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MAPPING PRECAMBRIAN BASEMENT STRUCTURE BENEATH THE WILLISTON BASIN IN CANADA: INSIGHTS FROM HORIZONTAL-GRADIENT VECTOR PROCESSING OF REGIONAL GRAVITY AND MAGNETIC DATA

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ABSTRACT

Horizontal-gradient vector (HGV) processing of regional gravity and aeromagnetic data from southeastern Saskatchewan and southwestern Manitoba is undertaken as part of a study of Precambrian basement geology beneath the Williston Basin in Canada. The HGV method resolves potential-field anomalies in more detail than do many other data enhancement techniques. In HGV maps, the horizontal gradient of the gravity or magnetic field is treated as a vector, having both a direction and magnitude. The gradient is represented on a map as an arrow with an origin at a grid node. Varying the arrow polarity (uphill or downhill – towards or away from local maxima in the potential field) provides HGV displays with differing images of potential-field anomaly fabric.

HGV patterns within the study area are highly variable and include linear and curvilinear anomalies of varying orientations, and circular and ovoid anomalies occurring singly and in curvilinear belts. These patterns indicate crystalline basement beneath this part of the Williston Basin is composed of a complex mosaic of crustal belts, faults, and plutons.

The analysis of HGV-processed potential-field data provides new insights into the crustal structure and tectonic fabric of the Archean Superior Province, Proterozoic Trans-Hudson Orogen, and intervening Churchill-Superior boundary zone beneath the northern Williston basin. East-west and north-south aligned potential-field anomalies outline the main Kenoran (2.8-2.4 Ga) and Hudsonian (1.9-1.8 Ga) age crustal fabrics, respectively. In magnetic HGV maps, the transition from E-W-trending (Superior Province) to N-S-trending (Churchill Province) crustal fabrics commonly appears gradational or irregular, suggesting the Churchill-Superior "boundary zone" within the study area is broad and structurally segmented. In gravity HGV maps, a prominent N-S aligned belt of ovoid-shaped anomalies appears to provide a regionally consistent potential-field signature for part of the boundary zone. The Tabbernor fault zone in the central Trans-Hudson Orogen can be identified in magnetic HGV maps, but is not readily apparent in gravity maps.

Interpretation of Precambrian basement domains and trends provides a regional framework for detailed investigations of basement-sedimentary cover interaction in this economically important part of the Williston Basin.

INTRODUCTION

In hydrocarbon exploration and sedimentary basin research programs, potential-field data can provide valuable information (at relatively low cost) about crystalline-basement geologic fabrics and structures that may have influenced the sedimentary cover. In this paper we present a summary of interpretations of Precambrian basement domains and structures beneath the northeastern Williston Basin, based on horizontal-gradient vector (HGV) processing of public-domain gravity and aeromagnetic data, and briefly discuss the utility of *regional potential-field studies in evaluating basement-sedimentary cover interaction*. The Williston Basin has substantial proven hydrocarbon resources and recent oil discoveries in Ordovician strata indicate the considerable potential for prospects and plays in deeper parts of the basin, many of which may have ties to basement geology.

We utilize regional (2 km-gridded) Bouguer gravity and IGRF-reduced magnetic data from the National Gravity and Aeromagnetic Database of the Geological Survey of Canada. Detailed information on the study-area potential-field data coverage and acquisition parameters, and a more comprehensive set of HGV displays, are contained in Geological Survey of Canada open file report 3614 (Lyatsky et al., 1998). Studies of basement-sedimentary cover interaction in the Williston Basin are the focus of continuing research (Dietrich et al., 1998).

Study Area

The study area covers some 120 000 km^2 of southeastern Saskatchewan and southwestern Manitoba (49° to 52° N latitude, 99° to 104° W longitude; Fig. 1). The thickness of Phanerozoic sedimentary strata (and depth to basement) increases in a southwest direction across the study area, from a few hundred metres in the northeast corner to over 3000 metres in the southwest corner. Precambrian crystalline basement beneath this part of the Williston Basin consists of parts of two major crustal provinces and their boundary zone: the Archean Superior Province to the east, the Early Proterozoic Trans-Hudson Orogen to the west, and the intervening Churchill-Superior boundary zone. The Churchill-Superior boundary zone (Fig. 1) is a complex transition zone between the Superior Province (that has a predominantly E-W fabric and has been stable since the 2.8-2.4 Ga Kenoran

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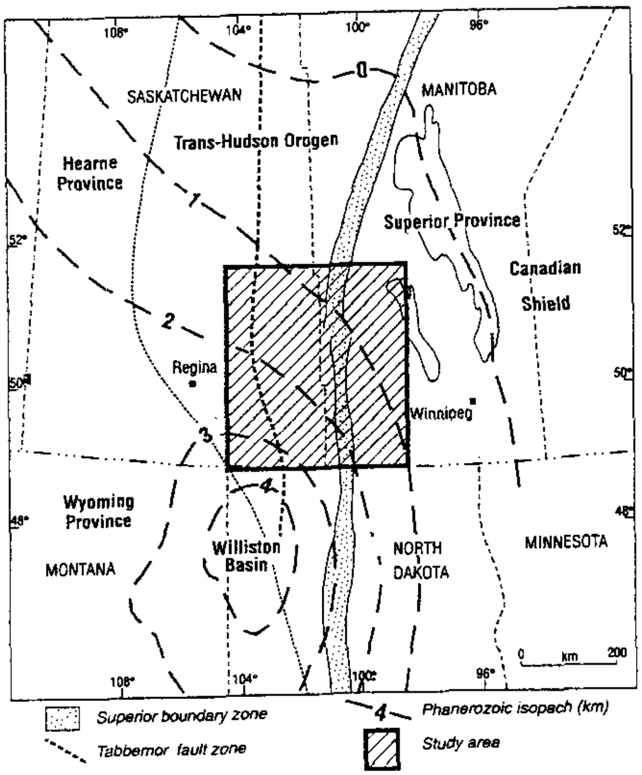

