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Shallow geothermal heat in Western Canada: climatic warming impact changes with time–depth

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Abstract. The gain in heat and temperature in the shallow subsurface over the last decades/century has been caused by the industrial-period increase in climatic surface air temperature (SAT). A detailed study of the available temperature–depth data based on 43 wells with single and repeated temperature logs done by the first author has been combined with database information (Jessop et al. 2005) to create temperature maps at depth. Based on these 43 logs, it is shown that the heat flux increases with depth in most cases for the available depth data range from surface to ~200 m. A model of heat flow versus depth based on surface air temperature changes through the industrial-period climatic warming explains the data. The spatial and depth distribution of available temperature and heat gain through the provinces of the Western Canadian Sedimentary Basin WCSB shows that drilling closer to the surface is more economic than drilling deeper to 50–100 m.

Key words:
shallow geothermal,
terrestrial heat flow,
geothermal heat
Western Canada

Introduction

Ground temperature is a key factor in the design of geothermal energy installations. Even small changes in degrees °C are significant. As shown in UMNY (2023), a seemingly small difference of 1°C in the fluid temperatures (ΔT) of a geothermal system can have a massive impact on the performance, efficiency and profitability of that system. Therefore, our knowledge of temperature–depth variability based on high-precision logs in observational wells and our understanding of this variability are important.

Background

A geothermal heat pump increases the efficiency of heating and cooling functions by substantially decreasing thermal lift (US Department of Energy 2023). Because rocks and soils are good insulators, they respond little to wide daily temperature fluctuations and instead maintain a nearly constant temperature that reflects the mean temperature averaged over many years. Thus, at latitudes and elevations where most western and northern Canadian people live in the WCSB (Western Canadian Sedimentary Basin), the temperature of rocks and soil of the ground surface typically stays within the range of 2°C to 8°C. As a result, the geothermal-based unit is almost always pumping heat over a temperature lift that is much smaller than that for an air-source unit, leading to higher efficiency through the lower amount of "extra" energy needed to accomplish the lift. The Coefficient of Performance (CoP) will vary with each installation. The CoP can rise to 4 for most ground-based installations, whereas it is 2–3 for most air-based ones. The CoP will vary with each installation, but the lower the output temperature to the heat distribution system, the higher the CoP will be. The input temperature is also critical to the CoP of the heat pump. The higher the input temperature from the ground, the lower the amount of work needed from the heat pump, and the higher the CoP will be. In fact, the critical factor is the "uplift" between the source temperature and the output temperature (Gehlin et al. 2015; UMNY INC. 2023; US Department of Energy 2023; Interseason Heat Transfer™ 2023).

Results

Surface versus ground temperature from wells

Temperature at 15–20 m depth is usually free of the influence of seasonal surface temperature variations and is related to mean annual surface temperature. Below, we show patterns of ground and subsurface temperatures. We mapped the distribution of wells for the Prairie Provinces + bordering areas and the pattern of the mean annual temperature extrapolated to the ground surface temperature (GST) (Fig. 1). This map of the mean annual GST (MAGST) is based on temperatures from well logs adjusted by the average magnitude of the GST temperature change over time (see chapter on that issue farther down). This was assessed as mean values (to an accuracy of 0.2 °C) for a decade. The dates on which temperatures were logged vary, and the most recent are from 2005 (Table 1 and Jessop et al. 2005). The logs commonly start at several meters to tens of meters below the surface. Extrapolation of the temperature depth logs from 15 m b.g.l. to the ground surface has followed. Commonly, at 15 m b.g.l., temperature will be independent from seasonal variations in the WCSB.

The well locations for which temperature–depth values were available are marked by triangles (green)

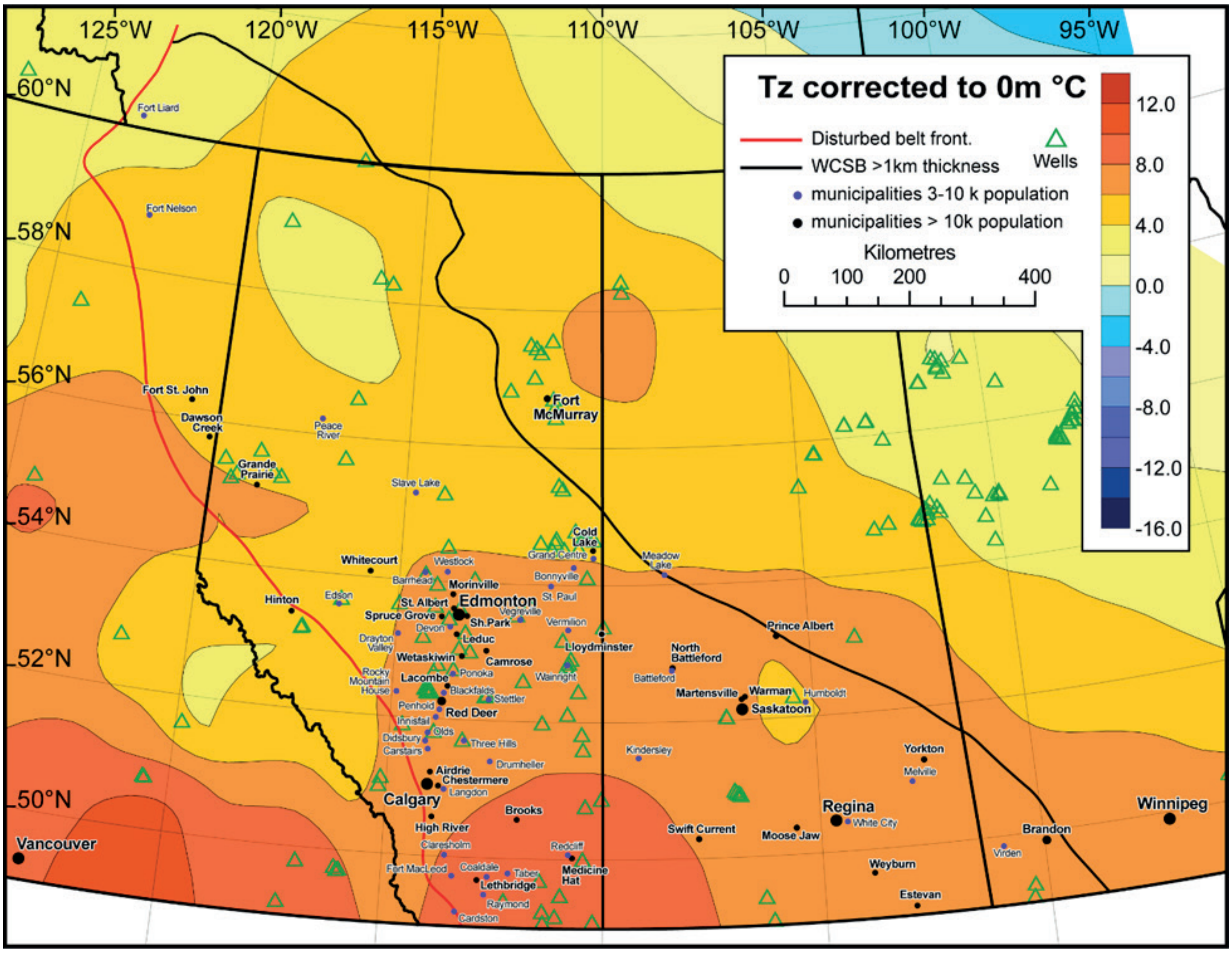

Fig. 1. GST mean annual temperature derived from temperature–depth logs from wells (green triangles) in Canadian database

