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The first deep heat flow determination in crystalline basement rocks beneath the Western Canadian Sedimentary Basin

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SUMMARY

Heat flow (Q) determined from bottom-hole temperatures measured in oil and gas wells in Alberta show a large scatter with values ranging from 40 to 90 mW m^{-2}. Only two precise measurements of heat flow were previously reported in Alberta, and were made more than half a century ago. These were made in wells located near Edmonton, Alberta, and penetrated the upper kilometre of clastic sedimentary rocks yielding heat flows values of 61 and 67 mW m^{-2} (Garland & Lennox). Here, we report a new precise heat flow determination from a 2363-m deep well drilled into basement granite rocks just west of Fort McMurray, Alberta (the Hunt Well). Temperature logs acquired in 2010–2011 show a significant increase in the thermal gradient in the granite due to palaeoclimatic effects. In the case of the Hunt Well, heat flow at depths >2200 m is beyond the influence of the glacial–interglacial surface temperatures. Thermal conductivity and temperature measurements in the Hunt Well have shown that the heat flow below 2.2 km is 51 mW m^{-2} ($\pm$3 mW m^{-2}), thermal conductivity measured by the divided bar method under bottom of the well *in situ* like condition is 2.5 W m^{-1} K^{-1}, and 2.7 W m^{-1} K^{-1} in ambient conditions), and the geothermal gradient was measured as 20.4 mK m^{-1}. The palaeoclimatic effect causes an underestimate of heat flow derived from measurements collected at depths shallower than 2200 m, meaning other heat flow estimates calculated from basin measurements have likely been underestimated. Heat production (A) was calculated from spectral gamma recorded in the Hunt Well granites to a depth of 1880 m and give an average A of 3.4 and 2.9 μW m^{-3} for the whole depth range of granites down to 2263 m, based on both gamma and spectral logs. This high A explains the relatively high heat flow measured within the Precambrian basement intersected by the Hunt Well; the Taltson Magmatic Zone. Heat flow and related heat generation from the Hunt Well fits the heat flow–heat generation relationship determined for other provinces of the Canadian Shield. However, this relationship could not be established for Q estimates from industrial temperatures data for the study area that includes the Taltson Magmatic Zone and neighbouring Buffalo High and Buffalo Utikuma domains to the west. It appears that the spatial wavelength of heat generation change is much smaller than that of heat flow. Thermal modelling of heat flow and heat generation data from the Hunt Well, using mantle heat flow contributions of 15 $\pm$ 5 mW m^{-2} results in lithosphere–asthenosphere boundary depth estimates of near 200 km. This mantle heat flow value is consistent with the range for the stable continental areas, 15 ($\pm$3) mW m^{-2}.

Key words: Heat flow; Composition of the continental crust; North America.

INTRODUCTION

In most sedimentary basins hydrocarbon exploration has produced hundreds of thousands of temperature measurements, but very few precise equilibrium temperature T logs (Grasby *et al.* 2011). This is the case for the Alberta basin, which is part of the Western Canadian Sedimentary Basin (WCSB), a foreland basin east of the Canadian Cordillera. To date, only two precise temperature

T logs and heat flow *Q* estimates have been reported from the upper part of the clastic sedimentary strata. The *Q* was determined indirectly as a result of temperature *T* log from which the geothermal gradient was determined, and measured thermal conductivity (TC) *k* of sedimentary rocks (Garland & Lennox 1962). The *Q* estimates of Garland & Lennox (1962) were both made from measurements at depths less than 1000 m (some as shallow as 300 m).

In this paper, we report a new precise *Q* from a 2363-m deep well drilled into basement granite rocks just west of Fort McMurray, Alberta (Borehole AOC GRANITE 7-32-89-10W4, referred to as the Hunt Well after its owner). The Hunt Well offers the ideal opportunity to study the *Q* and the thermal properties of the Precambrian (Pc) granitic rocks deep below top of the basement. Depth to the basement in Alberta varies from 0 to >5000 m in the deep foreland basin towards Rocky Mountains (Fig. 1). All that space between the surface and the top of Pc basement is filled with Phanerozoic sediments where over 300 000 wells drilled, however, few hundred reached top few metre of the Pc rocks and only one (Hunt Well) reached 1822 m deep into the granites below sedimentary succession. Temperatures measured within the shallow sedimentary rocks cannot be used for such determination since (1) they are highly variable and of poor quality and (2) heat transport by non-conductive mechanisms, such as fluid flow, may occur in the sedimentary rocks. It was shown by previous research that in these porous sedimentary rocks the calculated surface *Q* values are significantly different (up to 50 per cent) from the conductive *Q*, depending upon the nature of the hydrogeological system and its geometry which has been changing over time (Majorowicz & Jessop 1981; Jessop 1990; Bachu & Burwash 1991; Majorowicz *et al.* 1999). Hydraulic head has been diminishing and Darcy fluid flow rates with it reducing hydrodynamic influence upon heat flow. This is due to change in topography due to erosion. Some 2 km erosion in the area towards deep basin Foothill of Rocky Mountains has taken place (Majorowicz *et al.* 1990).

Thermal properties and *T* well log measurements in the Hunt Well were made within the Pc basement rocks well below the 0.54-km thick sedimentary cover. This well log is the only continuous temperature log from the Pc basement in Alberta and extends beyond the depths influenced by palaeoclimatic temperature changes (Čermak 1971; Jessop 1971; Gosnold *et al.* 2011; Majorowicz *et al.* 2012).

Using a deep well allows the opportunity to validate estimates of *Q* and heat generation (*A*) made commercially in the shallow wells shown in Fig. 2(b) and described by Gray *et al.* (2012) and Majorowicz *et al.* (2012). Note that the Hunt Well is located towards the east of the region sampled by the numerous shallow wells in Fig. 2(b). The Pc basement domains are shown in Fig. 1(a) and it can be seen that the Hunt Well intersects the Proterozoic Taltson Magmatic Zone (TMZ, labelled Taltson in Fig. 2a), which outcrops in the exposed shield to the north. The TMZ is bounded on the east by the Archean Rae domain, a subdivision of the Churchill Province, and to the west by the Bufallo High and Bufallo Utikima terranes. There is only one other *Q* measurement in the neighbouring Canadian Shield and this is to the east in the Athabasca basin (Drury 1985). Many new heat flux measurements have been made in the Trans Hudson (Orogen) since the paper of Drury (1985) by Mareschal *et al.* (2005); however, the Athabasca basin heat flow measurement described in Drury (1985) is the closest to our Hunt Well measurement.

It is important to quantify heat flow in this region, because it provides an estimate of the heat input from the Pc crust into the sedimentary rocks. These data are needed (1) to accurately model

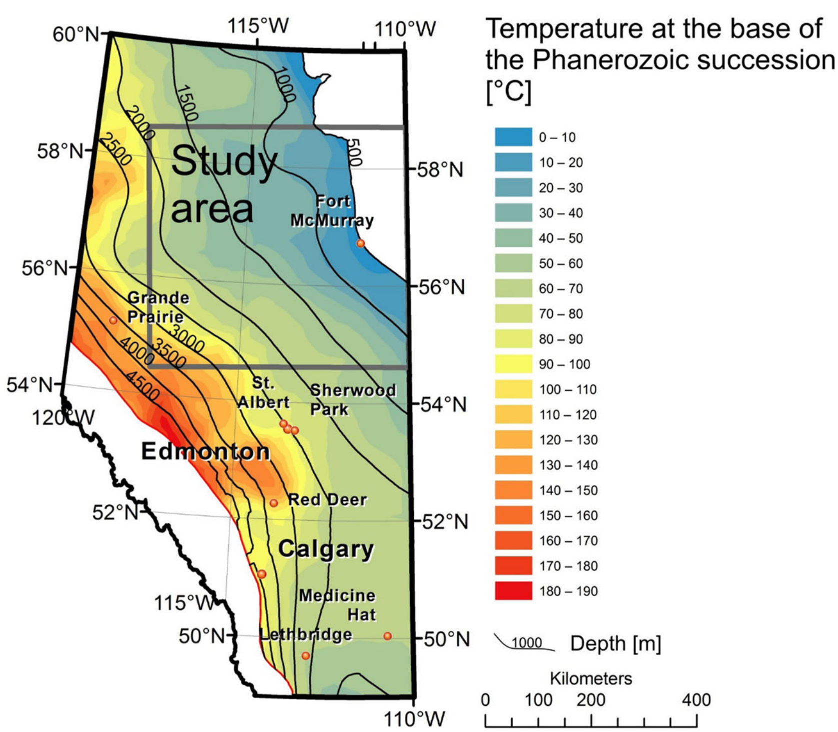

Figure 1. Temperature at the base of the Western Canadian Sedimentary basin (Phanerozoic) calculated from average for sedimentary fill gradients of temperature from corrected industrial point temperature records. Ordinary kriging for both the gradient map and the Precambrian depth map was used. The temperature map was calculated by multiplying depth and gradient map. 68 567 temperature values were used for the gradient map. Contours are in °C. Thickness of Phanerozoic sedimentary rocks in the basin is shown by contours in meters. Study area shown in detail in Figs 2(a) and (b) is marked as a rectangle.

