Final Project Report:

Geophysical Investigations of the Precambrian Basement of the Williston Basin in south-eastern Saskatchewan and south-western Manitoba

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Map list

The links provided below give the corresponding maps in PDF format suitable for viewing and printing page-size as well as in about 1m by 1m images. The image file names begin with the map numbers followed by self-descriptive abbreviated captions. Note that several images have multiple versions (typically, contoured or non-contoured maps), indicated by letters appended to the figure numbers.

1) Surface topography of TGI2 area;
2) Locations of gravity stations;
3) Bouguer gravity anomaly;
4) Contoured Bouguer gravity anomaly;
5) Aeromagnetic total residual intensity anomaly;
6) Horizontal derivative of Bouguer gravity;
7) Vertical first derivative of Bouguer anomaly;
8) Second vertical derivative of Bouguer gravity;
9) Analytic Signal of Bouguer gravity;
10) Tilt derivative (TDR) of Bouguer gravity;
11) Isostatic residual gravity anomaly;
12) Magnetic anomaly reduced to the pole;
13) Horizontal first derivative of magnetic anomaly;
14) First vertical derivative of magnetic anomaly;
15) Second vertical derivative of magnetic anomaly;
16) Analytic Signal of magnetic anomaly;
17) Tilt derivative (TDR) of magnetic anomaly;
18) Band-pass filtered magnetic anomaly;
19) Magnetic source pseudo gravity;
20) Magnetic basement structural pattern;
21) Precambrian model by well and seismic;
22) Precambrian topography inverted by Euler method;
23) Structural units and domains on magnetic field background;
24) Structural units and domains;
25) Lineaments;
26) Interpreted NW regional faults.

1. Abstract

Regional gravity and high-resolution aeromagnetic maps were compiled for the Williston Basin between N49-56º and W96-106º. The study provides a seamless tectonic framework of the Precambrian basement rocks buried beneath generally Phanerozoic sediments. We applied new high resolution imaging methods, inversion, and feature extraction techniques calibrated with well and seismic data to produce multiple attribute maps revealing the complex geological structure of the basement beneath the Basin.

The six principal basement zones recognized in the study area are confirmed: the Superior Province, Superior-Churchill Boundary Zone, Reindeer Zone (southern part of the Trans-Hudson Orogen), Sask-Reindeer Boundary Zone, the Sask and Wyoming Cratons. Within each of these principal zones, secondary domain and sub-domain elements were differentiated based on the distinctive combinations of their geophysical attributes. Within the Superior Province, clear differences in geophysical patterns between its western and eastern parts allow identification of several additional different sub-domains.

Mapping of peak gradients of magnetic-source pseudo-gravity and their correlation with gravity highlighted the detail of the structure of crystalline basement. In particular, based on its geophysical features, the Sask Craton is subdivided into six sub-blocks. The pseudo-structure map combining magnetic and gravity lineament maps of the Weyburn zone could be especially important in relating its fault-block structure to the zones of petroleum production.

In addition to delineation of domains, sub-domains, and structural lineaments, the study suggests the existence of a series of regional, NW-SE trending boundaries crossing nearly the entire study area across the Churchill Superior Boundary Belt. These features crossing the entire study area could be related to the primary NW-SE crustal faulting that occurred during the Laramide orogeny or related to paleotectonic boundaries proposed earlier.

2. Introduction

The Williston Basin occupies approximately 500,000 km² in SE Saskatchewan and SW Manitoba including areas of considerable oil and gas production (Map 1). The basin is underlain by complex Precambrian rocks, with the depth of the Precambrian basement exceeding 3000 m in south of Weyburn, Saskatchewan. Basement structures were recognized to play a major role in migration and entrapment of hydrocarbons in this area. Two types of processes are generally recognized as contributing to this influence: 1) development of porosity related to migration of brines along basement-related faults and fracture zones, and 2) basement relief leading to structural traps in the overlying strata.

Regional analysis of surface structural elements of the SE Williston Basin (Thomas, 1974; Brown and Brown, 1987) revealed pervasive north-easterly and north-westerly trending structural lineaments that were interpreted as related to the basement. Thomas (1974) suggested that simple shear involving the basement could create fracturing, faulting, and downwarps along zones of basement weakness and explain the present structural configuration of the Williston Basin. Brown and Brown (1987) suggested that pure shear along a wrench fault system with both vertical and horizontal displacements could create normal faults, grabens, half-grabens, and horsts found along block boundaries. Intersections of NW- and secondary NE-trending faults create structural lows and highs, the latter forming closures that may trap hydrocarbons and control their migration in suitable Phanerozoic strata.

Geophysical mapping of the major basement faulting could thus give important clues to understanding the generation and migration of hydrocarbon in the Williston Basin, and this is the focus of the present study. In this work, we aim at a seamless and integrated interpretation of the basement of the basin within SE Saskatchewan and SW Manitoba (Map 1).

In a previous work, Burwash et al. (1994) produced an outline of basement of the basin on the basis of drill-hole information. Based on high-resolution aeromagnetic and gravity surveys, Miles et al. (1997), Kreis et al. (2000), Pilkington and Thomas (2001), White et al. (2005) performed respectively regional gravity and magnetic mapping in Saskatchewan and Manitoba, leading to characterization of the principal tectonic elements and domains within these provinces. In the report, we extend our study region covering the entire Williston Basin area from W96º - W106º and N49º - N56º. We use new, high-resolution processing methods to confirm and update the definitions of the principal elements and domain boundaries, identify smaller-scale features, and also invert for the depth variations of the basement.

Our ability to learn about that Precambrian basement is limited by the availability of direct and indirect observations of basement rocks. Drill holes reaching the bedrock with reliable lithologic data are unevenly distributed and absent over large areas of the basin. However, owing to their near-continuous coverage, the available aeromagnetic and gravity data are particularly useful for continuous regional structural analysis, and they form the basis of our interpretation.

3. Data

Gravity and aeromagnetic signatures most closely reflect the tectonic and structural character of the area, and potential-field data also provide the necessary spatial continuity of coverage. Gravity data have been used successfully to map crustal-scale and basin-scale structures. Due to steeper distance dependence and higher susceptibility to the metamorphic and deformational processes within the crystalline rock, magnetic anomalies are the most sensitive indicators of the structural character of the basement covered by sediments. At the same time, due to its inherent limitations, potential-field mapping and inversion needs to be calibrated and constrained by the available borehole core and seismic data information.

