Implications of Post-Glacial Warming for Northern Alberta Heat Flow—Correcting for the Underestimate of the Geothermal Potential

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Implications of Post-Glacial Warming for Northern Alberta Heat Flow—Correcting for the Underestimate of the Geothermal Potential

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ABSTRACT

The research into a geothermal energy option for Northern Alberta basin is currently underway. Correct estimates of heat flow and geothermal gradient for the sedimentary strata (direct heat energy option) and deeper crystalline basement are needed. A series of detailed geophysical logs and boreholes studies have recently been collected in the Hunt well AOC GRANITE 7-32-89-10. The well was drilled 2.36 km into basement granitic rocks just west of Fort McMurray. A temperature log acquired as part of the University of Alberta Helmholtz-Alberta Initiative (HAI) geothermal energy project in 2010-2011shows that there is a significant increase in thermal gradient in the granites. Inversion of the measured T-z profile between 550 m – 2320 m indicates a temperature increase of 9.6+/- 0.3 ºC, at 13.0 +/- 0.6 ka and that the glacial base surface temperature was - 4.4+/- 0.3 ºC. This inversion computation accounted for granite heat production of 3 W/m^3. We find from the Hunt well study that heat flow in the basin has been underestimated for wells shallower than 2 km due to the paleoclimatic effect. A significant increase in surface temperatures since the end of the last ice age in northern North America causes a perturbation of shallow <2 km heat flows. For this reason, estimates of gradient based on single or numerous data from different depths are not necessarely characteristic of the whole sedimentary column and can lead to spurious predictions of temperature at depth needed for geothermal energy or hydrocarbon models.

The Need for a Heat Source in Northern Alberta

The northern Alberta area has oilsands (Fig.1) deposits what are one of the largest hydrocarbon deposits on Earth, and about 20% of these deposits are accessible to surface mining. The separation of bitumen from sand requires huge quantities of hot water, which is currently heated by burning natural gas. As a result, oilsands processing accounts for around 6% of Canada's natural gas consumption and incurs significant economic costs and environmental impact. The remaining 80% of oil sands reserves are too deep to mine but can be extracted using in-situ techniques such as Steam Assisted Gravity Drainage (SAGD). This process also requires large quantities of steam to be generated by burning natural gas. An alternative to burning natural gas could be geothermal heat extracted from the crystalline basement. Preliminary

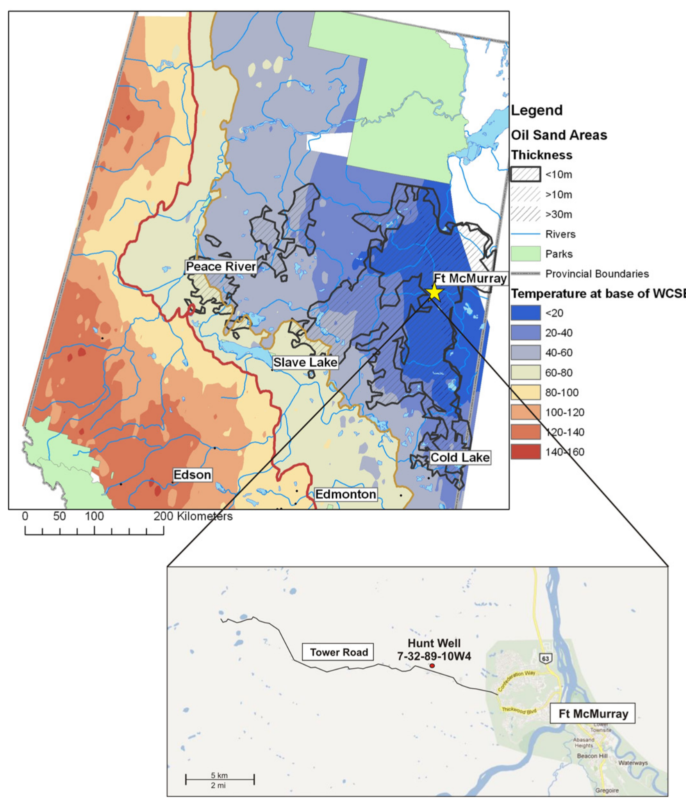

Figure 1. Location of Hunt well and the pattern of temperature at the base of the sedimentary fill of the Western Canadian Sedimentary Basin, (WCSB).