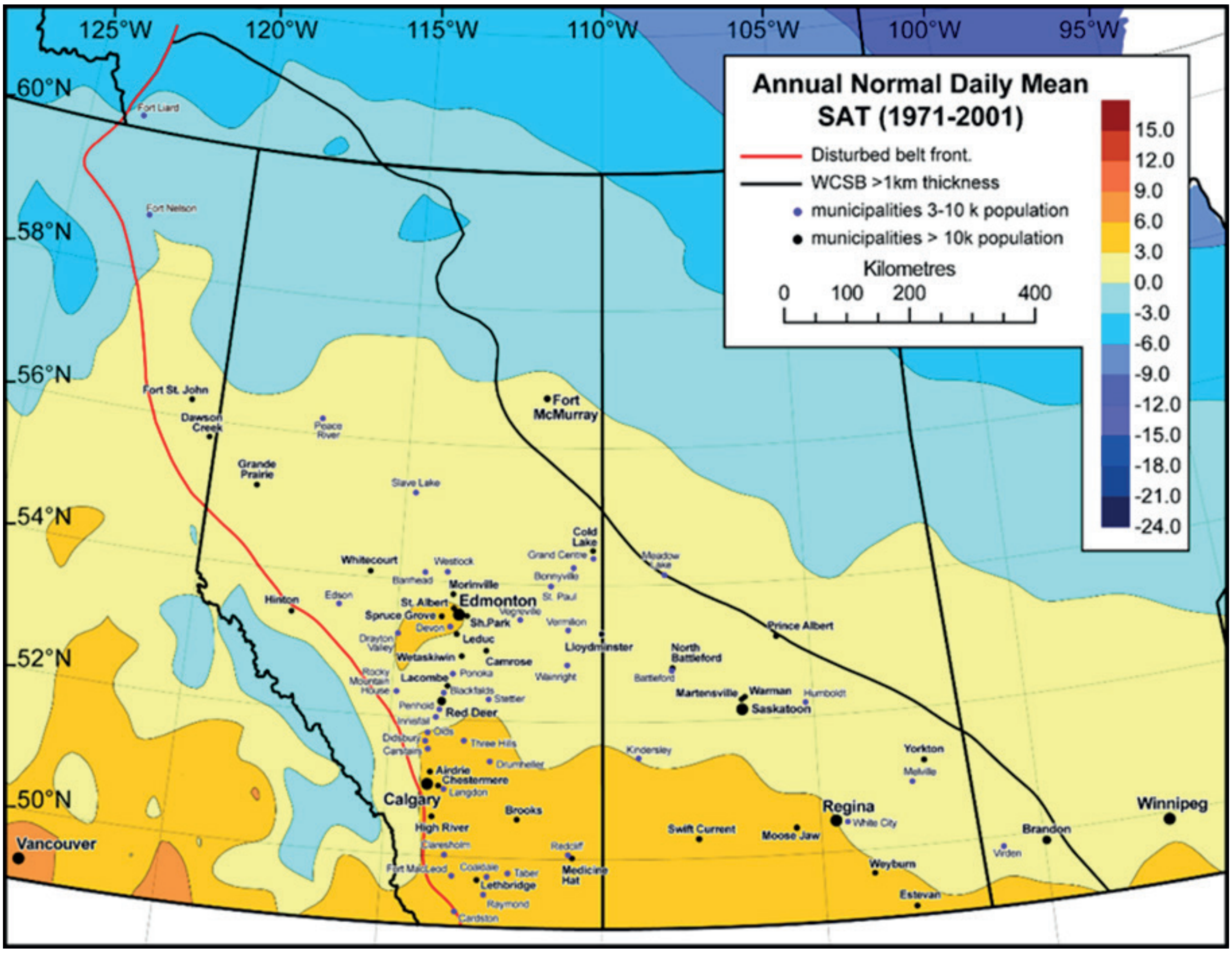

Fig. 2. Map of mean annual SAT (surface air temperature) based on daily time series of Environment Canada

in Figure 1. It is observed that the GST temperature shown in Figure 1 is higher than the mean annual surface air temperatures (MASAT) pattern shown in Figure 2. MASAT is recorded as time series at the screen level of the Canadian SAT stations (data in the Canadian Climate Normal Station Data, Climate Weather Government of Canada, access 2023). The temperature reduced to ground level (GST) is observed to be usually higher than the surface air temperature (SAT), which is also the case in most winter snow-covered, frozen-soil areas (Gehlin et al. 2015).

High-precision temperature logs in Alberta and Saskatchewan

Wells with temperature logs taken with thermistor probe are listed in Table 1. The map (Fig. 3) of well site locations in the Prairies' Western Canada Sedimentary Basin (WCSB) are numbered 1–43 as in Table 1. Temperature profiles come from logging trips done by the first author to the observational wells by the Environment Alberta and Saskatchewan. The wells are in a state of thermal equilibrium years to decades after the cessation of drilling using drilling mud fluid circulation. Temperature was recorded with a thermistor probe at 0.03°C precision.

In the northern wells, precise temperatures are much fewer and older (some from as early as 1974), (Jessop et al. 2015). These are largely controlled by the level of permafrost, which is largely related to climatic low surface temperature forcing of the Pleistocene and other periods. These are not included in our analysis of locations in Table 1. Permafrost thickness (depth to 0°C) is highly variable in Canada. For example, the thickness of permafrost in wells of Mackenzie Delta is several times smaller than in neighbouring areas of the continental part. Sporadic permafrost in the Mackenzie corridor spanning Northern Alberta and the southern Northwestern Territories is disappearing due to surface temperature increase because of industrial-age warming. The utility of the map of permafrost thickness in the *Ground ice map of Canada* (2020) as a tool to predict depth to 0°C for northern geosphere shallow geothermal heat feasibility is under discussion.

Shallow heat flow changes with depth in Alberta and Saskatchewan

Heat flow is calculated using the rock thermal conductivity, k, multiplied by the temperature gradient, Grad T(z), where z is depth. The standard units are mW/m^2. Thus, think of a flat plane of 1 meter by 1 meter: how much energy (mW) is transferred through that plane is the amount of heat flow Q [mW/m^2]. The results of these calculations are shown in panels in Figure 5:

$$Q = kGradT$$

where k is thermal conductivity [Wm^{-1}K^{-1}] and *GradT* is thermal gradient [°C/m].

Temperature gradient, *GradT*, was calculated from T-logs shown in Figure 4a–g. Thermal conductivity was estimated using net rock technique as in Majorowicz and Jessop (1981) and Majorowicz et al. (2012a,b) with the use of measured Alberta-Saskatchewan sedimentary rock average k values from Beach et al. (1987). These are estimates, as no in-situ measurements of k were ever done. There was no core available for these shallow sections of the boreholes for which high-precision temperatures have been logged. The estimates of k and *GradT* will be available in the online database to be posted with the article information on the first author's site on Research Gate. The error on the k is assessed at 20%. The effect of such variability upon heat flow vs. depth is shown farther in the article's modelling section.

