New thermal evidence related to carbonate-hosted metal ores in the Northwest Territories

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Abstract: A modern geothermal gradient map of an area in northwestern Alberta, northeastern British Columbia and southern Northwest Territories was constructed using temperature records obtained from geophysical borehole logs, all corrected for drilling disturbance. The map illustrates the thermal regime present in the Mackenzie shale basin to the north of the Presqu'ile Barrier Complex, and within the Barrier itself. It also covers the evaporitic Elk Point Basin behind the Barrier as well as the regime associated with the carbonate shelves situated in northern Alberta between the Barrier and the northern extent of the fringing reef rimming the Peace River Arch. The geothermal gradient varies from 20 to 80 mK/m (°C/km). A significant regional trend indicating a general northward increase of geothermal gradient is observed in the map area. The northward increase in heat flow likely signifies a transition between high-strength crust in the south to lower strength crust in the north.

Résumé : Une carte du gradient géothermique actuel d'une région dans le nord-ouest de l'Alberta, le nord-est de la Colombie-Britannique et le sud des Territoires du Nord-Ouest a été dressée à partir d'enregistrements de la température obtenus à l'aide de diagraphies géophysiques, toutes corrigées pour tenir compte des perturbations lors du forage. La carte illustre le régime thermique qui prévaut dans le bassin de shale de Mackenzie au nord du complexe de la barrière de Presqu'ile, et à l'intérieur de la barrière elle-même. Elle couvre également le bassin évaporitique d'Elk Point derrière la barrière, de même que le régime associé aux plates-formes carbonatées situées dans le nord de l'Alberta, entre la barrière et la partie nord du récif frangeant qui borde l'arche de Peace River. Le gradient géothermique varie de 20 à 80 mK/m (EC/km). Une tendance régionale marquée, indiquant un accroissement général vers le nord du gradient géothermique, a été observée dans la région cartographique. L'accroissement vers le nord du flux thermique signifie probablement qu'il existe une transition entre la croûte à résistance élevée, au sud, et la croûte à résistance plus faible, au nord.

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INTRODUCTION

High geothermal gradients in the northern part of the Western Canada Sedimentary Basin (WCSB) in Alberta and British Columbia were initially reported by Anglin and Beck (1965), who analyzed six wells between 56° and 60° North latitude and 114° and 122° West longitude. Their work indicated that these wells display thermal gradients ranging from 30 to 57 mK/m, greater than measured thermal gradients to the south. Farther north, a single, high heat-flow value of 80 mW/m^2 measured at Norman Wells, Northwest Territories by Garland and Lennox (1962), supports the observation of Anglin and Beck (1965) of the northward increase of geothermal gradient in the basin. Heat-flow patterns in the Western Canada Sedimentary Basin, derived from work by Majorowicz and Jessop (1981), were based on a limited number of deep shut-in wells and wells reaching Precambrian basement (some 120 wells and 20 wells, respectively). Majorowicz and Jessop (1981) confirmed the existence of high heat flow in northeastern British Columbia, Northwest Territories and in northwestern Alberta. Their analysis indicated geothermal gradients greater than 40 mK/m and heat flow ranging as high as 99 mW/m^2 in northeastern British Columbia.

The limited heat-flow analysis above was superseded by a more extensive analysis of the Western Canada Sedimentary Basin (WCSB) including areas north of 60°. A select number of wells from the University of Alberta database containing tens of thousands of wells were used (Majorowicz et al., 1984). The study of heat-flow patterns in Yukon and Northwest Territories (Majorowicz et al., 1988) indicates that the largest scale regional high-heat-flow zone occurs mainly in the foreland of the northern Rocky Mountains and southern Mackenzie Mountains, covering the North American craton south of 63° North latitude. In a later study (Majorowicz, 1996), a heat-flow map was constructed based on data obtained north of 60° N as well as that from selected wells from each 30 km by 30 km square area in the Alberta and British Columbia parts of the foreland basin. This map displays a large heat-flow anomaly extending from the Foothills in the western part of the basin to the western arm of Great Slave Lake and from northeastern British Columbia northward to the Norman Wells area (Fig. 1). This so-called Northern Prairies Heat-flow Anomaly (NPHFA) was found to be the largest-scale regional heat-flow anomaly in the Western Canada Sedimentary Basin and most likely in all of Canada. The transition from the area of high heat flow (exceeding 80 mW/m^2) associated with the NPHFA to areas of normal heat flow to the south occurs near 60° N in northwestern Alberta but extends further south to near 58°N in northeastern British Columbia (NTS map-sheet 094; Fig. 1).

Majorowicz et al. (1989) and Majorowicz (1996) hypothesized that a portion of the enhanced heat-flow associated with the NPHFA could be derived by an upflow component of a convective, cross-formational, coupled fluid flow-heat flow system within the Presqu'ile Barrier. However, most of the heat flow anomaly is found to the north of the barrier complex (Fig. 1). Estimated mean basement heat flow for this area of the Western Canada Sedimentary Basin surrounding the Presqu'ile Barrier is less than 60 mW/m^2 (Jessop, 1992), based on a limited number of radiogenic heat generation data points retrieved from core intersecting Precambrian basement in the WCSB (Jones and Majorowicz, 1987; Burwash and Burwash, 1989). These heat-flow measurements from basement do not readily explain the high heat-flow anomaly (NPHFA) situated to the north of the Barrier in southern Northwest Territories. Majorowicz (1996) suggested that residual heat flow, defined as the difference between the observed surface heat flow and the sum of the heat-flow contributions from basement and the sedimentary column, varies from 20 to 30 mW/m^2 north of the Presqu'ile Barrier. Majorowicz (1996) pointed out that this residual heat-flow pattern does not correlate well with the mapped spatial relationships of underlying basement terranes and does not seem to be influenced by the major northeast-southwest fault trends. Therefore, that author postulated that the excessive