study (Majorowicz et al., 2012) showed that we would need to drill deep into the basement to provide significant amount of heat (4 km to reach 80 ºC and 6 km to reach 120 ºC). Higher temperatures are seen to the west where the basin reaches depths of around 5 km near the Rocky Mountain foothills. If geothermal heat were tapped for oilsands mining, an additional use would be to provide heat for the communities in the area to offset CO2 emissions. The idea is being investigated in more detail as one of the research themes of the Helmholtz-Alberta Initiative (HAI), (Theme 4), which is research collaboration between the Helmholtz Association of German Research Centers and the University of Alberta.

The primary area of interest is in the Athabasca oil sands where the Western Canadian Sedimentary Basin (WCSB) is relatively thin and the Phanerozoic sedimentary succession thins towards the northeast and sub-crops onto the Canadian Shield. In this area the Precambrian basement is at a depth of 0.5 km and is being currently studied by HAI scientists through the analysis of the geophysical logs, core, and rock chip samples from a deep well drilled into the granitic basement rocks. A series of detailed geophysical logs and boreholes studies have recently been collected. Borehole AOC GRANITE 7-32-89-10, hereafter referred to as the Hunt well after its owner, is a 2.36 km well drilled into basement rocks just west of Fort McMurray (Fig. 1). It is by far the deepest well drilled into the basement below Alberta, and as such represents a unique opportunity to study the crystalline basement rocks of Northern Alberta. It thus provides important information for regional geothermal investigations.

Previous Study

The first regional Alberta basin analysis of geothermal patterns from industrial temperatures was done by Anglin and Beck (1965). This was expanded on in the 1980s by the University of Alberta geothermal group who expanded the database and conducted thermal conductivity, heat generation and heat flow studies (Majorowicz and Jessop 1981, Lam and Jones, 1984; Lam et al., 1985; Jones et al., 1985; Majorowicz et al., 1985). Specific focus was given to direct geothermal energy potential in western Canada (e.g. WCSB), (Jones et al., 1985; Majorowicz et al., 1985). In addition, EGS potential in all of Canada was investigated by Majorowicz and Grasby (2010).

Probably the most widely used thermal model for the WCSB is the Atlas of the WCSB produced by the Alberta Geological Society in 1994 (Mossop and Shetsen,1994). It was compiled from 1473 BHT measurements, each of which reached the basement and were manually verified (Mossop and Shetsen, 1994; Bachu 1993) The most recent map of heat flow in Canada, completed by Majorowicz and Grasby (2010), suggests heat flow values in the WCSB range from 40-80 mW/m². None of the above maps took into consideration paleoclimatic correction to heat flow data due to lack of deep temperature profiles in equilibrium which would be reaching depth below theoretically possible influence of the glacial-postglacial (Holocene) warming.

Majorowicz et al., (1999) identified significant overestimation of Alberta industrial well logs from shallow depths (<1000m) compared to hydro-geological observation wells confirming similar findings by Hackbarth (1978). No data exists below 1000 m with the exception of the Hunt Well in this region which has been drilled to 2400 m (Majorowicz et al., 2012). Following above finding Majorowicz et al., (1999) revised their interpretation of the extent of hydrodynamic influence based on across the basin 2D numerical model constrained by revised thermal data.

Tens of thousands of industrial temperature measurements in three independent datasets: Annual Pool Pressure surveys (APP), Drill Stem Tests (DST) and Bottom Hole Temperatures (BHT) coupled with 33 Thermal Conductivity wells were used provide a more accurate prediction of temperatures gradient of the northern Alberta part of the WCSB (Majorowicz et al., 2012 and Grey et al., 2012). A number of large systematic biases inherent to the industrial temperature data bases have recently been identified and removed from the original uncorrected data base (Gray et al., 2012).

