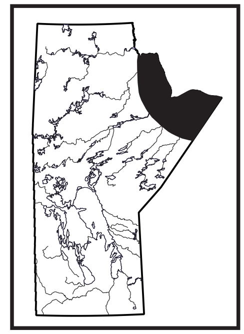
# GS-7 Lineament mapping of the Hudson Bay Lowland using remote-sensing methods, northeastern Manitoba (parts of NTS 53N, O, 54)

by M.P.B. Nicolas and B.W. Clayton[1]



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## Summary

Lineament mapping of the Hudson Bay Lowland was done by remote-sensing methods, using multiple GIS information layers that include digital elevation models, geophysical data, surficial-geology maps, and Precambrian and Phanerozoic bedrock-geology maps. Information layers were viewed at different scales, and lineaments not obviously related to glacial or postglacial landforms were digitized.

Lineament-trend data plotted on bidirectional rose diagrams reveal that the dominant trends are roughly north (005–010°) and east (095–100°), with less dominant trends in the southeast and northeast directions. The trend data are interpreted to reflect two sets of orthogonal fractures in bedrock. The dominant set is suggested to result from burial and exhumation events in the Hudson Bay Basin, whereas the secondary set is suggested to reflect Precambrian basement structure. Less abundant trend data in the east-southeast and east-northeast directions may result from the effects of glacial loading and isostatic rebound on recent sediments and sedimentary rocks.

Establishing potential fracture trends in the Phanerozoic bedrock and combining this with basin evolutionary history is a first step toward understanding basin dynamics over time. A compilation and statistical analysis of lineament-trend data, inferred to reflect fracture sets in bedrock, may also provide some indication of paleostress directions. Hence, lineament-trend data may provide some insight into potential fluid-flow directions, or migration paths, for groundwater, hydrothermal fluids and hydrocarbons.

## Introduction

The work described herein is part of the Manitoba Geological Survey's contribution to the second phase of the Geological Survey of Canada's Geo-mapping for Energy and Minerals program (Hudson-Ungava Project).

Quaternary sedimentary cover obscures the Paleozoic bedrock throughout most of the Hudson Bay Lowland (HBL). Although many surficial linear features in the HBL are related to glacial and postglacial landforms (moraines, eskers, beach ridges), modern hydrographic and erosional patterns are also influenced by fractures that occur regionally in the bedrock (e.g., McRitchie and Weber, 1970; McRitchie, 1997; Nicolas, 2012). These fractures can control the courses of streams and rivers, and documenting these deviations can provide insight into possible patterns of fractures (i.e., joints or faults) in bedrock.

Identifying fracture patterns by compiling lineament data has been done in Manitoba in the past using various methods and different types of information, such as mapped bedrock faults and fractures, structure and isopach maps, and erosional trends (e.g., McRitchie, 1997; Nicolas, 2012). Fracture patterns inferred from lineament data can help constrain the potential orientations of paleostresses that acted upon the bedrock through geological history, and can provide evidence for buried faults and other structural features.

The purposes of this study are to 1) survey the HBL in northeastern Manitoba, using remote-sensing methods, to establish the locations and trends of lineaments likely controlled by basement structure; and 2) compile the resulting trend data to gain insight into possible regional fracture patterns in bedrock and identify any other buried structural features.

## Regional geological structure

The bedrock beneath the HBL consists of several Precambrian domains made up of metamorphosed and deformed sedimentary, volcanic and plutonic rocks, overlain by the gently northeast-dipping Paleozoic carbonate-dominated sequence of the Hudson Bay Basin (HBB) and capped by Quaternary glacial and postglacial sediments.

Figure GS-7-1 shows major structural features in the Precambrian basement (McGregor, 2013) in relation to the overlying Paleozoic sequence. Precambrian domain boundaries are curvilinear, generally trend northeast and bound domains that contain highly variable structural trends, as inferred from regional aeromagnetic data. Dike swarms crosscut the domains, particularly south of the Nelson River; a few dike swarms also occur northwest of the Churchill River (McGregor, 2013), with general southeasterly trends. Trends of magnetic linears (e.g., McGregor, 2013) roughly parallel the domain boundaries but, in some instances, are truncated at near-acute angles