Fig.1. Location of study area in relation to Precambrian tectonic provinces (modified from Green et al., 1985., and Klasner and King, 1986) and Phanerozoic Williston Basin.

orogeny) and the eastern Churchill Province (Trans-Hudson Orogen), a region with a more variable fabric that was molded by the 1.9-1.8 Ga Hudsonian orogeny (Green et al., 1979; Weber, 1990). The Tabbernor fault zone (Fig. 1) is a N-S trending fault system in the core of the Trans-Hudson Orogen. The subsurface locations of these crustal elements were mapped in the 1970s and 1980s through extrapolation of potential-field and other geophysical signatures from exposed Precambrian Shield areas in northern Saskatchewan and Manitoba southward beneath the Williston Basin (Green et al., 1979, 1985; Klasner and King, 1986; Thomas et al., 1987). At the time of these studies, aeromagnetic data coverage was incomplete in many parts of southern Saskatchewan and Manitoba. As a result of several aeromagnetic acquisition programs in the 1990s, there is currently a complete-coverage magnetic data set for the study area.

HORIZONTAL-GRADIENT VECTOR (HGV) PROCESSING

The HGV method of processing potential-field data was proposed originally by Lyatsky et al. (1990) as a technique to enhance subtle anomalies. The first published applications of this method were from studies of the Queen Charlotte Basin offshore British Columbia, and the Peace River Arch region of Alberta (Lyatsky et al., 1992a, b). In these studies, HGV processing of public-domain GSC data helped resolve patterns of basement faults and plutons. In a more recent study of the central Alberta part of the Western Canada Sedimentary Basin, Edwards et al. (1998) integrated HGV-processed potential-field data with well-data information to infer basement controls on Phanerozoic geology.

Computational aspects of the HGV method were discussed by Lyatsky et al. (1990, 1992a, b, 1998), Thurston and Brown (1994). The HGV technique recognizes the horizontal gradient of a potential field as a vector quantity having both a magnitude and direction. The meaning of the horizontal gradient can be understood by considering a potential-field anomaly map in terms of relief. The direction of the gradient is perpendicular to the amplitude contours, and the gradient's magnitude is the "steepness" of the slope in that direction. At a point on a map, the horizontal gradient is represented by an arrow whose length is proportional to the gradient magnitude and whose pointed direction is the direction of the gradient. HGV arrows can be plotted either towards or away from the local maxima in the potential field ("uphill" or "downhill"), and scaled either linearly or logarithmically. Logarithmic scaling is particularly useful for regional magnetic data, which typically display wide ranges of gradient values.

For the study-area data sets, the benefits of HGV processing are apparent from a comparison of conventional gravity and magnetic contour maps (Figs. 2 and 3) and HGV maps (Fig. 4). The HGV displays significantly enhance anomaly details and trends. Synthetic modelling tests have demonstrated that HGV-processed data are particularly useful for identifying and mapping faults and block edges (Edwards and Lyatsky, 1996; Edwards, 1997). Linear gravity and magnetic gradients (that commonly mark regional faults) are visually enhanced in HGV displays, as the length and density of plotted vector arrows is greatest in steep gradient zones. Gravity HGV maps of the study area (Fig. 4) also appear to be particularly useful in outlining curvilinear belts of ovoid anomalies and anomaly clusters that may be signatures of plutonic or magmatic arcs.

SOURCES OF GRAVITY AND MAGNETIC ANOMALIES IN THE STUDY AREA

Bulk density is the rock property whose variations relate a gravity anomaly to its geologic source. While there is no precise correlation between density and rock type, igneous and metamorphic crystalline rocks are generally denser than most sedimentary rocks, with mafic crystalline rocks typically of higher density than felsic ones. Lateral rock-density contrasts that produce gravity anomalies can occur at any level within, above or below the crystalline crust.

For the Western Canada Sedimentary Basin, practical interpretation experience and quantitative modelling studies (e.g., Anderson et al., 1988) show that gravity anomalies from intra-sedimentary density variations are typically small in amplitude. In the study-area data set, the vast majority of gravity anomalies reflect lateral density variations within the crystalline crust.