Research on the American and European heat flow corrections for the post-glacial warming signal problem has been conducted recently for the large continental scale mapping by Gosnold et al., (2011) and Majorowicz and Wybraniec, (2010). These studies pointed out that temperature gradient disturbance due to post-glacial warming in the Northern Hemisphere have caused heat flow to be underestimated in shallow wells. We will show that the conclusions of this work are strongly supported by the Hunt well results and call for large corrections to northern hemisphere heat flow determinations in wells shallower than 2 km. The post-glacial warming signal appears to have been of the order of 10 °C to 15 °C (Gosnold et al., (2011), thus northern hemisphere heat flow may have been underestimated significantly depending on the depth of the original temperature gradient measurement. The implications for EGS in the northern hemisphere are that the resource may be at shallower depths than projected in recent studies.

Calculation of a Paleoclimatic Correction Term for Northern Alberta

Work on the refining the paleoclimatic correction for the Northern Alberta has progressed after completion of the latest equilibrium temperature log in well filled with water (near the top of the well), (Fig.2).

The four profiles (Fig. 2) correspond to 4 models of conductivity and heat production. The upward extrapolation starts at

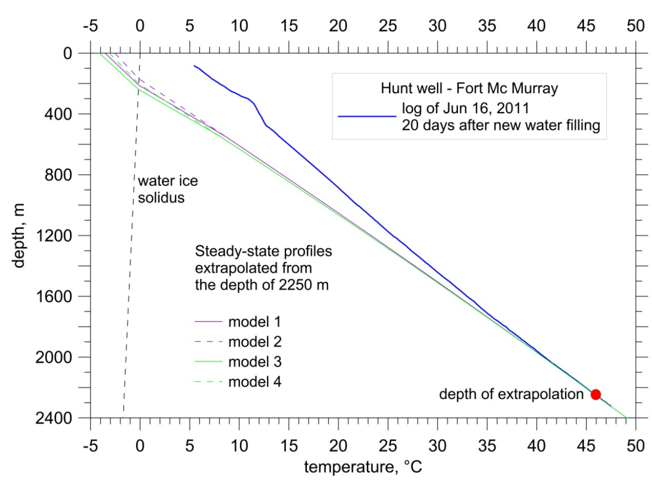

Figure 2. Precise equilibrium condition temperature depth temperature continuous logs in wells AOC GRANITE 7-32-89-10, (Hunt well) in equilibrium condition (log 6 of June 2011).

the depth of 2250 m, in the middle of the interval 2200 - 2300 m for which the gradient and heat flow was determined by linear fit of the measured curve. The heat flow was estimated here as a product of the mean gradient in this layer, 21 K/km and thermal conductivity assumed for this granite, 2.7 W/(m K). The heat flow value is therefore 56.7 mW/m^2. The two alternative values of heat production in the granite, 3E-6 or 4E-6

W/m^3 were considered upward to the granite/sediment boundary at the depth of 550 m. Heat production of sediments, which plays really a negligible role, was estimated at 2E-6 W/m^3. The two alternative conductivity values considered for sediments, 2.4 and 2.7 W/(m K), were increased by a factor of 1.62 in the assumed permafrost zone close to the surface at temperatures below the water ice solidus ($T_{solidus}$ = -0.000715* depth, for zero salinity of groundwater). The frozen/melted conductivity ratio is assumed (3.4/2.1 = 1.62).

Comparison of the Hunt well temperature log with other logs and corrected temperatures for the Phanerozoic shows that geothermal gradient data from the sedimentary cover are not sufficient to extrapolate (predict) temperatures to depth in the Precambrian basement. The increase of temperature gradient of the Precambrian section (Fig.3) is explained by a cooler paleo - temperature at surface than present (difference between glacial and Holocene climate) and a warming pulse that has propagated down to 2 km.

