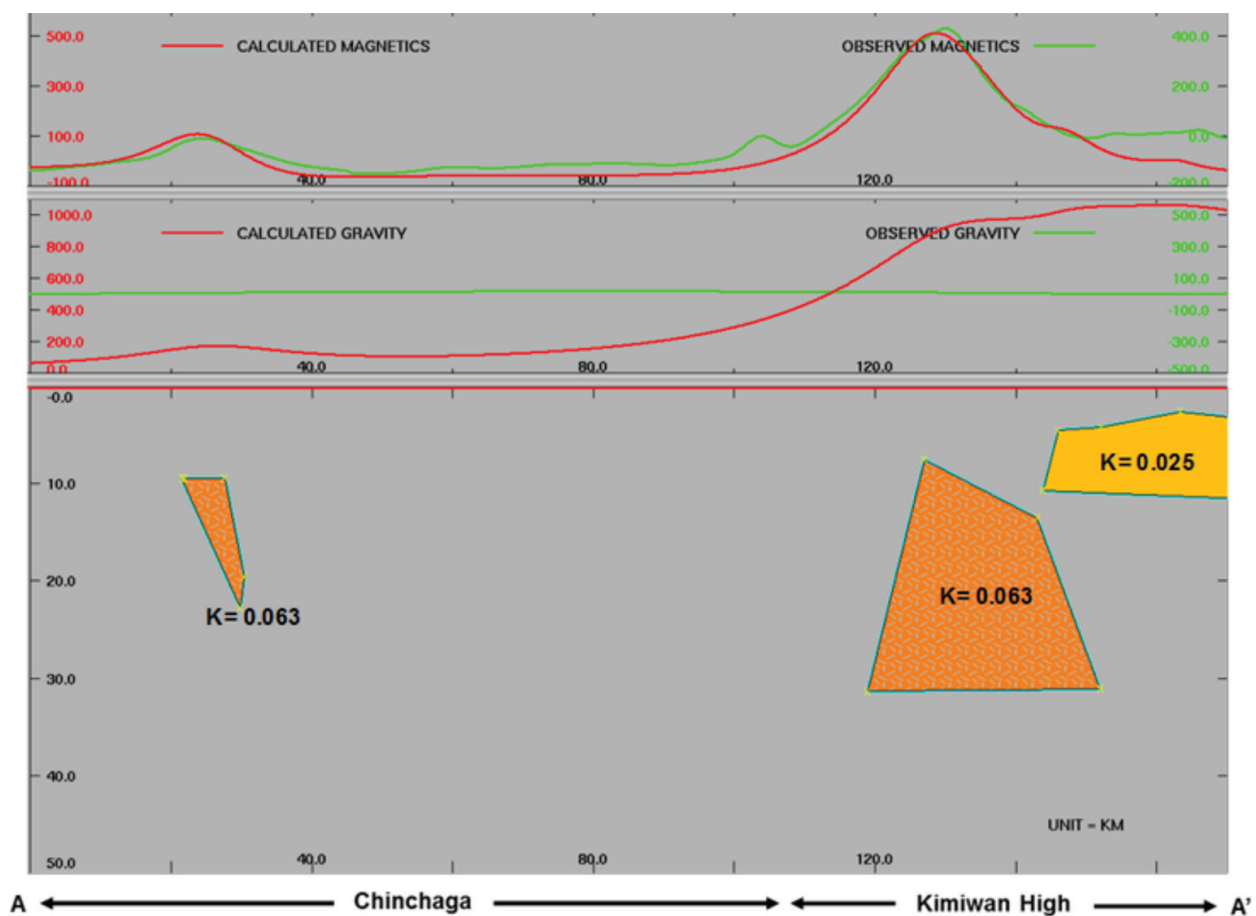


Figure 10. Magnetic model and observed gravity along profile A-A' (location shown in **Figure 4**). The profile crosses the Kimiwan Anomaly (KA), which forms the boundary between the Southern Chinchaga Domain (SCD) and the Buffalo Head Terrain. A smaller magnetic anomaly at $x \sim 30$ km is located within the SCD with a trend that is parallel with the KA as well as fault-plane solutions in the Duvernay region. Total magnetic field parameters used: inclination 74.80°N , declination 16°N and magnitude 56,930 nT. Magnetic susceptibility values (K) are in SI units.