Shallow terrestrial heat flow with depth is shown for the Canadian Prairies WCSB in Figure 5. Heat flow and temperature are observed to decrease with depth in upper parts of the ground as related to climate warming of the surface forcing such change. Heat gains due to climatic warming of the industrial age and anthropogenic land use result in surface forcing propagating downward with depth in the case of surface warming. In the shallow underground, energy storage is observed as seen in

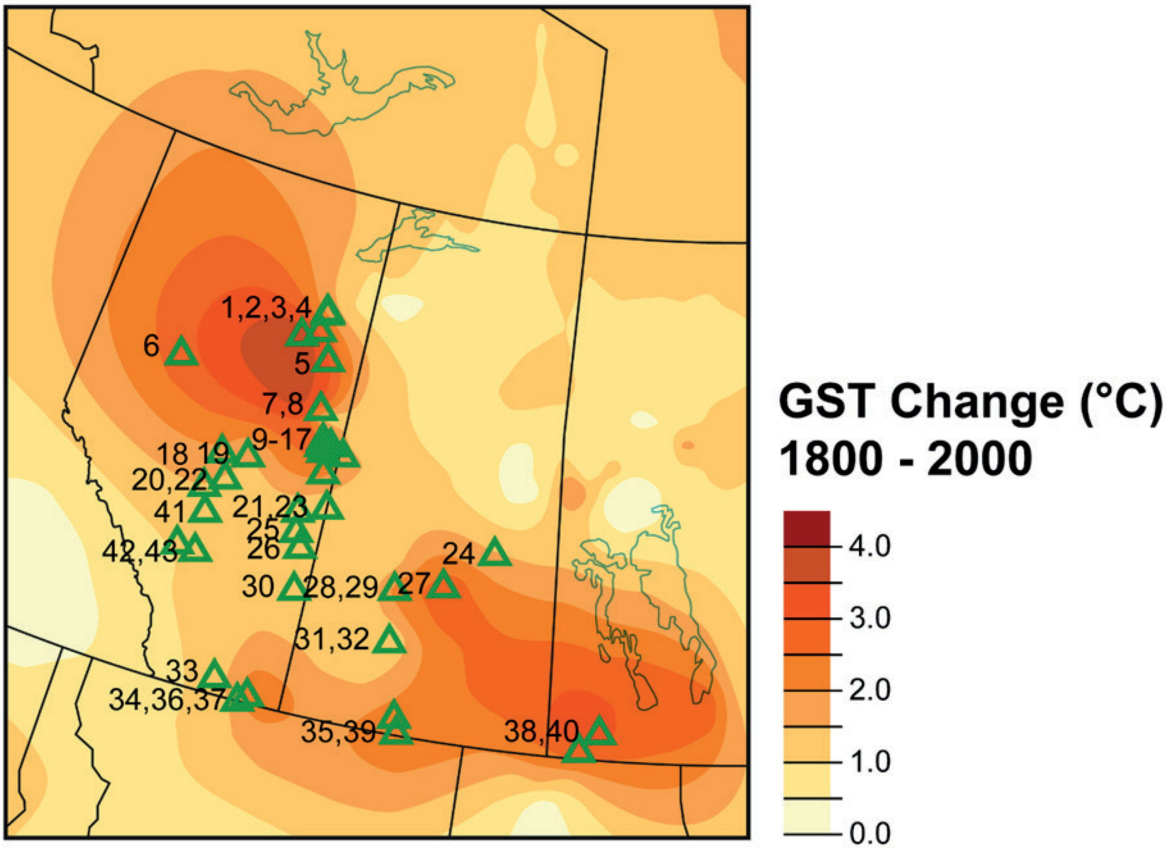

Fig. 3. Location of analyzed well sites in the Western Canadian Sedimentary Basin (WCSB) in western Canada – locations are numbered 1–43 as in Table 1 below. GST warming is derived from well temperature logs using a simple ramp model (Lachenbruch and Marshall 1986), from Majorowicz et al. (2012a)

Table 1. Location of wells with high-precision temperature logs made by the first author in Alberta and Saskatchewan, Canada

	Well	Province	Latitude	Longitude	Surface	Cover
1	TFM2	AB	57.39	-111.82	flat	forested
2	TFM1	AB	57.33	-111.69	flat	forested
3	TFM14a-b	AB	56.97	-111.85	flat	forested
4	TFM15a-b	AB	56.77	-112.49	flat	forested
5	Stony Mt.	AB	56.39	-111.27	flat	forested
6	Winagami	AB	55.61	-116.68	flat	grass
7	T963Kirby	AB	55.39	-111.13	flat	pasture
8	T962Wian	AB	55.35	-111.04	flat	pasture
9	BPTriad	AB	54.74	-110.71	flat	forested
10	Cold Lake944	AB	54.65	-110.51	flat	forested
11	TCL942	AB	54.62	-110.43	flat	forested
12	TCL1	AB	54.61	-110.25	flat	forested
13	TCL14	AB	54.57	-110.81	flat	forested
14	TCL10Lessard	AB	54.48	-110.62	flat	forested
15	TSAS941	SK	54.45	-113.88	flat	forested
16	Cold Lake4-5	AB	54.06	-110.41	flat	forested
17	Cold Lake3	AB	54.06	-110.41	flat	forested
18	T961	AB	54.01	-113.18	flat	cropland
19	T790Sion	AB	53.91	-114.11	flat	cropland
20	Devon	AB	53.41	-113.76	flat	grass
21	T765	AB	53.35	-110.01	flat	cropland
22	T791/Opal	AB	53.16	-110.98	flat	cropland
23	Warburg	AB	53.13	-114.36	flat	grass
24	T965Armley	SK	53.06	-103.95	flat	cropland
28	T966	SK	52.02	-107.12	flat	cropland
29	T967	SK	52.01	-107.11	flat	cropland
30	TSA2	AB	51.78	-110.51	flat	prairie
31	T9cRiveRhurst	SK	50.95	-107	flat	prairie
32	T8cRiverhurst	SK	50.88	-106.87	flat	prairie
33	TSA6	AB	49.38	-112.21	flat	prairie
34	TSA10/10B	AB	49.18	-111.07	flat	grassland
35	TKT1	SK	49.07	-106.25	flat	grassland
36	TSA12	AB	49.02	-111.36	flat	grassland
37	TSA13	AB	49.01	-111.32	flat	grassland
38	WAWANESA	MB	49.6	-99.84	flat	grassland
39	Wood Mt	SK	49.4	-106.4	flat	prairie
40	CA655	MB	49.06	-100.55	gentle slope	pasture
41	T784Gull lk.	AB	52.627	114.052	flat	grass
42	T767	AB	51.767	-113.968	flat	grass
43	T768	AB	51.828	-114.653	flat	Grass

