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REVIEW ARTICLE

Heat flow–heat production relationship not found: what drives heat flow variability of the Western Canadian foreland basin?

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Abstract Heat flow high −80 ± 10 mW/m^2 in the northern western parts of the Western Canadian foreland basin is in large contrast to low heat flow to the south and east (50 ± 7 mW/m^2) of the same basin with the same old 2E09 year's Precambrian basement and some 200-km-thick lithosphere. Over-thrusted and flat-laying sedimentary units are heated from below by heat flow from the old craton' crust and low 15 ± 5 mW/m^2 mantle contribution. The heat flow vs. radiogenic heat production statistical relationship is not found for this area. To account for this large heat flow contrast and to have 200-km-thick lithosphere, we would need to assume that high heat production layer of the upper crust varies in thickness as much as factor of 2 and/or that the measured heat production at top of Precambrian basement is not representative for deeper rocks. The other explanation proposed before that heat in the basin is redistributed by the regional fluid flow systems driven from high hydraulic head areas close to the foothills of the Rocky Mountains toward low elevation areas to the east and north cannot be explained by observed low Darcy fluid velocities and the geometry of the basin.

Keywords Heat flow · Heat production · Precambrian platform · Foreland basins · Western Canadian Basin

Introduction

Study of the thermal state of the Western Canadian Sedimentary Basin (WCSB) has been done for many decades (Anglin and Beck 1965; Garland and Lennox 1962; Majorowicz and Jessop 1981, 1993; Jessop et al. 1984, 2005; Jones et al. 1985; Beach et al. 1987; Jones et al. 1985, 1986; Jones and Majorowicz 1987; Jessop 1990a, b; Jessop 1992; Majorowicz et al. 1990, 1999, 2014a, b; Osadetz et al. 1992; Majorowicz 1996, 2005; Majorowicz and Grasby 2010; Gray et al. 2012; Weides and Majorowicz 2014; Majorowicz and Weides 2015; Nieuwenhuis et al. 2015).

Early on review of Canadian heat flow based on precise temperature logs and measured *k* was done by Jessop et al. (1984). The recent upgrade of the database can be found in Jessop et al. (2005). Majorowicz and Grasby (2010) compiled and critically reviewed heat flow data for all of Canada (Fig. 1) and for the first time included the WCSB heat flow estimates from industrial temperatures *T* and thermal conductivity *k* data for sedimentary rocks to estimate geothermal heat content at 3, 5, 7 km depth levels through Canada (locations shown in Fig. 1a).

Tens of thousands of industrial temperatures *T* from varying depth *z* in deep oil and gas exploration were used to determine averages of temperature grad *T*(*z*) with depth *z* and combined with thermal conductivity *k* estimates allowed heat flow estimates *Q*. The estimates of thermal conductivity *k* from rock composition averages of 13 main rock type thermal conductivities were first attempted for the WCSB by Majorowicz and Jessop (1981). Later over 1000 thermal conductivity values measured on cores of sedimentary rock of the WCSB (Beach et al. 1987) and net rock data were used in calculating *k* model for the entire basin from top to bottom (Majorowicz et al. 2014a; Majorowicz and Weides 2015).

First *Q* map for the WCSB (Majorowicz et al. 1990) showed the Northern WCSB heat flow high. This high was studied in detail (Majorowicz 1996). High heat flow in the

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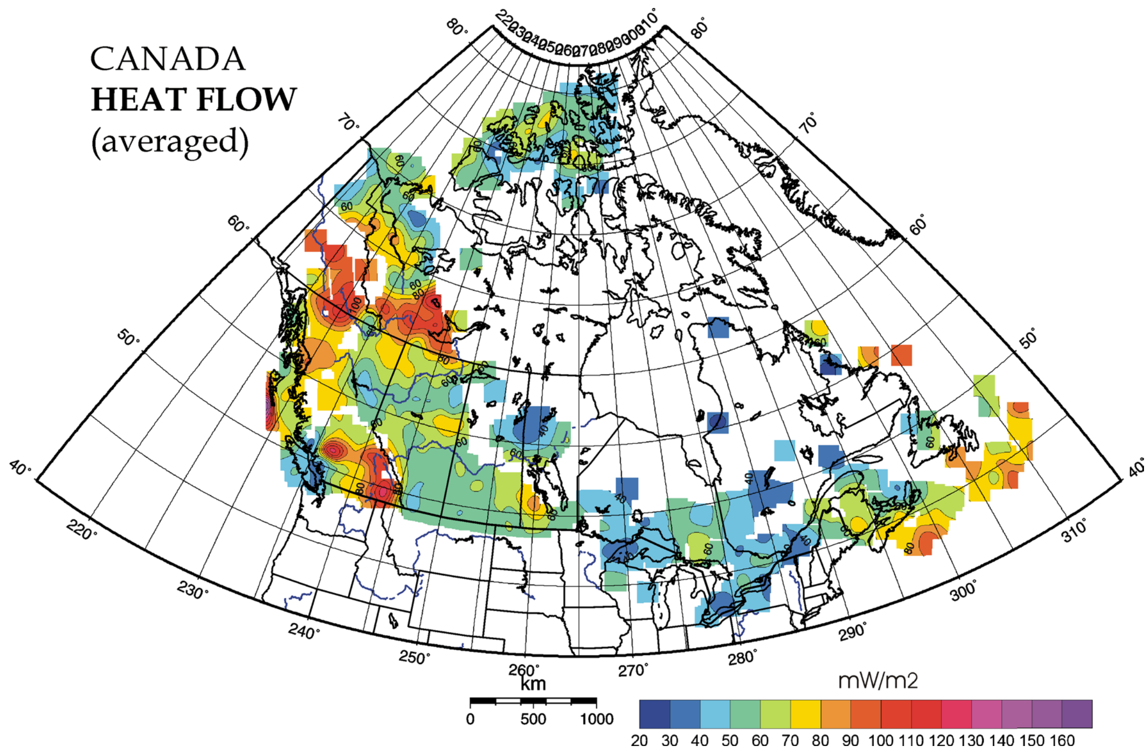

Fig. 1 Maps of heat flow data points (**a**) and heat flow patterns in Canada (**b**). Modified from Majorowicz and Grasby (2010)

northern part of the WCSB and to the west was confirmed by the Lithoprobe SNORCLE heat flow profile (Lewis et al. 2003). Compilation of *Q* data for the Heat Flow Map of N. America (Blackwell and Richards 2004) included these heat flow estimates from industrial temperatures from wells in the WCSB in Canada and from other basins in the USA.

An increased number of corrected temperature data from near 100 k Central and Northern Alberta data (Gray et al. 2012) and rest of the WCSB (Weides and Majorowicz 2014) lead to update of *Q* data and mapping *Q* for the entire WCSB (Majorowicz et al. 2014a; Majorowicz and Weides 2015).

The above-cited works discovered large variability of heat flow across Canada and showed that Northern WCSB heat flow high of some 70–90 mW/m^2 is comparable to the high heat flow areas of much younger tectonically Canadian Cordillera and twice as high as heat flow of the Canadian Shield.

In comparison with the map of heat flow of Northern America (Blackwell and Eds 2004a, b) which included Canadian data and showed extrapolated patterns for all of the area, Fig. 1 here (modified from Majorowicz and Grasby 2010) shows *Q* contouring which includes only the areas with the data and no spatial extrapolation is used for the area with no data. It is apparent that large areas of N. Canada have hardly any heat flow measurements.

The intent of this review is to present recent updated study of thermal regime of the WCSB basin. Answering question as to what drives this observed large heat flow variability of the Western Canadian foreland basin is the focus of this review.

Western Canadian Sedimentary Basin (WCSB)

The WCSB Phanerozoic sedimentary wedge overlies the Precambrian basement rocks (Burwash et al. 1994; Mossop and Shetsen 1994). This basement is composed of various accreted terranes of Archean to Proterozoic age. Its origin remains speculative, though the coeval assembly of the Hearne, Superior, Rae, Slave, and Wyoming provinces (Hoffman 1988; Ross et al. 1991) approximately 2.0 Gyr ago. Subdivisions and tectonic framework of the exposed and buried Canadian Shield is shown in Fig. 2.