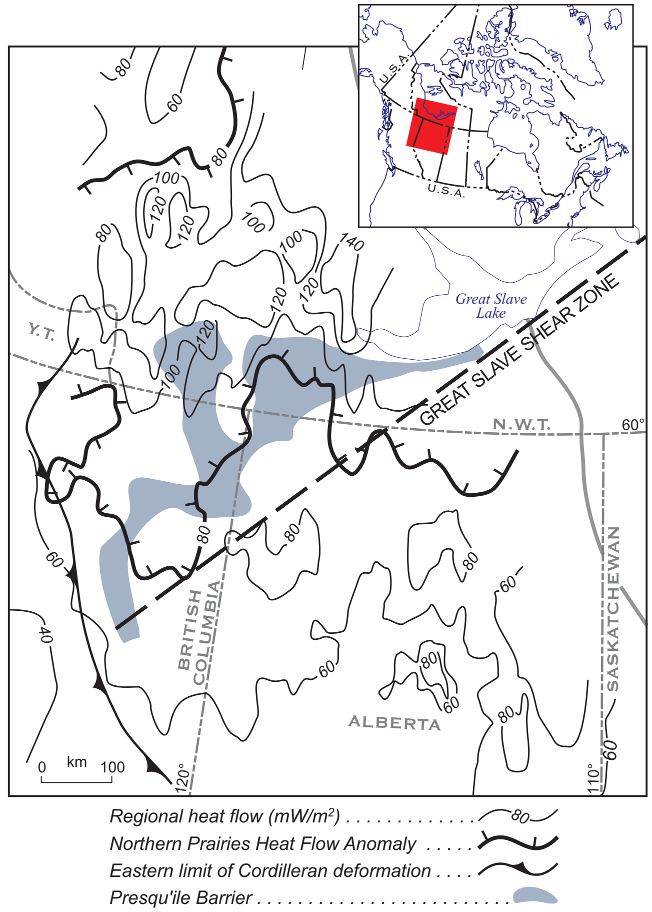

Figure 1. Regional heat flow in mW/m^2 and the Northern Prairies Heat-flow Anomaly (NPHFA) according to Majorowicz (1996). The spatial relationships between the Presqu'ile Barrier Complex, Great Slave Shear Zone (GSSZ), and the Northern Prairies Heat-flow Anomaly (NPHFA) are displayed.

heat input might be a result of enhanced mantle heat-flow. A LITHOPROBE project called the Slave Northern Cordillera Lithospheric Evolution project (SNORCLE) transects the study area across the cratonic platform south of Great Slave Lake. A most recent study of thermal controls along the transect (Lewis et al., 2002) clearly supports the conclusions of Majorowicz et al. (1988) and Majorowicz (1996) of high heat flow in the foreland basin succession covering the Wopmay Orogen of the North American craton beneath the southern Northwest Territories plains. The Lewis et al. (2002) SNORCLE transect average heat flow is 90 ±15 mW/m^2. Lewis et al. (2002) measured the heat generation from numerous crystalline crustal samples in cores or cuttings from a number of wells that reached basement in order to determine if the crustal heat generation was unusually high, thus producing the high heat flow. Measured heat generation ranges from 0.3 to 7.7 $\mu W/m^3$. The average is 3.2 ±1.8 $\mu W/m^3$. Lewis et al. (2002) speculated that these measurements are probably not truly indicative of the total heat generation capacity of the crust in the region. A number of factors may have reduced the measurement of heat-generating capacity, one of which is drilling disturbance, where samples preferentially lost their finest particles containing most of the enriched accessory minerals. Therefore, corrections were required in order to properly evaluate crustal heat generation. Corrected heat generation values ranging from 4.8 $\mu W/m^3$ to as high as 6.0 $\mu W/m^3$ were used for calculations of crustal temperatures in the area, but these temperatures are poorly constrained. According to Lewis et al. (2002), there are a number of proxy indicators of deep crust and upper mantle in the foreland area north of 59° N being not as hot as measured in the Cordillera to the west. Crustal thicknesselevation isostatic models and high seismic (Pn) velocities from the uppermost mantle confirm these moderate crustal temperatures. Both of these indicators corroborate that the favoured mechanism for the production of high heat-flow in this part of the study area is enhanced crustal heat generation.

This present study expands further on geothermal work in the area with special focus on the position of the Presqu'ile barrier (Fig. 1, 2) and areas of potential occurrence of Mississippi Valley-type carbonate-hosted lead-zinc deposits such as the Pine Point mine site area (Fig. 2). The role of the barrier in focusing the paleoflow of hot basinal fluids has been discussed in previous publications (Garven, 1985, 1995; Qing and Mountjoy, 1992; Mountjoy, et al., 1997).

GEOLOGICAL AND TECTONIC SETTING

The Western Canada Sedimentary Basin, a prolific hydrocarbon basin, dominates the study area. Numerous basement domains with characteristic potential field signatures are present in outcrop on the Canadian Shield north and east of the basin and extend beneath the basinal sediments (Hoffman, 1989; Ross et al., 1994; Morrow et al., 2006). Accretionary and collisional processes during the Early Proterozoic assembled various deformed and metamorphosed passive margin and foreland sedimentary sequences, island-arcs and continental margin magmatic arcs. These accreted assemblages welded the Archean cratonic provinces of the Canadian Shield (Hoffman, 1989). Some of the major discontinuities such as the Great Slave Shear Zone (GSSZ, Fig. 1) were formed during this collisional assembly and can also be traced into the subsurface beneath the basin. Heat generation due to the concentration of radioactive elements varies widely between the various basement domains. Archean provinces generally have low average heat-generation values whereas Proterozoic accretionary provinces exhibit higher average heat-generation capacity (Bachu and Burwash, 1994).

The Western Canada Sedimentary Basin consists of a northeasterly tapering wedge of Phanerozoic sedimentary rocks lying on the westward extension of the Precambrian continental craton (Porter et al., 1982). This sedimentary wedge thickens to the southwest from zero thickness on its eastern boundary to over 6.0 km east of the deformed belt. Two major westward-thickening sedimentary successions comprise the fill of the Basin. Although each succession has comparable volumes of sediment, they were products of very different tectonic settings. Dominantly marine strata comprise the Upper Proterozoic to Middle Jurassic lower succession. Units of this lower succession were deposited on the stable continental margin and adjacent craton by oceanward progradation. This cratonic platform phase was subsequently buried by the second succession of shallow-marine to nonmarine clastic sediments of Late Jurassic to Tertiary age. This upper succession was formed by cratonward progradation of clastic detritus supplied by the evolving Cordillera that coincided with accretion of foreign terranes onto the western margin of North America (Porter et al., 1982).