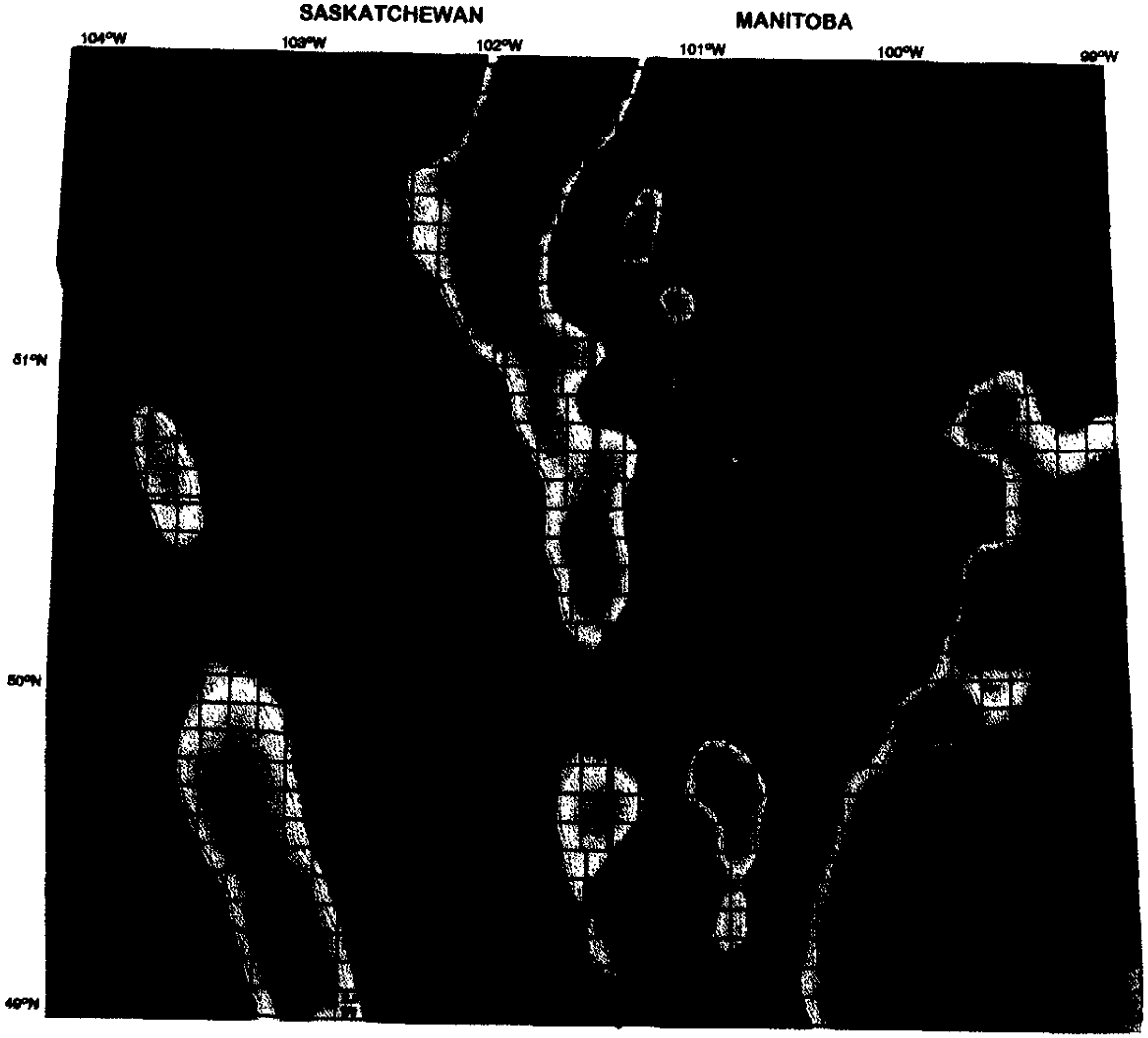

Fig. 2. Regional gravity anomaly map of southeast Saskatchewan/southwest Manitoba (Township/Range grid in background). Red and yellow colours outline gravity highs (> –40 mgal), blue and purple colours outline gravity lows (< –60 mgal).

Total magnetization is the rock property that relates a magnetic anomaly to its geologic source. The most common magnetic mineral is magnetite, and there is generally a correlation between rock magnetite content and its magnetic susceptibility. Magnetic minerals occur most commonly in igneous and metamorphic rocks, but there is no precise relationship between rock type and magnetic susceptibility. Sedimentary rocks are generally less magnetic.

Magnetic anomalies recorded over the Western Canada Sedimentary Basin are usually attributed to crystalline basement sources (Ross et al., 1994a). In the Alberta part of the basin, examples have been documented of local occurrences of intra-sedimentary magnetic anomaly sources, including igneous dykes and mineralized faults (Ross et al., 1994b; Peirce et al., 1998). While intra-sedimentary magnetic sources are likely present in parts of the Williston Basin, the vast majority of magnetic anomalies in the study-area data set are believed to reflect lateral variations in the distribution of magnetic minerals within the uppermost part of the crystalline crust.

In the western Canadian Shield and adjacent basement beneath the Western Canada Sedimentary Basin, spatial variations in rock density and magnetic-mineral content generally mimic regional fabrics associated with Precambrian magmatism, metamorphism and ductile deformation (Sprenke et al., 1986; Leclair et al., 1997). Detailed studies correlating gravity and magnetic data with geologic field maps and drill-core data have shown that linear and round potential-field anomalies are common signatures of basement fault zones and primary magmatic (plutonic) fabrics, respectively.