Gravity and aeromagnetic data were compiled from numerous sources and provided to this study by the Geological Survey of Canada (GSC). With some exceptions of more densely covered areas of petroleum exploration, gravity regional surveys were carried out since 1950's on the scale of 1:100,000.

This study used 235,413 levelled gravity data points which included 10,782 data points from regional surveys spaced with 10 – 20 km spacing and 224,631 points from denser grids acquired by the industry (Map 2). These point data within the entire area were further interpolated using a continuous equivalent source interpolator (Li and Morozov, 2004) onto a 2-km grid (Maps 3 and 4).

Aeromagnetic surveys in the Williston Basin were flown along generally north-south lines spaced at 1.6 km apart for older data and 800 m for more recent surveys, at an altitude of 300 m above the ground. For the purposes of digital analysis, aeromagnetic data from these surveys were levelled, pre-processed, and gridded and interpolated into 500-m grids by the GSC (Map 5).

As the sedimentary rocks covering the basins are mostly only weakly magnetic, the observed magnetic anomalies should be primarily due to variations in magnetization of the underlying crystalline basement rocks. The magnetic anomaly patterns and trends are often associated with geological units and structures of the Precambrian basement.

Several tectonic regions and structural domains were identified in the study area on the basis of geological mapping and potential-field studies. Below, we briefly describe these features in relation to the gravity and aeromagnetic anomalies found in the maps.

4. Gravity and magnetic anomaly descriptions

For distinguishing between gravity and magnetic anomalies, we label these anomalies with letters ***G*** and ***M***, respectively, followed by numbers. In the following, we discuss the most remarkable anomalies arranged by their structural/tectonic units.

4.1 Superior Province

Within the study area, the Superior Province block is bounded by a series of gravity highs representing the Churchill-Superior Boundary Zone (CSBZ). A series of W-E trending linear gravity patterns dominates the eastern part of the CSBZ area (Map 3). The following anomalies are of particular importance:

1) Between about N49º00´ and 49º30´, two long narrow NWW and trending connected gravity highs are recognized (labelled GSP1 and GSP2). Their peak values reach over -10 mGal, which is the strongest anomaly within the study area. An apparent high-gradient belt is also associated with these anomalies;

2) NNW of Brandon, GSP3 gravity anomaly is composed of an oval gravity high with a circular gravity low around it;

3) East and NE of Brandon, near W98º- 99º, N49º30´- 50º40´, a N-S sequence of two gravity highs GSP4 with peak magnitudes of -15 mGal is located. Their oval shapes and moderate gradients are very different from the area to the east, where the gravity gradients vary significantly more abruptly;

4) North of Winnipeg to N51º40´, the Bouguer gravity shows two small anomalies with high gradients, with closely spaced positive and negative zones (GSP5 and GSP6). This pattern is similar to the area of Flin Flon at the margin of the Precambrian Shield and is characterized by multiple disjoint small anomaly blocks;

5) The negative anomaly area in W101º ~ 100º and N51º30´ ~ 52º30´ (GSP7), which is the largest and strongest gravity low in the study area. This anomaly appears to consist of several localized parts. Based on its area and magnitude, this anomaly suggests the presence of a thick sedimentary or low- density basement rock;

6) North of about N51º30´, the patterns of gravity anomalies essentially follow those found within the Superior Province outside of the basin. In this area, GSP8 is a medium-intensity anomaly with gently varying gradients, and GSP9 shows a typical volcanic-rock gravity character, with multiple small blocks, high gradients and quick succession of positive and negative anomalies.

The most remarkable features of the magnetic field of the Superior Province are the clear boundary separating it from the western CSBZ and a clear south-north sequence of tectonic domains (Map 5). Within each of these domains, the dominant magnetic trend is W-E. The anomaly intensities are generally strong, particularly near their contact with the CSBZ. Magnetic anomalies MSP1 and MSP2 have clear spatial trends, and MSP3 is very similar to GSP3. Magnetic anomaly MSP4 does not have a gravity counterpart and appears to be a group of several smaller anomalies.

In the Superior Province, the magnetic anomalies appear as large blocks, with clear margins forming the natural demarcation lines between the domains (MSP7, MSP8 and MSP9). By contrast to the gravity map where there is a localized gravity low near the contact with CSBZ at N52º (GSP7 in Map 4), the magnetic field shows no apparent correlation with this gravity anomaly (Map 5). The most extensive strong magnetic lows (MSP5 and MSP6) covering ~10,000 km within this region extend into the basin from the margin of the Canadian Shield to ~W99º, with a clear dividing line from its neighbouring positive anomalies in the north and west.

Within the region between N 50º30' to 51º, which is defined as the English River domain (Pilkington and Tomas, 2001), the magnetic pattern is different, with the positive anomaly extending S-N near the CSBZ. Within the adjoining Bird River domain, the magnetic anomaly corresponding to the gravity anomaly GSP3 resembles a series of 4-5 ridges symmetrically arranged about a common centre. These anomaly shapes are very different from other domains of the Superior Province.

4.2 Churchill-Superior Boundary Zone (CSBZ)

Within the northern part of the CSBZ (north of N52º00´), the gravity field shows a band of strong positive anomalies generally trending NNE. The band extends for ~350 km and consists of five local anomalies, with average widths of about 30 km The anomalies are labelled GCS1–GCS6 in Map 3.

Similarly, within the northern part of the CSBZ, magnetic anomalies appear as a series of clear, narrow, thin, and linear structures that are parallel to the boundary of the Superior Province. In this part of the CSBZ, the dominant magnetic anomaly is negative (Map 5) while the gravity field shows strong highs. Near N52º, the gravity anomaly GCS4 and the corresponding magnetic anomalies (MCS4) show the same characters indicating that they may come from same sources.

A narrow (~15-km) high-intensity gravity anomaly belt GCS6 extends for ~130 km along the eastern part of CSBZ. North of it, another narrow anomaly GCS5 appears independent of the GCS6. Its detailed character suggests that it could be caused by a thin and dense tabular intrusion (Map 3).

South of N51°47´, gravity anomalies trends change into a southward direction, and their amplitudes drop to medium intensity. The anomaly shapes also change from distinct trends into less tidy smaller blocks. Such structures could be created, for example, by extrusion of crustal blocks during collision of crustal terranes.