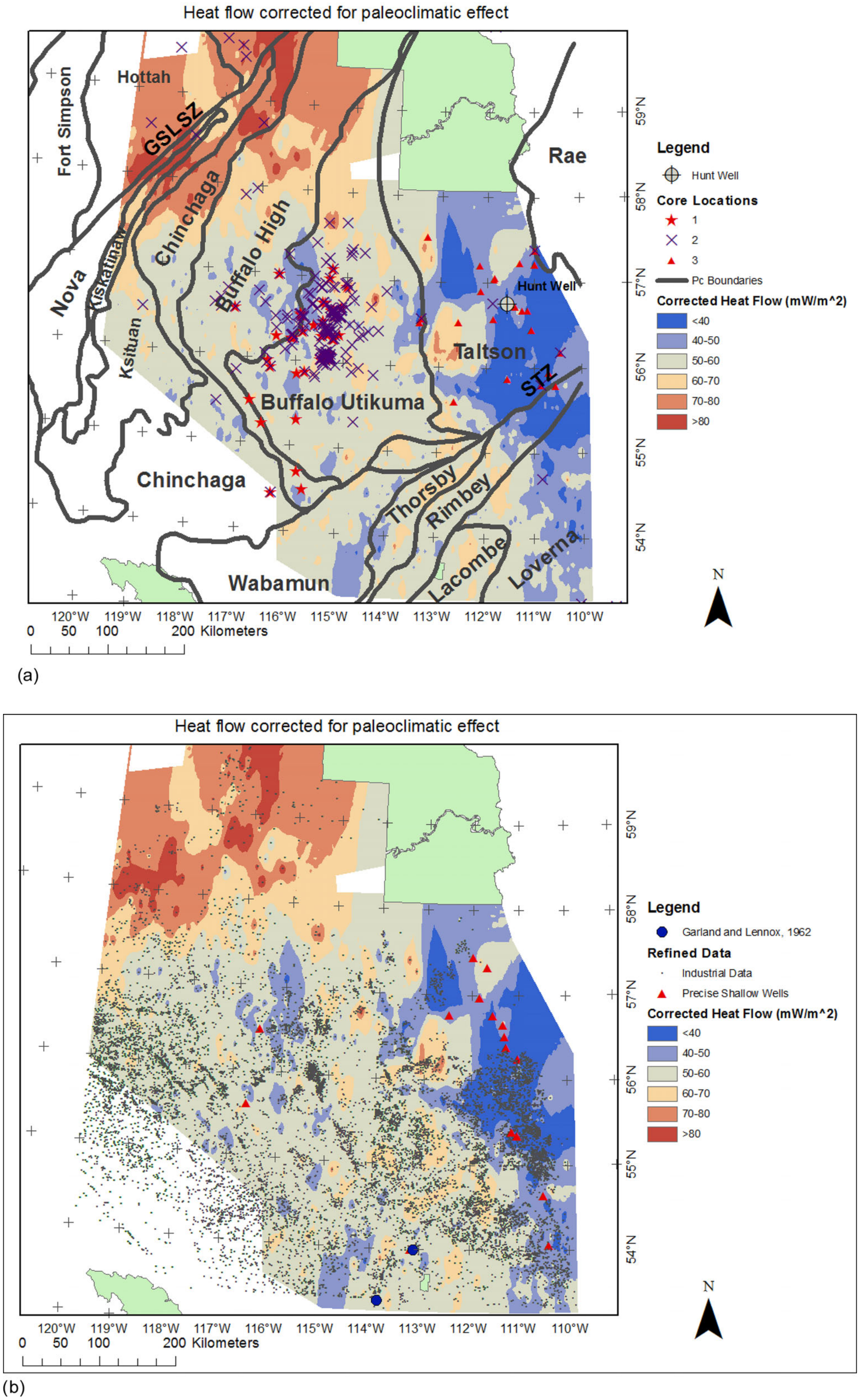

Figure 2. (a) Location of the Hunt Well and other wells used in this study (modified from Majorowicz *et al.* 2012). Precambrian basement domains boundaries and lineaments (STZ is the Snowbird Tectonic Zone, GSLZ is the Great Slave Lake Shear Zone) are shown as thick black lines and are taken from Pilkington *et al.* (2000). National Parks (Buffalo in NW Alberta and Jasper in W Alberta) are shown in green. Well locations are: (1) Wells with thermal conductivity and heat generation data from University of Alberta Geothermal Lab; (2) Wells with U and Th concentration determinations (Jones & Majorowicz 1987; Burwash & Burwash 1989; Bachu & Burwash 1991); (3) Location of wells where precise temperature T measurements were made in the upper 300 m as also shown in (b). Locations of two Q measurements from Garland & Lennox (1962) are shown by blue dots in (b), the locations of all the industrial data points are shown as light grey dots, and the red triangles indicate shallow (<300 m) high-precision T logs.

temperatures within the sedimentary basin and (2) to look at the lithosphere–asthenosphere boundary (LAB) depth estimates as a constraint on heat inputs from below the crust.

Regional temperature setting at the top of Pc basement

The Hunt Well lies in a shallow part of the basin near Fort McMurray (Figs 1 and 2a) where the temperature at the base of the sediments (top of Pc granites) is near 10–15 °C as shown by the temperature contour map in Fig. 1. Temperatures at the top of the Pc basement (base of the Phanerozoic sedimentary rocks) have been calculated for the northern Alberta portion of the WCSB from industrial temperature measurements made in oil and gas wells. Due to westward deepening of the WCSB from the exposed shield in northeastern Alberta to more than 5000 m in the southwest, the basement sedimentary rock interface temperature increases from nearly 0 °C at the surface to 180 °C in the deepest part of the basin. At the Hunt Well, located in the Fort McMurray area, the Pc basement is intersected at a depth of 541 m and has a relatively low temperature of 13 °C measured by T log.

Previous heat flow measurements in Alberta

The first precise Q measurements in Alberta were made in wells near Leduc (67 mW m^{-2}) and Redwater (61 mW m^{-2}) in the vicinity of Edmonton, in shallow wells that were 300–1000 m deep (Garland & Lennox 1962). Applying a palaeoclimatic correction (Majorowicz *et al.* 2012, 2013) increases these values by 12 per cent to 75 mW m^{-2} for the Leduc well and 68 mW m^{-2} for the Redwater well.

Majorowicz & Jessop (1981) estimated that the effective TC in Central Alberta was 2.1 W m^{-1} K in the sedimentary rocks, the average geothermal gradient was 33 mK m^{-1} and the average Q was 69 mW m^{-2}. This estimate of heat flow used the geothermal gradient from bottom-hole temperature (BHT) measurements, the annual shut in well pressure–temperatures, the TC measurements of the Alberta basin rocks, the net rock mineralogical composition data and the porosity estimates from the well logs. Similarly, Beach *et al.* (1987) estimated Q in the Pc basement rocks at 24 locations in Alberta. They used corrected geothermal gradients from corrected BHT data and TC data measured with a divided bar to give an average heat flow of 71 ± 12 mW m^{-2}. The contribution of heat flow from heat generation in the sedimentary rocks was measured as $A < 0.67\,\mu$W m^{-3} which in the case of the 541 m of sediments overlying the Pc granites results in <0.36 mW m^{-2} (smaller than the expected error in the heat flow estimate). These estimates were close to the Q values reported by Garland & Lennox (1962). These are not the highest heat flow values reported in Alberta, since heat flow values as high as 90 mW m^{-2} have been observed in northwestern Alberta (Majorowicz & Jessop 1981). However, they are considered elevated for the Pc basement beneath the Alberta basin.

All other heat flow determinations from the WCSB were based on single point industrial measurements of temperature and TC approximations. The heat flow estimate of >69 mW m^{-2} for Central Alberta by Majorowicz & Jessop (1981) lies within the measurement uncertainty of the average heat flow of Canada which is 64 mW m^{-2} with a standard deviation of 16 mW m^{-2} (Majorowicz & Grasby 2010). The Q values from Alberta reported previously are higher than that in the exposed shield. In the Churchill Province heat flow is 44 ± 7 mW m^{-2} according to Drury (1985).

The most recent Q estimates based on the industrial temperatures from 29 100 wells in Northern Alberta are shown in Figs 2(a) and (b). The values were calculated from edited industrial temperature data sets, using a TC model described in Majorowicz *et al.* (2012) including palaeoclimatic corrections (Majorowicz *et al.* 2012). The location of wells with TC and heat generation data in the basement, and some less numerous precise temperature logs are shown in Fig. 2(a). The heat flow Q data are based on well data from BHTs, drill stem test temperatures, temperature measured annually in shut in wells (Gray *et al.* 2012; Majorowicz *et al.* 2012) and shallow few hundred metres precise logs in equilibrium (Majorowicz *et al.* 2009).

These highly elevated Q values in Alberta may be related to elevated heat generation within the Pc basement (median = 2.5 μW m^{-3}, Jones & Majorowicz 1987).

Geological setting—general description of Pc basement in the study area

Phanerozoic sedimentary rocks cover more than 95 per cent of the surface of Alberta. Only in a small area in the northeast corner of the province are Pc crystalline rocks exposed. The thickness of the sedimentary rocks increases from zero in northeastern Alberta to greater than 7 km in southwest Alberta (Fig. 1) The eastern half of the study area is primarily occupied by the TMZ (Fig. 1a). The TMZ is part of a 3200-km-long north–south trending Pc belt (Hoffman 1989; Chacko *et al.* 2000), the southern portion of which is largely buried and covered by Phanerozoic sedimentary rocks. It includes the Taltson Basement Complex (TBC), dominantly Paleoproterozoic crust composed of massive and banded gneisses, which includes pelitic metasediments, amphibolites and felsic orthogneisses (Hoffman 1989; Chacko *et al.* 2000). The TBC was later intruded by two suites of granitoids (1.986–1.963 Ga and 1.955–1.928 Ga; Villeneuve *et al.* 1993; McDonough *et al.* 2000; Walsh 2013). Three major shear zones cut the southern TMZ in a roughly north–south trend. The most extensive shear zone is the Charles Lake shear zone, which is exposed for over 300 km of strike length in the exposed TMZ. The Hunt Well, located in the southern half of the buried TMZ, and core samples were recovered from depths of 1655 m and below 2350 m. The shallower cored section (∼1655 m) sampled a metasedimentary gneiss unit with a maximum age of 2037 ± 26 Ma while the deeper cored section (∼2350–2360 m) is a deformed orthopyroxene-bearing granite (charnockite) unit with age ∼2400 Ma (Walsh 2013). Rock units in the exposed TMZ match the lithologies and ages of the Hunt Well at depths of 2363 m. No other rock samples were available to study from the Hunt Well.