The temperature logs of February 14 and June 16, 2011 are nearly identical below 1 km. The June 16, 2011 log is considered

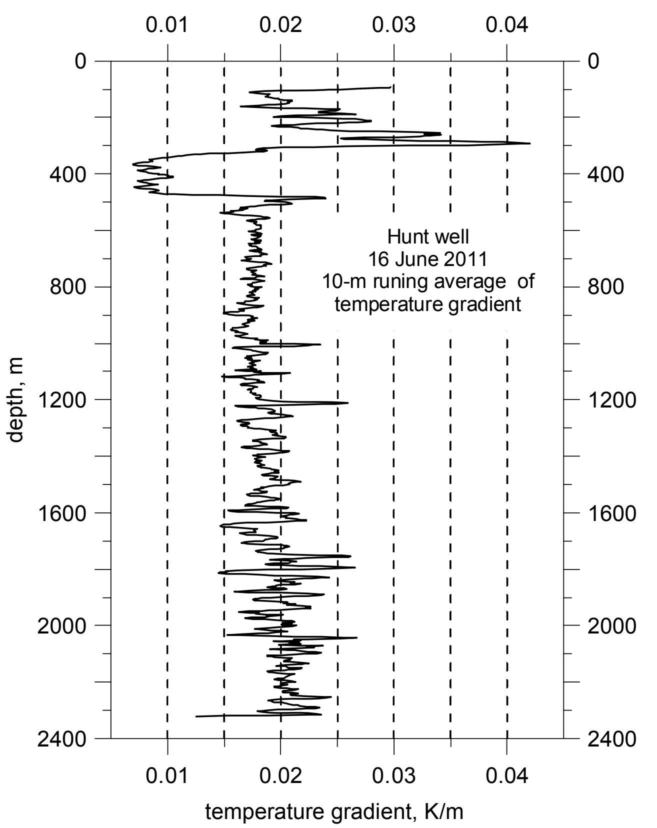

Figure 3. Temperature gradient with depth in Hunt well based on the equilibrium log shown in Thermal gradient in granitic rocks below 540 m is increasing with depth from 17^{o}C/km near the top of Precambrian granite to 21 ^{o}C/km at the bottom.

to be in thermal equilibrium conditions. The temperature gradient in the lowermost part between 2200 – 2300 m is 21 ^{o}C/km. Thermal conductivities determined for this section (2.7 W/m K +/- 0.2 W/m K) by divided bar measurements at *in situ* like conditions of well pressure and temperature in saturated conditions yield a heat flow for the Hunt well of 56.7 mW/m^2 at 2250 m. The mean heat production in granite, 3 μW/m^3, comes from calculation based on recent Gamma spectral log (U TH K channels). We have also considered heat generation of 4$\mu W/m^3$ found in the upper part of the granites. For the two alternative values of conductivity in sediments, 2.4 and 2.7 W/(m K) the resulting steady-state surface temperatures are:

1. -5.6 °C for ($A_{granite}$ = $3\ \mu W/m^3$, $k_{sediment}$ = 2.4 W/(m.K))
2. -4.1 °C for ($A_{granite}$ = $3\ \mu W/m^3$, $k_{sediment}$ = 2.7 W/(m.K))
3. -6.6 °C for ($A_{granite}$ = $4\ \mu W/m^3$, $k_{sediment}$ = 2.4 W/(m.K))
4. -4.9 °C for ($A_{granite}$ = $4\ \mu W/m^3$, $k_{sediment}$ = 2.4 W/(m.K))

Present temperature is near 5 *°C.*

Inversion of the new profile in granites between 550 m – 2320 m was done for two alternative values of heat production in granite, 3 and 4 μW/m^3, measured granite's thermal conductivity (TC) of 2.7 W/(m.K) and diffusivity of 1.44 * 10^{-6} m^2/s. The diffusivity value was calculated according a formula:

$$\text{Diffusivity } (10^{-6}\ m^2/s) = 0.503*TC+0.0839 \qquad (1)$$

TC is thermal conductivity in W/m K.

It is a value very close to 1.42*10^{-6} m^2/s, which we would get as 2.7 W/(m.K) / 1.9*10^6 J/(K.m^3).