A major episode of tectonic uplift and extensive erosion preceded Middle Devonian sedimentation. This erosional episode effectively removed all lower Paleozoic sediments in the study area. Gentle folding of the pre-Devonian surface developed basins and arches that greatly affected subsequent Devonian sedimentation. Two of the major positive topographic elements affecting sedimentation in northern Alberta and southern Northwest Territories are the Tathlina and Peace River arches. A major elongate northwest-southeast seaway developed in the basin where abundant carbonate sedimentation took place. This seaway was open to the north and northwest but became restricted to the south. Initial Devonian sedimentation took place in a restricted, shallow, coastal, hypersaline sea bounded on the west by the Peace River Arch and to the east by the Laurussian hinterland (Kent, 1994). Subsequent to this restricted basinal environment, an open-marine carbonate-depositing sea transgressed the platform. These Devonian carbonate deposits appear to be the principal host rock for Mississippi Valley-type lead and zinc mineralization in the area. During this depositional episode, an extensive reef complex called the Presqu'ile Barrier developed on the south flank of the Tathlina Arch, which formed an

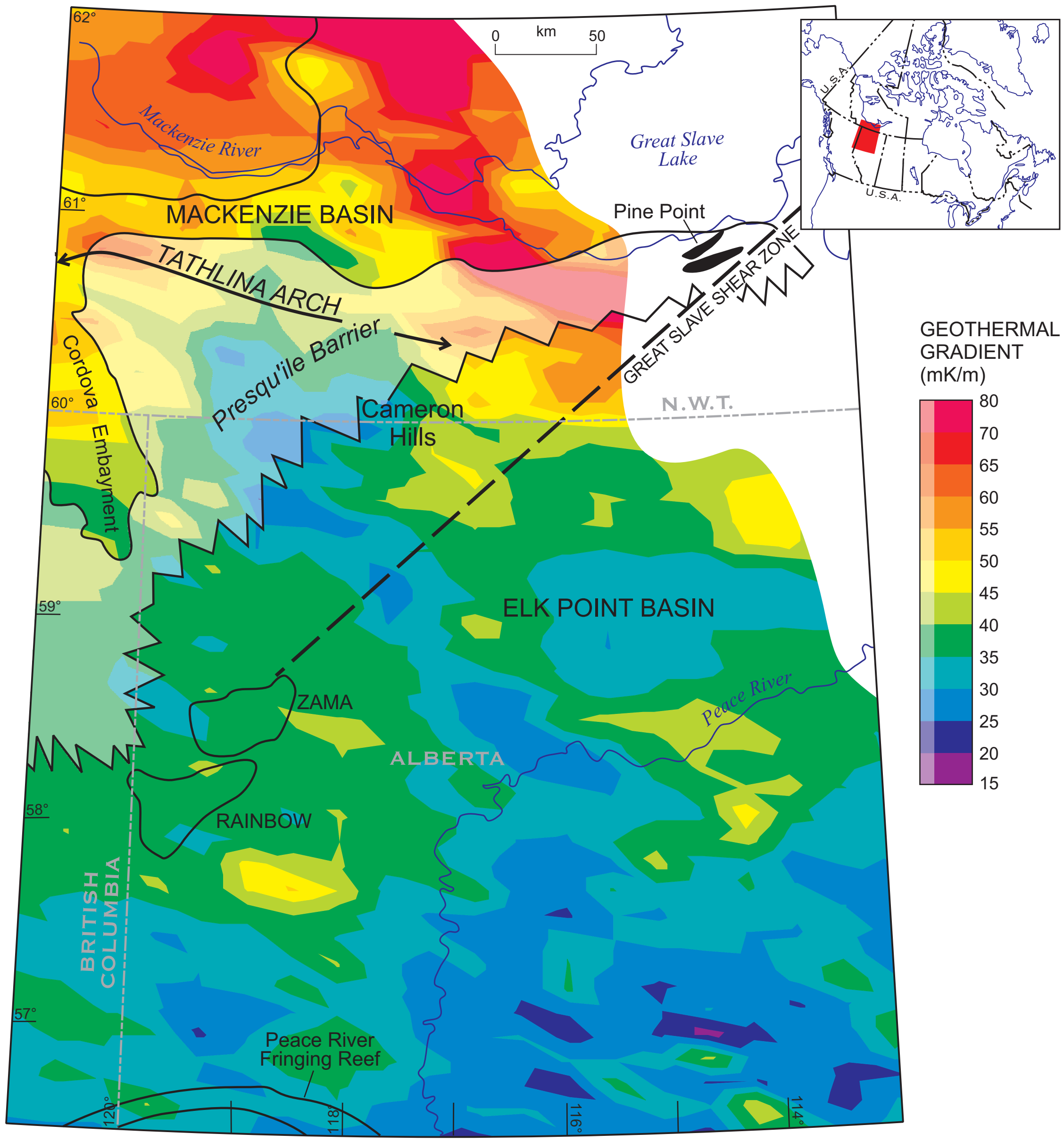

Figure 2. Geothermal gradient of the study area in northern Alberta, southern Northwest Territories, and northeastern British Columbia (contour interval 5 mK/m). The location of the Presqu'ile carbonate barrier and Pine Point mine site are shown.

extensive barrier across the northern end of the basin (Fig. 1, 2). The Barrier separated normal marine sedimentation taking place in the Mackenzie Basin to the north from a carbonate-evaporite shelf and evaporite basin that developed in the Elk Point Basin to the south in northern Alberta. Intrashelf, small, deep basins at Rainbow and Zama containing patch and pinnacle reefs also developed immediately behind the Presqu'ile Barrier (Fig. 2). In the Mackenzie Basin, in front of the Barrier, deeper marine muds were deposited subsequent to the growth of isolated reefs on a broad carbonate platform (Fig. 2). In the Late Devonian, marine sediments gradually buried the positive features in the study area leaving only the Peace River Arch. During Late Devonian to Carboniferous time, a multi-stage diagenetic episode affected much of the Barrier, forming the coarse-grained, highly porous Presqu'ile dolomite and secondary evaporite minerals and also forming the low-temperature hydrothermal sulphide and gangue minerals at Pine Point (Krebs and Macqueen, 1984).