5. Discussion and conclusions

In this study, potential-field methods are combined with seismic and well data to investigate basement structure in Alberta. Our analysis shows that regional gravity anomaly patterns primarily reflect large-scale crustal features, such as a Bouguer gravity low that marks the isostatic root beneath the Rocky Mountains (**Figure 3a**), an isostatic gravity high that reflects a flexurally supported topographic load in the Rock Mountain front ranges of Alberta (**Figure 3b**), and NE-SW linear fabrics associated with the Snowbird Tectonic Zone (STZ). On the other hand, magnetic-anomaly maps provide the primary method for delineating the extent of basement tectonic domains [14]. Isostatic-residual gravity anomalies (**Figure 4a**) are characterized by longer wavelength than magnetic anomalies (**Figure 4b**). While the magnetic anomalies predominantly reflect the magnetic susceptibility of the uppermost basement [15], due to the wavelength difference the gravity anomalies are primarily sensitive to deeper crustal levels. This difference in depth sensitivity may explain why the observed isostatic gravity and magnetic intensity fabrics are poorly correlated (**Figure 4**). Moreover, based on the available regional datasets the (likely subtle) magnetic and gravity expression of basement faults appears to be overwhelmed by anomalies produced by large-scale crustal features. This suggests that a good strategy to improve the sensitivity of potential-field methods to detect and constrain basement faults is to acquire densely sampled data and apply a well-characterized regional-residual separation.

There is evidence to suggest that the southern Chinchaga domain is a distinct block from the northern Chinchaga domain, although basement drillcore samples are too sparse to either validate or falsify this interpretation. The Chinchaga domain has primarily negative magnetic anomaly values throughout its north-south extent, but there are distinct characteristics of the magnetic anomalies in the southern part that are dissimilar from magnetic-anomaly characteristics in the north. Specifically, the southern Chinchaga domain has a more muted negative character, with distinct internal positive anomalies that are absent in the north. In contrast, the northern Chinchaga domain is characterized by high-amplitude negative anomalies. In addition, the southern Chinchaga domain has strikingly rectilinear boundaries, in contrast to the arcuate nature of internal and bounding fabrics in the north. There are north-south trending magnetic anomalies in the southern Chinchaga domain that have an orientation consistent with observed induced-seismicity focal mechanisms, so this distinction may be important in terms of fully understanding the relationships of magnetic anomalies to induced seismicity.

As indicated by a LITHOPROBE seismic profile across the Tangent fault in the Peace River Embayment, despite a sharp offset at the top of crystalline basement, the seismic expression of faulting of Paleozoic layers is dominated by folding. This draped seismic expression supports the use of seismic curvature attribute analysis [6] for mapping potential fault structures. In the shallow basement, faults in the WCSB are difficult to map due to the lack of coherent reflections and the obscuring effects of multiple reverberations. On the other hand, disruption and offset of reflections within the Winagami Reflection Sequence (WRS) provides a potential opportunity to pinpoint loci of crustal-scale faulting at depth as an aid in the interpretation of basement faults. This interpretation approach relies on an assumption that these bright

reflections represent mafic sills that were originally more laterally continuous than at present, such that observed offsets can be reasonably interpreted as post-intrusion fault deformation. Extrapolation to the top of basement of the tentatively interpreted crustal-scale reverse fault (Figures 6 and 7) would bring this fault to the base of the WCSB close to several interpreted faults in close proximity to a major Leduc reef edge.