Source: own elaboration

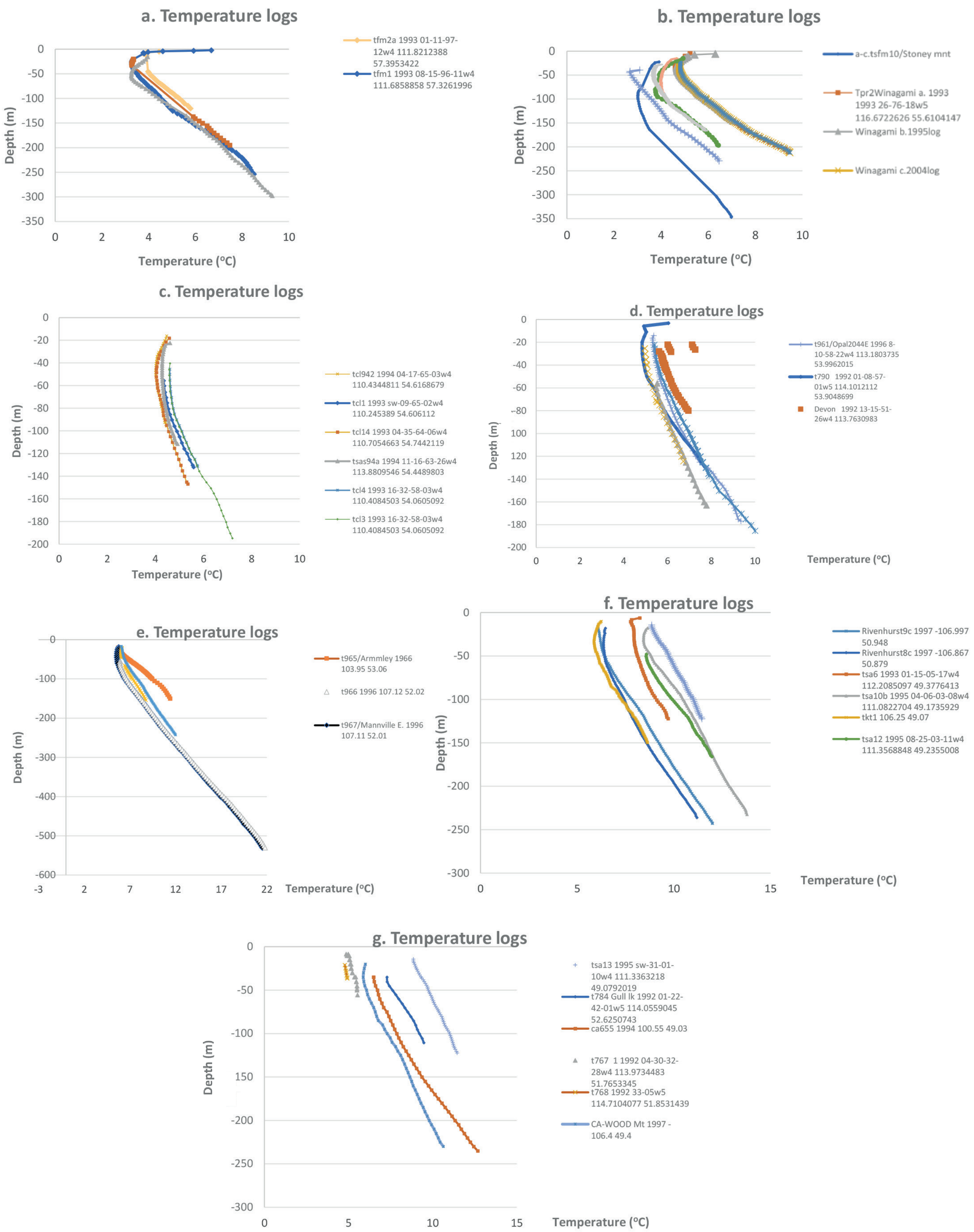

Fig. 4. Precise temperature logs from well sites listed in Table 3

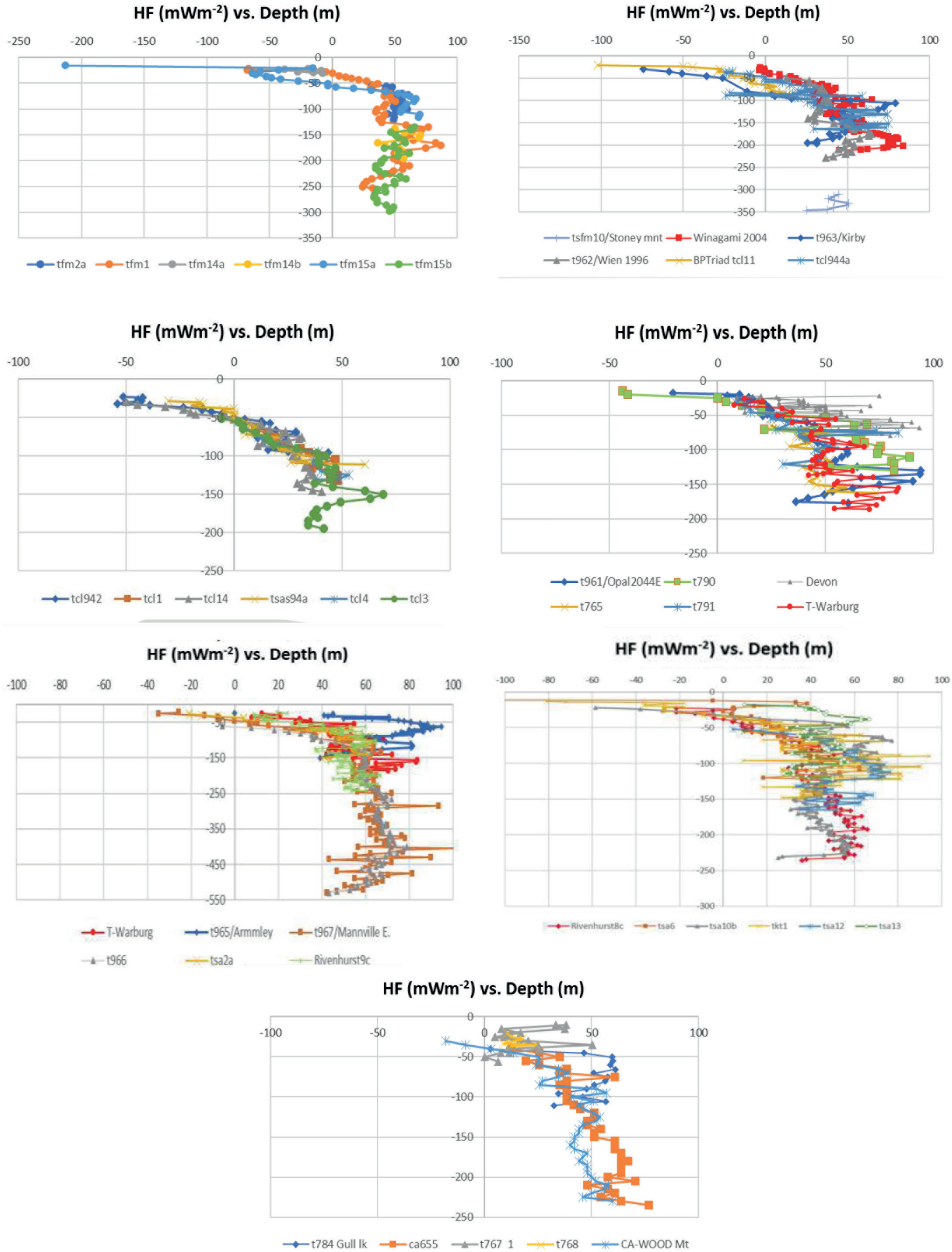

Fig. 5. Calculated heat flow vs. depth for the wells listed in Table 1

the compilation of the temperature depth logs (i.e., the increase in geothermal gradient with depth in Fig. 4). The average temperature anomaly (transient temperature) of the Alberta Saskatchewan logs shown in Fig. 6 is a proof of heat energy being stored over time due to surface warming. The transient profiles were determined as a part of the ground surface temperature history reconstruction from the individual logs by a frequently used inversion method called the "functional space inversion" (Majorowicz et al. 2012a; Shen and Beck 1991). The observed increase in heat flow with depth is, in most cases, evident for the heat flow profiles shown above (Fig. 5). Logs give us a precise way to determine heat gain in the ground and aquifers over the industrial age when temperature depth is inverted using FSI (Functional Space Inversion) to ground temperature vs. time. In most cases of the WCSB Prairie Provinces' wells, we observe subsurface temperature increasing with time (see example of the repeated logs from Majorowicz et al. [2012a]). In the grassland of the Canadian Prairies, the change in temperature with depth can be modeled as a resulting of surface temperature change due to climatic warming. In most of cases, however, the change over a century can be explained as climatic warming plus anthropogenic changes like land clearing for farming and municipal expansions (Majorowicz et al. 2004, 2012a). This is apparent from the analysis of Figsures 4–5 for the Alberta and Saskatchewan well logs. The heat gain over any period ranging from a decade to a century of industrial-age warming is the highest in the upper parts of the ground; this is shown in Figure 6, which shows anomalies of temperature vs. depth in the WCSB (Western Canadian Sedimentary Basin) wells for approximately the whole period of industrial warming. The amount of energy stored in the ground due to GST warming can be calculated by integration of the anomaly dT(z) (Fig. 6). Ground warming observed from the repeated logs decade-2 decades apart is a result of surface temperature forcing, which was shown to result in gaining heat ¬– an effect found to be strongest near the ground surface and to dissipate with depth. Over the period of a century, the surface temperature and the subsurface temperature in the upper ~200 m have been rising, as shown in Figure 6.

Heat gain contribution

Heat gain can be calculated from the temporal variation of temperature versus depth, $dT(z)$, (see Fig. 6) for the transients based on the repeated temperature logs and specific heat capacity, c:

$$H = c\,DT(z)$$

where $DT(z)$ is temperature transient (°C) versus depth (m) related to industrial climatic warming and c is specific heat 2.5×10^6 J m^{-3} K^{-1} and H is in J m^{-3}.

The total heat energy E for the surface area S (m^2) is:

$$E = S\int H dz$$

where E is in Joules.

The shallow underground energy storage is observed in the compilation of the temperature depth logs (i.e., the increase in geothermal gradient with depth) in Figure 4, the heat flow increase with depth in Figure 5, and the heat gain in Fig. 6. The temperature anomalies (transients of temperature) in Alberta Saskatchewan logs were calculated using functional space inversion (FSI) technique. Heat energy is being stored over time due to climatic surface warming and land changes such as deforestation. The observed heat flow increase with depth is evident for most of the heat flow profiles shown above (Fig. 5).

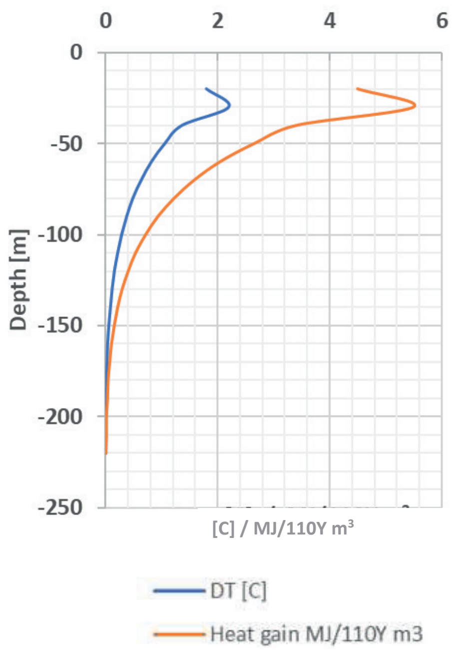