Further South, a sequence of low-magnitude, elongated, positive magnetic anomalies define the western boundary of CSBZ (Map 5). Unlike in the northern part but similarly to the gravity pattern in the same area (Map 3), the negative magnetic lows are not continuous but break into two areas of magnetic lows. The boundary contact with the Reindeer Zone is not as clear as the one with the Superior Province in the east.

4.3 Reindeer Zone

Within the study area, the northern part of the Reindeer Zone (Flin Flon area) consists largely of low metamorphic grade, mafic volcanic and granitoid rocks. Its gravity field is dominated by small-extent anomalies, generally no more than ~15 km in size and having circular or arc-type shapes. As the basement is exposed or at very shallow depths in this area, these gravity anomalies should correspond to lighter and heavier masses within the crystalline crust, and therefore it could be particularly useful for locating granitic, mafic and ultramafic rocks within the Precambrian basement.

Similarly to the gravity field (Map 3), the magnetic anomaly in the Flin Flon region shows quickly varying amplitudes in isolated anomalies (Map 5). These features could correspond to volcanic intrusions and clastic sedimentary rocks, and also their metamorphic equivalents that characterize the Flin Flon belt within the Williston basin (Miles et al., 1997).

The area south of ~N52º30´ was formed by a collision between the Superior Province and Sask Craton. The gravity field in this area shows an S-N extended, narrow anomaly with some internal blocky texture at a smaller scale. There is also a notable gravity low between N51º00´ ~ 51º30´ (GRZ2 in Map 3).

Flin Flon area is located within the northern part of Reindeer Zone. It represents the part of Trans-Hudson Orogen extending below the Phanerozoic rocks of the Williston basin. The basement is very shallow, and thus the gravity and magnetic signatures can be considered as representative of the basement rock.

4.4 Sask-Reindeer Boundary Zone (SRBZ)

Within the Sask-Reindeer Boundary Zone, the gravity anomaly trend is from north to south, but consists of four gravity highs and several medium-intensity segments (Map 3). The western boundary of SRBZ is marked with the well-known Tabbernor Fault System (Miles et al., 1997). The two notable anomalies are GSK2E and GSK7 (the latter is also corresponding to magnetic anomaly MSK7).

From the edge of the Phanerozoic margin to the south, nearly the entire SRBZ shows a continuous negative magnetic signature (Map 5). The northern part of this anomaly is a high-magnitude low, whereas in the southern part, the anomaly intensity becomes moderate.

Note that the area of the SRBZ is the only one where the character of magnetic anomalies appears to change across the edge of the Phanerozoic cover (Map 5). The intensities of the anomalies appear to be consistently higher within the sediment-covered parts of this area. This observation suggests that sedimentation could have taken some role in contributing to the magnetization of the rocks into this zone.

4.5 Sask Craton

Seven major blocks can be recognised in the gravity anomaly patterns of the Sask Craton (Map 3). In its western part, GSK3 and GSK4, the two mid-intensity gravity highs and a gravity low cut the northern Sask Craton into two parts. In the southern part, from Regina through Weyburn to Estevan (for this discussion, this area is also included in the Sask Craton region), gravity field forms a band of NNW-trending anomalies. In the south-western corner, a group of gravity lows outlines the Wyoming Craton whose triangular part also enters our study area.

The Tobin domain has a gun-like shape with a central high positive gravity anomaly (GSK1; Map 3). The eastern edge of this anomaly forms a very clear boundary with the SRBZ. Smeaton domain is represented by a positive gravity anomaly GSK2 and low-magnitude negative magnetic anomaly MSK2 located between two positive anomalies (Map 5). The Humboldt positive magnetic anomalies MSK5 and MSG6 are composed of four sub-blocks, in which the two northern blocks have moderate amplitudes and the two southern are weaker, with structural trend extending south-east. The Weyburn block (MSK8) shows a strong negative magnetic anomaly, with stable and gradual variation of the magnetic field. In addition, a narrow and small positive anomaly extending south is located between Weyburn and Estevan. In the following discussion, we recognise seven blocks in this area with distinct gravity and magnetic signatures.

4.6 Wyoming Craton

Within the SW corner in the study area, the Wyoming Craton is characterized by prominent low gravity values. Much of this gravity (Map 3) correlates with high topography (Map 1). A narrow boundary zone is visible between the two cratons. Even within this small area, a blocky geological structure is quite apparent. We distinguish three large and one smaller block, with relative gravity lows and three local gravity highs. The magnetic map of the Wyoming Craton is represented by a triangular, moderate-magnitude magnetic high surrounded by a distinct belt of magnetic lows. The boundary with the Sask Craton is marked by a narrow low negative anomaly. This magnetic trend correlates with the North American Central Plains (NACP) conductivity anomaly belt (Kreis et al, 2000). Comparing the magnetic to the gravity data, we observe a consistent positive correlation between them within the region of the Wyoming craton and its surrounding belt. This suggests a common source of both anomalies, which should be related to the crystalline basement.

5. Processing methods

To improve the resolution and also to sharpen the geophysical contacts critical for the definition of structural framework of the study region, our data processing generally focused on enhancement of the short-wavelength features. In addition to the standard methods, such as interpolation, filtering, various spatial derivatives, reduction of magnetic field to the pole, analytic signal, we also attempted to employ special techniques targeting accurate determination of basement topography and source distribution. These methods included: spatial band-pass filtering, downward and upward continuation, Euler deconvolution, local wavenumber analysis, a modification of magnetic pseudo-gravity, and feature extraction. Below, we briefly outline three major features of the processing methods in this study.

5.1 Determination of the boundaries of structural elements via field derivatives

The horizontal and vertical derivatives as well as their functions are the most important tool for determining structure element boundary and reveal possibility faults. A variety of derivatives and filtering techniques were employed in order to enhance the data sets used in this study (Maps 6-15).

The horizontal derivative and the first vertical derivative are often used for definition of major element boundaries. Recently, Analytic Signal (total derivative; Map 16) has been often applied to resolving structural elements of the subsurface (Roest et al., 1992). This study also employed the second vertical derivatives which revealed a great amount of detail not apparent in the total and first vertical derivative maps. In particular, a new attribute based on second derivatives, such as the Tilt Derivative (Map 17; Verduzco et al., 2004), was introduced to help highlighting subtle variations of structural and geological properties.