The basement beneath the western half of the study area comprises the Buffalo Head (BH) terrane, a 1.9–2.3 Ga domain with rock types ranging from felsic to intermediate metaplutonics as well as high-grade gneisses and metavolcanics (Villeneuve *et al.* 1993). The upper parts of the BH terrane can only be studied from drill core samples as it is entirely covered by 1000–2000 m of sedimentary rocks. There is some information about the nature of the deeper lithosphere in the BH terrane from xenoliths entrained in kimberlite magmas (Aulbach *et al.* 2004).

Both the TMZ and BH terrane are bounded to the north by the Great Slave Lake Shear Zone and to the south by the Snowbird Tectonic Zone. The BH terrane is bounded to the west by the Chinchaga domain and the TMZ is bounded to east by the Archean Rae Province (see Fig. 2a for locations of the above geological divisions).

HEAT FLOW DETERMINATION IN NORTHERN ALBERTA: THE FIRST MEASUREMENT IN THE Pc BASEMENT

Precise temperature—depth in Pc granites: the first high precision temperature gradient, Grad*T*, in the granitic crust of Alberta

A series of detailed geophysical logs and borehole studies were recently collected in the Hunt Well. The 2363 m well drilled into basement rocks just some 30 km west of Fort McMurray (Figs 1 and 2a). It is by far the deepest borehole drilled into the Pc basement rocks in Alberta. This borehole was logged after it was drilled in 1994 and deepened in 2003. More recent logging was performed 2011 July 12–16 as a collaborative research effort between the Operational Support Group of the International Continental Scientific Drilling Program (ICDP-OSG) from the Geoforshung Zentrum (GFZ) Potsdam and the University of Alberta. This logging campaign focused on open borehole measurements from the bottom of the casing collar (1005.7 m) to a depth of 1880 m. The comprehensive logs available from these two studies include: natural and spectral gamma ray (GR), caliper, neutron porosity, self-potential, resistivity, magnetic susceptibility, sonic and Formation Micro-Imager logs. These logs allow us to investigate physical properties of basement rocks and provide important information for regional geothermal investigations.

A logging campaign in 2011 obtained an equilibrium temperature *T* log with a digital Sondex tool 3 yr after previous logging activity and 10 yr after drilling disturbance had ceased in 2003 (Fig. 3). The platinum resistance thermometer used gives a high precision reading of the wellbore temperature. The temperature sections from which the heat flow *Q* was calculated (below 2200 m) are shown in Fig. 3. The section below 2200 m is chosen as the depth below which recent glacial–interglacial warming would influence the temperature gradient. Post-glacial warming significantly affects the temperature gradient above ∼2200 m. The magnitude of palaeoclimatic correction will increase as the surface is approached (Majorowicz *et al.* 2012). The other reason for choosing this depth interval is that the bulk of the TC measurements on rock core comes from this deepest part of the well bore.

Similar to the heat flow, the geothermal gradient (Grad*T*) was also calculated at >2200 m depths where they are not influenced by palaeoclimate changes (Fig. 4), specifically, the temperature change. Inversion done for Hunt Well temperature profile in granites indicates a temperature increase of 9.6 ± 0.3 °C, at 13.0 ± 0.6 ka and that the glacial base surface temperature was 4.4 ± 0.3 °C at the start of the present interglacial (Majorowicz *et al.* 2012. Holocene Optimum period may had been characterized by higher temperature than following period with latest millennium, Little Ice Age and Recent Warming Period of the Industrial Age (Majorowicz & Safanda 2001). These events influenced upper few hundred metres of the temperature regime underground.

TC measurements

In addition to the geothermal gradient, Grad*T*, TC *k* is needed to indirectly calculate *Q*. The *k* values (see Table 1) were measured using core samples from the bottom of the Hunt Well (>2300 m) and depth of 1656–1657 m. Cores were collected from the Energy Research Conservation Board core centre in Calgary (Fig. 5). We have used a heat impulse method under ambient conditions. These measurements were checked against the optical scanner method giving very close results from GFZ (Geoforshung Centrum, Potsdam) and Geophysical Institute Czech Academy of Sciences labs. The same rocks were also measured on the stationary divided bar at minimal pressure, at room temperature at the University of North Dakota. We have also investigated the dependence of *k* on pressure and temperature up to the conditions observed at the base of the Hunt Well. This involved TC measurements on the stationary divided bar at about 50 °C, and pressurized to 8 *k* psi (pound per square inch), represent the *in situ* conditions and sufficient to close microcracks (Fig. 6). Approximately 20 per cent of the samples did not survive the pressure long enough to get the final measurement because the

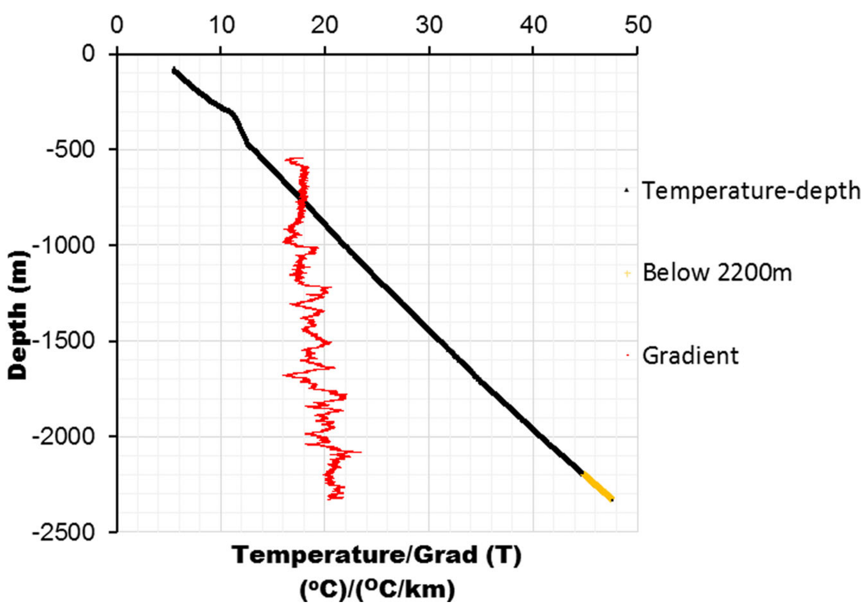

Figure 3. Equilibrium precise high-resolution temperature log (Sondex tool) measured in Spring 2011 in the Hunt Well. Boundary between Phanerozoic sedimentary rocks and Precambrian basement is at a depth of 0.5 km. Grad*T* profile calculated from the granitic part of the log shows increase with depth interpreted as an effect of the post-glacial warming effect (Fig. 4).

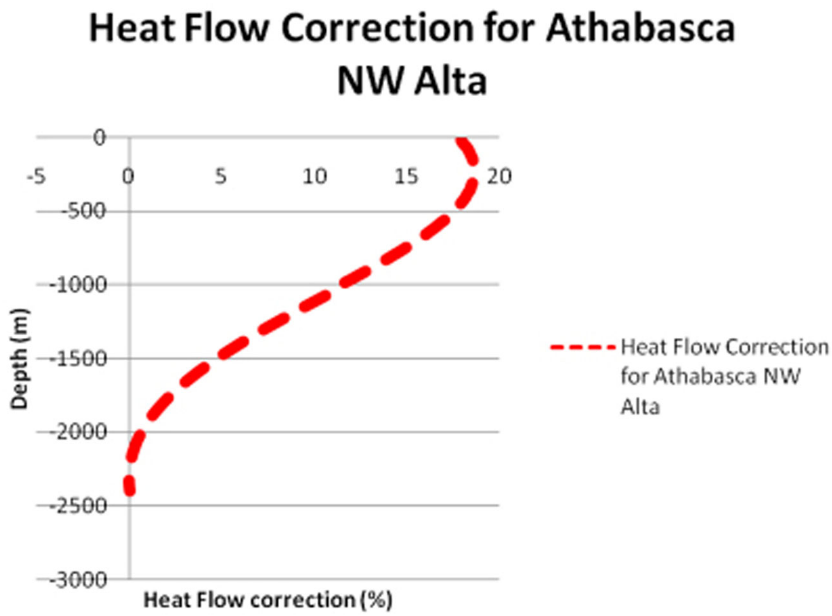

Figure 4. Heat flow Q disturbance with depth due to palaeoclimate changes as derived from inversion of the Hunt Well temperature log (modified from Majorowicz *et al.* 2012).

samples shattered. Unless a sample had a very high porosity the uniaxial pressure along the Z-axis when measuring TC along the Z-axis is an adequate replication of the *in situ* conditions. Micro-cracks in the X/Y directions should close with the Z-axis pressure. Micro-cracks in the Z direction should not affect conductivity in the Z direction, so there was no need confining (3-D) pressure. Since all our samples had very low porosity (<1 per cent), using uniaxial pressure along the measurement axis was a close approximation of the conditions at depth, with respect to vertical heat flow.

In order to account for the dependence of k on pressure and temperature, we have used a pressure–temperature correction developed by Chapman & Furlong (1992). We have considered granite throughout the borehole below the sedimentary rocks of the Alberta Basin. Correction of $k(z, T)$ as a function of depth z and temperature T was considered in the form

$$k(z, T) = k_o(1 + cz)/(1 + b(T - 293)), \tag{1}$$

where k_o is TC at room temperature of 293 K and atmospheric pressure. Typical values of coefficients c and b for the granitic upper crust are $c = 1.5 \times 10^{-6}\ \mathrm{m}^{-1}$, $b = 1.5 \times 10^{-3}\ \mathrm{K}^{-1}$ (Chapman & Furlong 1992).