The WCSB has been drilled into by thousands of deep wells in which temperature records have been taken. This has been studied for individual wells and groups of wells (Fig. 3). Precambrian basement (see Fig. 4 for the Precambrian basement depth) has a profound influence on the distribution of thermal conductivity and temperature field. Northeastward thinning wedge of sedimentary rocks of the WCSB reaches a maximum thickness of 6000 m (Fig. 3)

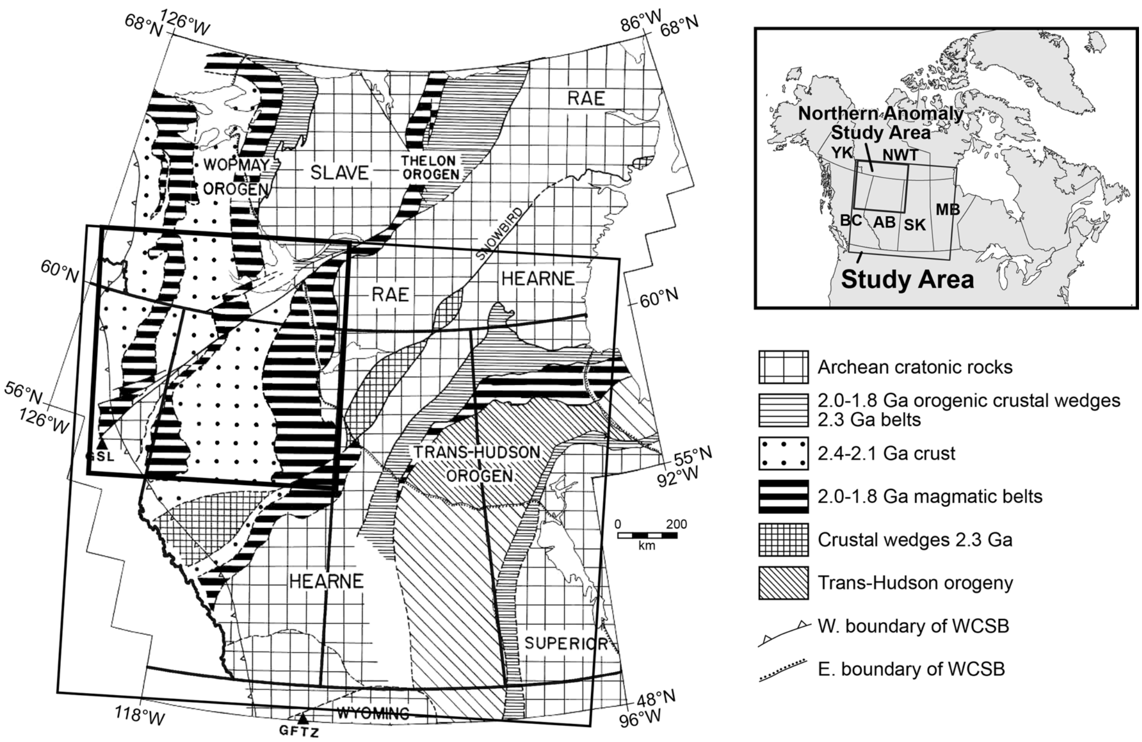

Fig. 2 Subdivisions and tectonic framework of the exposed and buried Canadian shield from Ross et al. (1991). The large *rectangle* is the regional study area from Majorowicz et al. (2014a) and Majorowicz and Weides (2015); the *small rectangle* represents the "Northern Anomaly study area" of this paper. The major subdivisions of the exposed and buried Canadian Shield are from Ross et al. (1991). WCSB is bounded by the *eastern* limit of the Cordilleran deformation and the *western* limit of the Canadian Shield. Abbreviations of the western Canadian Provinces are explained here; *YK* Yukon, *NWT* Northwestern Territories, *BC* British Columbia, *AB* Alberta, *SK* Saskatchewan, *MB* Manitoba

East of the foothills of the Rocky Mountains (Foreland basin type) and terminates to the northeast-east where the Precambrian basement outcrops as the exposed Canadian Shield.

Only few hundreds out of 300,000 wells drilled reached Precambrian basement. The deep basement structures have been mainly mapped using magnetic and gravity data and samples from the limited number of drill holes that have reached the basement (Burwash et al. 1994; Ross et al. 1991, 1994; Pilkington et al. 2000).

Industrial temperature data and precise temperature logs in the WCSB

The main bulk of information about deep temperatures in sedimentary basins comes from industrial wells drilled mainly for oil and gas exploration. These are measured at various depths depending on the oil and gas well targets. In the WCSB basin, over 300,000 wells were drilled and logged. These temperatures are not high-precision temperature logs but point temperature records and measured in thermal disequilibrium. Unless continuous logs are done in wells that have reached thermal equilibrium (±1 °C), determination of deep equilibrium temperatures and of grad $T(z)$ is just an approximations and correcting the data is needed and done (Harrison et al. 1983; Blackwell et al. 2004a, b; Crowell et al. 2012; Gray et al. 2012). It was observed from recent study of the WCSB industrial temperature database (Gray et al. 2012; Nieuwenhuis et al. 2015) that comparison of the different temperature record (Annual Pool Pressure surveys APP; Drill Stem Tests DST and Bottom Hole Temperatures BHT) is proving that Horner-corrected BHTs (Bullard 1939; Lachenbruch and Brewer 1959; Drury 1984) are an underestimate comparing to higher thermal equilibrium state measurement like DST and annual APP with APP being the highest. APPs are pressure test temperature logs in 'shut in' observational wells. While the Horner correction is one of the more frequently used temperature correction methods for BHTs attempting to correct the recorded temperatures to equilibrium conditions in a well (i.e., to conditions prior to the disturbance of the temperature field by drilling activities), it has its limitations as even corrected temperature values are less than equilibrium temperature from other types of measurements (Hermanrud et al. 1990; Crowell et al. 2012).

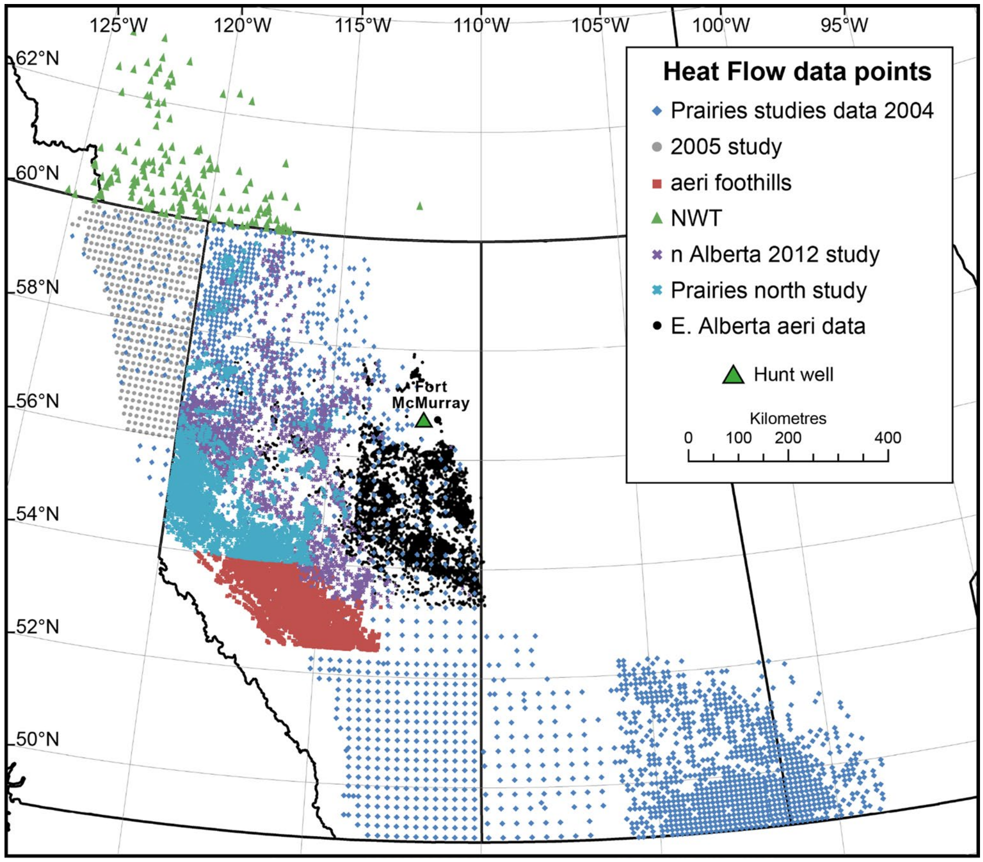

Fig. 3 Data coverage (*black points*) for grad $T(z)$ used in heat flow mapping of the study area