In addition to attribute extraction, several spectrally filtered versions of the original grid data set were used in Williston basin basement interpretation. The purpose of band-pass filtering is to remove the unwanted shallow- and deep-source effects to enhance the desired Precambrian basement signal. Although the low-frequency information is lost in such filtering, it can be recovered by using the basement trend surface is controlled by drill holes or from low-pass filtered maps. The band-pass filter for 2 – 32 km wavelengths was thus found to best emphasize the effects gravity and magnetic fields caused by Precambrian structural features (Map 18). Magnetic band-pass filtering result show more clear domain structure distribution than the magnetic total intensity map, especially band-pass filtering map reveal Weyburn structure pattern which is vague in total intensity map and some other attribute maps.

5.2 Locating edges of magnetic sources by magnetic pseudo-gravity gradients

This technique transforms magnetic field into an equivalent “gravity” field that would have been produced by a density distribution proportional to the magnetic source (Map 19). The resulting field can be directly correlated to the gravity field, and both fields can be processed using the same methods for pattern enhancement. After transformation, the magnetic field becomes smoother and attains maxima and minima located over the corresponding source structures, which makes it easier for identification of geological structures. By suppressing strong but shallow magnetic disturbances, this magnetic source pseudo-gravity map provides a clearer outline of the principal magnetized elements within the Williston Basin basement.

Another useful technique for locating edges of magnetic source bodies is the use of the gradient maxima of magnetic source gravity (Map 20; Cordell and Grauch 1985; Pilkington et al, 2000). By computing the horizontal gradient **g** of the magnetic-source pseudo-gravity field and identifying the surface points *P* at which it attains maxima in the direction of the gradient, we obtain the inflexion points of the pseudo-gravity field. This method gives an efficient way for mapping the edges of source bodies, as lateral pseudo-density contrasts correspond to the lateral changes in magnetization. In this study, we used the maxima of magnetic source gravity gradient to analyse the internal character and boundaries of basement domain and sub-domain in the sediment-covered Williston basin. Pseudo-gravity horizontal gradient maxima result in high-resolution mapping of geophysical features and highlight trend directions of magnetic sources (Map 20).

5.3 Estimation of basement depth using the Euler deconvolution

Euler deconvolution is a technique that estimates the locations of magnetic sources in three dimensions by solving Euler equation about magnetic filed as well its derivatives (Reid et al., 1990). For estimation of the Precambrian basement depth of the Williston Basin from magnetic data, a smoothed starting basement depth model was employed to constrain Euler deconvolution solution in our processing (Map 21).

Euler deconvolution is a technique that estimates the positions of magnetic sources in three dimensions (x_0,y_0,z_0) by inverting the following relation (Reid, 1990):

$$(x - x_0)\frac{\partial}{\partial x}T(x,y,z) + (y - y_0)\frac{\partial}{\partial y}T(x,y,z) + (z - z_0)\frac{\partial}{\partial z}T(x,y,z) = N \cdot T(x,y,z),$$

or, in logarithmic form:

$$(x - x_0)\frac{\partial}{\partial x}\ln T(x,y,z) + (y - y_0)\frac{\partial}{\partial y}\ln T(x,y,z) + (z - z_0)\frac{\partial}{\partial z}\ln T(x,y,z) = N,$$

where T is the magnetic field and N is the Euler structural index. Note that because the magnetic field entering this equation only through ln$T$, the method is sensitive to the shapes of anomalies (related to their depths) but not to the absolute magnitude of the field (which is generally proportional to the magnetization). For estimation of the Precambrian basement depth from magnetic data, Euler deconvolution was constrained by using a smoothed starting basement depth model (Map 19). Two important parameters of Euler deconvolution were the choice of a 3.5-km wide window and structural index of N=0.5, as recommended by other researchers (Williams et. al., 2005) and also suggested from our previous work (Li and Morozov, 2006).

Because the Euler method relies on the gradients of the magnetic field, the resulting depth readings relate primarily to the areas of basement heterogeneities identified as distinct sources of the field. These depth values from adjacent spatial windows are further interpolated to produce a map (Map 20) showing the positions of magnetic sources. Thus, by the nature of this interpolation favouring high depth values, only the local maxima in the resulting maps should be taken into consideration. In the subsequent interpretation, we are most interested in the relative local variations and positions of the boundaries. Estimation of the absolute depth proved not reliable, and our model relies mainly on the constraints from well log and seismic data. However, compared to the Precambrian depth map, the Euler method provides additional information leading to further discussion of the basement structure below.

This method primarily responds to the gradients in the data and effectively traces the edges and defines the depths of the source bodies. Horizontal source position estimates are generally more reliable than the vertical, and thus they can be used for delineation of structural and lithological trends.

Two important parameters influence the results of this inversion: window size and structural index (Pilkington et al., 2000). In our inversion, the window size was related to the wavelengths of the magnetic field and target depths. After several trials, the structural index was chosen to equal 0.5. For an initial estimate of basement depths, we used a model obtained from basement depth picks made from 239 wells penetrating the basement and from several seismic sections (Map 21). The result of the inversion is shown in Map 22.

6. Key structural elements

The structural pattern of the basement revealed from combined gravity and magnetic interpretations can be characterized by a hierarchy of structural elements. We distinguish three tiers in this classification: 1) primary structural zones, 2) tectonic domains, and 3) sub-domains. The largest-scale structure of the Williston basin is considered to be related to the plate-forming structural crustal elements (such as terranes and orogenic belts), each of them having a distinct movement history and structure. The secondary structural level of the basin is considered to be the domain-block subdivision within each of these structural elements. Finally, the smallest, sub-domain structures could potentially be related to fracturing and deformation of the secondary structural domains.

The primary structural elements within the study area were identified and discussed in detail by Green et al. (1979), Miles et al. (1997), Kreis et al. (2000), Pilkington and Thomas (2001), White et al. (2005), and Li and Morozov (2006). These elements are: the Superior Province, Churchill-Superior Boundary Zone (CSBZ), Reindeer Zone, Sask-Reindeer Boundary Zone (SRBZ), Sask Craton, Wyoming Craton, and Hearne-Reindeer-Sask Boundary Zone (HRSBZ) (Maps 23 and 24). Of these zones, only HSRBZ, which is only marginally represented in the study area, shows little of internal domain structure. Boundaries of the primary structural elements show strong gradients in both gravity and magnetic maps, with each of these structural units having clear interior features that differentiate it from its neighbours.