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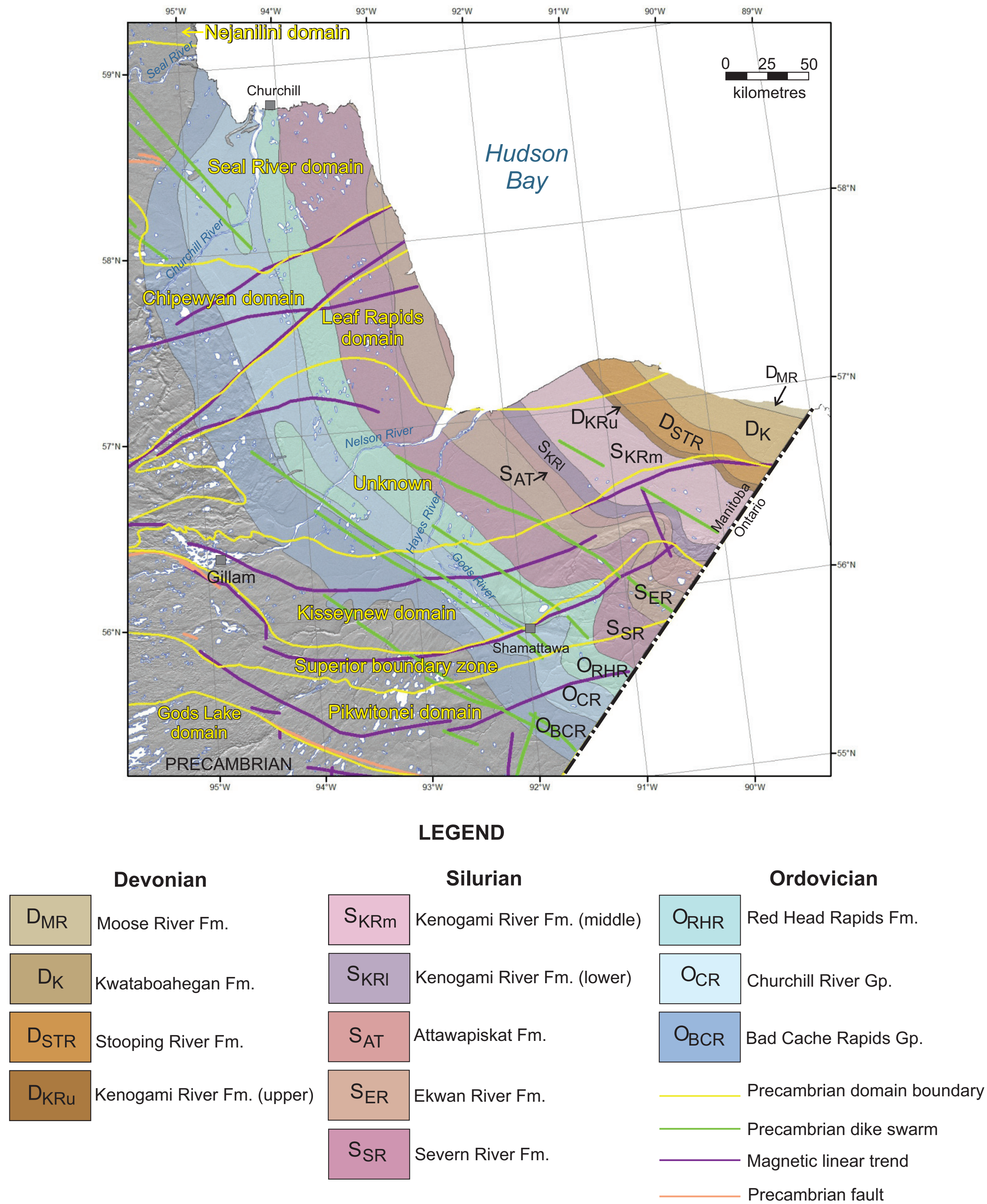


***Figure GS-7-1:** Paleozoic geology of the Hudson Bay Lowlands, northeastern Manitoba (modified from Nicolas et al., 2014) superimposed on a 90 m pixel-spacing digital elevation model (United States Geological Survey, 2002), and overlain with the Precambrian domain boundaries, magnetic linear trends, faults and dike swarms (from McGregor, 2013).*

to these boundaries, suggesting the presence of discordant basement faults. Domain boundaries in the exposed Precambrian shield are often associated with major shear zones or faults, but the exact nature of the domain boundaries beneath the HBL is unknown. Basement faults can form zones of weakness in the lithosphere during crustal loading or under applied tectonic stress and will invariably affect overlying sedimentary sequences during sediment deposition and postdepositional compaction.