Inversion of the measured T-z profile (between 550 – 2320 m) assuming a single step from glacial to interglacial surface temperature yielded a temperature step of 9.6 ± 0.3 °C at 13.0 ± 0.6 ka. This yielded a glacial surface temperature of - 4.4± 0.3 °C for granite heat production of 3 μW/m^3. The corresponding values inverted for granite heat production of 4 μW/m^3 are 10.1 ± 0.3 °C, 12.2 ± 0.5 ka ago and - 4.9± 0.3 °C.

We have chosen model 1 to calculate percentage correction to heat flow due to the Glacial –postglacial climatic change resulting

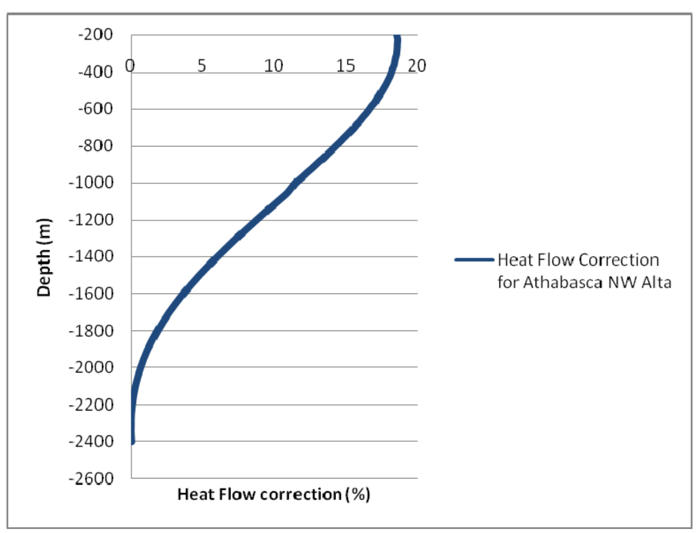

Figure 4. Paleoclimatic correction to heat flow derived from results of model 2.

in increase of heat flow with depth (i.e. reduction of shallow strata <2 km heat flow. The correction is significant and in the upper 1000 m it is 10-18% (Fig.4).

It means that uncorrected heat flow values in shallow wells are underestimates of deep heat flow by10-18%. The example of underestimate of heat flow can be the first heat flow determinations in wells with equilibrium precise temperature logs and measured thermal conductivity on cores by Garland and Lennox (1962). These were the only high precision heat flow data till measurements we did last year in Hunt well. All the other heat flow determinations are from estimates based on single point industrial measurements of temperature (DST, BHT etc..) and thermal conductivity approximations. The heat flow measurements of Garland and Lennox in 1962 were both made at depths less than 1000 m (some 900 ft). Their values for Leduc and Read Water (both in Edmonton area are 67 mW/m^2 and 61 mW/m^2. Applying paleoclimatic correction would bring these values up by 12% to 75 mW/m^2 and 68 mW/m^2, respectively.

Influence of Heat Flow Correction upon Heat Flow and Deep Temperature Predictions

After removing the large errors present in each database (Gray et al., 2012), a much more reasonable model of subsurface temperatures was created. The geothermal gradient (gradT) calculations are based on corrected surface temperature (Majorowicz et al., 2012) and corrected temperature at depth.

The estimates of thermal conductivity of the Phanerozoic WCSB fill has been described in detail in Majorowicz et al., (2012) and Grey et al., (2012). The trend of TC change has been found similar pattern to the findings of Bachu (1991, 1993). The main trend in this area is a trend of increasing thermal conductivity that is approximately parallel to the Phanerozoic isopach. The lower thermal conductivities in the deep basin are the result of a combination of two factors. First, low conductivity shales are relatively more abundant in the fore-deep to the SW while sandstones and carbonates are much more abundant in the shallow basin succession. Secondly, many rocks experience decreasing thermal conductivity with increasing temperature. Therefore, the deeper parts of the basin experience a stronger "blanketing effect" by low conductivity sediments causing higher gradients to the west.

The heat flow at depth z (Q_z) therefore becomes:

$$Q = Q_{rc} + TC_z \times grad(T_z) \qquad (2)$$

where: Q_{rc} = heat flow correction; grad (T_z) = uncorrected geothermal gradient effected by to the post-glacial warming at depth z. The units are mW/m^2.