POTENTIAL-FIELD ANOMALY PATTERNS

Major potential-field anomaly trends are E-W, NNE and

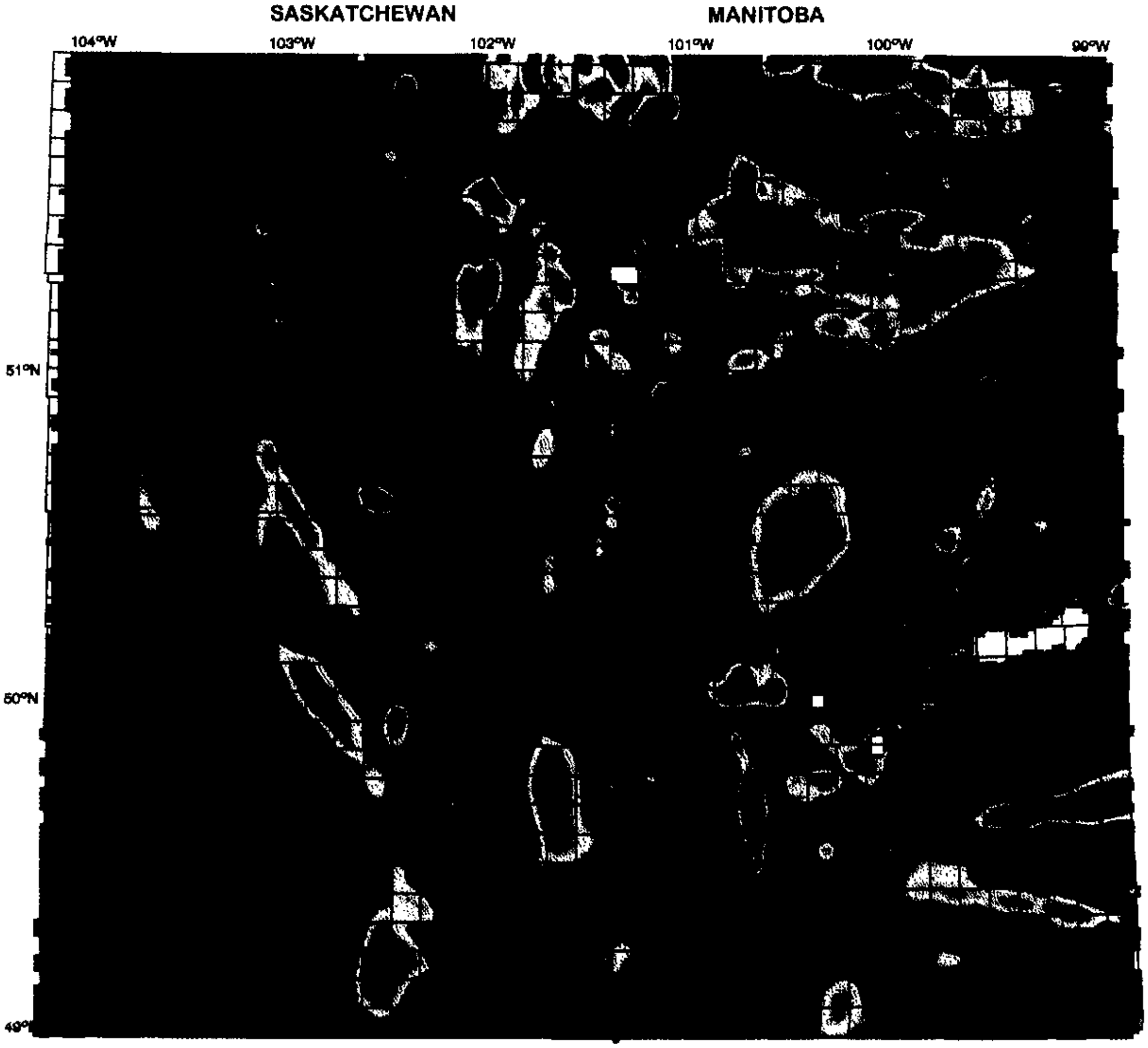

Fig. 3. Regional magnetic anomaly map of southeast Saskatchewan/southwest Manitoba (Township/Range grid in background). Red and yellow colours outline magnetic highs (> 300 nT), blue and purple colours outline magnetic lows (< 50 nT).

N-S in southwestern Manitoba, and N-S and NNW in southeastern Saskatchewan (Figs. 2 and 3). As defined in previous studies (Green et. al., 1979, 1985), E-W magnetic anomaly trends are characteristic of the Superior Province, and N-S magnetic anomaly trends are characteristic of the Churchill Province and Churchill-Superior boundary zone. In the study area, E-W anomaly trends are apparent in the southeastern and northeastern parts of the magnetic map. North-trending magnetic and gravity anomalies are prevalent west of 101° W. The eastward transition from N-S to E-W trending magnetic anomalies commonly appears gradational or irregular. In previous studies, the location of the Churchill-Superior boundary zone was correlated to a "magnetic quiet zone", a series of magnetic lows extending across western Manitoba and North Dakota (Green et al., 1979, 1985; Klasner and King, 1986). Within the study area, the magnetic quiet zone is represented by several disconnected and irregular-shaped magnetic lows, located along or near 101° W longitude (Fig. 3) Overall, the magnetic signature of this zone appears variable and complex.