Temperature (T) at depth and geothermal gradient (grad $T(z)$) of the sedimentary succession of the WCSB recently analyzed like in Weides and Majorowicz (2014) comes from such corrected industrial thermal database record (APPs, DSTs and BHTs). Corrections like Horner, Harrison, SMU (Lachenbruch and Brewer 1959; Harrison et al. 1983; Blackwell and Richards 2004a, b respectively) were applied. Measurement and systematic errors inherent to the APP, DST, and BHT data are significant (Hackbarth 1978; Majorowicz et al. 1999; Gray et al. 2012) and can result in large data noise (Lam and Jones 1984; Majorowicz et al. 1999; Gray et al. 2012; Majorowicz et al. 2014a; Weides and Majorowicz 2014; Nieuwenhuis et al. 2015). To this end these data were initially cleaned to remove erroneous data as described by Gray et al. (2012) (e.g., a significant overestimation of Alberta industrial well logs from shallow depths was removed <1000 m).

Data coverage is shown in Fig. 3.

The first precise temperature measurements in WCSB in Alberta were made in two wells near Leduc (Q = 67mWm^2) and Redwater (Q = 61 mWm^2) in the vicinity of Edmonton, in shallow wells that were 300–1000 m deep (Garland and Lennox 1962). Deep well in Regina in Saskatchewan allowed Jessop (Jessop 1990b) to log high-resolution $T(z)$ in equilibrium condition down to just over 2 km and compare this to industrial thermal data in there and other wells through WCSB which came close. Deep precise temperature log in the Hunt well (Majorowicz et al. 2014b) near Fort McMurray (see Fig. 3 for location) allowed several equilibrium temperature logs down to 2.3 km. The upper 0.5 km is in the Phanerozoic sediments and 0.5–2.3 km is in the Precambrian granites. This log is being the first temperature log below the sedimentary cover in the WCSB in Precambrian granites and allowed measurements of heat production A and thermal conductivity vs. depth. This confirmed that grad T(z) increases with depth due to glacial–postglacial surface temperature change and that heat flow values need to be corrected for the effect or determined below the depth of major influence (>1.5 km), (Majorowicz et al. 2014b; Majorowicz and Safanda 2015).

Geothermal gradient maps

Except a few precise temperature logs (4), geothermal gradient grad $T(z) = dT/dz$ for the WCSB wells has been determined from corrected for return to equilibrium industrial temperature measurements. For temperatures taken at large depths >1.5 km, surface temperature of 0 °C was

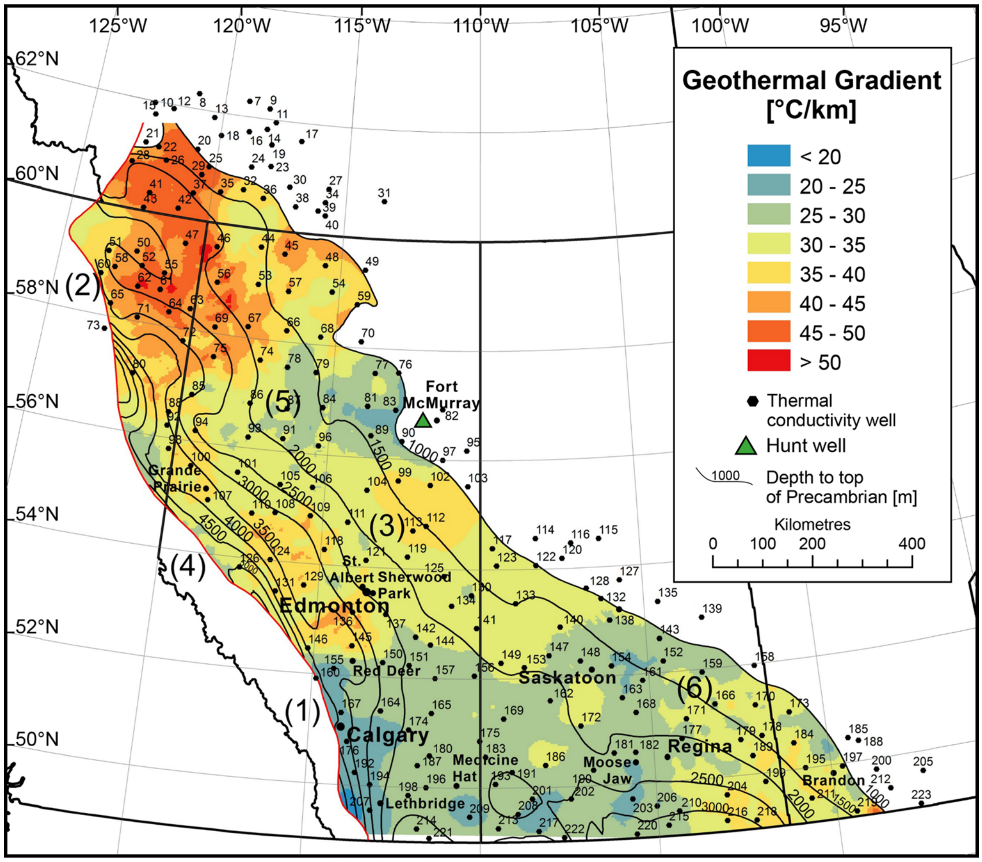

Fig. 4 Averaged Grad $T(z)$ through the sedimentary strata. Catalogue numbers refer to wells with k estimates (available upon request from the author). Depth to Pc surface is shown every 500 m. Numbers 1–6 relate to areas with previous studies of geothermal energy potential as reviewed in Majorowicz and Weides (2015)

commonly taken as the surface constraint (Majorowicz and Safanda 2015) related to latest glacial–postglacial history of surface temperature. Recent temperatures are much higher and partly related to recent post-Little Ice Age warming of the ground (Majorowicz and Safanda 2001) and land use effects upon ground surface warming due to clear cutting and others (Majorowicz and Skinner 1997). The deep measured >1.5 km temperatures are not in equilibrium state with recent-present surface temperatures some 5 °C higher than glacial temperatures some 11–13 k yeas before (Majorowicz and Safanda 2015).

Several editions of grad T maps has been done from as early as 1965 (Anglin and Beck 1965) to as recent as 2015 (Majorowicz and Weides 2015; Nieuwenhuis et al. 2015).

These grad $T(z)$ maps show large variability from as low as 20 °C/km in the southern Alberta Rocky Mountains Foothills to as high as 50 °C/km in the northern part of the basin in the forefront of the Mackenzie Mountains range (Figs. 4, 5). These are related to variability in heat flow Q and thermal conductivity k as:

$$Grad\,T(z) = Q/k \tag{1}$$

Grad $T(z)$ in the sedimentary cover built of Phanerozoic rocks allowed calculation of temperature at Precambrian top = base of Phanerozoic (Fig. 6).