Fig. 6. Example of heat gain MJ/110 Y m^3 (Y stands for years) calculated from the average temperature transient DT(z) for Alberta-Saskatchewan well logs in Table 1 from the observed well measurements with depth shown in Figure 4

Simple forcing model explaining observed shallow heat flow changes with depth in the Canadian Plains, Alberta, and Saskatchewan

Ground surface warming lowers the temperature gradient below the ground and reduces the upward steady-state heat flow from the Earth's interior. When the surface warming is fast enough, the temperature gradient close to the surface can even become negative, i.e. temperature decreases with increasing depth and heat flows downward from the surface. That is what we observed in most of the wells studied (Fig. 4). The retained heat coming from the depth – and, in the case of negative gradients, the heat flowing from the surface downward – warms up the rock and the water in pore spaces. The zone of warming is identical with the zone where the heat flow increases with depth. As Figure 5 shows, this is typically in the upper 100 m of the logs. From this depth upwards, the heat flow starts to decrease and becomes negative at about 50 m.

We simulated the observed heat flow versus depth profiles by solving the transient heat conduction equation with ground surface temperature as a boundary condition approximated by mean annual surface air temperatures from 29 selected Canadian meteorological stations (see the list in Table 2). Because transient temperature in the considered depth range of ~300 m is influenced by ground surface temperature changes of the last few centuries, and because the oldest Canadian SAT series start in 1895, we had to estimate temperature before the year 1895. In accordance with the current knowledge about the climate recovery from the Little Ice Age at the end of the 19th century, we considered temperature in the period 1790–1895 to be 1°C lower than the 1895–1910 mean (the "boxcar model", Figure 7). The temperature prior to 1790 (the "pre-observational mean", hereafter also "POM") was alternatively considered to be either equal to the 1895–1910 average or 0.5°C higher. The first alternative provided the best fit of transients obtained in reconstructing the ground surface temperature histories from 51 Canadian temperature logs (Majorowicz et al. 2012a).

The ground surface temperature forcing can be approximately represented as a series of N jumps in the temperature with amplitude $\Delta Ti = Ti - T_{i-1}$ at time distance t_i from the moment of the borehole-temperature measurement. The subsurface temperature response $T(z)$ to this forcing at depth z is:

$$T(z) = \sum_{i=1}^{N} \Delta Ti \times erfc\left(\frac{z}{\sqrt{4kti}}\right)$$

where k is thermal diffusivity and *erfc* is the complementary error function (Carslaw and Jaeger 1959).

Results of the simulations are shown in Figure 8. The figures depict transient heat flow related to the year 1993 (the mean date of temperature logging) in superposition with the deep steady-state heat flow of 50 mW/m^2 for three alternative values of thermal conductivity from the range expected for the individual studied boreholes. The considered thermal diffusivity, $0.6 \cdot 10^{-6}$ m^2/s, is a typical value for the Western Canadian Sedimentary basin (Majorowicz et al. 2002).

The calculated profiles reproduce fairly the observed heat flow decrease in the upper 100 m of the log up to the negative values in the uppermost part of the boreholes depicted in Figure 5. The synthetic profiles are slightly above the steady-state value below the depth of approximately 100 m. This is a consequence of the considered ground surface cooling of 1–1.5°C before the 19th century. The observed profiles are too noisy to clearly display this feature.