The HBB is an intracratonic basin that has a long axis oriented roughly north-south and the typical bowl shape in cross-section, with thickest and youngest sedimentary rocks occurring in the middle and thinning outward (Sanford and Grant, 1999). However, reinterpretation of historical seismic profiles within Hudson Bay, in combination with new stratigraphic and geochemical information (Zhang and Barnes, 2007; Hu et al., 2011; Lavoie et al., 2013; Pinet et al., 2013), reveal a more complex morphology.

During and after sediment deposition, the basin underwent several burial and exhumation events, which included tilting of the entire basin (suspected to be caused by large-scale mantle flow in the continental interior) that resulted in changes in the depositional centre over time, and complex normal (or transtensional) faulting in the centre of the basin (Pinet et al., 2013). The model of Pinet et al. (2013) indicates that tectonic subsidence during the Devonian provided the depths and temperatures necessary for organic-rich mudstone and shale to reach the critical conditions for hydrocarbon formation. Of particular interest to this study are the fault arrays described by Pinet et al. (2013), which trend subparallel to the long axis of the basin (i.e., roughly north-south).

More recent stresses on the HBB sedimentary rocks and underlying Precambrian rocks result from crustal loading during the last ice age. The Laurentide Ice Sheet is estimated to have had a peak thickness of ~3.4 km during the last glacial maximum, as measured just west of Hudson Bay near Arviat, Nunavut (Simon et al., 2014). This ice sheet is estimated to have depressed the crust 100–300 m from its current elevation (Shilts, 1986), with the result that isostatic rebound is still occurring today at a rate of 9.3 ±1.5 mm/year near Arviat (Simon et al., 2014). Although most bedrock fractures relate to ancient tectonic stresses, late-stage glacial loading is potentially significant and should be considered when evaluating fracture development and fluid flow (Grasby et al., 2000; Grasby and Chen, 2005).

## Bedrock fractures and lineaments

During erosion of the landscape, bedrock fractures can serve as preferred conduits for water, thus becoming more susceptible to dissolution (karsting) and resulting in topographic expressions and areas of structural disturbance. In such cases, bedrock fractures can be manifested as linear topographic features (lineaments); hence, lineament-trend data can be reflective of basement structure. Distinguishing whether a lineament is due to a joint or a fault is generally impossible without physical evidence, so the general term 'fracture' is used here. Lineaments can also be observed in aeromagnetic or gravity data, depositional trends or isopach/structure trends.

In outcrop, fractures can be more easily characterized as joints or faults. Figure GS-7-2 shows examples of joints in outcrop, which commonly occur as near-orthogonal sets (Figure GS-7-2a, b) and parallel multiples (Figure GS-7-2c, d). Joint spacing (as measured between parallel multiples) in outcrop can provide some insight into the expected joint spacing in the subsurface.

## Methodology

Using ArcMap software, a series of GIS layers was compiled and surveyed for topographic, geological and geophysical lineaments. Layers included a digital elevation model at 90 m and 20 m pixel resolution (topography), hydrography, SPOT satellite imagery, Landsat imagery, regional aeromagnetic maps, dike swarms (McGregor, 2013), interpreted Precambrian faults (McGregor, 2013), surficial (glacial) linear-feature compilations (Trommelen et al., 2013), sub-Phanerozoic geology (including domain boundaries; McGregor, 2013) and Paleozoic formation edges (Nicolas et al., 2014). This remote-sensing mapping was done at three scales: 1:1 000 000 (1M); 1:500 000 (500k) and ≤1:250 000 (250k). Straight vector polylines were drawn along linear features that did not appear to be related to surficial glacial landforms, such as eskers, moraines or beach ridges. The surficial glacial features layers were derived from Trommelen et al. (2013) and were used to screen and remove as much surficial 'noise' as possible. Field measurements of joints in outcrop were also included. A total of 7616 lineaments was measured: 1027 at the 1M scale, 1112 at the 500k scale, 5432 at the ≤250k scale and 45 from outcrop. Figure GS-7-3 shows a map of the linear vectors, colour coded according to the mapping scale at which they were identified. Not all linear features were mapped due to the large numbers that occur; however, the authors are confident that the large volume of vector information provides a good representation of all lineament trends.