TEMPERATURE DATA AND CALCULATION OF GEOTHERMAL GRADIENT

Bottom-hole and drill-stem test temperature data from thousands of wells in Alberta were gathered and analyzed from well log headings (Majorowicz et al., 1984, 1985). Data from wells in British Columbia and the Northwest Territories were derived from the geothermal database compiled by the Geological Survey of Canada (A.M. Jessop, pers. comm.). In areas of great density of data points such as northwestern Alberta, a grid size area of 9x9 km was adopted (Jones et al., 1984), from which a single representative temperature gradient was derived. Sites where temperature gradient was calculated are shown in Figure 3. The data are unevenly distributed.

Prior to determination of the geothermal gradient, corrections to the measured bottom-hole temperatures are required. These corrections are needed in order to resolve the equilibrium temperatures in the rocks surrounding the borehole. The determination and recovery of equilibrium temperature depend on numerous factors such as circulation time of the drilling fluid, elapsed time since circulation ceased, depth in the well, and surrounding rock properties. In most wells the recorded data are incomplete, particularly circulation time (Jessop, 1990). Therefore, a statistical method was needed to estimate temperature corrections. By plotting ‘time-corrected’ bottom-hole temperature (BHT) data using Horner-type temperature corrections (Jones et al., 1984) and uncorrected BHT values versus depth for the area, a regional temperature correction was obtained. The statistical corrections of bottom-hole temperature for the study area were determined as follows:

$$T_c = T_{bht}\,(a + b \ln(t_e)) \qquad (1)$$

where T_c is corrected temperature, T_{bht} is the bottom-hole temperature, and t_e is the elapsed time since circulation ceased; a and b are constants (a=1.1 and b=-0.03) (Jones et al., 1984). The circulation time is not known in most cases. Because of a lack of data, in many instances these temperature corrections were approximated. With respect to common circulation times, it was found the temperature correction (equation 1) amounts to 7 to 10% of the true static temperature for elapsed times of 2 to 4 hours, respectively, decreasing to 5% after 10 hours and 3% after 20 hours.

The corrected temperature data were derived from individual wells or clusters of wells and thermal gradients were then calculated from these data constrained by near-surface temperature conditions. Mean annual surface temperatures ranging from 0 to 2°C were used.

The geothermal gradient was calculated from the equation:

$$\text{grad}\,T = (T_c - T_{0m})/(Z_{bhd} - Z_{0m}) \qquad (2)$$

where T_c and T_{0m} are corrected bottom-hole and average surface temperatures, respectively, at bottom-hole depth (Z_{bhd}) and at surface (Z_{0m}). Contour maps of calculated geothermal gradient derived from equation 2 are illustrated in Figures 2 and 3 (contour intervals of 5 mK/m and 10 mK/m, respectively). An additional map with the smaller contour interval of 3 mK/m was also constructed, but it displayed some thermal gradient variation below the level of data reliability and thus is not included. As a result of uncertainties in the corrected temperatures, the possible error in temperature gradient is estimated near 5 mK/m, although it may be greater in individual wells.

The analysis of regional trends and patterns of thermal gradients in relation to the regional geology and hydrodynamics indicate that:

1) There is an approximate north-trending increase in geothermal gradient from 20 to 80 mK/m (Fig. 2). Higher thermal gradients are generally found north of 60°N, with the exception of the Cameron Hills area where thermal gradient is low (25–35 mK/m, Fig. 2).

2) Generally, the Presqu’ile Barrier occupies the transition zone between high thermal gradient to the north and low thermal gradient to the south (Fig. 2). The thermal field contained by the confines of the Barrier is not uniform and higher thermal gradients are present in its northwestern and eastern parts. The eastern portion of the Barrier occurs within the thinnest part of the wedge of strata filling the Basin.

3) Background ‘normal’ geothermal gradients are mainly in the 25 to 40 mK/m range (Jessop, 1990). Gradients ranging from 40 to 60 mK/m are considered to be high and they are typical for most of the northern and northeastern portions of the study area. Values greater than 60 mK/m are considered anomalous. Geothermal gradients in the area south of 59°N are in most cases representative of background.

THERMAL CONDUCTIVITY DATA AND CALCULATION OF TERRESTRIAL HEAT FLOW

Thermal conductivity, K (W/mK), varies with depth as a result of variable lithology and water content in pores. No in-situ or laboratory measurements of thermal conductivity are available from wells in the study area. Thermal conductivity determinations were, therefore, based on net thicknesses of various rock types from selected boreholes as well as assumed average rock conductivities of these rock types (Jessop, 1990). They are also based on known (Majorowicz and Jessop, 1981; Majorowicz et al., 1999) regional thermal conductivity patterns in the study area. Thermal conductivities range from 1.1 W/mK for pure shale to 4.8 to 6.05 W/mK for anhydrite and salt, respectively (Jessop, 1990). Coal has