Thermal conductivity of sedimentary basin

Thermal conductivity k model of sedimentary strata has been based on net rock analysis and assigned rock thermal conductivities for all of the sedimentary succession above Precambrian basement. The spatial pattern of the integrated thermal conductivity of sedimentary strata is shown in Fig. 7 together with control well points. The k of sediments $k_{sed.}$ of Cenozoic, Mesozoic, upper to lower Paleozoic rocks varies in relationship with overall composition and influence of compaction/porosity with depth whose function has been incorporated in calculation of k of the entire sedimentary section from the top of the surface to the bottom of sediments (top Precambrian surface). In general average porosity changes from low k shales 1.2 W/m K to high k of carbonates 3 W/m K and quartzites and salts (4–7 W/m K). The variability in thickness of lithostratigraphic units changes in facies and presence or missing these when eroded in different places of the basin results in variability of k both laterally and with depth. Calculated depth interval and integral $k_{sed.}$ shows (Fig. 7) a trend of eastward increase of k toward the shield. Some very low k zones like the one in North Western Alberta-BC part of the basin ($k_{sed.}$ = 1.4–1.6 W/m K) can explain some of the highest deep temperatures observed in the basin in the

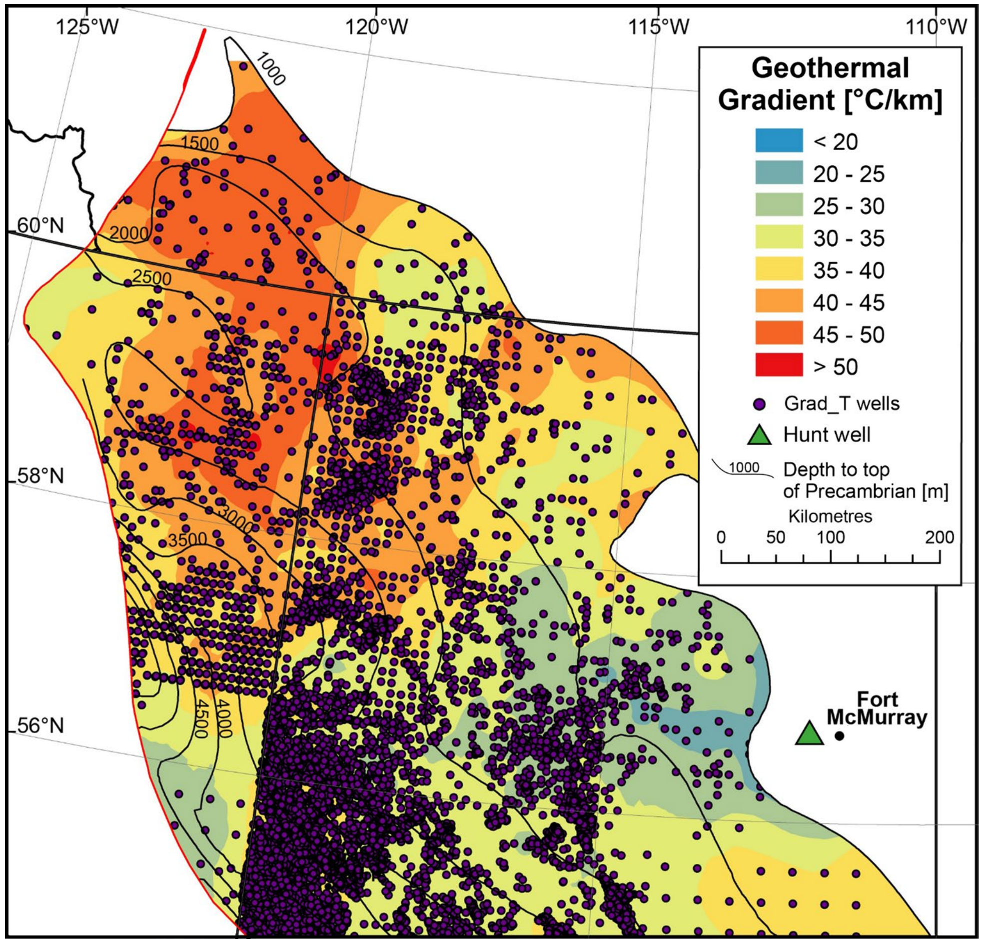

Fig. 5 Geothermal gradient data control for the northern 'hot' spot. Data control consists of single well BHTs, Annual pressure–temperature tests in shut in wells and DSTs. In some areas, well data were grouped and averaged in 1X1 township or 3X3 townships (Dominion system township area is some 9.6 × 9.6 km^2). (Modified from Majorowicz and Weides 2015)

northern heat flow high zone (see Nieuwenhuis et al. 2015). Very high integrated $k_{sed.}$ (2.6–2.8 W/m K) in the eastern shallow basin are close to k of Precambrian rocks below and reason of low temperatures at depth. The areas with the lowest k are prosperous for deep high temperature mining as rate of temperature increase with depth be the highest for the constant heat flow. The areas with cases of highest heat flow-lowest $k_{sed.}$ are the areas with highest deep temperatures and thermal heat in store.

WCSB k map shows that lowest $k_{sed.}$ we observe is in the western part of the basin in AB and in south eastern Sk. This low $k_{sed.}$ at high heat flow in the BC-NWT—North Western Alberta part of the WCSB results in highest temperatures at relatively low depths. This creates relatively shallow to drill (2–3 km) economic geothermal heat and power opportunity (Weides and Majorowicz 2014).

Heat production

Heat production A was determined from U235, Th232 and K40 for Precambrian basement rocks drilled into several meters under sedimentary cover (Burwash and Burwash 1989; Jones and Majorowicz 1987; Majorowicz et al. 2014a, b). The pattern (Fig. 8) shows large variability (logarithm scale).

The heat flow vs. heat generation relationship (2) has been used to predict heat flow in the WCSB before (Jessop 1992). If such found, Q_o is interpreted as heat flow from below high heat generating crust layer D.

$$Q = Q_o + DA \tag{2}$$

Such relationship can be found for the large basement provinces across Canada (Fig. 9); (Jessop 1990a, b, 1992).

The spatial wavelength of heat generation A changes is much shorter than the corresponding changes in heat flow Q, which reflects changes in A only in the large regional tectonic scale as apparent when large-scale averaged Q–A domains are compared across Canadian stable areas of the craton (Fig. 9).

Statistically, A data are distributed lognormal through whole of the WCSB (Jones and Majorowicz 1987) and through its northern high heat flow "Study Area" part (Fig. 10). The mean value $A = 2.06$ μW/m^3 (SD = 1.22) for the WCSB basement (Jones and Majorowicz 1987) with mean 61.4 mW/m^2 (SD = 15), (Majorowicz and