Linear features were mapped in the entire HBL area from the edge of the Paleozoic in the southwest to the Hudson Bay coastline. Field measurements were done on all outcrops visited in 2014 (Nicolas and Young, 2014) and on some outcrops from 2015 (Nicolas and Young, 2015) along the Churchill River and the coastal region around the community of Churchill. Linear features include abrupt deviations of streams and rivers, sharp topographic changes, aeromagnetic linears, and Precambrian geology terrane boundaries and known Precambrian faults and dikes.

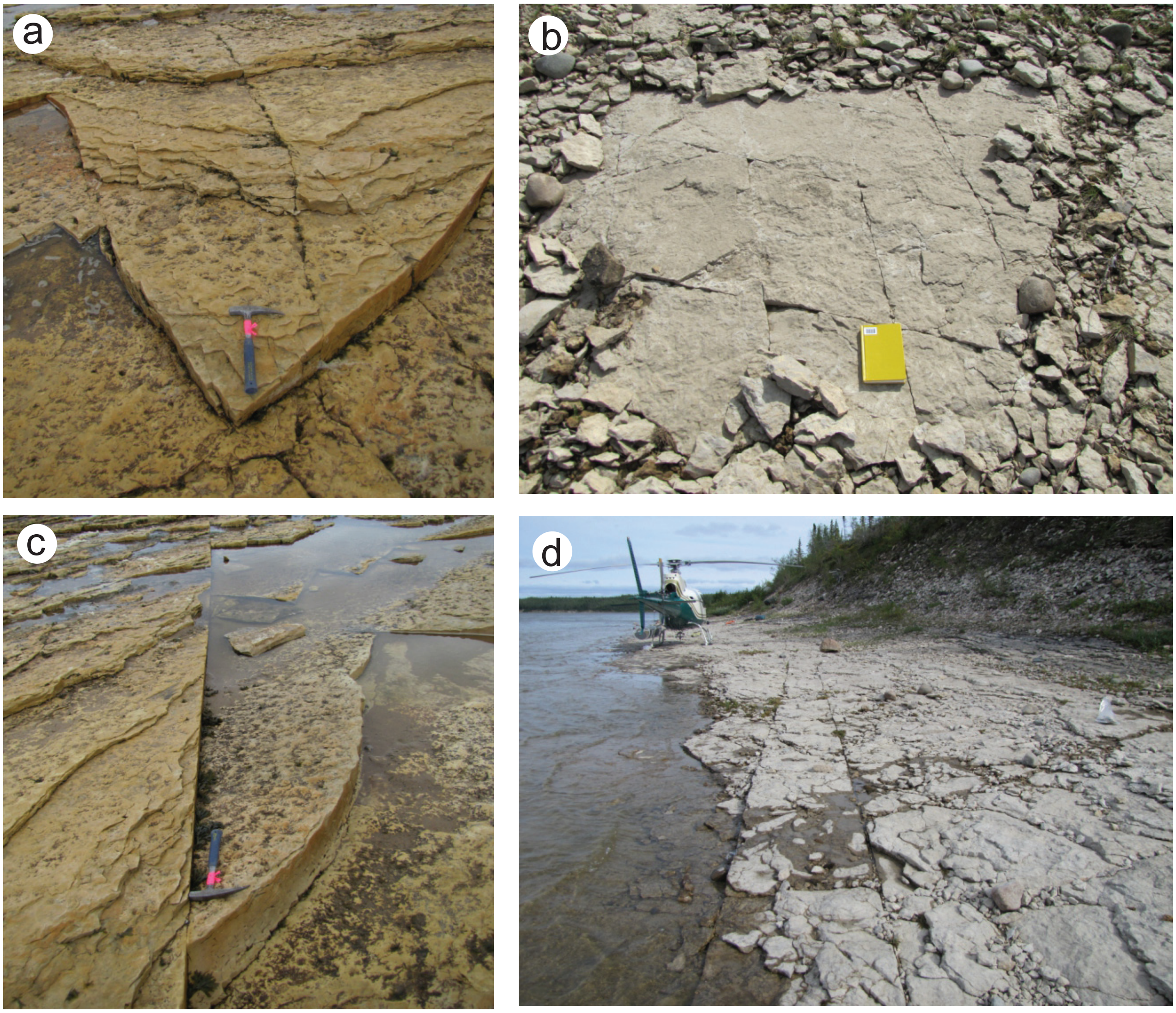


***Figure GS-7-2:** Well-developed joints in outcrop, northeastern Manitoba: near-orthogonal joint sets in the Churchill River Group, near Churchill **(a)** and the Chasm Creek Formation along the Churchill River **(b)**, prominent north-trending joints in the Churchill River Group near Churchill **(c),** and parallel joints in the Chasm Creek Formation along the Churchill River **(d)**.*

The azimuth of each linear feature was measured using ArcMap based on the start and end points of the line as it was digitized, exported to a spreadsheet for compilation and plotted bidirectionally (i.e., each measurement includes its reciprocal azimuth) on rose diagrams using Rockware® StereoStat v. 1.6.1 software.

