Chapter 30 – Geothermal Regime in the Western Canada Sedimentary Basin

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Introduction

The thermal regime in a sedimentary basin is one of the main factors affecting the formation and accumulation of energy and mineral resources. The generation of hydrocarbons and the types produced are dependent on the temperature reached by the organic-rich source rocks during their burial history. Also, the processes leading to the formation of metallic mineral deposits of the Mississippi Valley Type are highly dependent on temperature. Thus, knowledge of the geothermal regime and understanding of the factors controlling it are very important in the analysis of sedimentary basins.

Two categories of geothermal information are presented in this chapter: radiogenic heat production by the rocks at the top of the Precambrian, based on the analysis of 424 unweathered core samples, and the geothermal regime in the sedimentary rocks of the Western Canada Sedimentary Basin, based on bottom hole temperature (BHT) measurements. There have been approximately 200,000 wells drilled in the basin, the majority having associated BHT measurements. Processing all the data would have been a task beyond the scope and magnitude of this publication. Also, it should be kept in mind that the wells reach various depths, and an analysis of the geothermal regime by stratigraphic and/or lithological units (e.g., Bachu, 1985, 1988) requires prior knowledge of the stratigraphy, geometry and lithology of the sedimentary rocks, precluding execution of the work and publication of the results within the framework of this Atlas. Thus, the geothermal regime is described at every possible point in the basin by the two most important characteristics: the maximum temperature and the average geothermal gradient. Given the general increase of temperature with depth, the maximum temperature at any location is found at the base of the sedimentary column (top of Precambrian). In addition, knowledge of the geothermal gradient and of the thermal conductivity of rocks allows calculation of basement heat flow. Thus, the geothermal regime in the Western Canada Sedimentary Basin is presented in terms of distributions of radiogenic heat production, heat flow and temperatures at the top of the Precambrian, and of the average geothermal gradient across the basin.

Factors Controlling the Geothermal Regime

The geothermal regime in a sedimentary basin is determined by the magnitude and interaction of various heat sources and transfer mechanisms by which the terrestrial heat is transported to the surface. The two main types of heat are that which flows upward from the mantle, and that which is generated internally in the crust by the decay of radioactive isotopes. The main mechanisms of heat transfer are convection by moving fluids, and conduction. In sedimentary basins there is a fluid continuum throughout the entire thickness, with the possible exception of evaporite beds, which may act as aquicludes. The movement of fluids is caused by various processes and phenomena such as compaction, buoyancy and gravity. Thus, there is always a measure of fluid movement in a basin, depending on the particular condition of the basin. However, the transport of heat can be dominated by conduction or by convection, or neither. In a basin dominated by heat conduction, the geothermal regime is controlled basically by the distribution of heat sources and the thermal conductivity of rocks. In a convection-dominated basin, the main controlling factors are the amount and the direction of fluid movement. Finally, the scale of the basin and of the fluid and heat flow processes are important in establishing the type of geothermal regime in the basin. Various processes manifest themselves at different scales, a factor which must be taken into account in the analysis of the geothermal regime (Chapman and Rybach, 1985; Bachu, 1988).

The terrestrial heat in the Western Canada Sedimentary Basin has three sources: the mantle, the crystalline basement and the sedimentary rocks. The heat flow from the mantle has a steady state component from the deep interior of the Earth, establishing the base level over which episodic components are superimposed. The latter are usually linked temporally to the movement of continental plates. These movements may be: 1) compressional events, characterized by orogenesis with magmatic heat transfer and regional metamorphism (e.g., the Hudsonian Orogeny below almost all of the Western Canada Sedimentary Basin; the Columbian Orogeny along the western margin of the basin); or 2) extensional events characterized by crustal thinning and the rise of isotherms, and volcanic and hypabyssal igneous activity (e.g., the Mackenzie Dyke Swarm across most of northwestern North America).