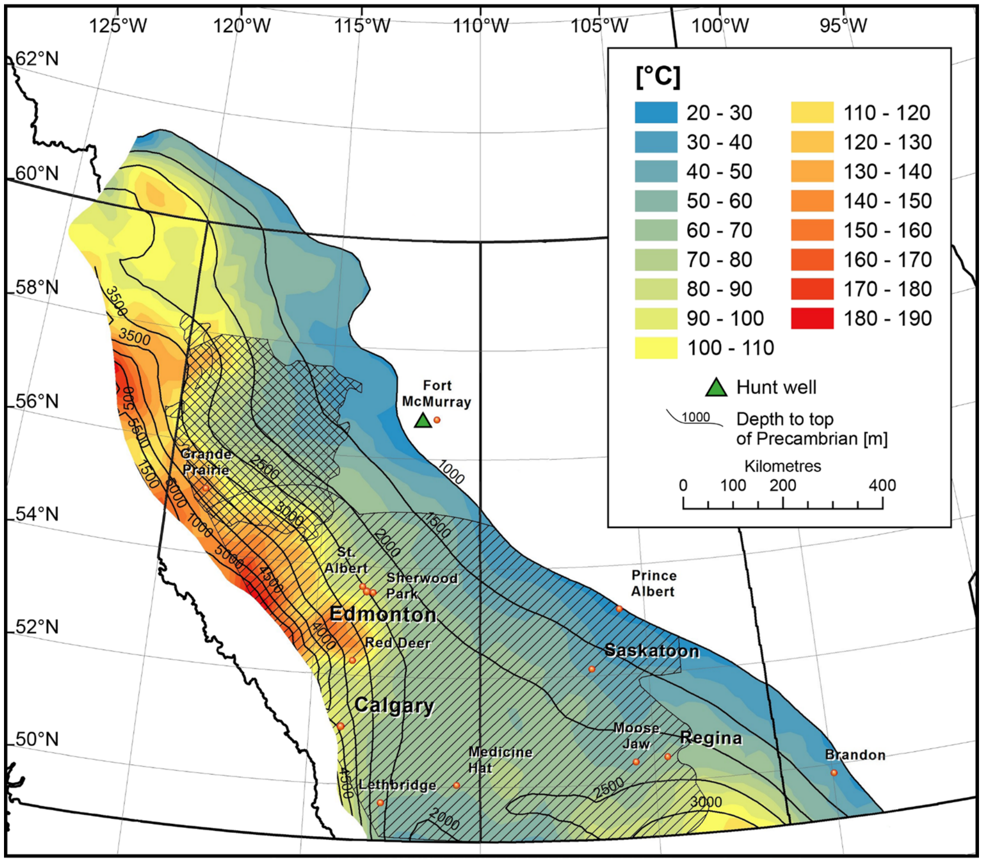

Fig. 6 Temperature at the base of Phanerozoic (*top* of Precambrian basement) of westward deepening basin based on grad *T*(z) from industrial temperature records from wells, depth z to basement and surface temperature. Aquifers *above* Precambrian basement potential for geothermal heat are shown, and deep sedimentary formations of Basal Sandstone (*hatched*) and Granite Wash Unit (*cross-hatched*) *above* Precambrian are shown. (Modified from Weides and Majorowicz (2014))

Weides 2015) is much larger than the radiogenic heat generation values reported for the lower mean $Q = 42$mW/m^2 (SD = 9) exposed Canadian Shield with mean $A = 1.15\ \mu$W/m^3, (SD = 0.9), (Jessop 1992).

Also, *A* varies with depth and example of this is shown in Fig. 11 (Hunt well *A* vs. depth based on gamma spectrometry log, Majorowicz et al. 2014b). Also another well in Precambrian basement Flin Flon Manitoba shows variability of *A* with depth over 3 km (Lachenbruch and Bunker 1971).

Heat flow map

Few (4) high-precision temperature logs in equilibrium wells were used to determine heat flow (*Q*) starting with first determinations of Garland and Lennox (1962). These show modest *Q* 60 ± 10 mW/m^2; however, it is on the average 20± higher than in the exposed Canadian Shield (Jessop et al. 1984). The first high-precision *Q* measurements in the Precambrian granites below the sedimentary cover were done in 2012–2014 in shallow sediments (0.5 km thick) and in >0.5 km deep granitic section in NE Alberta down to 2.3 km (Majorowicz et al. 2014a, b). Measurements of thermal conductivity *k* and heat production *A* with depth allowed calculation of heat flow variation with depth (*Q* at surface 50 and 60 mW/m^2 at 2.2 km).

Except a few precise temperature logs (4), geothermal gradient Grad $T(z) = dT/dz$ for the WCSB wells has been determined from corrected industrial data. Surface temperature 0 °C as heat flow at depth of >1.5 km is found to be in equilibrium with long-term average related to glacial times (Majorowicz et al. 2014a, b; Majorowicz and Safanda 2015). For the updated new version (Fig. 12) of the heat flow map of Majorowicz et al. (2014a, b) modification has been applied. Data from wells <1.5 km were rejected due to difficulty in determining likely disturbance by glacial–postglacial effect (Majorowicz and Safanda 2015).

Newly updated *Q* map shows that northern *Q* high extends through north eastern BC, southern NWT and northern Alberta part of sedimentary basin. It is a large regional feature in-between the exposed Canadian Shield and the Canadian Cordillera in BC and NWT.

Discussion

We considered here conductive heat flow. While quantitative early on work suggested that regional fluid flow plays

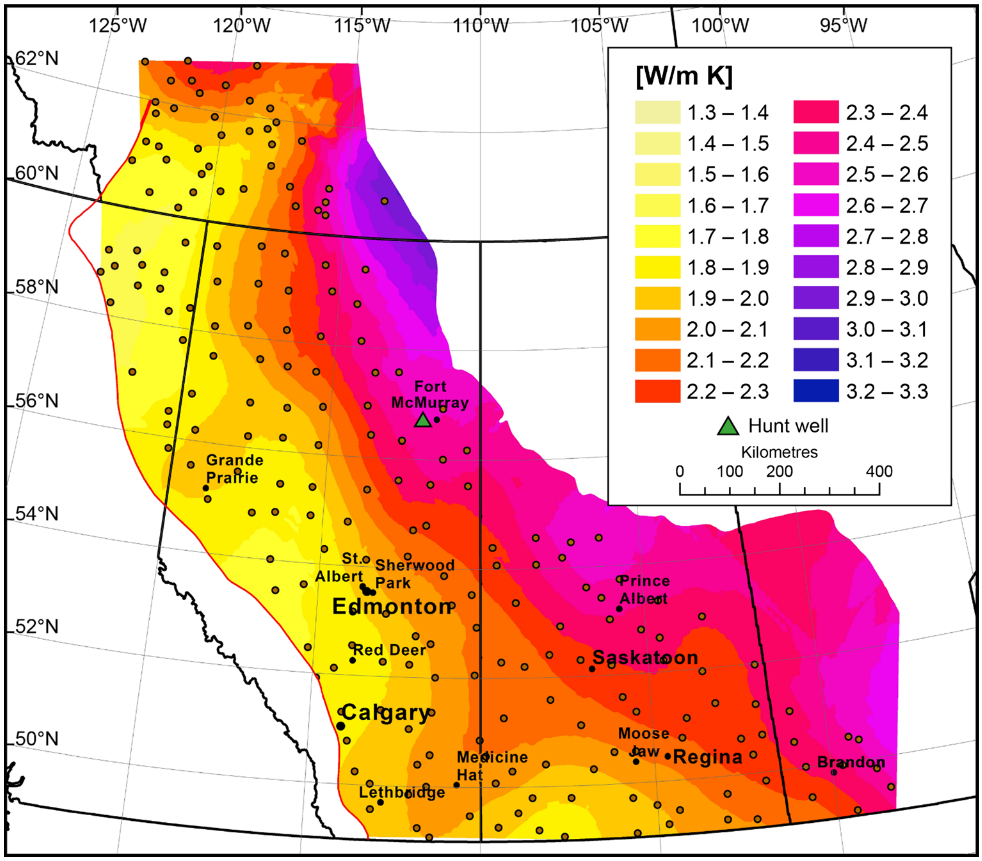

Fig. 7 Integrated thermal conductivity for the whole of the WCSB Phanerozoic fill based on *k* data (see Fig. 4 for the catalogue reference numbers of wells with *k* estimates (available upon request from the author) used in mapping of the pattern applying the simple kriging algorithm (see Weides and Majorowicz 2014)