## Results

Rose diagrams for each mapping scale are shown in Figure GS-7-4. The diagrams show several preferred trend directions, and typically include two near-orthogonal trend pairs. In particular, the 1M- and 250k-scale diagrams show near-identical trend pairs, with dominant north and east trend directions and less dominant southeast and northeast directions. The 500k-scale diagram shows distinct populations of data in the north and east directions but also shows considerable scatter, with three subdominant trend directions (south-southeast, east-southeast and east-northeast). The available field measurements (n = 45) show a dominant population of east-northeast trend directions, which is not well represented in the other data sets.

To provide an overall representation independent of mapping scale, a rose diagram with all the trend data is shown in Figure GS-7-5. This diagram shows near-orthogonal trend sets, with the dominant one at roughly north and east (5–10° and 95–100°, respectively; green sections in Figure GS-7-5); a secondary pair at roughly southeast and northeast (50–75° and 320–340°, respectively; blue sections in Figure GS-7-5); and a weak tertiary pair at east-southeast and east-northeast (305–330° and 75–85°, respectively; yellow sections in Figure GS-7-5).

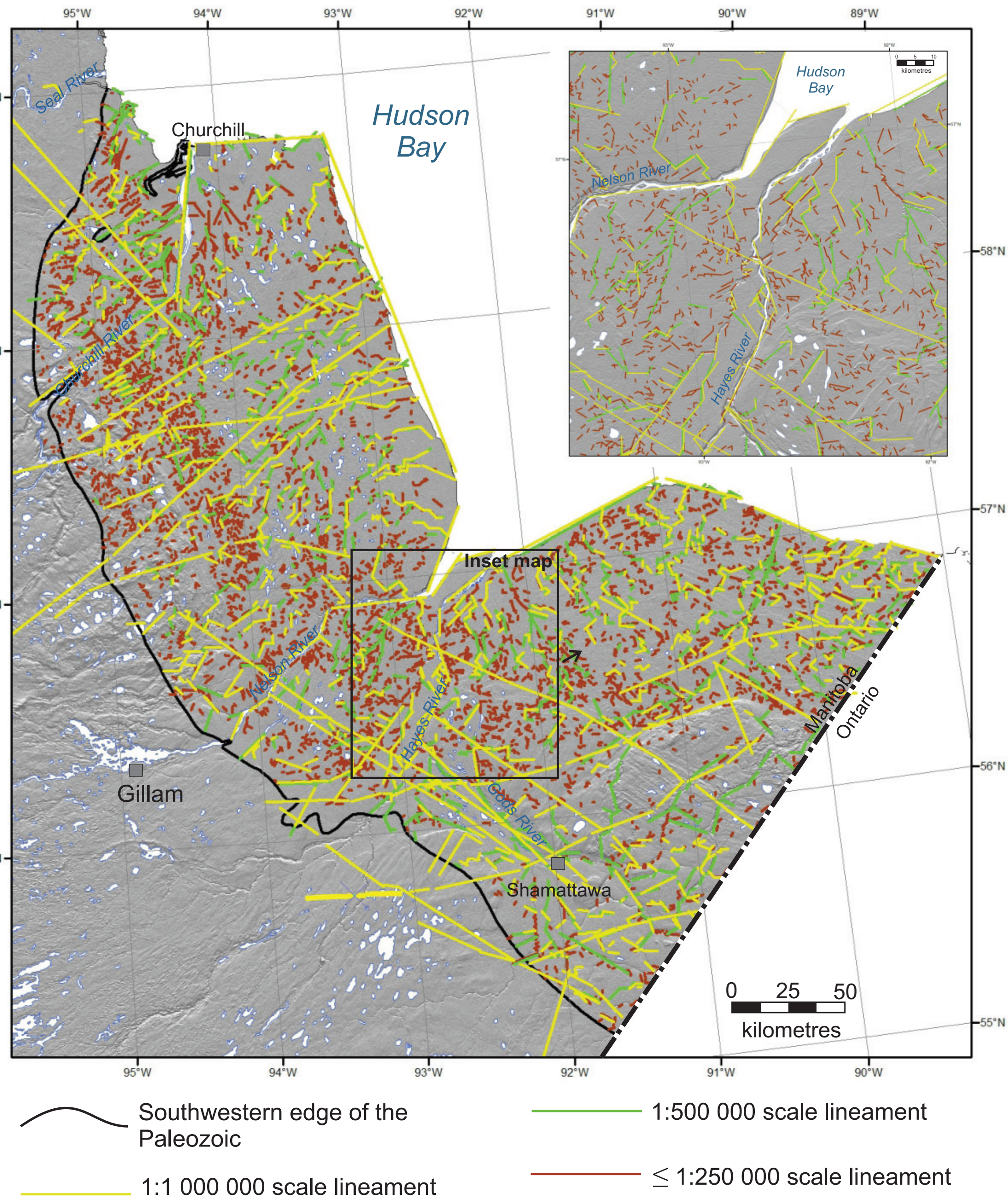