Conventional analysis methods for emphasizing potential-field gradients usually use the first-order horizontal and vertical derivatives. However, as the source response of the gravity field (point-source) is by one order lower than that of the magnetic field (dipole), the first vertical derivative of gravity does not always correspond well to magnetic information. Magnetic pseudo-gravity (Map 19) is often used to equalize these two responses, which is essentially achieved by integrating the magnetic field. In this study, we used an alternate approach and computed the second vertical derivative of gravity in order to highlight the boundaries of the primary structural elements with the basin (Map 8).

Within each of these primary elements, domains were defined based on their geophysical-field attributes such as the amplitude, trend, texture, and continuity. As aeromagnetic anomalies are more closely related to the Precambrian basement than gravity and also provide higher resolution, we mainly relied on them in delineating of the domains. In particular, the aeromagnetic tilt derivative attribute (Verduzco et al., 2004) is highly suitable for mapping shallow basin basement structures and shows distinct advantages over other derivative-based attributes.

The domains recognised within the Superior Province, listed from north to south, are (Map 23): the Gods Lake, Island Lake, Berens River I, Berens River II, Berens River III, Molson, Uchi, English River, Bird River, Winnipeg River, Wabigoon, as well as an unnamed domain in the south (Figure 3 and Map 5). In addition, the area from Uchi to Winnipeg River domains shows clear differences in geophysical attribute within its western and eastern parts, which we identify as sub-domains (indicated using a dashed line in Maps). Based on two distinct types of magnetic field attributes, the Reindeer Zone may also be subdivided into Flin Flon zone in the north and Reindeer Zone in the south. Finally, the Sask Craton is subdivided into six domains: Tobin, Smeaton, SC-1, SC-2, Humboldt, and Weyburn (Li and Morozov, 2006).

7. Domain definitions

The lineament and curved-lineament of the gravity and magnetic field mainly reflect the geophysical features of the structure and lithological elements. Extraction of the lineaments was based on integration of multiple data attributes. Because gravity and magnetic field anomalies inherently represent spatial integration of physical properties, derivatives of the fields typically better correspond to block boundaries and other structural features. Different geophysical attributes reflect only certain aspects of the physical causes of these anomalies, and therefore by combining the observations from various attribute maps and dismissing the effects of noise and processing artefacts, a unified lineament structure can be extracted.

The principal geological elements within the study area were identified in previous studies by Green (1979), Miles et al. (1997), Lyatsky (1998), Kreis et al. (2000), Pilkington et al. (2001), and White et al. (2005). While generally following the domain classification suggested by these authors, we also propose additional lineament distribution of the inner sub-domain structures as suggested by the new attribute maps (Map 23). These sub-domains and lineaments thus provide the second level of structural elements within the study area.

7.1 Superior Province

The western boundary of the Superior Province is well defined by its magnetic field with distinct contrast of the magnetic gradient. It includes an N-S sequence of eight sub-domains, with a generally west-east structural trend within in each of them. Most of these domains also show interior structures, or lithological hypo-units, and magnetic and gravity lineaments, as summarized below (Maps 23 and 24).

(1) **Molson**: Molson domain in the NE part of the investigated area may be subdivided into two paralleled W-E oriented blocks with slight connection between them. The lineaments are parallel to their boundaries, and another subtle lineament trend is inclined to NNE.

(2) The **Berens River** sub-domain has the distinct parts:

(2-1) **Berens River I**: It is the northernmost sub-set. This sub-set displays negative magnetic values whereas its gravity field shows small polygonal blocks of gravity highs. These features are typical manifestations of non-magnetic rocks buried in shallow subsurface.

(2-2) **Berens River II**: The magnetic field intensity gradually increases while the gravity trend decreases from north to south in this area. A group of NNE-oriented lineaments separate four anomalous zones apparent on both magnetic and gravity maps.

(2-3) **Berens River III**: Strong magnetic high and gravity low near the western boundary of this sub-set are prominent feature within the basin. Four W-E trending bands of anomalies are separated by a group of NNE lineaments.

(3) **Uchi**: By its magnetic character, this area is subdivided into two parts, of which the western is represented by strong positive and the eastern part by a very strong negative magnetic values. The division line between these parts is sharp and clear. By contrast, the eastern sub-area shows several irregularly scattered, small, positive and negative gravity anomalies.

(4) **English River**: It may be subdivided into three parts (west to east): a magnetic high in its western part, a transitional part, and a negative magnetic low at the eastern end. The magnetic high in the western part contains not just a single anomaly but also a distinct group of relative low values around it.

(5) **Bird River**: It also has a west-east two-part subdivision similar to Uchi and English River. The magnetic low in its eastern part appears to be comparable is the English River domain north of it, with its gravity field also showing similar chaotic anomalies. The western part is composed of several local magnetic anomalies. The gravity anomaly magnitudes here appear to anti-correlate with the magnetic field, with high gravity corresponding to low magnetic anomalies and vice versa.

(6) **Winnipeg River**: This domain can be subdivided into three parts by their respective magnetic and gravity features. The western sub-set is distinguished by a relatively low magnetic and gravity field zone; the NE part shows moderately high magnetic and gravity fields, and the SE part has both magnetic and gravity fields of relatively low magnitudes. In its western part, two strong NW-oriented magnetic lineaments follow the line from gravity anomalies GSP1 to GSP2, and the W-E lineaments are parallel to the sub-set boundary.

(7) **Wabigoon**: The magnetic and gravity fields correlate in this area and appear to be caused by the same source. The strong gradient line cuts this domain into two sub-zones located in the north-west and south-east of the area.

(8) **Unnamed southernmost zone** of the Superior Province: Its northern boundary is separated from the Winnipeg River and Wabigoon domains by two long elliptical-shaped strong gravity highs. It may even be subdivided into five sub-zones: western boundary zone, mid-intensity positive anomaly zone, negative magnetic zone in the SE, and two high-magnitude gravity and magnetic field belts.