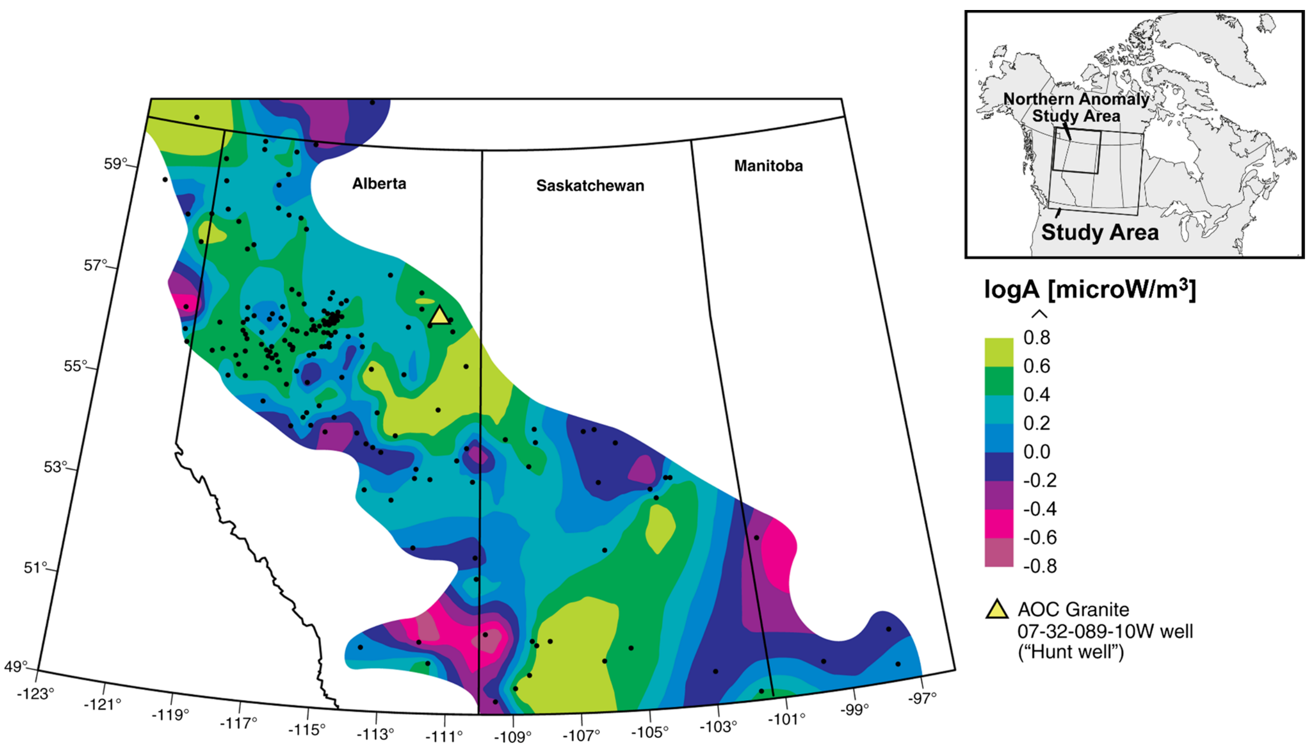

Fig. 8 Pattern of WCSB heat production (*A*) in mW/m^3 based on radiogenic isotopes of U, Th, K content in the Precambrian basement rocks. (Modified from Jones and Majorowicz 1987 and Majorowicz et al. (2014a, b))

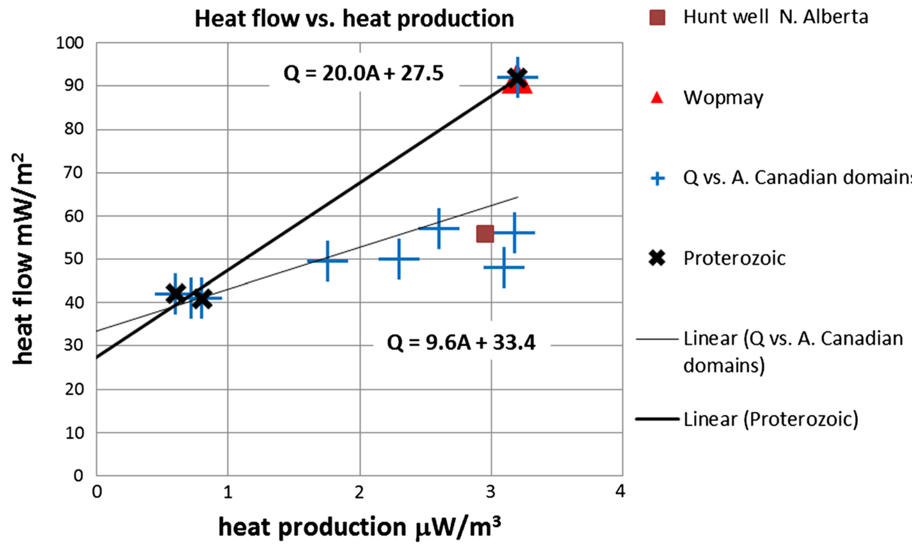

Fig. 9 Q vs. A statistical *plot* for the Canadian Precambrian-Paleozoic (Apalachians) units. Note that Northern Geothermal Anomaly Wopmay Proterozoic data is anomalous comparing to other regions. Hunt well data are from Majorowicz et al. (2014b). Adopted from Jessop (1990a, b, 1992), Jaupart and Mareschal (2011)

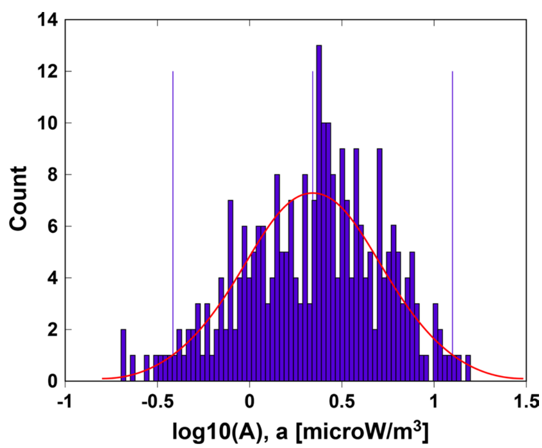

Fig. 10 Histogram of heat production in the northern Q anomaly study of the WCSB. Mean $A = 2.2\ \mu\text{Wm}^{-3}$. (Modified from Majorowicz et al. 2014a, b)

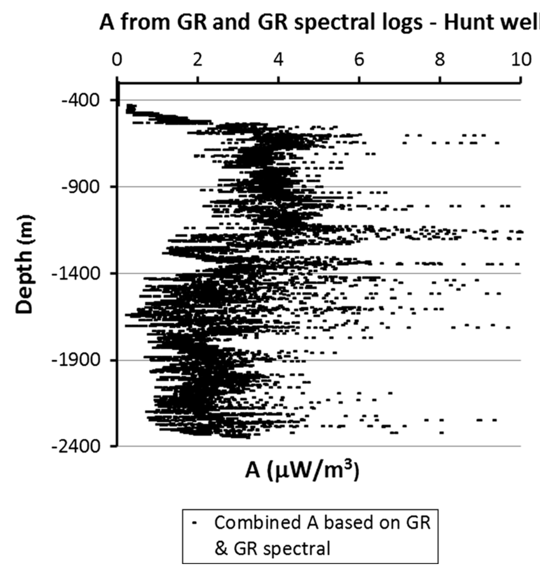

Fig. 11 Heat production vs. depth from Gamma spectrometry. (Modified from Majorowicz et al. 2014b)

its role in redistribution of heat in the basin (Majorowicz and Jessop 1981), recent numerical models of heat flow-fluid flow (Adams et al. 2004; Majorowicz et al. 1999; Weides and Majorowicz 2014) cannot explain regional heat flow variability for the observed Darcy fluid velocities of just mm/year and the geometry of the basin (2D Peclet number constraint for the high ratio of large across the basin's length of hundreds of km vs. its thickness of just few km). (Majorowicz et al. 1999) numerically tested the extent of hydrodynamic influence across the basin using a 2D numerical model constrained by revised thermal data. For this model, a finite element mesh was generated which rebuilds the geometry of the across the basin sections. For the major fluid conduits like the Devonian carbonates or the Cambrian Basal Sandstone Unit, the range of hydraulic conductivities was estimated. The Tertiary and Cretaceous shale units were assumed to have minimal permeability. Topography controls gravity-driven flow patterns. Analysis showed that Darcy velocities of 0.01 to 1 m/yr cannot alone explain Q observations. Likely, higher vertical Darcy velocities in faulted deep basin in the foothills of the Rocky Mountains could disturb vertical heat. These are, however, mainly west of the discussed here heat flow pattern.