Acknowledgements

We are grateful for support from the Natural Sciences and Engineering Research Council of Canada (NSERC) and Chevron for the Industrial Research Chair (IRC) in Microseismic System Dynamics. Warner Miles is thanked for helping with access to gridded aeromagnetic data, and Brian Roberts is thanked for providing LITHOPROBE data. CGG is gratefully acknowledged for licensing of the Geoview suite and LCT software through CGG's world-wide university program. Patrick Quist CGG Houston is thanked for help with answering questions relating to the LCT software and troubleshooting of the seismic and magnetic data. Geosoft software was also used for visualization and interpretation of potential field data. Lydia Dicaprio and Andrew Poulin are thanked for help with GMT and ArcGIS softwares.

Author details

Eneanwan Ekpo^{1*}, David Eaton¹ and Ronald Weir²

*Address all correspondence to: eneanwan.ekpo@ucalgary.ca

¹ MIC, University of Calgary, Calgary, Canada

² CREWES, University of Calgary, Calgary, Canada

References

- [1] Schultz R, Corlett H, Haug K, Kocon K, MacCormack K, Stern V, Shipman T. Linking fossil reefs with earthquakes: Geologic insight to where induced seismicity occurs in Alberta. *Geophysical Research Letters*. 2016 Mar 28;**43**(6):2534-2542
- [2] Bao X, Eaton DW. Large variations in lithospheric thickness of western Laurentia: Tectonic inheritance or collisional reworking? *Precambrian Research*. 2015 Sep 30;**266**:579-586
- [3] Schultz R, Wang R, Gu YJ, Haug K, Atkinson G. A seismological overview of the induced earthquakes in the Duvernay play near Fox Creek, Alberta. *Journal of Geophysical Research: Solid Earth*. 2017 Jan 1;**122**(1):492-505
- [4] Eaton DW, Ross GM, Hope J. The rise and fall of a cratonic arch: A regional seismic perspective on the Peace River Arch, Alberta. *Bulletin of Canadian Petroleum Geology*. 1999;**47**(4):346-361

- [5] Green DG, Mountjoy EW. Fault and conduit controlled burial dolomitization of the Devonian west-central Alberta Deep Basin. *Bulletin of Canadian Petroleum Geology*. 2005;**53**(2):101-129
- [6] Chopra S, Sharma RK, Ray AK, Nemati H, Morin R, Schulte B, D'Amico D. Seismic reservoir characterization of Duvernay shale with quantitative interpretation and induced seismicity considerations—A case study. *Interpretation*. 2017 Feb 27
- [7] Eaton DW, Milkereit B, Ross GM, Kanasewich ER, Geis W, Edwards DJ, Kelsch L, Varsek J. Lithoprobe basin-scale seismic profiling in central Alberta: Influence of basement on the sedimentary cover. *Bulletin of Canadian Petroleum Geology*. 1995;**43**(1):65-77
- [8] Pilkington M, Miles WF, Ross GM, Roest WR. Potential-field signatures of buried Precambrian basement in the Western Canada Sedimentary Basin. *Canadian Journal of Earth Sciences*. 2000 Nov 1;**37**(11):1453-1471
- [9] Hope J, Eaton D. Crustal structure beneath the Western Canada Sedimentary Basin: Constraints from gravity and magnetic modelling. *Canadian Journal of Earth Sciences*. 2002 Mar 1;**39**(3):291-312
- [10] Shah AK, Keller GR. Geologic influence on induced seismicity: Constraints from potential field data in Oklahoma. *Geophysical Research Letters*. 2017 Jan 16;**44**(1):152-161
- [11] Hope J, Eaton DW, Ross GM. Lithoprobe seismic transect of the Alberta Basin: Compilation and overview. *Bulletin of Canadian Petroleum Geology*. 1999;**47**(4):331-345
- [12] Clowes R, Cook F, Hajnal Z, Hall J, Lewry J, Lucas S, Wardle R. Canada's LITHOPROBE Project (collaborative, multidisciplinary geoscience research leads to new understanding of continental evolution). *Episodes*. 1999 Mar 1;**22**:3-20
- [13] Hoffman PF. United plates of America, the birth of a craton: Early Proterozoic assembly and growth of Laurentia. *Annual Review of Earth and Planetary Sciences*. 1988 May;**16**(1):543-603
- [14] Ross GM, Parrish RR, Villeneuve ME, Bowring SA. Geophysics and geochronology of the crystalline basement of the Alberta Basin, Western Canada. *Canadian Journal of Earth Sciences*. 1991 Apr 1;**28**(4):512-522
- [15] Villeneuve ME, Ross GM, Parrish RR, Theriault RJ, Miles W, Broome J. Geophysical subdivision, U–Pb geochronology and Sm–Nd isotope geochemistry of the crystalline basement of the Western Canada Sedimentary Basin, Alberta and northeastern British Columbia. *Geological Survey of Canada Bulletin*. 1993;**447**:86
- [16] Burwash RA, Chacko T, Muehlenbachs K, Bouzidi Y. Oxygen isotope systematics of the Precambrian basement of Alberta: Implications for Paleoproterozoic and Phanerozoic tectonics in northwestern Alberta. *Canadian Journal of Earth Sciences*. 2000 Nov 1;**37**(11):1611-1628