7.2 CSBZ

Two remarkable gravity and magnetic features subdivide the CSBZ into two parts: the NNE trending strong gravity highs and magnetic lows north of ~N52º and an N-S- trending band of bead-like anomalies south of this latitude. The gravity high in the northern zone is composed of two sub-bands, in which four local anomalies comprise the wider western band (GCS1 to GCS 4; Map 3), and the narrow eastern band may be associated with termination of a shallow thin plane (GCS5 and GCS6). Comparison of the gravity to magnetic features shows that, with one exception in the SE part (GCS4), gravity highs generally correspond to negative magnetic lows. This suggests that these bands are caused by a dense and weakly magnetized rock. The interval between the two bands of gravity highs shows a relative gravity low and small magnetic high. Inside the zone, there are two extended, very long, thin, and strong magnetic belts (MCS5 and MCS6; Map 5) whose magnetic field character suggests a thin and near-vertically oriented sheet. The southern part of CSBZ gravity shows a series of small fragmented density blocks.

7.3 Reindeer and Flin Flon Zone

The southern part of the Flin Flon zone represents a part of the Trans-Hudson Orogen covered by the sedimentary fill of the Williston Basin. Its eastern boundary contacting the CSBZ was extruded by an east-west compression (Hajnal et al, 1996). A moderate positive magnetic anomaly in its middle divides this zone into two parts. The northern part, referred to as the Flin Flon block is characterized by distributed shallow-source gravity anomalies and an isolated small magnetic anomaly, which are arc-type granitic intrusions and mafic volcanics that characterize the belt (Miles et al., 1997). Although the anomalies are scattered, two distinct patterns of NNE and NW-trending magnetic lineaments are still apparent. Near the edge of the exposed Shield, and also near the western boundary of this zone, there are several lineaments nearly parallel to this edge. In the southern part, along boundary with the Sask-Reindeer Zone, four N-S-oriented extended positive magnetic anomalies are apparent on the otherwise negative background. These structures appear to be the evidence of collision and extrusion of the basement.

7.4 SASK-Reindeer Boundary Zone (SRBZ)

The SRBZ is distinguished by its negative magnetic anomaly with a strong gradient delineating the demarcation line. The western boundary of SRBZ is the Tabbernor Fault System. Although the entire eastern and western boundaries of this zone are well-defined by their potential fields, location of the SW boundary is somewhat problematic. We place it along the negative lows in the magnetic field map. Based on multiple processed attributes, vertical derivative and pseudo-gravity maxima, its boundary extends west of Estevan.

7.5 SASK Craton

The gravity and magnetic signatures of the SASK Craton is complex and lead to definition of six potentially distinguishable domains (Maps 23 and 24):

(1) Tobin gravity and magnetic high: Near the northern border, a narrow gun-shaped anomaly, this may also be subdivided into three distinct parts. The NE part is a body with correlated gravity and magnetic highs, the NW part combines magnetic high and gravity low, and the southern part is elongated toward south, with mid-intensity positive gravity and magnetic anomalies. The eastern edge of Tobin domain forms a clear boundary with SRBZ.

(2) **Smeaton**: This area consists of two parts, northern and southern. The northern block is Smeaton itself, which displays a characteristic negative magnetic low and positive gravity high. This could be associated with mafic granulites (Miles et al., 1997). Here, we find an abundance of NNNE-trending magnetic lineaments.

(3) **Southern Smeaton**: (SC2). This area reveals strongly different gravity and magnetic attributes and therefore is more likely to represent an intermediate zone.

(4) **SC1**: Strong gravity high extents into the study area from the west. This gravity high and its vertical derivative clearly separate this block from the adjacent zones. On the magnetic-source (pseudo) gravity maps, this anomaly also has a clear boundary.

(5) **Humboldt Zone**: This zone has clear NNW anomaly trends. The amplitudes of gravity and magnetic anomalies decrease from NW to SE forming long band-shaped, gradient trends. The magnetic lineaments follow these bands.

(6) **Weyburn Block**: It corresponds to gravity low including two sub-blocks. Its magnetic field suggests that the magnetic basement of this zone should be comparatively uniform and flat. Such topography could be beneficial for accumulation of hydrocarbons. Based on its magnetic and gravity attributes, the block may consist of three parts.

(7) **HRSBZ**: Two segments of this zone are present in our study area: the Wyoming Craton boundary and a short segment in the north-western corner. In both of these areas, the HRSBZ shows a characteristic strong negative magnetic low.

7.6 Wyoming Craton

Several short linear magnetic structures and four blocks are determined in the studied part of Wyoming Craton. Its eastern edge is defined by the North American Central Plains (NACP) electrical conductivity anomaly; however, in our study area the magnetic boundary appears somewhat different from the gravity field. In the western part of HRSBZ, gravity boundary practically coincides with NACP (Hajnal et al., 1996). However, near the southern edge of our study area, a belt of magnetic lows corresponds to the western part of HRSBZ.

8. Lineaments

Over any area of past or present active tectonics, surface structural alignments are often visible as expressions on topographic, geologic and geophysical maps. These lineaments become less distinct with age but are still important as indicators of past stresses, displacements, and disturbance patterns. Because the buried sediment-basement contact is not affected by erosion, these structural patterns remain imprinted in it and could be revealed from potential fields. Alignment of anomalies in geophysical maps provides important information for structural analysis; however, it still remains an open question whether all or most magnetic and gravity lineaments correspond to basement faults, folds, or other structural patterns.

At the same time, because gravity and magnetic field anomalies inherently represent spatial integration of physical properties, derivatives of the fields typically better correspond to block boundaries and other localized structural features. Therefore, in order to reveal such lineaments, high-resolution computational methods removing the slowly varying regional background and emphasizing gradients are required.

In this study, extraction of the smaller-scale lineaments was based on combining multiple data attributes. By combining the observations from various attribute maps and reducing the effects of noise and processing artefacts, a unified lineament structure was extracted. Our lineament extraction mostly relied on transformations of the magnetic and gravity fields that included the vertical and horizontal gradients, analytic signal, tilt derivative and several variants of local wavenumber mapping. Among these methods, the vertical gradient was the most important. The initial pattern of the lineaments was drawn mainly based on the vertical gradient contrasts, followed by and their refinement using other attribute maps extracted from the magnetic and gravity fields. As basement heterogeneities should affect both gravity and magnetic fields, we were preferentially looking for collocated contrasts in both of these fields.