We can observed from Fig. 12 that the westernmost North American Craton (about 2 billion years old) located between the Cordillera and the exposed Canadian Shield has high heat flow which is some 70–90 and 100 mW/m^2 in places. This is quite unexpected as modest A of its granitic rocks is observed in comparison with the rest of the basin. This, however, is based on much fewer data due to

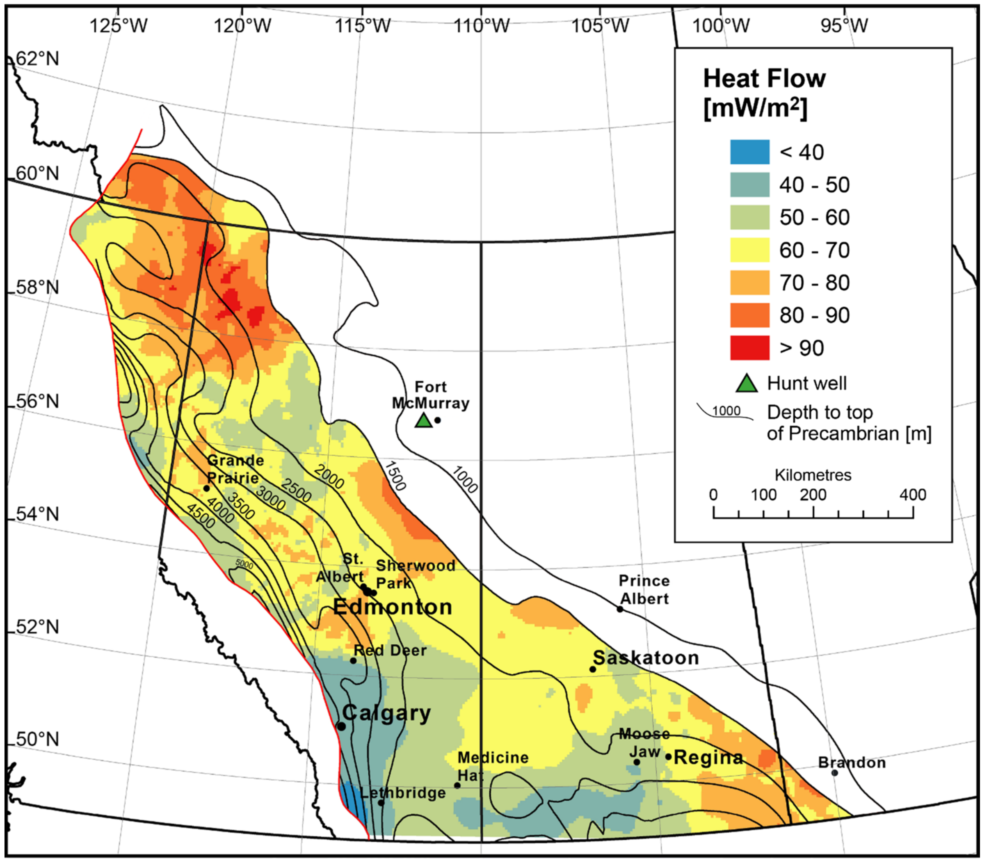

Fig. 12 Heat flow calculated from culled temperature data in sedimentary cover and integrated thermal conductivity. Data from wells <1.5 km were rejected due to difficulty to likely disturbance by glacial postglacial effect (Majorowicz and Safanda 2015). (Modified from Majorowicz et al. 2014a, b; Majorowicz and Weides 2015)

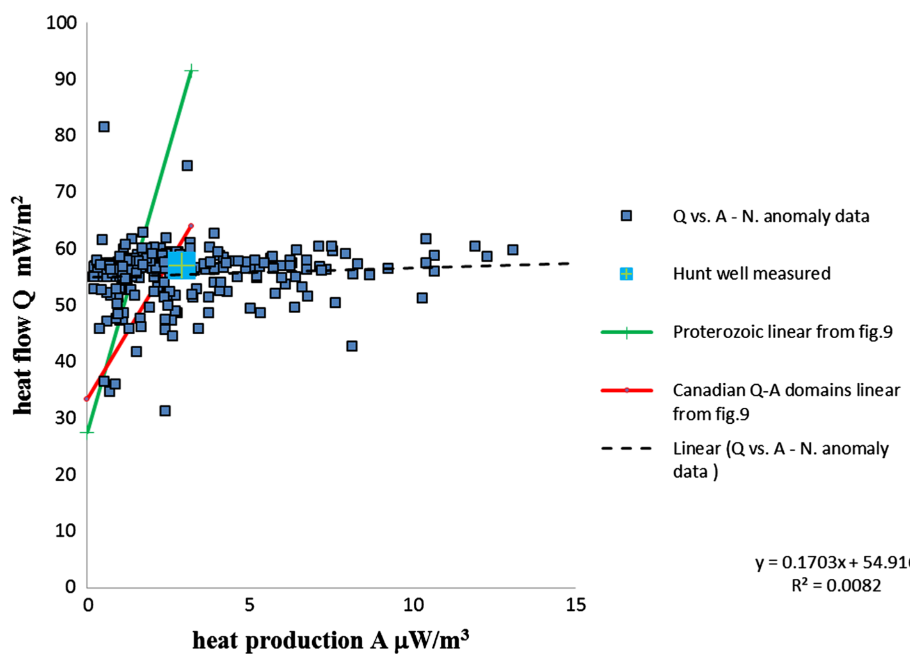

Fig. 13 Heat flow Q in the northern part of the WCSB vs. heat production A compared to Canadian Q–A relationships averaged for large Precambrian basement domains from Fig. 9

seldom Precambrian basement cores in the area. Overall, estimated Q between 49 and 62°N through the foreland basin (WCSB) shows a northward increase of Q along the forefront of the disturbed belt.

Comparison of Q (Fig. 12) and A (Fig. 8) shows that there is very little or no spatial correlation. This is well corroborated by the observation that the Q data do not correlate well with corresponding A (Fig. 13) for the smaller northern area of the WCSB. There, good Q and A data control exists.

One of the reasons that it is difficult to find regional Q vs A statistical relationship (Fig. 13) in case like northern WCSB is fact that surface of Precambrian basement A values may not be characteristic for the whole of granitic basement. The distribution of A is statistically lognormal (Fig. 10 and Jones and Majorowicz 1987), while the distribution of Q in the basin is normal (Weides and Majorowicz 2014). Average heat production A is generally higher (2.1 μW/m^3) than heat generation from the exposed shield to the east which is closer to 1 μW/m^3 (Jessop 1992). In the northern Q high study area, mean $A = 2.2$ μW/m^3. In the Wopmay Orogeny in the Northern part of the study area (see Fig. 2 for location) which is part of the northern heat flow anomaly (Majorowicz 1996), mean measured $A = 3.2$ μW/m^3 (Lewis et al. 2003).

In the study area, high heat flow areas are not necessarily related to high heat production as expected from Q–A (Eq. 2) relationships found in many other areas of the Canadian Shield (Jessop 1992). Such a relationship cannot be used practically in our study area as the statistical relationship between Q and A does not exist (Fig. 13). Sediments contribute little comparing to granitic crust as found from analysis of gamma logs for several wells in Alberta (Majorowicz et al. 2014b). Jaupart and Mareschal (2011) observe that Q–A relationship is not seen in many areas of the cratons, commonly. The fact that Q–A correlation is hard to find may be related to difference in wavelength between Q and A.

High Q of the Northern Geothermal Anomaly would create anomalous temperature conditions in the lithosphere—mantle boundary LAB in the Wopmay (see Fig. 2 for location) where measured $A = 3.2$ μW/m^3 (Lewis et al. 2003). When Q vs A relationship standard slope $D = 10$ km is assumed, hot crust and shallow asthenosphere would be the case. This slope D (Eq. 2) relates well to the slope of the relationship shown for the Canadian Shield domains and is interpreted as a thickness of the high heat generation layer of the upper crust. However, at such model ($D = 10$ km at $A = 3.2$ μW/m^3), the LAB would be located at a depth of about 60 km. LAB (Lithosphere–Asthenosphere Boundary) at such shallow depth is not realistic and not supported by seismology in the area and Lewis et al. (2003) assumed that A must be higher than measured and as high as 6 μW/m^3 to meet the constraints.