Measured heat generation values for the sedimentary rocks of the WCSB have been found too low (<0.5 μW/m^3) to significantly affect heat flow and so they have been ignored in this calculation (Majorowicz et al., 2012).

The resulting map of heat flow (Q) map uncorrected for paleoclimate compared to heat flow map corrected for the paleoclimatic effect is shown in Figures 5 and 6 respectively. The pattern in the maps is similar however the corrected for paleoclimate heat flow map shows significantly higher heat flow and will result in higher temperature estimates at depth for EGS potential.

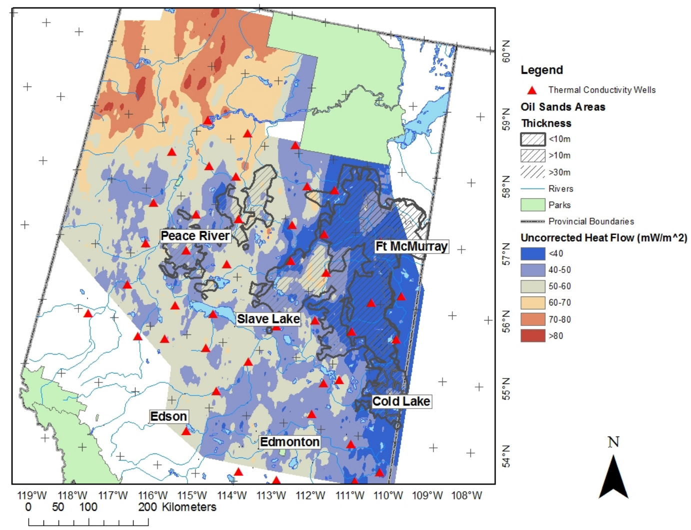

Figure 5. Heat flow (mW/m^2) calculated from geothermal gradient and thermal conductivity not corrected for the paleoclimatic effect of post—glacial 10^{o}C warming.

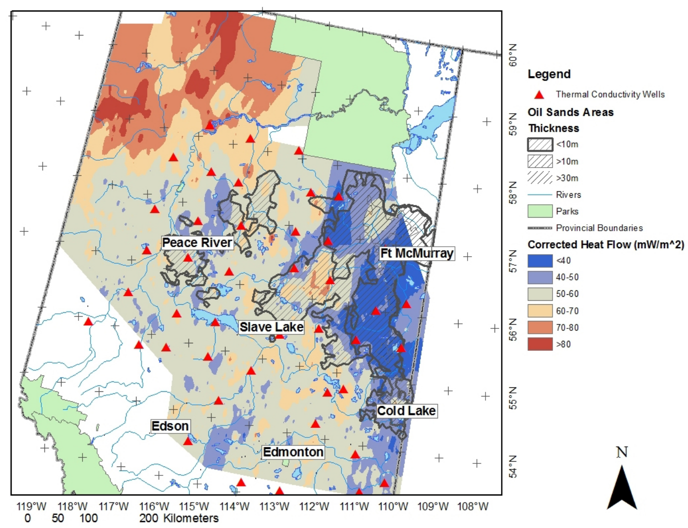

Figure 6. Heat flow (mW/m^2) calculated from geothermal gradient and thermal conductivity corrected for the paleoclimatic effect (postglacial warming).

In order to show the significance of correcting heat flow for temperature potential we have modeled temperature depth down to 7 km in Peace River based on the uncorrected and corrected heat flow (Fig. 7) and base of WCSB temperature map (Fig.1) as well as the assumed heat generation and thermal conductivity from previous studies Jones and Majorowicz, (1987), Beach et al., (1987), Jessop, (1990) and recent data in Majorowicz et al., (2012).