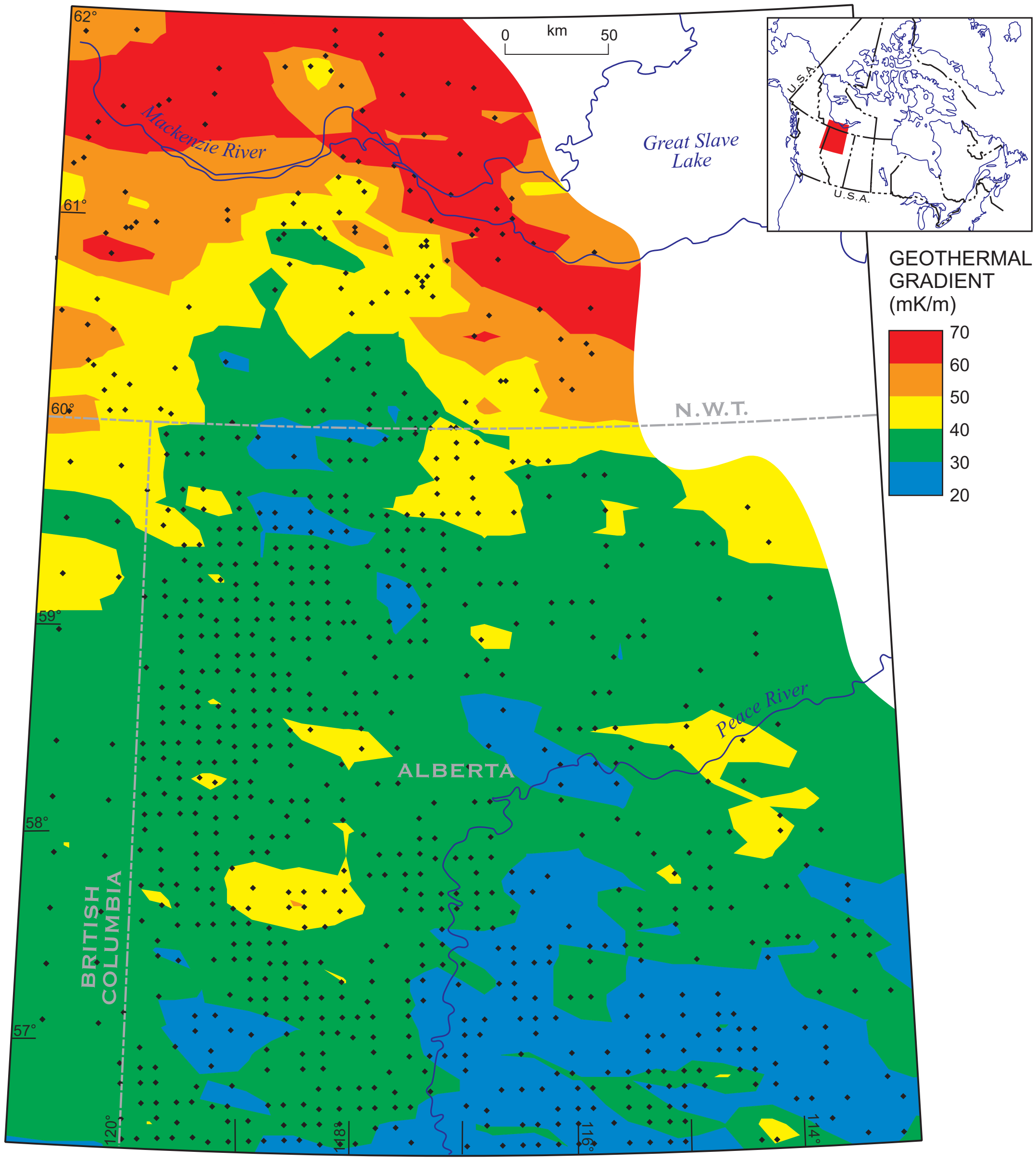

Figure 3. Geothermal gradient (10 mK/m contour interval). Locations of well data points are displayed. In areas of dense well coverage, such as northwestern Alberta, the black dot indicates centres of 9x9 km grids, where single representative gradients calculated from appropriate temperature data associated with numerous wells within the grid, are shown.

the lowest assumed conductivity, ranging from 0.2 to 0.5 W/mK. There is a general increase of average conductivity to the west and northwest of the study area from 1.4 W/mK to greater than 2.0 W/mK. Otherwise, conductivity is quite variable throughout the area.

The estimates on heat flow (Q in mW/m^2) in the study area were then calculated as follows:

$$Q = K \, \mathrm{grad} \, T, \tag{3}$$

where, grad T is geothermal gradient in mK/m and K is effective thermal conductivity in W/mK.

Within the limits of uniform tectonic zones that, in turn, constitute individual unique heat-flow provinces, conductive terrestrial heat flow, Q, can be linearly related to heat generation from radiogenic elements in crustal rocks by the following expression (Birch et al., 1968):

$$Q = Q_r + A\,D, \tag{4}$$

where, A is the heat generation at the surface in mW/m^3 and is assumed to extend to a depth, D in km, representing the characteristic thickness of upper crust where the heat-producing radiogenic elements are distributed, and Q_r is the "reduced heat flow" below the heat-producing layer and constitutes the heat flow if the crust above depth D contained no radioactive elements.

Calculated heat flow (equation 3) in the project area is illustrated in Figure 4. The study area encompasses both high and low thermal gradient zones. Thermal gradient is governed primarily by heat flow. Heat flow is controlled by tectonic features such as lithosphere thickness, radiogenic sources in the upper crust (approximately above depth D=10 km), and possibly by forced convection within aquifer formations. The thermal gradient is then inversely proportional to thermal conductivity. An important consideration to address is what proportion of the thermal gradient is a result of thermal conductivity attributed to the sedimentary cover and what proportion is derived from the contribution of heat from the heat-generation layer in the underlying basement.

Heat flow varies from 40 to >140 mW/m^2 but most areas have heat flows in the 50 to 90 mW/m^2 range (Fig. 4). Extreme differences in terrestrial heat flow suggest that a substantial contribution is derived from the highly variable heat generation derived from radiogenic elements occurring in the upper crust. Heat flow is also affected to a certain extent by the influence of hydrodynamic processes upon generally high heat flow derived from the deeper crystalline crust and upper mantle (Majorowicz and Jessop, 1981; Majorowicz et al., 1999). The extreme complexity of water movement in the sedimentary cover can create both local and regional heat-flow anomalies that effectively mask the heat generated from the basement. This interpretation has not been confirmed and is, in fact, disputed by others (i.e. Bachu and Burwash, 1994).