The course of mean annual SAT after 1993 is marked in green in Figure 7 compared to the temperatures in Central Europe, where there has been a marked warming in recent decades (Šafanda et al. 2023), SATs in Alberta show only a very slight (if any) increase in temperatures after this date. Comparison of the synthetic transient heat flow-depth profiles for the years 1993 and 2021 that are based on data from the Beaverlodge meteorological station (see Fig. 7) is shown in Figure 9 also shown is a heat flow profile observed in a borehole 40 km east of the station in the year 2021 (Huang et al. 2021).

Shallow Geothermal Space Heating

Since the geothermal-based heating units are pumping heat over a temperature lift, it is important to calculate it to assess efficiency of the system. It is important for the use of GHP systems and for deep direct geothermal energy use. Below (Fig. 10), we show examples of calculation of the available temperature lift between surface, 20 m, 200 m and Manville deep aquifer depth. The Manville aquifer and surface air daily temperature for the Edmonton Blatchford meteorological station are

Table 2. Historical and Homogenized Temperatures for Canada, Version Dec 2002

StnId	Station Name	POM°C	boxcar°C	after 1910	SAT from
3011120	Calmar	1.35	0.35	1.61	1915
3015524	Rocky Mtn House Cr10	0.12	-0.88	0.38	1915
3023722	Lacombe CDA 2	1.64	0.64		1907
3031093	Calgary Int'l A	3.20	2.20		1895
3031400	Carway	3.15	2.15	3.41	1914
3032800	Gleichen	2.77	1.77		1903
3033890	Lethbridge CDA	4.69	3.69		1902
3034480	Medicine Hat A	3.92	2.92		1895
3035206	Pincher Creek Aut	4.38	3.38		1895
3050519	Banff CS	1.16	0.16		1895
3061200	Campsie	0.74	-0.26	1	1912
3062246	Edson Cr10	1.23	0.23	1.49	1914
3062440	Entrance	1.86	0.86	2.12	1917
3062693	Fort McMurray A	-0.51	-1.51		1908
3065999	Slave Lake A	0.34	-0.66	0.6	1922
3070560	Beaverlodge CDA	1.56	0.56	1.82	1913
3072658	Fort Chipewyan A	-3.69	-4.69		1895
3072920	Grande Prairie A	0.32	-0.68	0.58	1922
3073146	High Level A	-2.74	-3.74		1908
4012400	Estevan A	1.53	0.53		1900
4013480	Indian Head CDA	1.14	0.14		1895
4016560	Regina A	1.00	0.00		1898
4019040	Yellow Grass	1.67	0.67		1911
4024080	Klintonel	0.81	-0.19		1910
4028040	Swift Current A	1.34	0.34		1895
4048520	Waseca	0.22	-0.78		1907
4056120	Pilger	0.18	-0.82		1911
4056240	Prince Albert A	-0.56	-1.56		1895
4057120	Saskatoon A	0.66	-0.34		1895

taken as reference. The difference relative to the surface and -20 m varies considerably over the year and closely follows the air temperature. At ~2 m depth, the temperature is more uniform, averaging about 4 +/-2 °C. There is a lag time of about eight weeks between the maximum surface temperature and the maximum soil temperature at this level, which is helpful in winter heating and summer cooling. At 200 m, temperature will be higher (range is 5–16°C), as shown in the map in Figure 11 The lower depth 50 m and 100 m levels (Figs 12–13) show that the upper level </100 m increase in temperature-depth is low comparing to deeper sedimentary rock temperature increases in degrees C. This low-grade heat can still be used with a heat pump for greenhouse or building heating requirements. A much higher temperature of >35°C can come from deep wells with hot water aquifers like that of the Manville geological formation. Previously exploited oil and gas aquifers containing saline water can be used directly for space heating (Majorowicz and Grasby 2020).

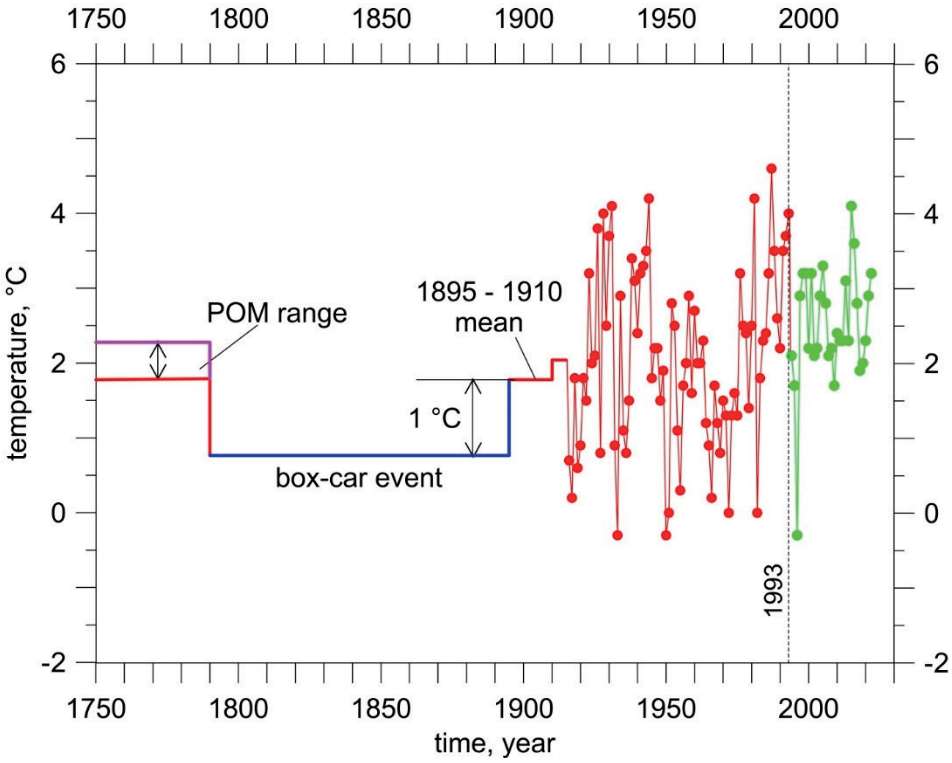

Fig. 7. Forcing surface temperature: pre-observational mean before 1790, box-car event 1790–1895, and the Beaverlodge SAT series. Mean annual air temperatures are shown in red for before 1993, and in green for after 1993

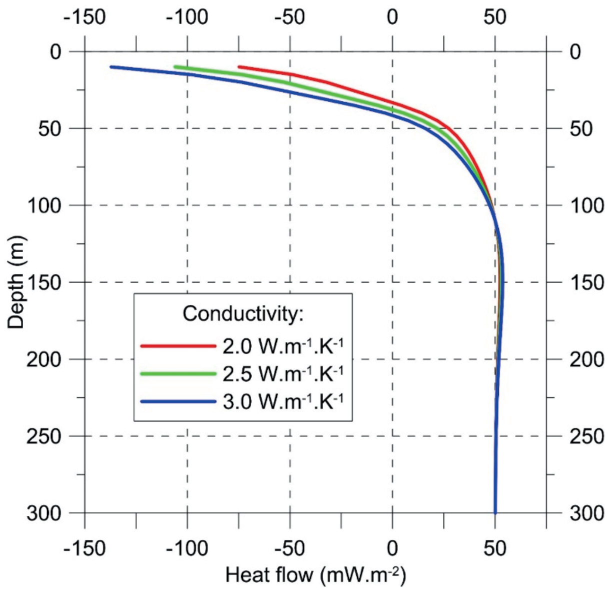

Fig. 8. Subsurface synthetic heat flow (superposition of the transient component and the deep steady state heat flow 50 mW/m²) for three alternative values of thermal conductivity. The transient component was calculated as a mean response to the surface forcing of 29 SAT series from the W Canadian Plains plus boxcar model (1790–1895) with temperature 1°C lower than the 1895–1910 mean SAT. The pre-observational mean prior to 1790 equals the 1895–1910 mean. Diffusivity for wet sedimentary rock is $0.6 \cdot 10^{-6}$ m^2s^{-1}