In the western part of the study area (near 103° W longitude), a prominent change in the general character of the magnetic anomaly field is apparent: from relatively high-relief anomalies in the east to low-relief anomalies in the west. The boundary between these two magnetic domains lies on trend with the Tabbernor fault zone, located in the central part of Trans-Hudson Orogen.

Gravity HGV Anomaly Domains

Two regional-scale anomaly domains are apparent in gravity HGV data (Fig. 5).The gravity domain division and anomaly trends are also apparent in the gravity contour map (Fig. 2), but with much less clarity than in the HGV maps.

Domain I is characterized by a diffuse collection of circular and ovoid HGV anomalies, with little coherent regional

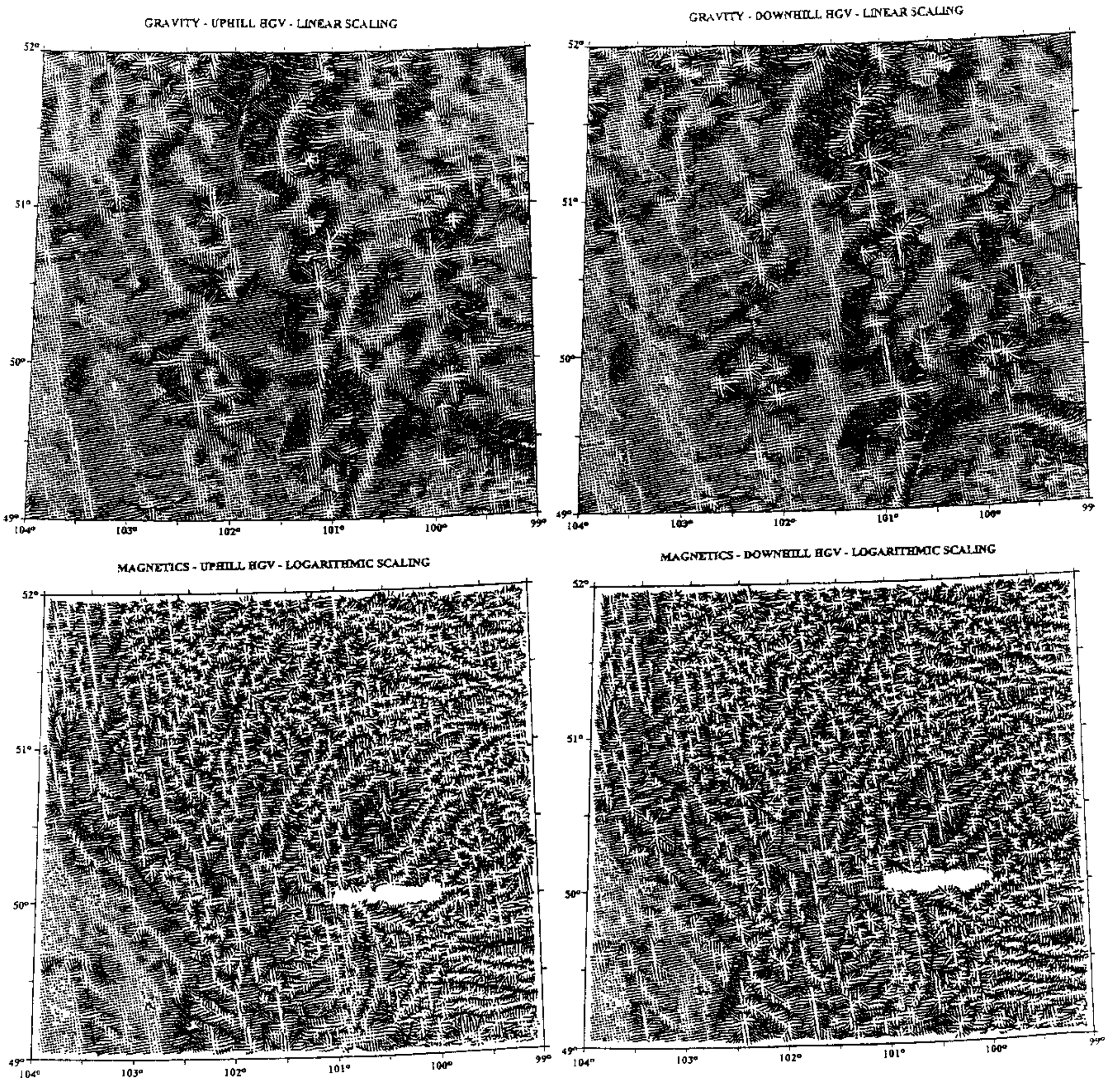

Fig. 4. Gravity and magnetic horizontal-gradient vector maps of study-area data. Top left – gravity uphill; top right – gravity downhill; bottom left – magnetic uphill; bottom right – magnetic downhill. Gravity vector arrows are scaled linearly, magnetic vector arrows are scaled logarithmically. Small blank area in magnetic HGV maps indicates a data-coverage gap at the time of our HGV processing. Compare HGV displays with more conventional gravity and magnetic anomaly displays in Figs. 2 and 3.

fabric. A few linear anomalies with E-W and WNW trends occur in the southern and western parts of Domain I. In contrast, Domain II (to the west) is characterized by a pronounced anomaly fabric, expressed by N-S, NNW, and other less prevalent HGV anomaly trends. Linear HGV anomalies are significantly more abundant in Domain II than in Domain I. The eastern margin of Domain II is marked by a prominent N-S trending band of circular/ovoid anomalies (II-B in Fig. 5). This anomaly zone appears to be laterally offset in an E-W direction, near 51° N. A second, somewhat more irregular, N-S aligned band of ovoid anomalies and anomaly clusters occurs within Domain II (II-C in Fig. 5).