The lineament map (Map 25) summarizes the most significant gravity and magnetic lineaments of which at least some should represent basement faults or other significant structures within the Williston Basin. The most prominent magnetic lineaments crossing the entire Williston Basin are the CSBZ and SRBZ boundaries. These structures change their trends from NWW in the south to N-S and NE in the north of the study area. Within the CSBZ, the lineament is better pronounced in the long-wavelength anomalies, suggesting that it should be associated with large-scale, structural deformation. Reindeer zone is clearly subdivided into two sections, northern and southern. Its northern part, the Flin Flon zone, is dominated by high-gradient, short-wavelength magnetic anomalies. By contrast, the southern part of this zone shows pronounced N-S trends. The Tabbernor fault extends for over 400 km along the western boundary of SRBZ (Miles et al., 1997), and some near N-S lineaments with moderately short wavelengths are located south of latitude ~51º.

Within the five primary elements, several major lineament features can be confidently recognized (Map 25). In the Superior Province, the dominant lineaments consist of approximately NNE and W-E-trending lineaments. Inside the Sask Craton, two lineament directions, NW and NE, form a criss-crossing pattern with the middle- and short-wavelength scale-lengths. Within the southern part of Reindeer zone, short-wavelength N-S trending lineaments are observed. Within the CSBZ and SRBZ, the dominant lineament patterns are parallel to their boundaries.

Longer-scale structures generally follow the directions of the domain and structural zone boundaries; at the same time, the shorter-scale features are often discordant with them and criss-cross each other, predominantly in the NE-SW and NW-SE directions. Note the abundance of NW-trending lineaments, with some of them even appearing to be connected into longer lines (Map 25).

Several long, linear, NW-SE trending regional lineaments extend from the Sask Craton across nearly the entire study area and into the Superior Province, overprinting the basement blocks of different tectonic origins and potential-field signatures (Map 26; Li and Morozov, 2005). The middle line of these structures separates the NE-trending structures within the CSBZ north of it from N-NNW trends to the south. This directional change also includes a change in smaller-scale structural patterns. Within the Reindeer Zone, magnetic anomalies south and north of this line also appear to change (Map 26). Such a contrast in gravity and magnetic patterns should undoubtedly correspond to a major regional NW-SE structure within the basement.

Three possible explanations of such regional structures were considered (Li and Morozov, 2006). First, as suggested by Thomson (1974) from regional structural analysis south of the study area, such NW-SE trends could be created by crustal faulting during the Laramide orogeny. This system was later overprinted by a secondary, NE-SW trending fault system. Alternately, Redly (1998) proposed that such lineaments could correspond to deep-seated basement structures related to the inferred paleo-tectonic boundary separating the Sask Craton and the western Superior Province from the Wyoming Province. However, the observed lineaments appear to cross-cut the Sask Craton and the western part of the Superior Province blocks, and therefore they should post-date the formation of these blocks. Finally, we also considered (Li and Morozov, 2005) whether such NW-trending structures could be of Phanerozoic age and potentially related to faulting associated with basin deposition. However, in such a case, one would expect such faults to correlate with the shape of basin, which does not appear to be the case. Instead, the lineaments appear to cross-cut the basin and maintain a consistent sub-parallel pattern.

Comparing the three hypotheses above, we suggest that the NW-SE-trending features should correspond to the primary crustal fragmentation identified by Thomson (1974). However, the entire lineament pattern of the Williston Basin (Maps 25 and 26) appears to be complex at can be described neither as the "lineament-block structures" suggested by Thomas (1974) nor as a simple fault pattern between plate units (Redly, 1998). When considered in more detail, the Williston Basin basement lineaments represent a combination of a criss-crossing NW-SE and NE-SW pattern with a more complex arcuate lineaments style.

9. Basement topography

The general structure of the Precambrian basement of the Williston Basin based on the bore-hole data was published by Burwash et al. (1994). This model provides the most important reference for regional analysis of the basin, but it lacks detail related to the potential basement faulting and block structure. Here, we attempt to improve this model by using the Euler deconvolution method (Reid et al. 1990; Pilkington et al. 2000), which is a semi-quantitative method for determining magnetic source depth.

In agreement with the starting drill-hole model (Map 21), Euler deconvolution of the aeromagnetic anomaly data shows that the depth to the basement increases from ~300 m near the margin of the Canadian Shield to over 3000 m towards the centre of the basin south of Weyburn. As the Euler method relies on the gradient of the magnetic field, the resulting depth readings relate primarily to the areas of basement heterogeneities, and thus only the local maxima in the resulting depth maps should be taken into consideration. In the subsequent interpretation, we are most interested in the relative local variations and positions of the boundaries, and estimation of the absolute depth relies mainly on the constraints from well log and seismic data.

The boundaries of the primary elements and major domains can be clearly recognized in the Euler depth map (Map 22). In addition, the map reveals some notable features that are not apparent in the original magnetic maps and in the basement map based on well data (Figure 4 and Burwash et al., 1994): (1)

generally shallower magnetization within the CSBZ and Reindeer Zone; (2) a significant structural low within the CSBZ (near N53º W100º, labeled *L* in Map 22), (3) south of Flin Flon, a circular structural group (labeled *H* in Map 22; this group is also clear in the gravity derivative Maps 6 and 7); (4) within the Sask craton, especially in its Weyburn block, several clear local structures can be recognized. These structures are discussed in the following section.

Interestingly, some of the interpreted basement lows appear to align across significant distances within the basin (Map 22). These alignment directions are not apparent in the original magnetic maps and in the localized lineaments and appear to cross the boundaries of the tectonic and structural zones and domains. Unlike the NW trends discussed above, they are oriented in NNE and NEE directions, and appear to converge near the edge of the basin. The nature of these regional anomalies is unclear; however, from their affinity to the edge of the basin and oblique orientation relative to the depth contours of the basin, they could potentially be related to basement faulting caused by loading associated with accumulation of the sediments.

Due to compositional variations, heterogeneity, and differences in its cooling history, magnetization of basement rocks should be non-uniform, and therefore magnetic sources should also be present within the basement. This appears to be the case that within the Kisseynew domain, where a distinct ~200-km wide area with 2.3 to 3.5-km deep magnetic sources is present. This suggests that a pronounced variation in rock properties should be located at that depth, with a change in magnetic susceptibility, direction of magnetization, or composition.