Hunt Well heat flow at depths below palaeoclimate influence

Heat flow Q is not usually measured directly, but is obtained from the temperature gradient (Grad$T$) in a borehole and the laboratory measurement of the TC at *in situ* temperature and pressure $k(P, T)$ (or corrected for temperature and pressure). Assuming only vertical heat flow in a 1-D earth, these quantities are related through:

$$Q = k(z, T)\ \mathrm{Grad}(T), \tag{2}$$

where Q is in $\mathrm{mW\,m^{-2}}$ and calculated using eq. (2). Calculated values for depths below 2 km and below 2.2 km are as follows (Table 2):

Crustal heat production

Heat production A controls Q above the LAB and together with TC determines the temperature distribution. We can only measure A the upper crust from borehole samples, which at the Hunt Well extends to almost 2.4 km. The concentration of radiogenic isotopes (U, Th and K) can be measured with GR spectrometry. This gives a better estimate of concentrations of radiogenic isotopes than estimates from only measuring the total gamma intensity. The first set of logs was run at 600 m before setting surface casing, the second set at 1650 m when drilling was stopped. Both of those runs were in 1994 collected by Schlumberger and included gamma logs. When the well was deepened to 2363 m in 2003, a third set of logs was run. GR spectrometry measurements using U, Th and K channels were made in the Hunt Well and in 2011 by the Geo Forschungs Zentrum—University of Alberta team from 1005–1874 m. Description and analysis of all the logs can be found in Chan (2013). Mean concentrations of U (1.71 ppm), Th (33.53 ppm) and K (2.85 per cent) were calculated from the recorded logs (Fig. 7).

The heat production A can then be calculated from abundances of uranium (cU), thorium (cTh) and potassium 40 (cK40) using the equation of Bucker & Rybach (1996):

$$A = 10^{-5}\rho(c\mathrm{U} + 2.56\ c\mathrm{Th} + 3.48\ c\mathrm{K}),\ \text{in}\ \mu\mathrm{W\,m^{-3}}, \tag{3}$$

where concentrations c of U and Th are in parts per million (ppm), K in weight% and ρ is the rock density.

The mean A was then computed from these spectral gamma results and gave a relatively high value of close to 3.46 $\mu\mathrm{W\,m^{-3}}$. The A variability with depth is shown in Fig. 8.

The data are available upon request from the Helmholtz Alberta Initiative Theme 4 (University of Alberta, Department of Physics; Martyn Unsworth, Project Leader).

Measurements were also made on 1 m sample of core recovered from 1656.5–1657 m depth, coincident with the region where gamma spectroscopy measurements was made. Core from depth below 2350 m comes from interval where no gamma or gamma spectral exists. Considering that it is difficult to correlate depth

Table 1. Thermal conductivity k (W m^{-1} K) data for Hunt Well granites.

Depth D m	Avg k ambient W/(m K) heat impulse core plugs	Avg K ambient W/(m K) optical core plugs	Avg k ambient W/(m K) optical core slices	Avg_k *in situ* W/(m K) divided bar core plugs	Additional information
1656.700	3.120		3.270		
1656.200	2.800				
1657.000	2.600				
1656.500	2.930		2.910		
2347.500	2.704				
2348.700	2.788				
2349.000	2.488	2.220			
2349.600	2.976	2.620			
2350.100	2.303	2.310			
2351.300	3.061	2.980	3.060		
2351.400	2.757		2.920	2.320	(About 25 per cent of this sample shattered during the high pressure measurement, so the result of 2.32 is suspect)
2352.600	3.160			2.904	
2353.000	2.997			Nil	(Sample completely shattered at high pressure)
2353.700	2.796			2.187	
2354.000	2.862			2.854	
2354.800	2.283			2.684	
2354.800	2.680			2.249	(About 4 per cent of this sample shattered during the high pressure measurement, so the result is close, but not prefect)
2355.000	2.553			2.644	
2355.900	2.522			2.497	
2356.000	2.409			2.397	
2357.000	2.644	3.098		2.433	
2358.300	2.726	2.650		2.240	
2358.600	2.548			Nil	(Sample completely shattered at high pressure)
2359.400	2.812				
2360.000	2.348				
2361.000	2.317	2.100			
2361.100	3.050	2.550	2.590		
2363.000	2.930	2.850	2.730		
2364.200			3.120		
2364.200					
2364.500	2.542	2.270	23.50		
2357.500	2.936				
Average	2.721	2.565	2.869	2.492	
Count	31.000	10.000	8.000	11.000	
SD	0.254	0.339	0.300	0.249	

Figure 5. Granitic core from the deepest section of the Hunt Well (below 2300 m). The diameter of the core is 4 inches (10 cm).

measurements of log data and core samples, good correlation is observed. This is the zone where in both measurements (core samples and spectral log) show a decrease in A below 1 µW m^{-3} as shown by Walsh (2013).

As the spectral logs did not reach to the top and bottom of the well, we need to extend the A profile to larger depth by estimating A from the gamma logs that were made from the surface to the base of Hunt Well. In case there is no spectral GR readings for U, Th and K channels, A can also be approximated by well log measurements of the total (=entire registered) intensity of radiation caused by radioactive decay. Rybach (1976, 1986) developed an empirical relationship between rock radioactivity measurements and 'A' determinations on corresponding rock samples, which can be used for indirect heat generation estimates from gamma logs. The Rybach (1986) relationship is of general use with standard GR units (American Petroleum Institute [API]). The empirical relationship between GR (API units) and A (µW m^{-3}), eq. (4), has been further developed and revised in the equation of Bucker & Rybach (1996):

$$A = 0.0158(\mathrm{GR[API]} - 0.8). \quad (4)$$

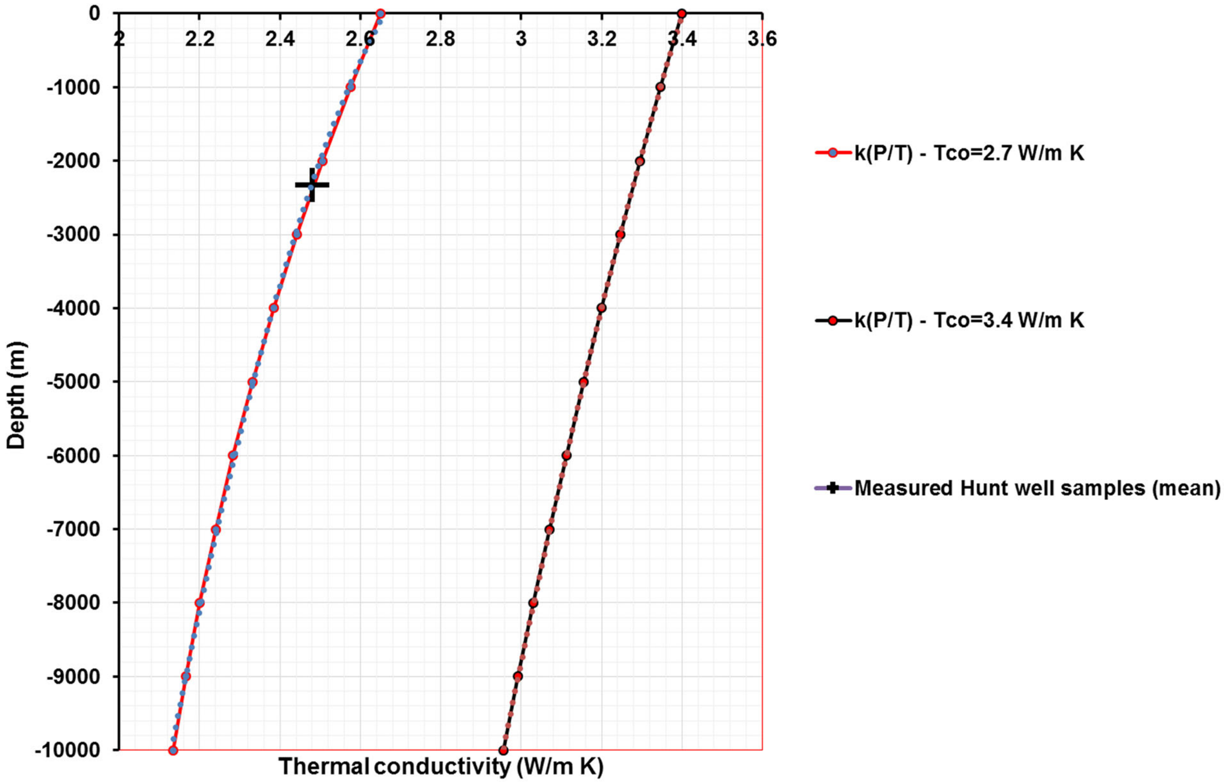

Figure 6. Dependence of k upon temperature and depth for two cases. Measured TC for Hunt Well samples (under pressure and temperature of 50 °C). The theoretical curve on the left side of the graph fits the Hunt Well data properly. The one on the right side is for the Canadian Shield average conductivity of granites (Jessop 1990).

Table 2. Calculated geothermal gradient (in °C m^{-1}), k (W m^{-1} K) and Q (mW m^{-2}).

Depth (D) Range (m)	Average–Avg Grad(T) (°C km^{-1})	*SD*	P/T related k W/(m K)	*SD* W/(m K)	Heat flow Q mW m^{-2}	*SD* mW m^{-2}
2200–2323.9	20.4	1.76	2.5	0.2	51	4.4
2200–2323.9	20.5	0.83	2.5	0.2	51.3	2.1

However, we have developed the statistical relationship (5) specific for the Hunt Well granites based on A derived from spectral data from GFZ shown in Fig. 7 and total GR (Fig. 9). The statistical relationship is shown in Fig. 10:

$$A = 0.0487\mathrm{GR[API]}^{0.7989}. \quad (5)$$

Correlation coefficient for this statistical relationship is 0.7, which is considered statistically good for this type of measurements.

The fit between A (Fig. 8) for the 1005–18 754 m derived from spectral log (Fig. 7) and A calculated from the relationship (Fig. 10 and eq. 5) between that A and GR log (in Fig 9) is within *SD* 0.2 μW m^{-3}. Heat production A has been calculated for the whole depth interval for which high resolution GR (API) log exists as shown in Fig. 11.

Heat flow balance

The model used to explain the relationship of heat flow (Q) as a function of A is a modification of the simple step model, which is also called the Roy model (Roy *et al.* 1968):

$$A(z) = A_s + A_o(0.5 < z < D), \quad (6)$$

where A_s is heat production of the sedimentary cover (in the study case it is 0.67 μW m^{-3}), z is depth and A_o granitic rocks average heat generation 2.95 μW m^{-3} for the whole depth range in the well, D is thickness of the radioactive layer. In fact, there is variability of A versus D in granites (Fig. 11). In measured upper 0.5–2.35 km it will be 3.52 μW m^{-3} for the 0.5–1.5 km and 2.25 W m^{-3} for the 1.5–2.35 km.