The long, linear gravity HGV anomalies in Domain II are believed to be indicative of intra-basement fault zones or crustal block edges. The faults/block edges are commonly straight and vary in length from 10 to 90 km. The longest, most regionally consistent gradient anomaly (fault zone?) occurs in the westernmost part of the study area (II-D in Fig.

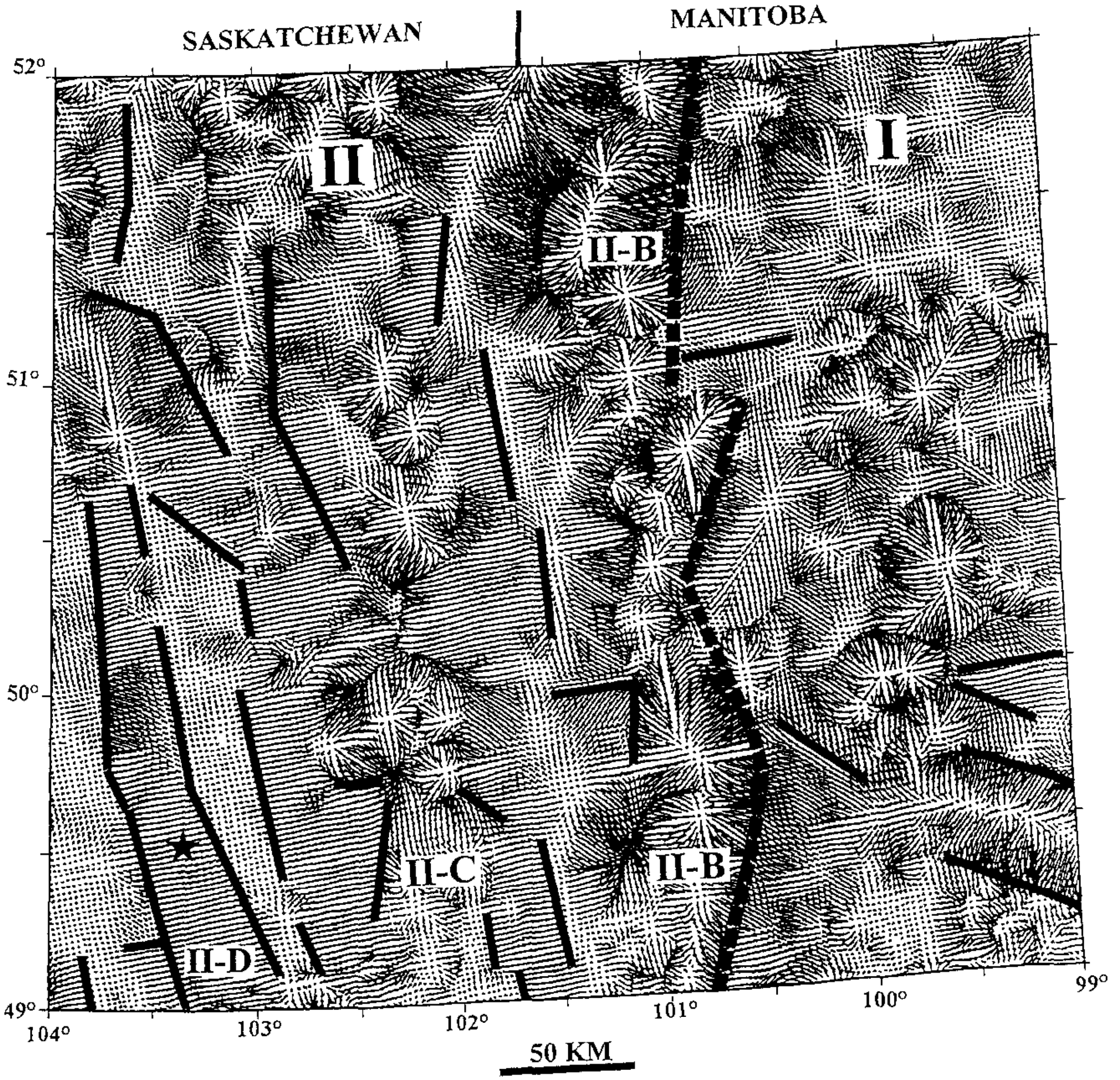

Fig. 5. Gravity HGV map (arrows point "downhill", away from maxima), with interpreted gravity anomaly domains I and II, and anomaly features II-B, II-C and II-D. Heavy dashed line indicates domain I-II boundary and corresponding eastern edge of II-D anomaly belt. Solid line segments indicate edges of (linear) gravity gradient zones. Star in SW corner of study area indicates location of Midale (Ordovician) oil field. See text for discussion.