The calculations were done for a range of heat flow values. These are 54 mW/m^2, for the uncorrected heat flow and, 66 mW/m^2 for corrected heat flow. The model of exponential decay of heat generation in the crystalline crust has been assumed (Majorowicz et al, 2012). This has been based on the interpretation of empirical relationship between heat flow and heat generation for the Churchill Province of Precambrian crust underlying study area. The difference of 12mW/m^2 correction makes in prediction

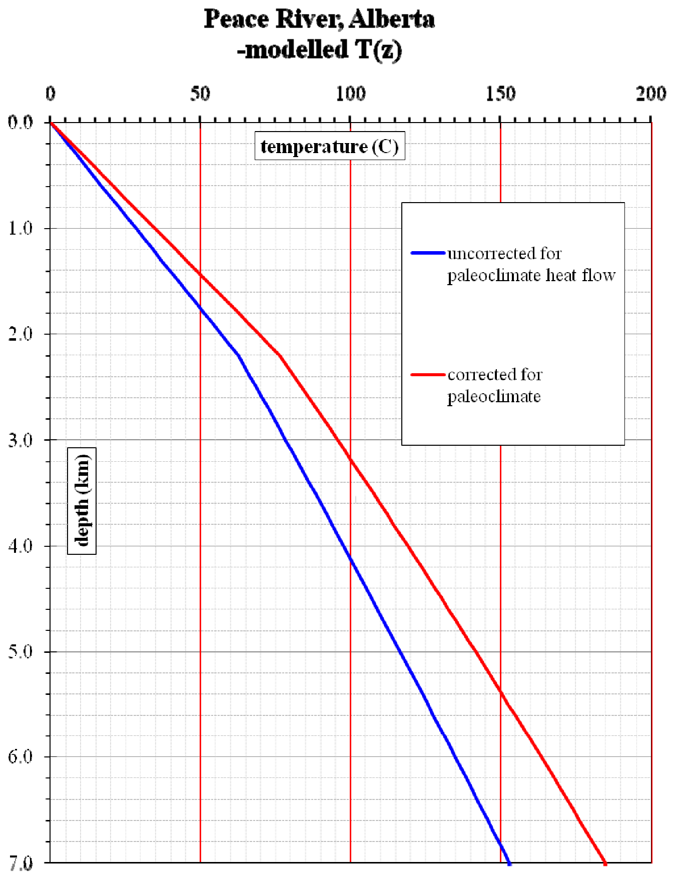

Figure 7. Comparison of the influence of paleoclimatic correction to heat flow vs. no correction for the calculation of temperature with depth. Illustrated case is Peace River in North Alberta where correction needed is 12 mW/m^2. Note that temperatures in this site are significantly higher than in Hunt well (Fig.2) due to higher heat flow (Fig 6) and larger thickness of the sedimentary cover thermal blanket overlying granites below (2.2km for Peace River area vs. 0.5km in Hunt well area).

of deep temperatures is significant (Fig. 7). Estimates of depth to drill to 120°C and 150°C depths can be overestimated by 1km and 1.5 km respectively.

Conclusions

- Recent results from a 2.3km deep temperature log in northern Alberta, Canada acquired as part of the University of Alberta Helmholtz-Alberta Initiative (HAI) geothermal energy project in 2010-2011shows that there is a significant increase in thermal gradient in the granites.
- Inversion of the measured T-z profile between 550 – 2320 m indicates a temperature increase of 9.6 °C +/- 0.3 ºC, at 13.0+/- 0.6 ka and that the glacial base surface temperature was - 4.4+/- 0.3 °C.
- This the large amplitude of Pleistocene - Holocene surface warming in northern Alberta inferred from borehole temperature logs is reflected by depletion of heat flow in the upper 2km (mainly upper 1.5km). It is a cause of significant underestimate of deep EGS resource in Alberta from shallow geothermal data.

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References

Anglin, F. M. and Beck, A. E., 1965, Regional heat flow pattern in Western Canada, Can. J. Earth Sci. , 2, 176-182.

Bachu, S., 1991, On the effective thermal and hydraulic conductivity of binary heterogeneous sediments. Tectonophysics, 190, 299-314.

Bachu, S., 1993, Basement heat flow in the Western Canada Sedimentary Basin, Tectonophysics, 222, 119-133.