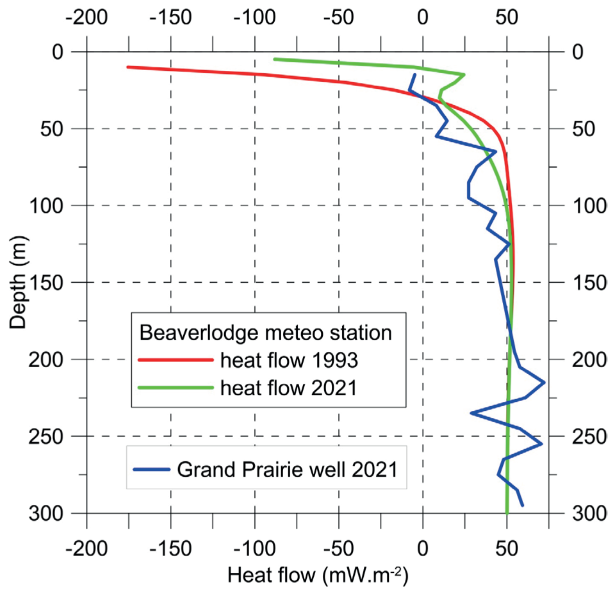

Fig. 9. Synthetic transient heat flow-depth profiles for the years 1993 and 2021 based on SAT series from Beaverlodge meteorological station together with a heat flow profile observed in a borehole located 40 km east of the station in the year 2021

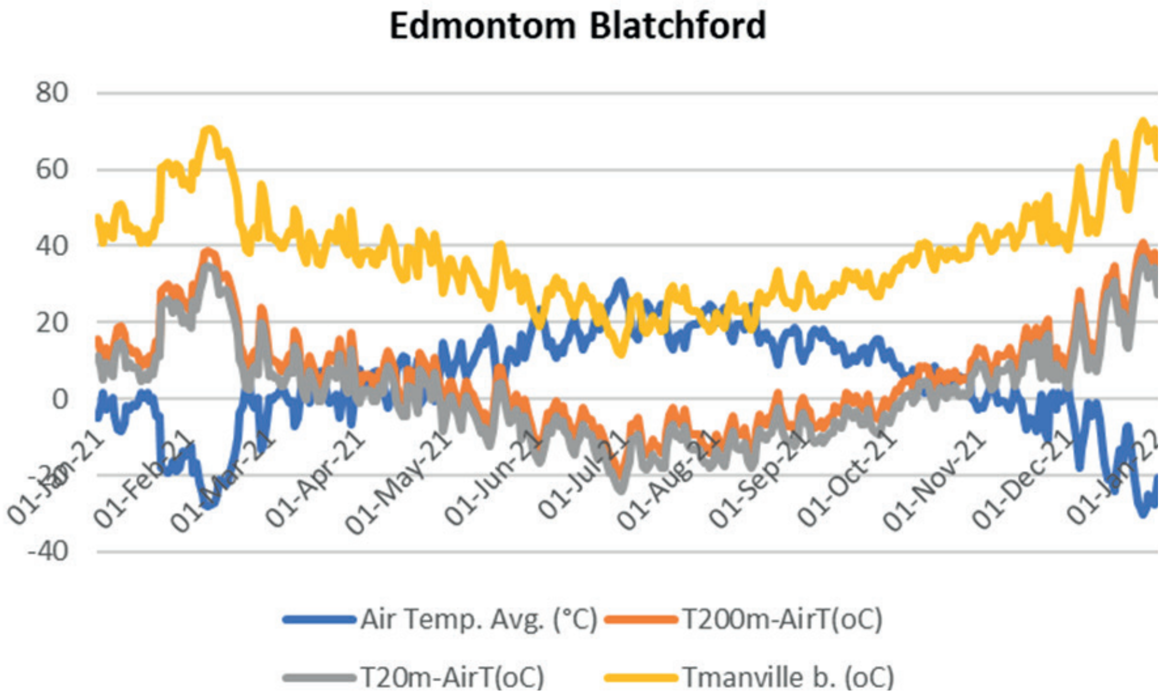

Fig. 10. Example of surface temperature °C and difference between temperature at 20 m, 200 m b.g.l. and deep Manville formations base and the SAT daily time series calculated for the SAT station near Edmonton

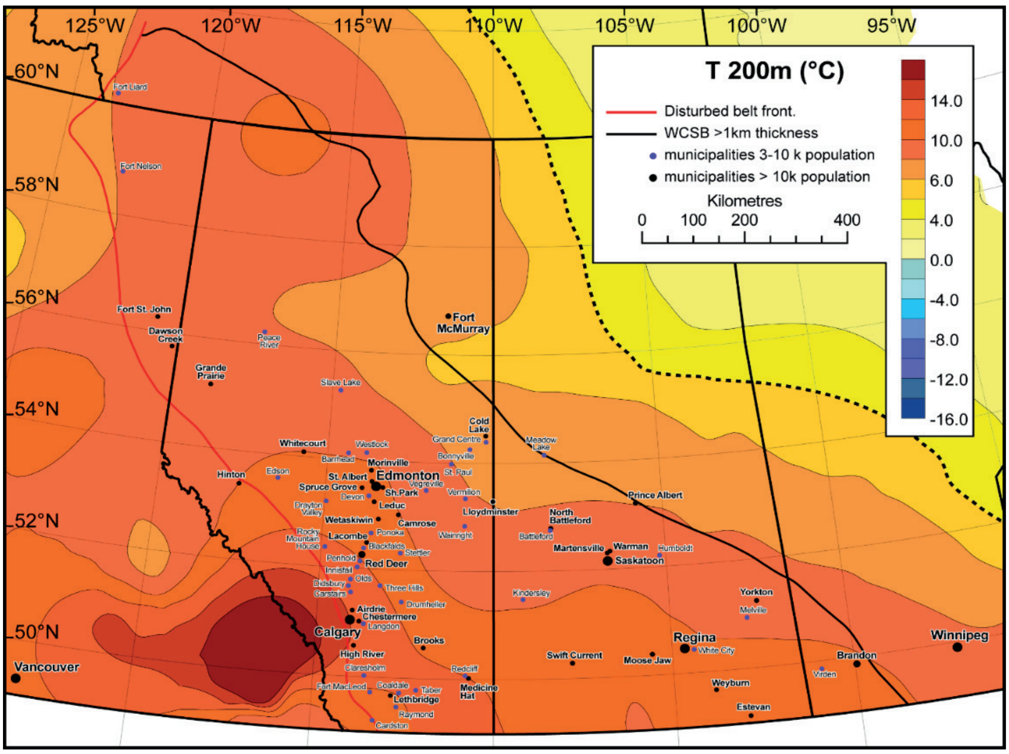

Fig. 11. Map of temperature at 200 m b.g.l.