In both cases, heat flow will decrease with depth z as:

$$Q_z = Q_o - \int A\mathrm{d}z, \quad (7)$$

where Q_o is surface heat flow.

As we measured heat flow at 2.3 km at 51 mW m^{-2} we will have surface heat flow Q:

57 mW m^{-2} = 51.3 mW m^{-2} + 0.5 km*0.67 μW m^{-3} + 1.0 km* 3.52 μW m^{-3} + 0.8 km*2.25 μW m^{-3}.

Heat generation model and heat flow versus depth

The heat production model used to calculate geotherms is partly based on A from measured U–Th–K concentrations and the model for the lower crust and mantle that is as follows (Table 3). In the upper 11 km of the crust we use high granitic values measured by

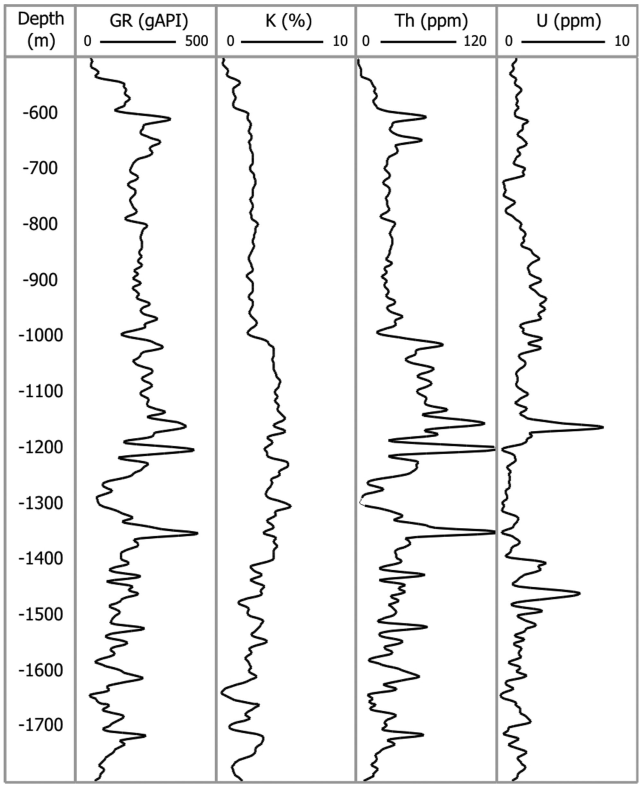

Figure 7. U, Th, K channels of the GFZ spectral log and gamma log done in 2011 in 1005–1874 m part of the granites in the Hunt Well (modified from Chan 2013).

gamma spectrometry (upper part above 1874 m) and gamma logs (through all of the well depth down to 2350 m) in the Hunt Well and for granites 3.62 μW m^{-3} for 0.5–1.5 km and 2.25 μW m^{-3} below. In the Phanerozoic sediments heat production A is 0.67 μW m^{-3} in the upper 0.5 km. We assume $A = 0.02$–0.03 μW m^{-3} for mantle rock (Rudnick *et al.* 1998; Hyndman & Lewis 1999); 0.2–0.5 μW m^{-3} for the lower basic crust, 0.5–0.9 μW m^{-3} for the mid-crust (Fig. 12). We consider these models as lower and upper bounds of resultant geotherms (Figs 13 and 14).

Fig. 12 shows the results of calculating heat flow as a function of depth for the crust using the Q corrected to the surface (57 mW m^{-2}) and the heat generation A model. Q at base of crust is low (near 15 mW m^{-2}) based on this modelling. This value is in agreement with the range proposed by Mareschal & Jaupart (2013) for the Pc areas; however, the geotherm based on this model predicts upper-mantle temperatures lower than the xenoliths-based geotherm of MacKenzie & Canil (1999). In order for the model in this paper to agree with their data, the mid-crustal heat generation needs to be reduced.

Geotherms

In calculating the temperature depth profile, we have used an analytical solution of the 1-D steady-state heat conduction equation for a homogeneous medium containing radiogenic heat sources (Wilhelm 1994). The TC was determined at ambient temperature $\lambda_o = 2.7$ W/(m.K), (surface temperature = 0 °C) and heat flow was determined from measurements in the Hunt Well, mW m^{-2}, corrected to the surface. The temperature gradient of the temperature depth profile decreases with depth in granites below 541 m sedimentary cover.

The calculated range of crustal geotherm shown in Fig. 13 reaches approximately 500 °C at the Moho. This is generally higher than the estimate of Hyndman *et al.* (2009) made for the Canadian shield/craton (Fig. 13), but is close to estimates based on studies using xenoliths for the Slave domain to the north of our study area (e.g. MacKenzie & Canil 1999; Russell *et al.* 2001; Kopylova & Caro 2004). Note that the main period of granite production in the Slave craton occurred during final amalgamation at circa 2.7 Ga (Davis *et al.* 2003; Helmstaedt 2009) and is ∼700 Myr older than the 1.99–1.93 Ga peak of granite magmatism in the TMZ (e.g. McDonough *et al.* 2000) and the age of granite dated in the Hunt Well (Walsh *et al.* 2012; Walsh 2013). The decay of AQ versus time due to the long half-life of heat producing elements U, Th, K would cause heat flow to reach a similar cooling stage at the time of granite intrusion (see fig. 3 in Jessop 1992). The difference in Q between 2.7 and 1.9 Ga granitic crust is <5 mW m^{-2}, which is less than the error in heat flow measurement.

It should be noted, however, that geotherms computed from xenoliths studies reflect temperatures at the time when xenoliths were brought to the surface by kimberlite eruptions (170 to 50 Myr ago). Given this young age, there may not have been completed cooling from eruption to the present day and the geotherm is an upper limit of expected temperatures.

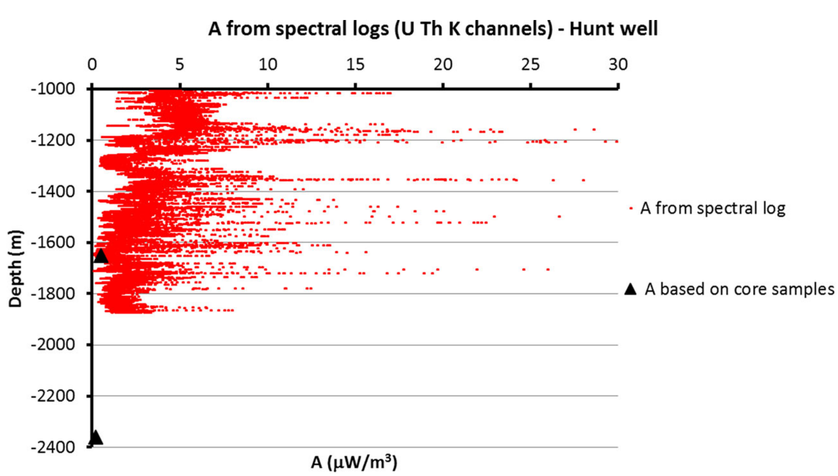

Figure 8. The mean heat production computed from the spectral gamma data smoothed results shown in Fig. 7.

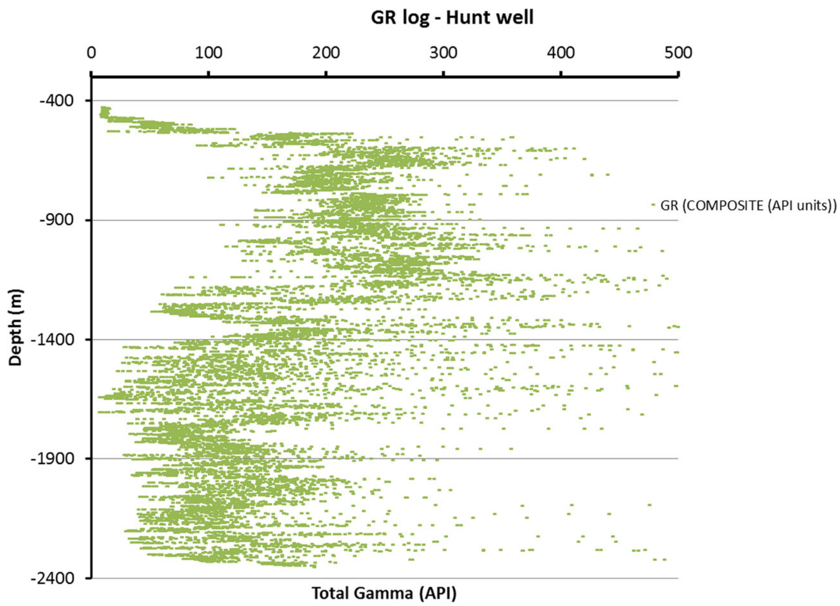

Figure 9. Gamma GR (API) log in Hunt Well.

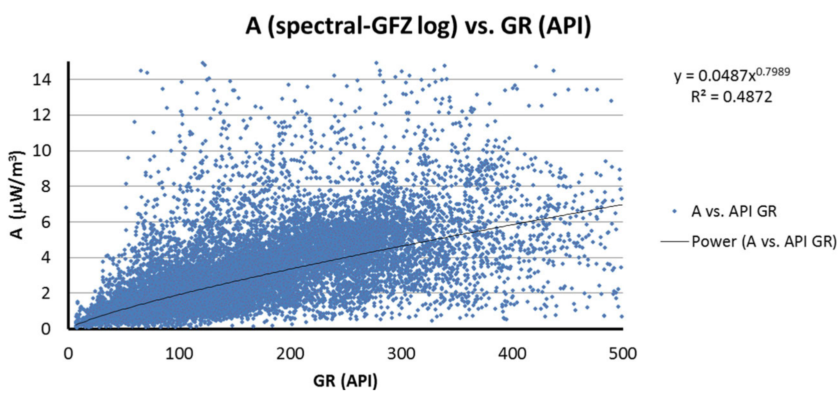

Figure 10. Established relationship between A based on U, Th, K, channels of the GFZ spectral log in part of the granites in the Hunt Well and GR (API) log for the same depth interval (Fig 7).