- [17] Hanmer S, Parrish R, Williams M, Kopf C. Striding-Athabasca mylonite zone: Complex Archean deep-crustal deformation in the East Athabasca mylonite triangle, northern Saskatchewan. *Canadian Journal of Earth Sciences*. 1994 Aug 1;**31**(8):1287-1300
- [18] Ross GM, Eaton DW. Winagami reflection sequence: Seismic evidence for postcollisional magmatism in the Proterozoic of Western Canada. *Geology*. 1997 Mar 1;**25**(3):199-202
- [19] Cant DJ. Regional structure and development of the Peace River Arch, Alberta: A Paleozoic failed-rift system? *Bulletin of Canadian Petroleum Geology*. 1988;**36**(3):284-295
- [20] Edwards DJ, Brown RJ. Understanding the influence of Precambrian crystalline basement on Upper Devonian carbonates in central Alberta from a geophysical perspective. *Bulletin of Canadian Petroleum Geology*. 1999;**47**(4):412-438
- [21] Ross GM, Eaton DW. Basement reactivation in the Alberta Basin: Observational constraints and mechanical rationale. *Bulletin of Canadian Petroleum Geology*. 1999;**47**(4):391-411
- [22] Barclay JE, Krause FF, Campbell RI, Utting J. Dynamic casting and growth faulting: Dawson Creek graben complex, Carboniferous-Permian Peace River embayment, Western Canada. *Bulletin of Canadian Petroleum Geology*. 1990;**38**(1):115-145
- [23] O'connell SC. Geological history of the Peace River arch. *Geological Atlas of the Western Canada Sedimentary Basin*, GD Mossop and I. Shetsen (comp.). Canadian Society of Petroleum Geologists and Alberta Research Council Special Report. 1994;**4**:431-438
- [24] Goodacre AK, Grieve RA, Halpenny JF, Warren LA. Isostatic Gravity Anomaly Map of Canada. Ottawa, Ontario, Canada: Surveys and Mapping Branch; 1987
- [25] Talwani M, Ewing M. Rapid computation of gravitational attraction of three-dimensional bodies of arbitrary shape. *Geophysics*. 1960 Feb;**25**(1):203-225
- [26] Eaton DW, Ross GM, Clowes RM. Seismic-reflection and potential-field studies of the Vulcan structure, Western Canada: A Paleoproterozoic Pyrenees? *Journal of Geophysical Research: Solid Earth*. 1999;**104**(B10):23255-23269