5). The circular and ovoid gravity HGV anomalies are generally considered to be indicative of plutons and pluton clusters, with the II-B and II-C curvilinear anomaly trends probably marking magmatic arcs. The occasionally observed off-centre position of their apices (relative to the anomaly base) indicates some of the causative plutons may be asymmetric or tilted. Ovoid gravity anomalies are both positive and negative (the former being more common), suggesting differences in pluton composition.

Magnetic HGV Anomaly Domains

Five major anomaly domains are apparent in the magnetic HGV data (Fig. 6). The domains are generally apparent in the total-field contour map (Fig. 3), but again with less clarity than in the HGV maps. Some HGV magnetic domain boundaries are abrupt, while others appear gradational. The locations of domain boundaries in some areas are only approximate.

Domain I, in the easternmost part of the study area, is characterized by a predominance of E-W aligned linear mag-

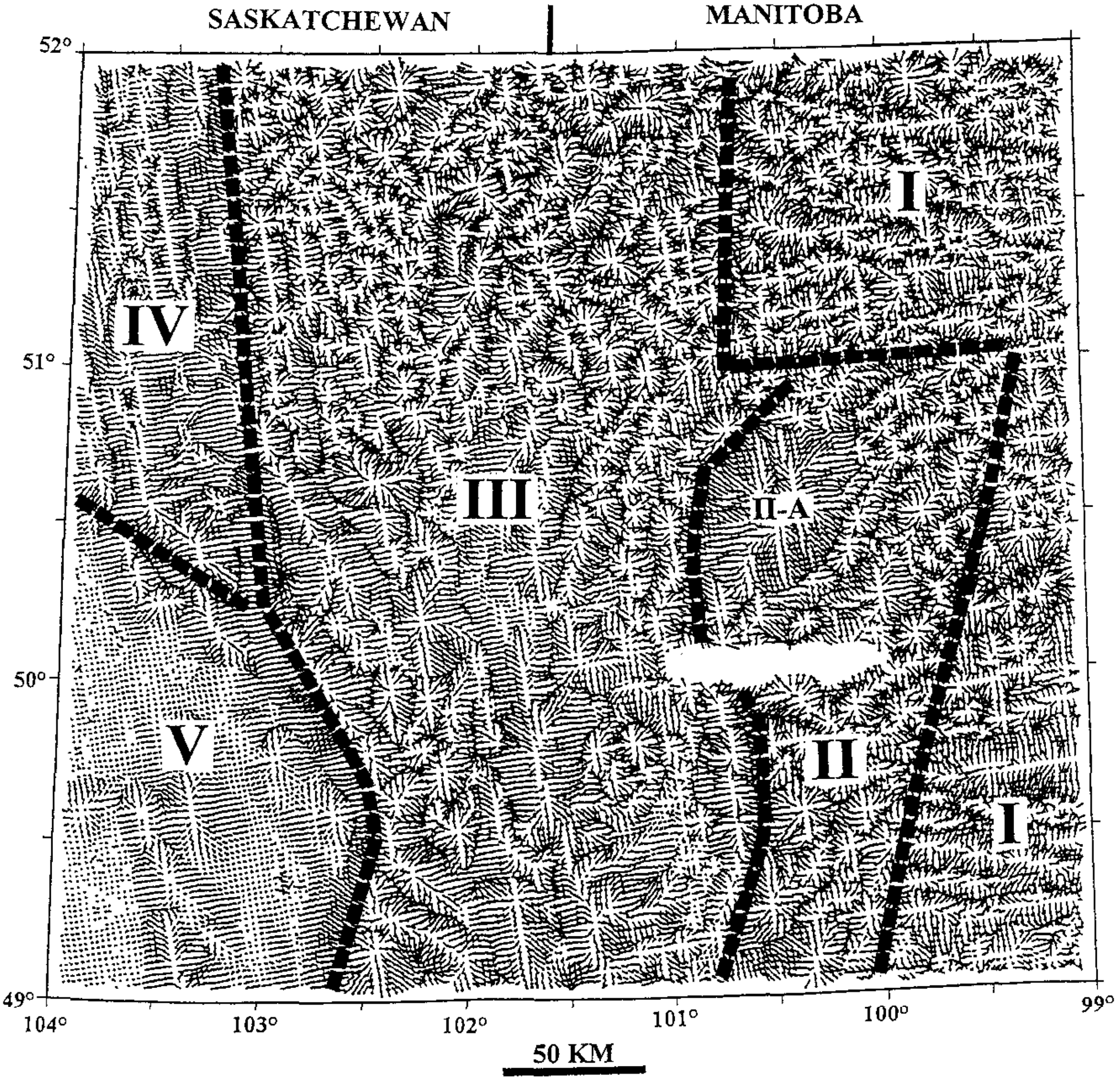

Fig. 6. Magnetic HGV map (arrows point "downhill", away from maxima), with interpreted magnetic anomaly domains I to V, and anomaly feature II-A. See text for discussion.

netic anomalies. The E-W anomaly trends extend farther west in areas north of 51°N than in areas to the south. This apparent offset in the domain's western boundary occurs at the same latitude as the gravity II-B anomaly offset.