***Figure GS-7-3:*** *Hudson Bay Lowland in northeastern Manitoba, showing the lineaments mapped using remote-sensing methods. Background is a digital elevation model with 90 m pixel spacing derived from Shuttle Radar Topography Mission data (United States Geological Survey, 2002). Inset map is a close-up of part of the area to better show the difference between the different scales of linear features captured. Not all linear features were drawn in any given area.*

The red sections in Figure GS-7-5 represent data scatter, likely from unfiltered surficial 'noise'.

## Discussion

Most of the lineaments recorded during this study are defined by streams and rivers, and are interpreted to reflect the orientations of fractures in the underlying Paleozoic bedrock. The east and north lineament-trend pair may represent factures formed in the basin during deposition and burial. As previously mentioned, the HBB has undergone several burial and exhumation events through its history (Pinet et al., 2013), and the north orientation corresponds closely to the long axis of the HBB, as well as to the orientation of the central fault array documented by Pinet et al. (2013).

Looking deeper into the subsurface, the effect of Precambrian basement structures on lineament patterns at surface is difficult to constrain; however, the secondary

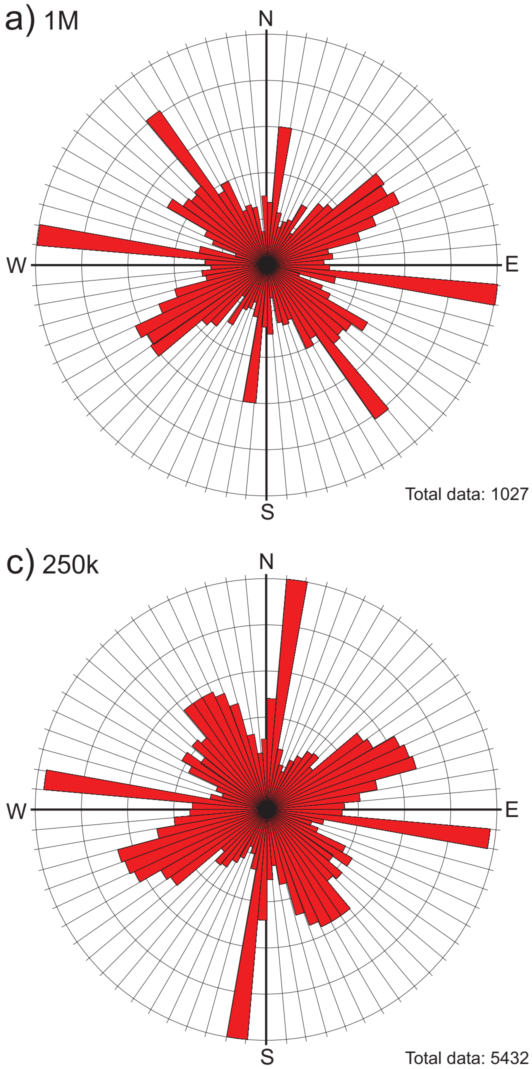


***Figure GS-7-4:*** *Linear-scaled rose diagrams showing the lineament-trend data broken down by scale of mapping: 1:1 000 000 scale* ***(a)****, 1:500 000 scale* ***(b)****, ≤1:250 000 scale* ***(c)*** *and field measurements taken on outcrops along the Churchill River and coastal area around the community of Churchill* ***(d)****.*