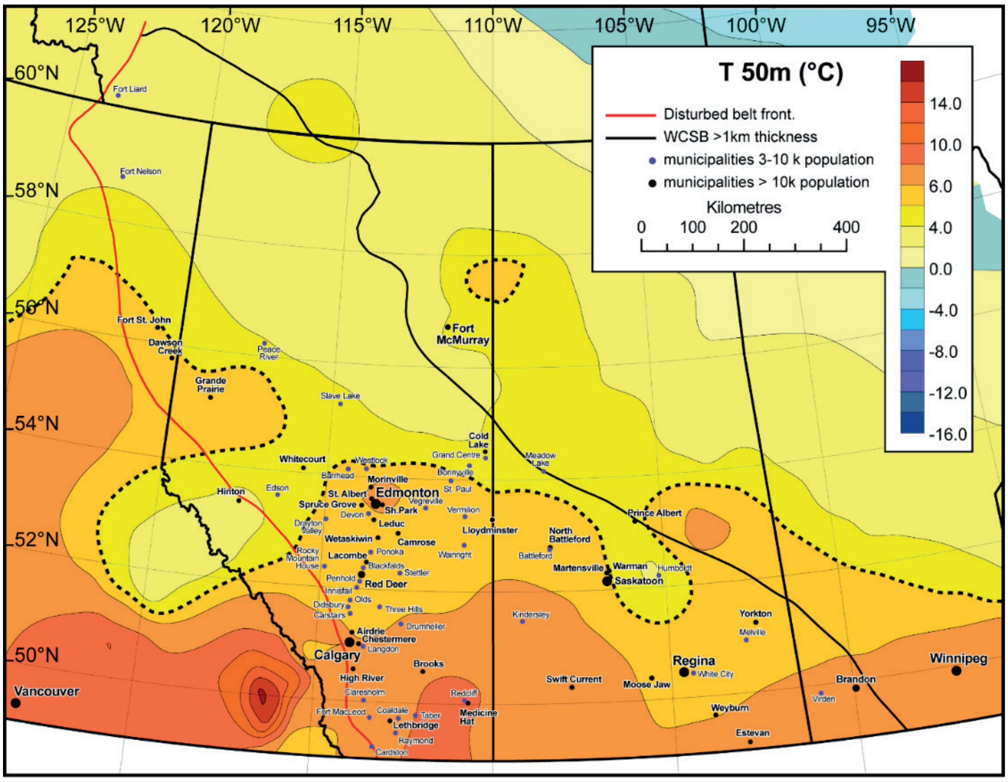

Fig. 12. Map of temperature at 50 m b.g.l.

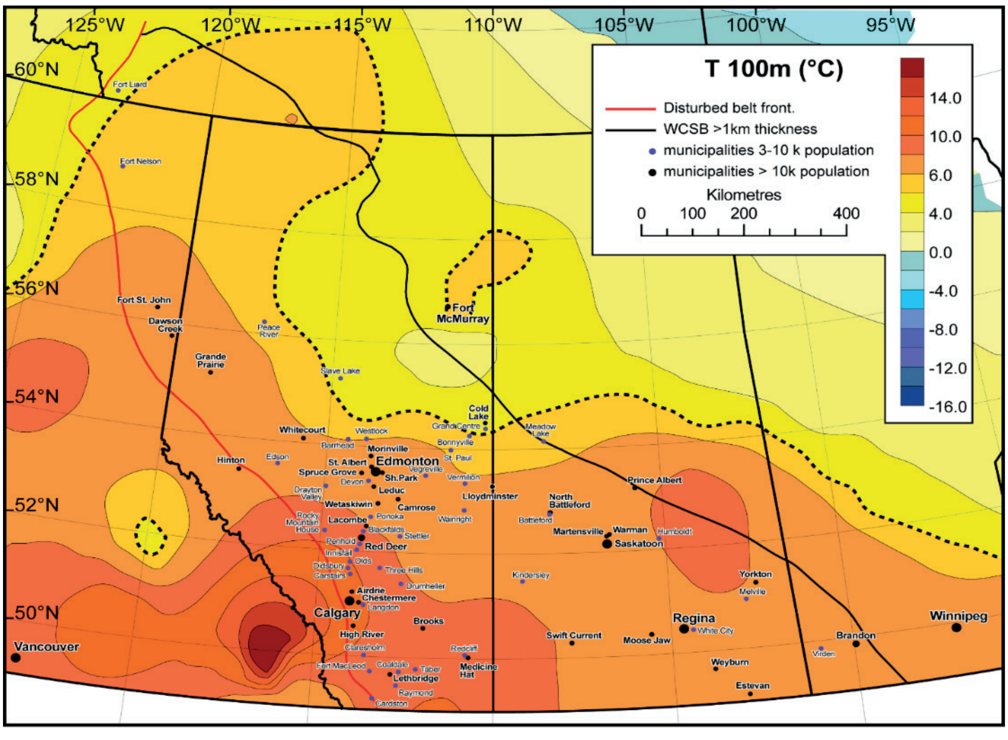

Fig. 13. Map of temperature at 100 m b.g.l.

Discussion and conclusions

Analysis of temperature data of the upper soil level and down to 300 m b.g.l. based on temperature logs and constructed temperature at depth levels maps for the study area of the Canadian Prairie Provinces and surrounding shows that temperature distribution is highly dependent on the surface climatic warming of the industrial age. Increasing surface temperature at the surface within that time caused positive temperature gains at ground surface, diffusing with depth. It was first shown by Cermak (1971) that a surface temperature change model can explain temperature depth changes as recorded in temperature well logging. Calculated heat flow from the precise equilibrium temperature logs and thermal conductivity model for the sedimentary strata show an increase in heat flow variations with depth. This can be explained by the model based on the observed SAT since the end of 19th century (mainly industrial age warming) with antecedent cold period 1790–1895 with temperature of 1°C lower than the 1895–1910 mean and temperature prior to 1790 equal to the 1895–1910 average or 0.5°C higher.

The calculations were done for diffusivity 0.6·10-6 m^2s^{-1}, which is typical for wet sedimentary rocks of the Western Canadian Sedimentary basin.

The upper tens of meters of soil gained a significant amount of heat due to industrial-era warming and anthropogenic changes. Geothermal gradient and heat flow increase with depth due to these forcings, as shown.

The rock and aquifers can be used with the ground heat pump for heating for the cold 6–7 months when the shallow geothermal field temperature is higher than the air surface temperature. For the rest of the year, heat can be stored underground, maintaining the system and, as the previous study shows, the recovery of the system will be at least as long as its exploitation time (Rybach 2021).

Use of ground heat pump (GHP) systems will be beneficial in buildings and agricultural greenhouse operations through the cold months due to their high COP (Coefficient of Performance). The average efficiency of the GHP is COP=4 – higher than that of the air heat pump (average COP=3). This makes the use of GHP beneficial in terms of economics and saving emissions.

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Author contributions

Study design: JM; data collection JM, JŠ; statistical analysis: JM, JŠ; result interpretation: JM, JŠ; manuscript preparation: JM, JŠ; literature review: JM, JŠ.

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