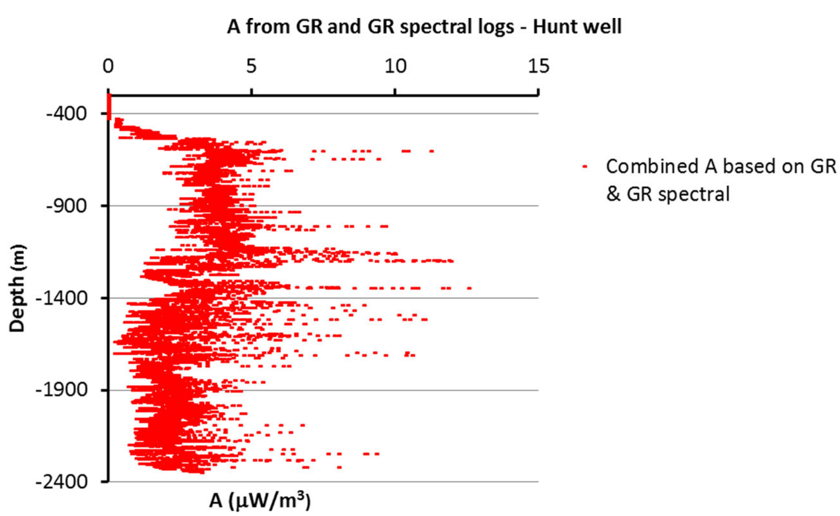

Figure 11. Heat production A calculated for the whole length of the Hunt Well. The granitic portion of the well is deeper than 500 m. The sedimentary strata are located above 500 m with average A value of 0.67 $\mu W\,m^{-3}$, that is, order of magnitude less than that for granites in the 540 m to 2.3 km interval average of 2.9 $\mu W\,m^{-3}$.

Table 3. Heat generation model and resulting heat flow at mantle.

Depth range	*A* Model 1	$Q_{\text{@bottom of interval}}$	*A* Model 2	*Q*	*A* Model 3	*Q*	Description
m	μW m^{-3}	mW m^{-2}	μW m^{-3}	mW m^{-2}	μW m^{-3}	mW m^{-2}	
0–500	0.67	57	0.67	57	0.67	57	Phanerozoic sediments measured *A*
500–1500	3.52	53	3.52	53	3.52	53	Upper crustal granites measured *A*
1500–2300	2.25	51	2.25	51	2.25	51	Upper crustal granites measured *A*
2300–12 000	2.25	28	2.25	28	2.25	28	Upper crustal granites assumed *A*
12 000–23 000	0.9	18	0.7	21	0.5	23	Mid-crust
23 000–35 000	0.7	10	0.5	15	0.2	20	Lower crust
Below 35 000	0.02	<10	0.02	<15	0.02	<20	Upper mantle

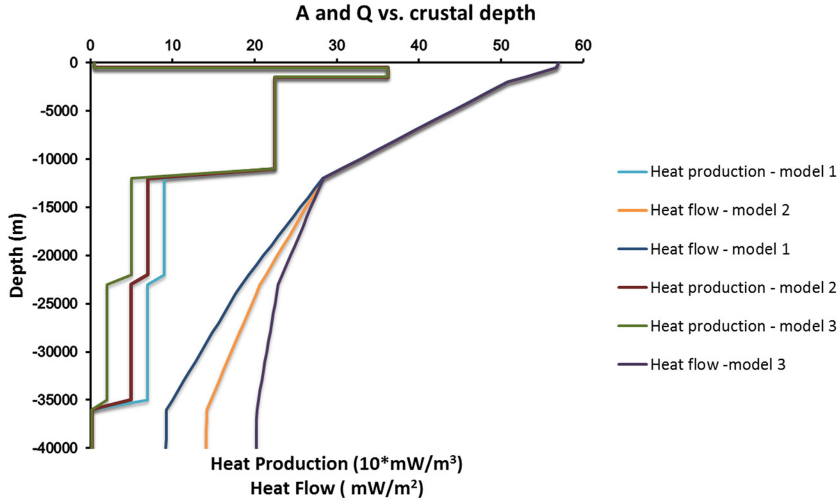

Figure 12. Heat production *A* models (models 1, 2, 3 from left to right) and heat flow *Q* with depth shown with corresponding colour lines for a crust 35 km thick (Bouzidi *et al.* 2002) and the top of the mantle based on Hunt Well surface heat flow. Note: Heat production scale is *10. Heat flow scale is *1. The heat production models 1–3 shown are described in the Table 3.

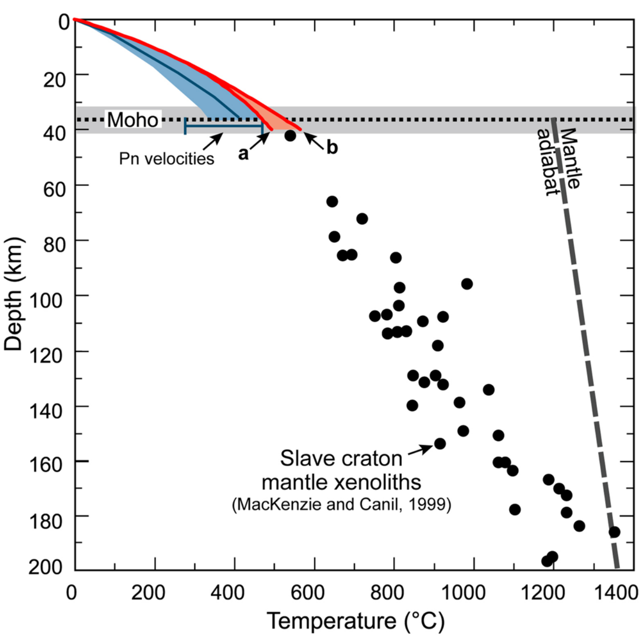

Figure 13. Hunt Well geotherm from this study is shown as red curves for the two models shown in Fig. 12. Blue curves shown crustal temperature estimates from Hyndman *et al.* 2009. The geotherm for Slave craton derived from xenoliths by MacKenzie & Canil (1999) is shown for comparison. The temperature profile projected from the Hunt Well (this figure) agree well with the xenolith-based geotherm of MacKenzie & Canil (1999).

Lithospheric geotherms (Fig. 14) have been calculated for three heat generation depth models (Table 3) with a range of mantle *Q*, 10–20 mW m^{-2} (Fig. 12). These calculations used a mantle TC value for a Pc under the WCSB and Canadian Shield from Hyndman & Lewis (1999).

Alternative heat production model

The alternative heat production *A* exponential model in which *A* measured at near surface of the granitic layer would decay with depth based on the approach of Lachenbruch (1970, 1971) has also been investigated. This model results in much higher heat flow at the Moho of some 25 mW m^{-2}. This rather high value results in higher temperature geotherm and LAB depth of only 100 km, which is unrealistically low for a 2-billion-year-old Pc lithosphere where diamonds are preserved. For this reason the exponentially decreasing heat production model has been abandoned.

LAB DEPTH

The mantle adiabat adopted here (Fig. 14) as in MacKenzie & Canil (1999) determines the depth to the thermal LAB. However, this method for estimating the depth to the LAB is somewhat simplified and may be significantly more complex (see Eaton *et al.* 2009, for a review on the LAB).

LAB depth estimates from northeast Alberta have been made from a variety of techniques:

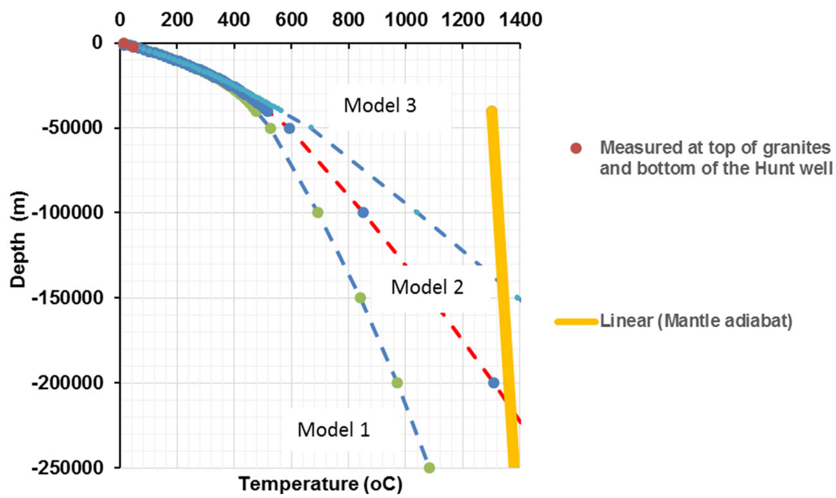

Figure 14. Predicted minimum and maximum geotherms (models 1–3) compared to the mantle adiabat. Note that model 1 predicts a heat flow of 10 mW m^{-2} at the Moho and predicts a LAB depth at an unreasonable depth >300 km. Model 2 (mantle Q 15 mW m^{-2}) predicts LAB depth at the expected depth of 200 km and gives a better fit to the xenolith data of MacKenzie & Canil (1999) than model 1 (LAB depth > 300 km) and model 3 (mantle Q 20 mW m^{-2} and rather shallow LAB depth <140 km.