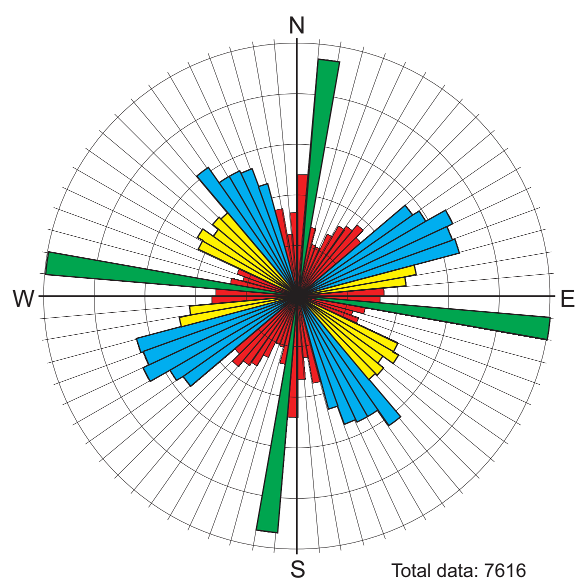


***Figure GS-7-5:*** *Bidirectional, linear-scaled rose diagram with all the lineament-trend data compiled from all map scales and field measurements. Green sections are interpreted as the dominant trend, blue sections are the secondary trend, yellow sections are the tertiary trend and red represents data scatter.*

(weaker) northeast and southeast trends may be reflective of deeper basement structure. In particular, some correlation can be seen between this secondary trend pair and such basement features as magnetic-linear trends, Precambrian domain boundaries and Paleozoic geology (Figure GS-7-1). One area of interest is in the subsurface northeast of the community of Shamattawa. Lying beneath the area informally referred to as the 'Kaskattama highland' (Nicolas et al., 2014), the Kaskattama trough in the Paleozoic sequence (Nelson and Johnson, 1966; Nicolas et al., 2014) has a northeast orientation and is interpreted to be part of a complex syncline and anticline fold pair. This trough directly overlies the domain boundary between the southern edge of the Kisseynew domain and northern edge of the Superior boundary zone (SBZ), as inferred from geophysical data, and runs parallel to magnetic-linear trends (Figure GS-7-1) identified by McGregor (2013), perhaps indicating that the common orientation and spatial relationship of all these features may relate to basement structure.

It should be noted that, in the Williston Basin in southwestern Manitoba, structural disturbance related to the sub-Phanerozoic extension of the SBZ is one of the major factors in creating the structural traps for oil accumulation. This structural disturbance occurred through fault reactivation along the SBZ, which propagated upward into the Paleozoic and Mesozoic sedimentary sequences, creating excellent oil migration paths and traps (McCabe, 1967; Nicolas, 2012). The effect of the SBZ on the Phanerozoic is not limited to the oil fields but can also be seen farther north (toward the northeastern rim of the Williston Basin), where basement faults are associated with sulphide accumulations in the overlying carbonate rocks (Bamburak and Klyne, 2004; Fedikow et al., 2004). It is therefore possible that such geological conditions are replicated in this area of the HBL.

The effects of glacial loading and isostatic rebound are likely minimal in generating fractures in the bedrock. The weak tertiary orientations of east-southeast and east-northeast in Figure GS-7-5 (yellow sections) may be reflective of fracture patterns in lithified sections of Quaternary sediments rather than in the underlying Paleozoic sedimentary rocks. Although glacial loading and rebound may be the least effective at generating fractures in the HBL, it is the dominant mechanism to consider when looking at fluid-migration directions during the Holocene (Grasby et al., 2000; Grasby and Chen, 2005), thus affecting oil-field placement.

## Economic considerations

Lineament studies using remote sensing are a cost-effective way to map large areas in order to better understand the possible trends of basement fractures masked by recent sediments. Correlations of lineaments with subsurface geology may help to focus exploration efforts for mineral and petroleum companies; in particular, knowing the potential orientations of fractures is important in designing geophysical exploration programs to get the clearest possible survey results, and in predicting the most probable migration path of oil and gas, and other fluids. Data on fracture patterns and orientations are also useful for groundwater studies, aquifer use and water-well placement.

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