Beach, R.,D.,W., Jones, F.,W., and Majorowicz, J.,A., 1987, Heat Flow and HeatGeneration Estimates for the Churchill Basement of the Western Canadian Basin in Alberta, Canada, Geothermics, 16-1, 1-16.

Garland, G.,D., and Lennox, D.,H., 1962, Heat flow in Western Canada, Geophys. J. R. Astr. Soc., 6, 245-262

Gosnold, W., Majorowicz, J., A., Klenner, R., and Hauk, S., 2011, Implications of Post-Glacial Warming for Northern Hemisphere Heat Flow, GRC Transactions, 35, 795-800.

Gray, A., Majorowicz, J., and Unsworth, M, 2012, Investigation of the geothermal state of sedimentary basins using oil industry thermal data: Case study from Northern Alberta exhibiting the need to systematically remove biased data. IOP J.Geoph. Eng., JGE/428217/PAP/128312 (in press)

Hackbarth, D., A., 1978, Groundwater temperatures in the Athabasca oil sands area, Alberta, Canadian Journal of Earth Science, 15, 1689–1700.

Jessop, A.,M., 1990, Thermal Geophysics. Elsevier, Amsterdam, 306 pp.

Jones, F. W., and J. A. Majorowicz, 1987, Regional trends in radiogenic heat generation in the Precambrian basement of the Western Canadian Basin, Geophysics Resource Letters, 14, 268–271.

Jones, F., Lam, H., and Majorowicz, J., 1985, Temperature distributions at the Paleozoicand Precambrian surfaces and their implications for geothermal energy recovery in Alberta, Canadian Journal of Earth Science, 22, 1774-1780.

Lam, H, Jones, F, and Majorowicz, J (1985), A statistical analysis of bottom-hole temperature data in southern Alberta: Geophysics, v. 50, no. 4, p. 677-684.

Lam, H., and Jones, F., 1984, Geothermal gradients of Alberta in western Canada, Geothermics, 13- 3, 181-192.

Majorowicz, J.,A., and Jessop, A.,M., (1981). Regional heat flow patterns in the Western Canada Sedimentary Basin, Tectonophysics, 74, 209-238.

Majorowicz, J., and Grasby, S., 2010, Heat flow, depth–temperature variations and stored thermal energy for enhanced geothermal systems in Canada, IOP J. Geoph. Eng., 48,232-241.

Majorowicz, J., and Wybraniec, S., 2010, New terrestrial heat flow map of Europe after regional paleoclimatic correction application, International Journal of Earth Sciences (Geol. Rundsch.), DOI 10.1007/s00531-010-0526-1

Majorowicz, J.,A., Jones, F.,W., Lam, H-L., Linville, A., and Nguyen, C.,D., 1985, Topography and the subsurface temperature regime in the Western Canadian Sedimentary Basin: Implications for low-enthalpy geothermal energy recovery,Geothermics,14, 175-187.

Majorowicz, J.A., Garven, G., Jessop, A., and Jessop, C., 1999, Present heat flow along a profile across the Western Canada Sedimentary Basin: the extent of hydrodynamic influence, in: A. Forster, and D. Merriam, eds., Geothermics in Basin Analysis, Computer Applications in the Earth Sciences,. 61-80, Kluwer Academic / Plenum Publishers.

Majorowicz, J., Unsworth, M., Chacko, T., Gray, A., Heaman, L., Potter, D., Schmitt, D., and Babadagli, T., 2012, Geothermal energy as a source of heat for oil sands processing in northern Alberta, Canada, in: Heavy Oil/ Bitumen Petroleum Systems in Alberta and Beyond, co-edited by F. J. Hein, D. Leckie, J. Suter and S. Larter, AAPG Mem, in press.

Mossop, G., and Shetsen, I., (Eds), 1994, Geological atlas of the Western Canada Sedimentary Basin; Canadian Society of Petroleum Geologists and Alberta Research Council, Special Report 4, URL <http://www.ags.gov.ab.ca/publications/wcsb_atlas/atlas.html>.