The lowest heat flow is observed in the southern part of the study area (Fig. 4) whereas the highest occurs generally north of 60° 30'N, with values exceeding 100 mW/m^2 (Fig. 4). This distribution of heat-flow probably correlates to a transition between regions of high-strength crust in the south to lower strength crust to the north. The southern area displays an average heat flow of 50 to 70 mW/m^2, typical of the Western Canada Sedimentary Basin, with occasional local zones of enhanced heat-flow above 80 mW/m^2 (Fig. 4). A significant heat-flow transition observed around 58–59°N immediately to the west of the project area in northeastern British Columbia (Figure 4 in Majorowicz, 1996) may represent a boundary between heat-flow provinces of contrasting heat-generation tectonic domains in the crystalline upper crust. The most significant transition in heat-flow in the study area occurs near 60°30'N (Fig. 1, 4). Heat-flow greater than 100 mW/m^2 (Fig. 4) (also found within the NPHFA defined by Majorowicz, 1996) occurs generally to the north of the Presqu'ile Barrier (Fig. 1) and does not seem to be directly related to forced convective heat transport along the Barrier.

TEMPERATURE–DEPTH PREDICTIONS

This knowledge of heat-flow, Q, and the variation of thermal conductivity, K, with depth allow for the calculation of continuous temperature-depth profiles that are important in the determination of burial temperature histories. Predicted temperature at depth can be expressed as:

$$T = T_{0m} + Q\sum_{i=1}^{n} Di / Ki \qquad (5)$$

where, T_{0m} is temperature at surface and Di and Ki are thickness and thermal conductivity of units i = 1...n, respectively.

If present heat flow stayed constant throughout the history of post-Laramide development of the basin, then the calculated temperature (equation 5) at time of maximum burial of the Presqu'ile Barrier would be more than 90°C near 1500 m in the Pine Point area, 100°C to 160°C from 2000 to 3500 m in southern Northwest Territories and up to 180°C at 4000 m in northeastern British Columbia. These estimated temperatures are much higher than maximum burial temperatures calculated by Qing and Mountjoy (1992), who assumed a much lower thermal gradient of 30 mK/m.

DISCUSSION

There are numerous factors contributing to the highly variable areal distribution of observed heat flow, such as groundwater fluid flow, topography, radioactive heat generation, sediment thickness, and surface temperatures from solar heating. The most important factors in the study area are groundwater fluid flow and heat generation from the upper crust.

Groundwater fluid flow

An important causal factor of the broad, regional heat flow pattern in the Western Canada Sedimentary Basin seems to be directly related to the thermal effect of groundwater fluid-flow. There is a general increase of both heat flow and geothermal gradient toward the northeast into areas of lower topographic elevation away from the Cordilleran Front (Majorowicz et al., 1989). Topography associated with the Laramide Orogeny bears directly on the distribution of heat flow and the geothermal gradient pattern in Mesozoic and Cenozoic strata. Elevated areas, especially along the Cordilleran Front to the west of the project area, correlate very well with zones of reduced heat flow and geothermal gradient. The downward seepage and percolation of groundwater through numerous open fracture systems within the regional recharge zone of the Rocky Mountain Foothills and in local recharge zones associated with isolated elevated regions such as Cameron Hills in the midst of the Presqu'ile

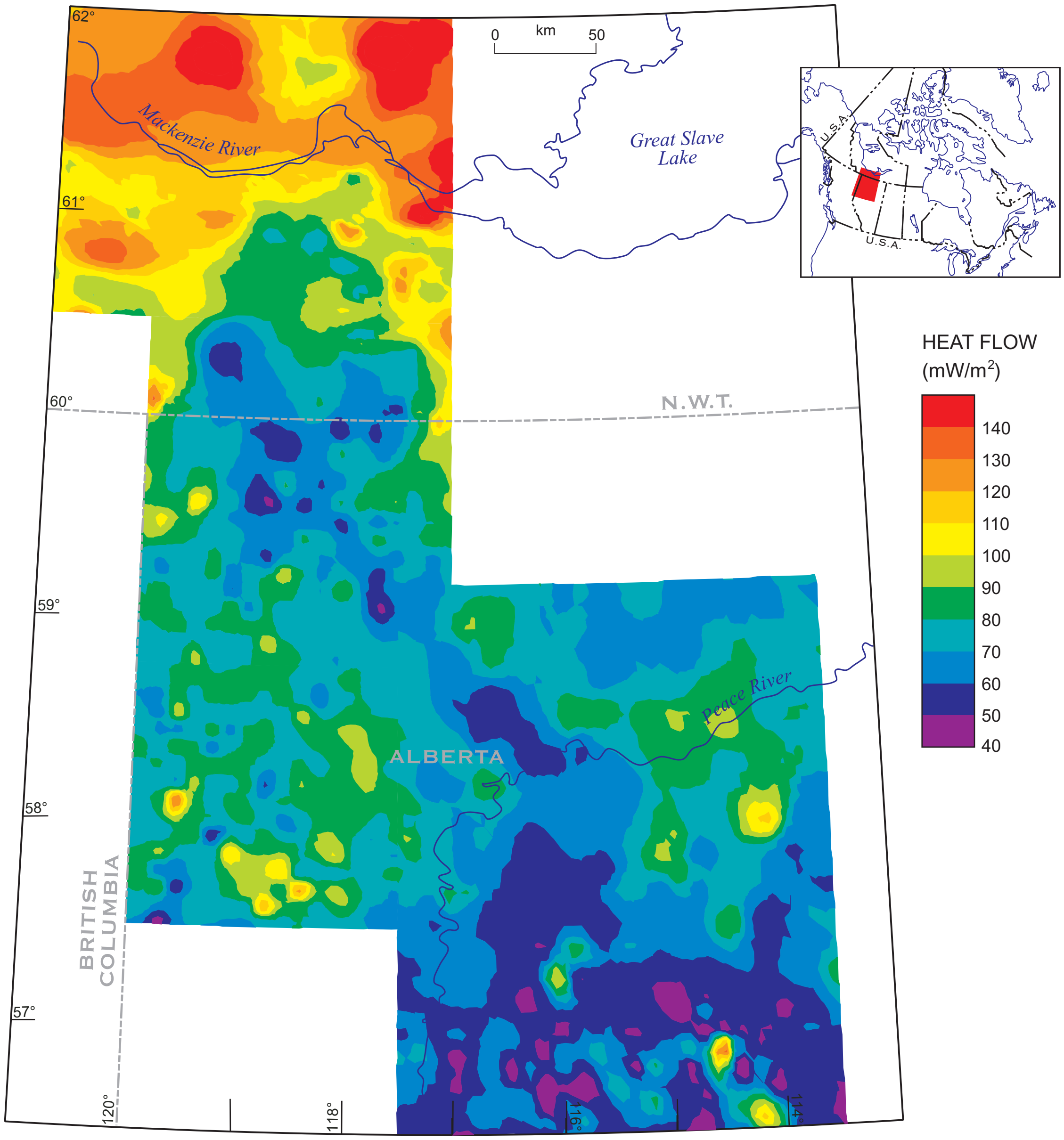

Figure 4. Heat flow in the study area. Contour interval is 10 mW/m².