10. Conclusions

Regional Bouguer gravity and aeromagnetic anomaly mapping of the Williston Basin covering the region approximately between 49º – 56º N and -96º – -106º W resulted in a continuous tectonic framework of the Precambrian basement rocks within the SE Saskatchewan and SW Manitoba parts of the Williston Basin. Several new high-resolution imaging methods, such as extraction of the local wavenumbers, magnetic source pseudo-gravity gradient, Euler deconvolution, and feature extraction resulted in new attribute maps sensitive to the structural elements of the basement at different scale lengths. These maps reveal the complex geological structure of the Precambrian basement beneath the basin.

Major basement blocks and structural elements were identified from the integrated attribute maps. The Williston Basin was subdivided into six main regions with distinct internal structural patterns: (1) Superior Province which include nine domains; (2) Churchill-Superior Boundary Zone with two distinct sub-regions, (3) Reindeer and Flin Flon region; (4) Sask-Reindeer Boundary Zone; (5) Sask Craton subdivided into six sub domains; (6) Wyoming Craton. Within these structural zones and domains, geophysical lineament patterns were identified at different scale lengths, indicating the potential basement faults and lineament structures.

Across nearly the entire study area, a NW-SE magnetic lineament structure was observed that appeared to overprint the structural zones and domains. These structures were interpreted as associated with he initial crustal faulting during the Laramide orogeny. Smaller-scale lineament patterns within the basin were apparently created by further basement fragmentation during the subsequent tectonic evolution of the region.

New geophysical maps reveal the detail of the basement structure in oil-producing areas near Weyburn, SK. Compared to its surrounding areas, Weyburn basement is represented by a relatively uniform and deep basement block. Within this block, local structural subdivision is indicated by weaker linear contrasts.

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12. References

Brown, D. L., and D. L. Brown, 1987. Wrench-style deformation and paleostructural influence on sedimentation in and around a cratonic basin; in Williston Basin: Anatomy of a Cratonic Oil Province: Longman, M. W. (ed.): Rocky Mountain Association of Geologists, P. 37-70.

Burwash, R.A., McGregor, C.R. and Wilson, J.A., 1994, Precambrian Basement Beneath the Western Canada Sedimentary Basin, Geological Atlas of the Western Canada sedimentary Basin, 49-56. Alberta Research Council, 1994.

Cordell L. and Grauch V, 1985, Mapping basement magnetization zones from aeromagnetic data in the San Juan basin, New Mexico, The Utility of Regional Gravity and Magnetic Anomaly Maps, William J. Hinze Editor, Society of Exploration Geophysicists, P181-197.

Green, A.G., Cumming, G.L. and Cedarwell, 1979, Extension of the Superior-Churchill boundary zone into southern Canada. Can. J. Earth Sci., 16, 1691-1701. .

Hajnal, Z., Lucas, S., White, D., Lewry, J., Bezdan, S., Stauffer, M.R., and Thomas, M.D. 1996. Seismic reflection images of high-angle faults and linked detachments in the Trans-Hudson Orogen. Tectonics, v.15, 427-439.

Kreis, L. K., Ashton, K.E., and Maxeiner, R.O., 2000, Interpretive Geophysical Maps of Saskatchewan, Sask. Energy Mines, Open File Rep, 2000-2.

Li, J and Morozov, I. and Chubak G., 2004, Continuous Equivalent Surface approach for accurate interpolation and continuation, 2004 CSEG Convention, Calgary, Canada. www.cseg.ca/conventions/2004/technical.html.

Li, J and Morozov, I. and Chubak G., 2005, Potential-field Investigations of the Williston Basin Basement, In Summary of Investigations 2005, Volume 1, Saskatchewan Geological Survey, Sask Industry Resources, Misc. Rep. 2005-4.1, Paper A5,11p.

Li, J and Morozov, I., 2006, Structure Styles of the Williston Basin Basement from Geophysical Mapping, In Summary of Investigations 2006, Saskatchewan Geological Survey, Sask Industry Resources.

Lyatsky, H. V. and Dietrich, J. R., 1998, Mapping Precambrian basement structure beneath the Williston Basin in Canada: Insight from horizontal-gradient vector processing of regional gravity and magnetic data. Canadian Journal of Exploration Geophysics, Vol.34, Nos. 1&2, 40-48.

Miles, W., Stone, P.E. and Thomas, M.D., 1997, Magnetic and Gravity Maps with Interpreted Precambrian Basement, Saskatchewan, Scale 1:1500000, GSC Open file 3488.

Pilkington, M. and Thomas, M.D., 2001, Magnetic and Gravity Maps with Interpreted Precambrian Basement, Manitoba, Scale 1:1500000, GSC Open file 3739.

Pilkington, M., Miles, W.F., Ross, G.M. and Roest, W.R., 2000, Potential-field signatures of Buried Precambrian basement in the Western Canada Sedimentary Basin, Can. J. Earth Sci., 37: 1453-1471.

Redly P., 1998, Tectonostratigraphic evolution of the Williston Basin, PhD Thesis, University of Saskatchewan, Saskatoon, SK, 360pp.

Reid, A.B., Allsop, J.M., Granser, H., Millete, A.J., and Somerton I.W., 1990, Magnetic interpretation in three dimensions using Euler deconvolution, Geophysics, 55, 80-91.

Roest, W.R., Verhoef, J. and Pilkington, M., 1992, Magnetic interpretation using the 3-D analytic signal, Geophysics, 57, pp116-125.

Thomas, G. E., 1974. Lineament-block tectonics, Williston-Blood Creek Basin, American Assoc. Of Petroleum Geologists Bull., 58, 1305-1322.

Verduzco B., Fairhead J., Green M., and MacKenzie C., 2004, New insights into magnetic derivatives for structural mapping, The Leading Edge, 23, 116 – 119.

Wessel, P. and Smith, W.H.F. (1995): New version of the Generic Mapping Tools released; EOS Trans. Am. Geophys. U., v76, p329.

White, D. J., Thomas, M.D., Jones, A. G., Hope, J., Nemeth, B. and Hajnal, Z., 2005, Geophysical transect across a Paleoproterozoic continent-continent collision zone: The Trans-Hudson Orogen, Can. J. Earth Sci. 42: 385-402.