In order to explain observed Q high in quite average A area, we assume here that high A layer of the upper-mid crust varies in thickness as much as factor of two or more as in the models shown in Figs. 14a and 15b. D is 20 and 10 km, respectively. This way we are able to have low expected mantle heat flow close to other Precambrian cratons of some 15 mW/m^2 (Jaupart and Mareschal 2011)

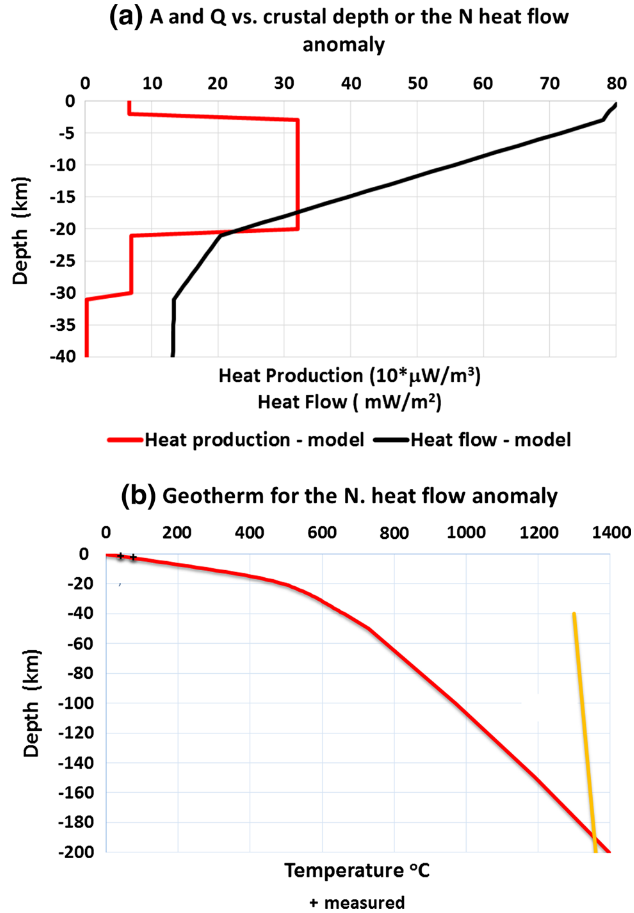

Fig. 14 Northern Geothermal Anomaly Q–A model (**a**) and geotherm (**b**) *Orange line* is mantle adiabat. Adopted from (MacKenzie and Canil 1999)

and reasonable thick thermal lithosphere (close to 190–200 km) in both cases of high and low Q (see: Figs. 14 vs 15 respectively).

Redistribution of radiogenic mineralization and creation of thicker radiogenic D layer related to anomalous high q zones like in the Wopmay orogeny general area could be a result of convergence, past crustal blocks collision, granitic intrusions (Blakey 2016) resulting in the redistribution of radiogenic bearing elements from buried sediments into cooling and thickening and strengthening crust similar to Trans-Hudson radiogenic element distribution model proposed by Drury (1985). Other explanation previously proposed by Majorowicz (1996) that in the heat flow high we have elevated mantle heat flow contribution of >30mW/m^2 would result in shallow (<100 km) LAB which was not confirmed by any other study. Near 200 km depth of LAB estimated for the model of measured A and large thickness $D = 20$ km make it comparable to just above 200 km estimate for the lower heat flow area toward the exposed shield where precise Q–A (z) was measured in deep well

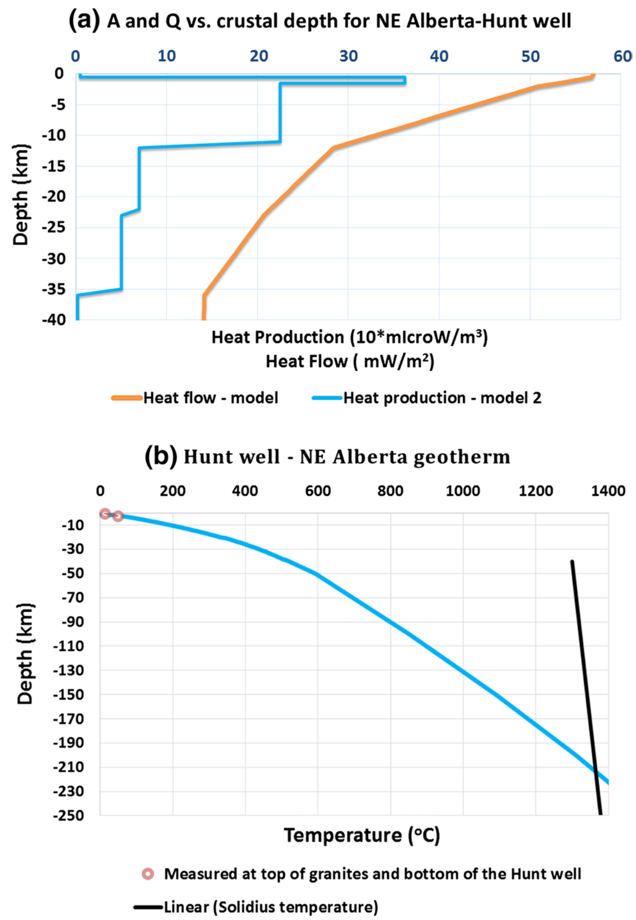

Fig. 15 Low Q area; Q–A (z) models (**a**) and geotherms (**b**). Mantle adiabat Adopted from MacKenzie and Canil (1999)

near Fort McMurray (Hunt well; Majorowicz et al. 2014b). There, LAB depth is close to previous estimates of thick 200 km lithosphere typical for old Western Canadian craton near Rocky Mountains Foothills in South-Western Alberta (Hyndman et al. 2009).

The LAB depth on the southern edge of the Slave Craton was estimated to be close to 200–250 km (MacKenzie and Canil 1999; Jones et al. 2003; Hyndman et al. 2009). Surface wave tomography (McKenzie and Priestley 2008) gives LAB at 180–220 km depth. Xenoliths from northern Alberta kimberlites give LAB at ca. 180 km (Aulbach et al. 2004) and magnetotelluric models from northern Alberta give 200–250 km (Türkoğlu et al. 2009). Majorowicz et al. (2014b) calculated lithospheric geotherms and determined 210 km LAB depth for model with a mantle Q 15 mW/m^2 based on Hunt well near Fort McMurray Q–A data. It is considered a reasonable estimate consistent with other independent continental geotherms for low to high Q (Hasterok and Chapman 2011) and LAB depth estimates as referenced above and illustrated in 2 examples of high and low heat flow in the WCSB (Figs. 14, 15).

Conclusion

1. Studies of the thermal state of the sedimentary basin in Western and Northern Canada have shown that there is no definitive explanation of the source of heat from the old Precambrian crust below the sediments and the ways this is redistributed through the Phanerozoic succession.
2. Interpretations of recently compiled Precambrian heat production data from cores, larger density of heat flow data distribution through the basin and of the first deep heat flow—heat production vs. depth determination in deep well into granite (Hunt well) points toward large variability of heat production A (statistically lognormal) and heat flow Q (normal) through the basin and its Precambrian basement with variable thickness D.
3. Most likely explanation of the observed heat flow variability from large regional lows of some 40–50 mW/m^2 to highs of some 70–100 mW/m^2 is the models in which thickness D of high heat production upper crustal layer varies by at least a factor of 2. Such models maintain uniform lithospheric thickness of some 200 km and low mantle heat flow of some 15 mW/m^2.
4. Other explanations like the redistribution of heat through the basin by fluid flow have been considered by numerical modes which point to low-scale effect at the observed and reasonable Darcy fluid velocities in the basin.

In conclusion of the analysis of the available facts, it can be summarized that no definitive explanation for the high heat flow is at hand and we just speculate on its origin. A thicker than normal upper crust high heat generation layer, ~20 km, is the preferred explanation. A fluid flow explanation seems less likely.

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