Barrier (Fig. 1, 2), might have reduced the heat flow in the upper several kilometres of Cenozoic and Mesozoic strata. Contrastingly, in areas of groundwater discharge near the cratonward margin, where regional fluid flow moved updip in a northeasterly direction within aquifers toward areas of low elevation and hydraulic head, the heat flow and geothermal gradient might have been enhanced. A similar regional thermal pattern for the area is interpreted both at present and in the past. In the past, as a result of uplift of the Rocky Mountains during the Laramide Orogeny, topographic relief was much greater. As a result, the magnitude of fluid flow and its associated heat-flow variations were likely greater in the past (Garven, 1995). Present-day influence of the hydrodynamic factor upon heat flow has been greatly reduced as a result of changes in topographic relief and hydraulic head.

Qing and Mountjoy (1992) and Mountjoy et al. (1997) argued that tectonic compression, uplift, and sedimentary loading along the western margin of the Western Canada Sedimentary Basin moved hot radiogenic basinal fluids eastward along the Presqu'ile Barrier and mixed and cooled them in contact with ambient formation waters at shallower levels. Such compression-driven movements of fluids, while important in the past, are not likely to cause significant thermal disturbance at the present time. In such a system, part of the heat flow is conductive and the remainder is derived by forced convection. Such models were previously proposed for the Alberta portion of the Western Canada foreland basin (Majorowicz and Jessop, 1981; Osadetz et al., 1992; Majorowicz et al., 1999). This model cannot be verified at this stage since no detailed hydrodynamic patterns are known. However, heat-flow observations show that the Presqu'ile Barrier is unlikely to redistribute heat along its whole length at present. High heat-flow areas are not exclusively restricted to the eastern part of the Barrier in the low-lying shallow basin where regional discharge of formation fluids with accompanying forced convection heat transfer is expected. In fact, high heat flow occurs mainly north of the Barrier. An initial analysis of the heat flow along the Barrier and its surrounding area was based on some 30 data points (Majorowicz et al., 1989). This preliminary study concluded that a northeastward increase of heat flow toward the shallower part of the basin is similar throughout the basin and thus does not support a unique role for the Barrier in concentrating coupled fluid and heat flow at the present time. Although there is uncertainty regarding the relation between past and present fluid and heat-flow regimes, it seems clear that radically different ground-surface topography and geological conditions would be required in the past if one surmised that the Presqu'ile Barrier possesses significant coupled heat-flow and fluid-flow focusing properties. The addition of hundreds more data points in this study does not refute this hypothesis.

Radioactive heat generation

The lowest heat flows (40 to 50 mW/m^2) occur in the southern part of the study area (Fig. 4). These low heat flows are only marginally greater than the reduced heat flow, Qr, emanating from the mantle and lower crust beneath Archean rocks in the Superior Province of the craton. According to Jessop (1992), the best determination of reduced heat flow (equation 4) for the Archean heat-flow province is 33 ± 3 mW/m^2 situated below an upper crustal thickness (D) of 9.6 ± 2.7 km. Even though the upper crust, commonly 8 to 12 km thick, is normally the most radiogenic layer and consequently the highest heat-generating unit beneath the basin, it is evident that the contribution from this layer in areas of lowest heat flow is reduced. Diminished heat generation in the upper crust, probably due to low concentrations of radioactive elements, is the most significant factor in areas of low heat flows. Therefore, in areas of lowest heat flow (40 mW/m^2), the most significant heat contribution is from the reduced heat flow of 33 mW/m^2 emanating from the upper mantle and lower crust. Since the contribution of heat from the overlying Phanerozoic sediment succession is not very significant, ranging from 0 to 2 mW/m^2, input of radiogenic heat from the upper crustal layer, D, is likely in the order of 5 to 6 mW/m^2.

Distribution of heat flow

The very abrupt changes observed between high and low heat-flow zones, especially in the northern part of the study area (lows of 40 to 50 mW/m^2 and highs of over 100 mW/m^2; north of 60°, Fig. 4) suggest either the presence of a highly variable conductive heat-flow source derived from radioactive decay of radiogenic elements in the upper crust, or represent the effects generated by fluid flow upon heat flow, or both. A prominent southeast-trending zone of low heat flow extending from the centre of the Presqu'ile Barrier east of Cordova Embayment (Fig. 2, 4) through the marked deflection of the Peace River in the south-central part of the study area and culminating in the widespread regional low in the southeast of the project area contrasts sharply with the zone of high heat flow to the north (Fig. 4). The major influencing factor for these highly contrasting heat flow anomalies is probably variations in basement heat flow. These differences in basement heat flow likely represent contrasting heat-generating zones in the upper crust that are due to abundance and concentration of appropriate radiogenic elements. Such large variations of heat generation, sometimes up to a factor of 6, have been observed in the basement of the Western Canada Sedimentary Basin (Jones and Majorowicz, 1987; Burwash and Burwash, 1989; Lewis et al., 2002). Majorowicz (1996) speculated that the background reduced heat flow (Qr) in the northern part of the study area is significant. This reduced heat flow generated from the lower crust and mantle beneath the richer heat-generative upper crust is likely some 10 to 20 mW/m^2 higher than the average 33 mW/m^2 proposed by Jessop (1992). Therefore, in the northern part of the study area, a combination of higher regional reduced heat flow or Qr in the order of 40 to 50 mW/m^2, and higher than average heat generation from the basement rocks in the upper crust ranging from 3 to 5 μW/m^3 (Lewis et al., 2002) produced a substantial portion of the northern high heat-flow anomaly (70 to 90 mW/m^2).