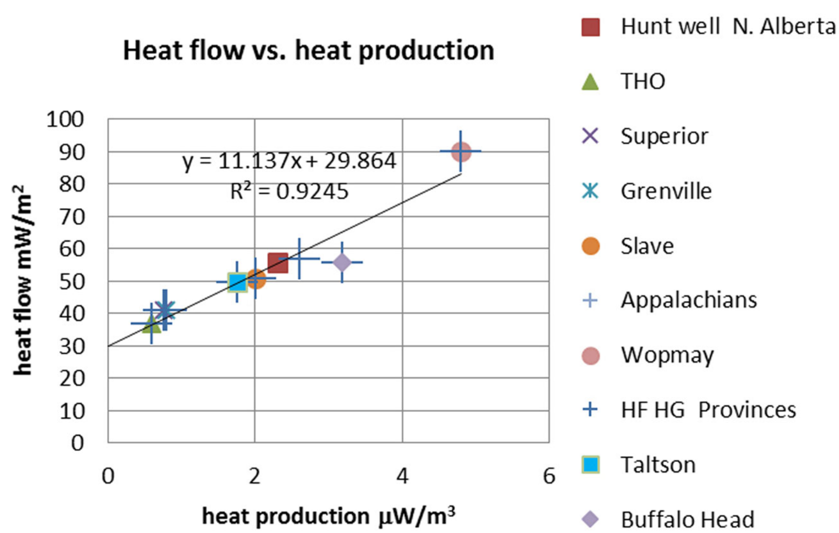

Figure 15. Heat flow–heat production statistical relationship from Canadian data including the new Q–A pairs determined for northern Alberta. Note that the new Q value determined from the granitic deep basement Hunt Well is shown and fits the general trend very well. THO– (Trans Hudson Orogen), Superior, Slave and Wopmay averages are from Perry *et al.* (2010).

(1) Changes in seismic azimuthal anisotropy: 200–230 km (Yuan & Romanowicz 2010).

(2) Surface wave tomography: 180–220 km (McKenzie & Priestley 2008).

(3) Xenoliths from northern Alberta kimberlites: ca. 180 km (Aulbach *et al.* 2004).

(4) Magnetotelluric models from northern Alberta: 200–250 km (Türkoğlu *et al.* 2009).

These estimates give a range of values between 180 and 250 km, therefore, as a reasonable estimate, a LAB depth of near 210 km is shown in Fig. 14, corresponding to a mantle heat flow of some 15 mW m^{-2}. This mantle Q value is well within the range 15 km (±3) for the stable continental areas as given by Jaupart & Mareschal (2011). Estimates of LAB based on models with higher mantle heat flow (20–26 mW m^{-2}) would result in unreasonably low for old shield LAB depths 80–140 km.

HEAT FLOW–HEAT PRODUCTION

The measured Q in Hunt Well below a depth of 2.2 km is 51 mW m^{-2} with a 20.4 °C per kilometre geothermal gradient and 2.5 W m^{-1} K TC measured under *in situ* well depth-like conditions.

When compared to other provinces of the Canadian Shield (Fig. 15), the TMZ and Hunt Well fit heat flow–heat production statistical relationship based on data from Trans-Hudson Orogen (Q = 37 mW m^{-2}, A_o = 0.6 µW m^{-2}), Superior (Q = 41 mW m^{-2}, A_o = 0.76 µW m^{-2}), Grenville (Q = 41 µW m^{-2}, A_o = 0.80 µW m^{-2}; see Jaupart & Mareschal 2011 for the review).

However, there is large variability of basement 'A' in northern Alberta seen in Figs 17 and 18. We observe also lower heat production and heat flow at other sites (Figs 1a and 17). In the Shield to the east, many heat flux values are as high as or higher than that the reported for the Hunt Well. The highest heat flow is in the Wopmay Orogen, a large-scale geothermal anomaly first discovered by Majorowicz *et al.* (1988).

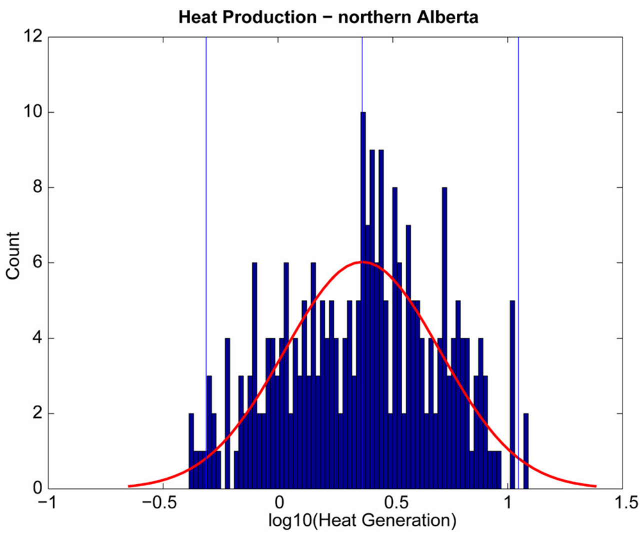

Figure 16. Histogram of A (in μW m^{-3}) from Jones & Majorowicz (1987) and Bachu & Burwash (1991) data compilations and new measurements at the time in Northern Alberta wells (Fig. 1a) drilled to Precambrian basement with recovered cores.

Generally, heat production for all the wells drilled into the Pc basement rocks (Fig. 1a) is high and higher than in the exposed Pc rocks of the Canadian Shield to the east as discussed above. Northern Alberta mean heat production $A = 2.2\,\mu\mathrm{W\,m^{-3}}$ (Fig. 16) and mean $Q = 53 \pm 9\,\mathrm{mW\,m^{-2}}$ ($N = 29\,100$ determinations from industrial thermal parameters in deep wells in northern Alberta; Fig. 2b for location).

However, the relationship shown in Fig. 15 for pairs of Q and A for large domains could not be established for Q estimates from industrial temperature data for the study area as shown in Fig. 1(a) and for A from the basement rocks for the same area (Fig. 17).

This lack of correlation is visible from comparing Q map in Fig. 1(a) and A map in Fig 17 and such lack of spatial correlation has been also found earlier for all of Alberta by Majorowicz & Jessop (1993). It is also apparent from the TMZ (Fig. 18) and neighbouring BH terrane to the west (Fig. 19).

It should be noted, however, that in the Q–A pairs, Q are estimates (other than Hunt Well data reported in this paper) and near-surface heat generation from ‘granitic’ crust is based on measured heat generating elements. These Q estimates from Majorowicz *et al.* (2012) are based on temperatures in the sedimentary section above the Pc basement and calculated k models from both: (1) net rock analysis from GSC (Geological Survey of Canada; Sproule Report data,

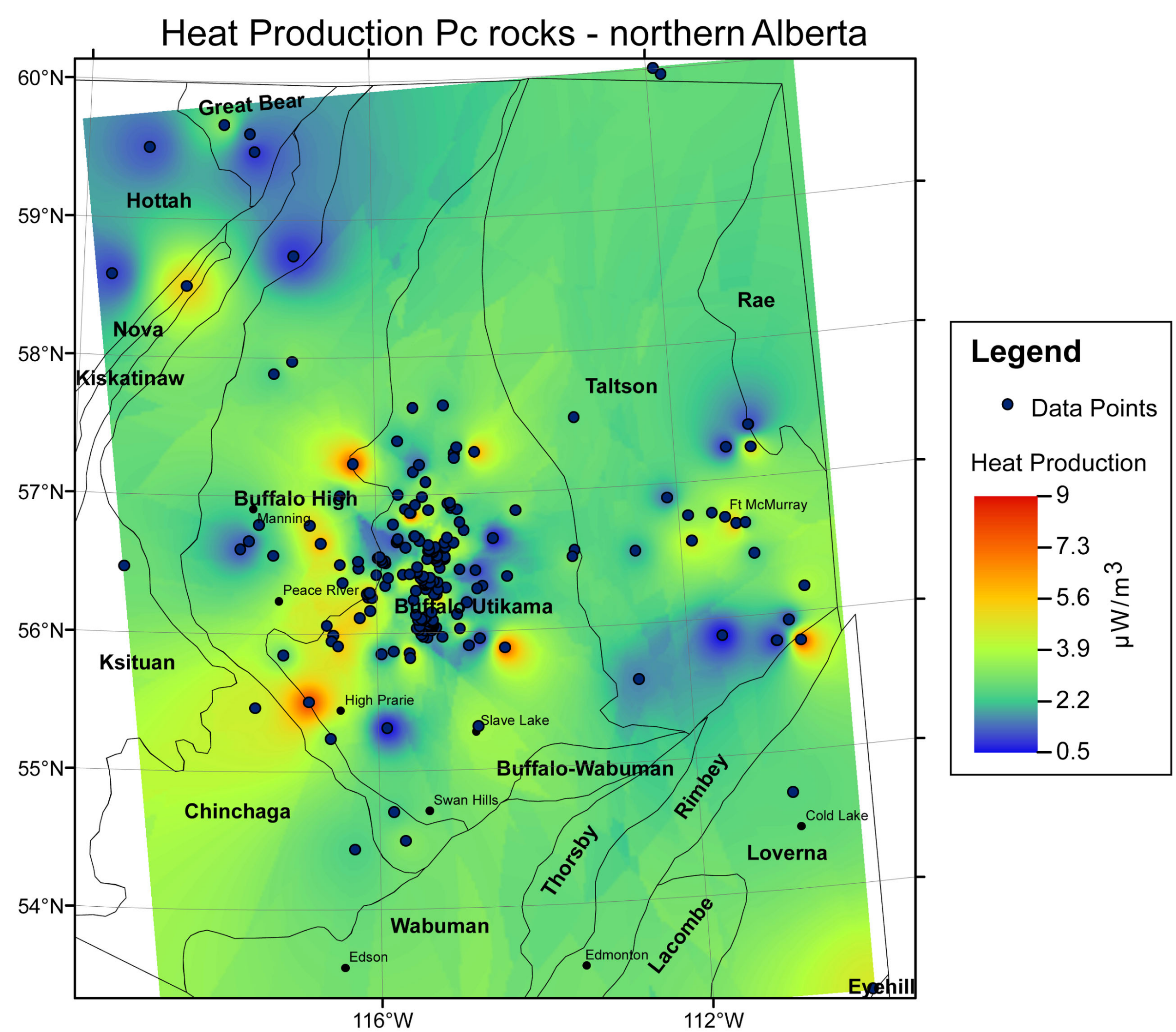

Figure 17. Pattern of A (μW m^{-3}) based on data compiled by Jones & Majorowicz (1987) and Bachu & Burwash (1991).