Domain II is characterized by more variable anomaly patterns, including NNE- and NNW-trending ovoid anomaly clusters, and a single large ovoid anomaly feature (II-A in Fig. 6). Domain III, in the central part of the study area, is characterized by a mix of linear and ovoid anomalies, with a predominance of N-S, NNE and NNW trends. Conjugate sets of NW- and NE-trending anomalies are locally apparent in parts of this domain.

Domain IV, in the northwestern part of the study area, is characterized by a predominance of NNW trending linear anomalies. Although some anomaly orientations are similar to those in parts of Domain III, Domain IV is differentiated on the basis of a more subdued anomaly field and a reduction in the number of small ovoid anomalies (which occur in abundance in Domain III). Domain V, in the southwestern part of the study area, is characterized by a subdued magnetic anomaly field and lack of a dominant fabric. The south-central part of the domain contains a cluster of linear and ovoid anomalies with NNW and NW trends. The margins of Domain V are marked by NW- and NE-trending linear anomalies, with a particularly sharp contact at the southernmost domain III-V boundary.

As in the Canadian Shield, many of the long, linear magnetic HGV anomalies in the study area are probably associated with basement shear zones. Most of the ovoid magnetic HGV anomalies are probably associated with igneous plutons or batholiths. The ovoid anomalies are most commonly associated with magnetic highs. The large ovoid anomaly II-A (in Domain II) is probably associated with an igneous batholith. Anomaly II-A appears as a broad, relatively uniform feature in the total-field magnetic contour map (Fig. 3), whereas magnetic HGV maps indicate the anomaly has significant internal complexity (Figs. 4 and 6).

INTERPRETATIONS OF PRECAMBRIAN CRUSTAL ARCHITECTURE

Based on anomaly patterns and trends, the areas of gravity Domain I (Fig. 5) and magnetic domains I and (?)II (Fig. 6) are interpreted to be part of the Superior crustal province, while gravity Domain II and magnetic Domain III probably encompass the Churchill-Superior boundary zone and eastern part of the Trans-Hudson Orogen. The north-trending, gravity II-B anomaly belt (Fig. 5) is a pronounced, regionally consistent feature that may provide the best signature of the Churchill-Superior boundary zone (or a part thereof) within the study area. This gravity anomaly trend can be traced NNE, beyond the study area to the Thompson Belt (Churchill-Superior boundary zone) within and adjacent to the exposed Canadian Shield (Lyatsky et al., 1998). Within the study area, the gravity II-B trend closely parallels the eastern margin of magnetic Domain III (Fig. 6).

The complexity of magnetic HGV patterns in the general area of the Churchill-Superior boundary zone (e.g., Domain II) suggest there may be considerable overlap and interpenetration of Superior (Kenoran) and Churchill (Hudsonian) tectonic fabrics. Both gravity and magnetic HGV patterns indicate the boundary zone is probably segmented by transverse structures, including at least one major east- or northeast-trending feature near latitude 51° N.

The most abrupt magnetic domain boundary within the study area is associated with the western margin of Domain III (Fig. 6). In detail, this domain boundary consists of at least three linear segments, each of different orientation (N-S, NNW, and NNE). These segments could represent strands of the Tabbernor fault system. The along-strike variation in fault orientation indicates complex or multi-phase tectonism. In the gravity data, Domain II contains many linear gravity HGV anomalies that are probably indicative of faults, but there is no single linear anomaly or anomaly zone that extends across the entire map area coincident with the magnetically-defined Tabbernor fault zone. Still, the gravity anomalies within this area generally follow the N-S and NNW trends that characterize much of the Tabbernor fault system.

BASEMENT-SEDIMENTARY COVER LINKAGES

Over the past decade, recognition has grown that steep basement faults have probably influenced development of many linear geologic trends in the platformal sedimentary cover in western Canada (e.g., Greggs and Greggs, 1989; Misra et al., 1991; Edwards et al., 1998). Published regional seismic profiles from central Alberta and Saskatchewan indicate faults and other basement-surface structures that affect Phanerozoic strata are relatively small-scale features (e.g., Zhu and Hajnal, 1993; Eaton et al., 1995). Most basement-surface and intra-sedimentary structures probably have very subtle if any signature in regional gravity and magnetic data sets (such as used here) that are overwhelmingly dominated by anomalies associated with Precambrian orogenic structures. Nonetheless, basement-cover linkages can often be interpreted from integration of regional potential-field data with seismic and well data. As one example in the study area, we note the spatial correspondence of a recently discovered Ordovician oil field in southeastern Saskatchewan with a regionally prominent, NNW-aligned gravity HGV anomaly (II-D in Fig. 5). The Midale field is known to be structurally controlled by small NNW-aligned basement-surface fault blocks (Haidl et al., 1996; Dietrich et al., 1998). These local basement structures may be linked to a larger-scale crustal fault zone, as suggested by the cospatial linear gravity gradient zone. If so, the gravity data may be useful in outlining an exploration fairway.

CONCLUSIONS

HGV-processed regional potential-field data are used in this study to interpret Precambrian basement domains and structural trends beneath the northeastern Williston Basin. This analysis provides a framework for more detailed evaluations of basement-sedimentary cover relationships, based on integration of potential-field, seismic and well data information.

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