Another rationalization for the generally high heat flow in the northern portion of the study area was discussed by Wu et al. (2002) who used magnetotelluric (MT) soundings along the SNORCLE transect to interpret a relatively shallow lithosphere–asthenosphere boundary in the area. The MT results show a zone of enhanced conductivity at maximum depths of 100 to 200 km across the mantle in Hottah, Great Bear, and Buffalo Head terranes (Ross et al., 1994; Wu et al., 1992). Since these depths are interpreted to be the base of the lithosphere, the source of enhanced conductivity is likely partial melt in the asthenosphere. The presence of partial melt at the lithosphere/asthenosphere boundary indicates temperatures of 1200 to 1400°C at depths as shallow as 100 km (Ringwood, 1969). These findings confirm enhanced heat flow and possibly elevated Qr of about 50 mW/m^2 in the north portion of the study area, which are still lower than heat flows measured in the Cordillera ranging from 60 to 70 mW/m^2. Whether these conditions continue farther southward within our study area is not well known because of the lack of MT studies. The northern high heat-flow anomaly does suggest elevated asthenosphere at least north of 59°N.

Burial history modelling and its associated temperature evolution in the Alberta Deep Basin just south of the map area (Poelchau et al., 1999) indicate the highest temperatures in the subsurface were attained during the period of most rapid sedimentation and subsidence in Late Cretaceous and Early Tertiary time when gas generation began. Erosion after uplift associated with the Laramide Orogeny removed more than 1500 m of the sedimentary succession according to Poelchau et al. (1999). Osadetz et al. (1992) interpreted that the highest maximum paleotemperatures may be related to great burial depths during Tertiary time in the Alberta Basin.

High geothermal gradients observed in this study exceed the 30 mK/m gradient assumed by Qing and Mountjoy (1992). If our calculated geothermal gradients prevailed during maximum burial of the basin, then the resulting maximum burial temperatures in high heat-flow areas could impart the elevated pressure-corrected homogenization temperatures observed by Qing and Mountjoy (1992). These homogenization temperatures in saddle dolomites, all measured along the Presqu'ile Barrier, range from 106°C for Pine Point area, 130 to 160°C for southern Northwest Territories west of Pine Point and 190°C for northeastern British Columbia. According to Qing and Mountjoy's (1992) stratigraphic reconstruction along the barrier, their corresponding maximum burial temperatures were calculated to be much lower, such as, respectively, 66°C at Pine Point, 90 to 143°C in southern Northwest Territories and 143 to 160°C for northeastern British Columbia, all based on an assumed average gradient of 30 mK/m and surface temperature of 20°C. Thus their pressure-corrected homogenization temperatures exceed their reconstructed maximum burial temperatures. Qing and Mountjoy (1992) and Mountjoy et al. (1997) speculated that advective eastward transport of hot fluids and their mixing with cooler ambient waters account for their corrected homogenization temperatures for the saddle dolomite deposits. We propose that these corrected homogenization temperatures are related to extensive burial and anomalous heat flow from basement rather than strong coupled heat flow-fluid flow as proposed by Qing and Mountjoy (1992) and Garven (1985, 1995).

There seems to be no direct linkage of enhanced heat flow with major lineaments and faults, such as the Great Slave Shear Zone (Fig. 1, 2). This observation may be related to an insufficient number of bottom-hole temperature measurements in these areas affected by faulting. In the immediate Pine Point mine area, there are no drillholes with bottom-hole temperature measurements. There is insufficient evidence in this study to hypothesize whether basement faults controlled migration of hot, deep-seated fluids upward into the Devonian carbonate hosts. The introduction of hydrothermal metal-bearing fluids into these carbonate deposits may have left a thermal imprint but this cannot be differentiated from the regional heat-flow patterns in the study. Even though we have proposed that homogenization temperatures in saddle dolomite (a commonly associated cement in lead-zinc ore in the Pine Point area) along the Barrier can be attributed to extensive burial and anomalous basement heat flow rather than coupled fluid flow and advective heat flow, it is not clear if the Northern Prairies Heat-flow Anomaly (NPHFA) had a direct impact on the subsequent introduction of metal-bearing fluids in the paragenetic sequence.

CONCLUSIONS

In the northern portion of the study area, anomalous heat flows greater than 90 mW/m^2 are most likely related to enhanced heat generation from zones richer in radiogenic minerals in the upper crust imprinted upon generally higher reduced heat flow derived from the lower crust and mantle. Upper crust basement heat flow is 10 to 20 mW/m^2 higher than the average Precambrian basement input of some 30 mW/m^2 and this enhanced heat-flow regime was likely in place during the depositional history of the basin's sediments and influenced temperatures of both host rock and migrating fluids. This extensive heat-flow anomaly viably explains high maximum burial temperatures obtained from homogenization temperatures of saddle dolomite deposits in the area.

Our work shows that if the observed present heat flow had stayed constant throughout the history of post-Laramide development in the basin, then predicted temperatures at maximum burial of the Presqu'ile Barrier would be greater than 90°C near 1500 m depth for the Pine Point area, 100 to 160° at 2000 to 3500 m in southern Northwest Territories and up to 180°C at 4000 m in northeastern British Columbia. These values are much closer to the measured homogenization temperatures and thus it is not necessary to invoke an enhanced coupled fluid flow-heat flow model to bring these temperatures to such levels.

We also find that the Northern Prairies Heat-flow Anomaly (NPHFA), the largest-scale regional heat-flow anomaly in the Western Canada Sedimentary Basin (Majorowicz, 1996) does not seem to be directly related to the Presqu'ile Barrier and occurs mainly to the north of the Barrier.

There is no significant evidence of any direct relationship of heat flow to major lineaments or faults, though this may be due to the coarse nature of the sampling program in the study area. Deep-seated hydrothermal processes may have had significant impact with respect to ore deposition at Pine Point, but the thermal imprint of this fluid circulation is not apparent. The metal ores at Pine Point may have been deposited by hydrothermal circulation, but there is no longer any measurable thermal signal to confirm this theory.

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