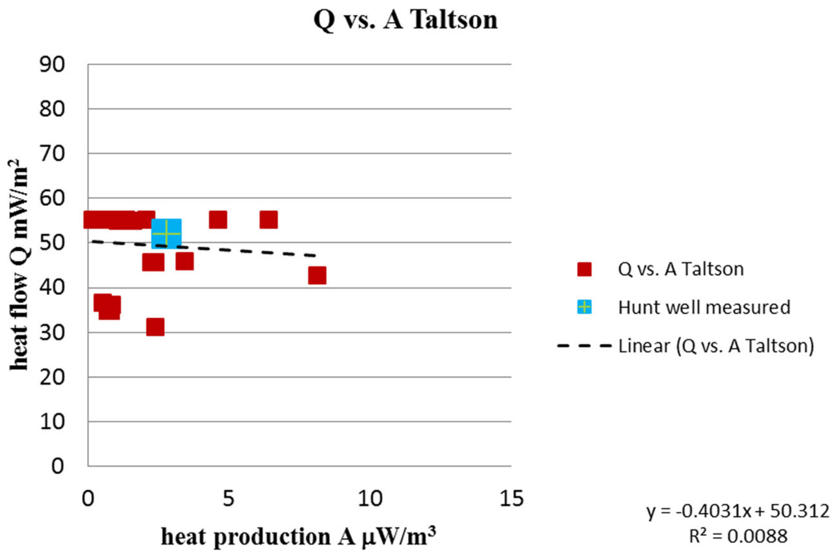

Figure 18. TMZ data (Q–A) pairs based on heat flow estimates from industrial data (Fig. 2a) in Phanerozoic sedimentary rocks and A of the Pc basement below based on U, Th and K isotope content (Bachu & Burwash 1991; Jones & Majorowicz 1987) and their corresponding heat production from decay.

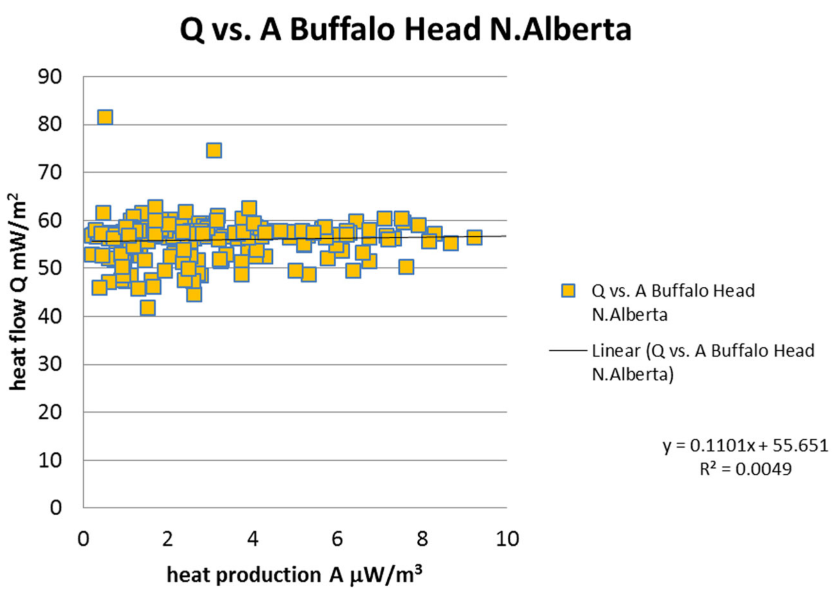

Figure 19. Buffalo Head data (Q–A) pairs based on heat flow estimates from industrial data (Fig. 2a) in Phanerozoic sedimentary rocks and A of the Pc basement below based on U, Th and K isotope content (Bachu & Burwash 1991; Jones & Majorowicz 1987) and their corresponding heat production from decay.

Alan Jessop, personal communication, 2013), and (2) k averages of measured over 1000 sedimentary rocks in the Alberta basin (Beach *et al.* 1987) and correction for saturation and P/T conditions. While great care was taken to obtain good quality results, it is important to remember that errors can be as high as 10–20 per cent depending on accuracy of noisy industrial temperature measurements.

The fact that no Q–A correlation exists based on the industrial data, is interesting to be observed. The spatial wavelength of heat generation changes is much smaller than the corresponding changes in heat flow, which reflects changes in A only in the large regional tectonic scale. This lack of a correlation between Q–A at such large to small (100 km/10 km, respectively) scale has been also noted within other Pc provinces in Canada (Mareschal & Jaupart 2013). There is no heat flow and crustal thickness correlation observed between these two variables (Mareschal & Jaupart 2013) which is interpreted by them as due to the large spatial variations in crustal composition and heat production that exist within a single geological province. Our result confirms above analysis in the continental scale for the North American continent.

DISCUSSION

Lithospheric geotherm, LAB depth and assessment of mantle heat flow cannot be resolved from geothermal data alone. There are large uncertainties in our knowledge of A in the mid and lower crust. Also,

Q–A relationship is hard to establish in some areas. With a large range of heat generation models considered above, the uncertainty in A versus depth results in a large uncertainty in determination of mantle heat flow (some 10–20 mW m^{-2}) with preferred value of 15 mW m^{-2} giving the most reasonable estimate of LAB depth (see above paragraph for a discussion). Heat generation models used above include step-like changes. An exponential decrease of radioactivity through the upper crust would result in higher mantle heat flow beneath the Hunt Well. While the lithospheric A models used above are derived from both the measured heat flow and heat generation A in the most upper parts of the crust and A are assumed for mid and lower crust similar to assumed by Hyndman & Lewis (1999) for the WCSB Pc basement/Shield, with some modifications. Exponential decrease of heat generation leaves us with a high mantle heat flow contribution (25 mW m^{-2}) in comparison to the step models we used (10–20 mW m^{-2}). So, the uncertainty is large. It is complicated by the fact that a robust heat flow–heat generation relationship is hard to establish for the study area.

The temperature profile projected from the Hunt Well to the upper mantle matches the curves of MacKenzie & Canil (1999) better than the general cratonic geotherm of Hyndman *et al.* (2009).

The LAB depth estimates from heat flow and heat generation model for the Hunt Well gives near 200 km for the models with mantle heat flow 15 mW m^{-2}. This mantle Q value is consistent with the range of low mantle Q for the stable continental areas in the review by Jaupart & Mareschal (2011), 15 ($\pm$3) mW m^{-2}.

A 210 km LAB depth as derived from our model 2 resulted in a mantle Q 15 mW m^{-2}, and is considered a reasonable estimate since it is consistent with an LAB depth in the range of other LAB estimates from northeast Alberta made by others from a variety of techniques: 180–250 km (Aulbach *et al.* 2004; McKenzie & Priestley 2008; Yuan & Romanowicz 2010) and 200–250 km (Türkoğlu *et al.* 2009). The model we have tried with a higher mantle heat flow of 20 mW m^{-2} is unreasonable, giving a much shallower LAB at 150 km.

While general Q background has been studied from industrial temperature data, we must remember that temperature data in sediments are known to be very noisy. These come from highly porous aquifers (these being targets of drilling) and we cannot exclude entirely non-conductive heat transport. In the porous sediments of the basin we may have surface heat flow significantly different from background heat flow, depending upon the nature of the hydrogeologic system and its geometry (Majorowicz & Jessop 1981; Jessop 1990).

Contrary to above, Q from low porosity, low permeability and deep below the influence of the palaeoclimate as at >2 km reported here is the only deep heat flow determined so far in Alberta, which can be used as a benchmark value representing this particular part of the Pc basement around Hunt Well. It is 57 mW m^{-2} (surface heat flow), 56.5 mW m^{-2} at the top of the Pc basement rocks and 51 mW m^{-2} at 2.3 km. This deep Q in conductive-only environment together with established measured heat generation and TC of the upper granitic crust and several models of the mid-lower crustal the range of heat generation and TC gives reasonable estimate of the depth of the LAB which is in general agreement with xenolith, teleseismic and magnetotelluric data. The above estimates point to low Q contribution (15 mW m^{-2}) and deep ca. 210 km depth to LAB boundary under the area of TMZ in the vicinity of the Hunt Well. This mantle Q value is consistent with the range for the stable continental areas, 15 ($\pm$3) mW m^{-2} by Jaupart & Mareschal (2011).

CONCLUSIONS

(1) Measurements in the Hunt Well constitute the first Q measurement in the craton from below the depth of the palaeoclimatic influence and from below the sediments. The results show surface Q of some 57 mW m^{-2}. It is significantly higher than Q in the neighbouring shield to the east (44 $\pm$ 7 mW m^{-2}), most likely related to high A measured in the upper granitic crust of the well. This precise measured result gives now more confidence in Q for the northern Alberta known from thousands of industrial lower quality measurements (average $Q = 53 \pm 9$ mW m^{-2} from $N = 29\ 100$ determinations from industrial thermal parameters in deep wells in northern Alberta).

(2) No statistically meaningful Q–A relationship have been observed in the regional scale of the study area (northern Alberta).

(3) The mantle Q contribution is some 15 mW m^{2}, which results in a reasonable estimate of the depth to the LAB. In relation to estimates of the LAB depth from other geophysical methods (LAB estimates from northeast Alberta made by others from a variety of techniques: 180–250 km), our estimate of 210 km for the A depth crustal model resulting in mantle Q contribution of 15 mW/m^{2} is quite reasonable. This mantle heat flow value is quite low in comparison to values obtained when we assume an exponential variation of A depth for which the modelled mantle Q is some 25 mW m^{-2}. On the other hand, the mantle Q contribution 15 mW m^{-2} does not appear to match the intercept of the stable continental heat flow–heat generation relationship suggesting significant contribution from mid-lower crust, although it results in a prediction to the depth of the LAB which matches other methods much better.

(4) The mid crust (below 8–10 km highly radioactive layer) and upper crust must be generating at least 0.5 μW m^{-3}. The shallow upper crustal contribution as measured in the Hunt Well (0.5–2.3 km in granites) is 2.9 μW m^{-3}.

ACKNOWLEDGEMENTS

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