On the basis of heat generation and transfer, the basement underneath the Western Canada Sedimentary Basin can be divided into a Lower and Upper Crust. During orogenic events, the Lower Crust had a plastic character because of high temperatures and pressures, and volatiles introduced from the mantle. After orogenesis and the escape of volatiles to the Upper Crust, the end product may have been anhydrous granulite facies rocks. The main radiogenic elements, thorium (Th) and especially uranium (U) and potassium(K), were remobilized during the Hudsonian Orogeny and transferred to the Upper Crust by K and U metasomatism. Lower crust of Archean age apparently underlies most of Alberta (Theriault and Ross, 1990).

The Upper Crust is mechanically brittle, with temperatures in the higher metamorphic range. Because no magma is generated and most of the Lower Proterozoic sedimentary or volcanic rocks underlying the Western Canada Sedimentary Basin have lost permeability by being metamorphosed to high grade, the heat is transported only by conduction. Although transport by fluids moving along fractures and fault zones is possible, no such cases have been identified. The Upper Crust is a major source of terrestrial heat because of high concentrations of large-ion lithophile elements, including U, Th and K, the three major sources of radioactive heat generation.

The radioactivity of the Phanerozoic cover rocks is generally low. The only exceptions are the sylvite and carnallite beds in the Elk Point Group, and the organic-rich Exshaw shale. However, these units are relatively thin within the sedimentary succession, with a limited heat-generation capability. More specific studies by Majorowicz et al. (1984), and dimensional analysis by Bachu (1985) have shown that the heat production by the entire sedimentary column is negligible compared to other heat generation and transfer processes.

Current Knowledge

Generally, information available for the analysis of the geothermal regime in a basin is scarce and incomplete. The Western Canada Sedimentary Basin is no exception if the abundance of BHT measurements available from the energy industry is excluded. Approximately two percent of the wells drilled reach the Precambrian basement, but none penetrate it to any significant depth. Thus, there is no direct information about the thickness of the basement or about radiogenic heat production at depth in the basement. Nor are accurate measurements of heat flow available. Nevertheless, core samples from the top of the Precambrian, bottom hole temperatures, and measurements of the thermal conductivity of rocks have provided data used in various studies of the geothermal regime in the Western Canada Sedimentary Basin.

A northerly trending increase in heat flow was identified at the scale of the basin by Anglin and Beck (1965). They attributed it to crustal thickening, which would provide a greater amount of radioactive heat-generating material. Anomalies in this trend detected in southern and central Alberta were explained by granitic basement intrusions inferred from gravity and borehole data. A geothermal map of North America, published by the U.S. Geological Survey and the American Association of Petroleum Geologists (USGS-AAPG, 1976), shows the same north-northeast trend of increasing geothermal gradient in the Western Canada Sedimentary Basin. The geothermal gradients were calculated using BHT data and mean annual air temperatures.

Hitchon (1984) analyzed the geothermal map of North America (USGS-AAPG, 1976) and, based on qualitative reasoning, concluded that regional hydrodynamic features control the regional geothermal pattern, with perturbations caused by local effects. Using BHT data, thermal conductivity measurements for various sedimentary rocks, and heat generation data published by Burwash and Cumming (1976) about the rocks at the top of the Precambrian, Majorowicz and Jessop (1981) analyzed the regional heat flow pattern in the basin and suggested that the basin-scale geothermal pattern results from the movement of formation waters rather than from high mantle heat flow and thickening of the lithosphere. The geothermal gradients and the heat flow for Paleozoic and Mesozoic-Cenozoic rocks in Western Canada were estimated by Majorowicz et al. (1984, 1985, 1986) and Jones et al. (1985a, b) using regression techniques applied to BHT data. In these studies, the effective thermal conductivity of the entire sedimentary column, needed in heat flow calculations, was estimated based on net-rock lithological analyses at selected wells in the basin, and either literature values (Majorowicz and Jessop, 1981; Majorowicz et al., 1984) or data from actual measurements (Jones et al., 1985b; Beach et al., 1987) for rock thermal conductivity. The geothermal gradients used in the same heat flow calculations were not corrected for the effect of Pleistocene glaciations, while only Beach et al. (1987) considered the heat generated by radioactive decay in the sedimentary column. The temperature distributions at the top of both the Precambrian and the Paleozoic were estimated by extrapolating temperature-versus-depth regression lines. The results obtained using this technique show a difference between the estimated heat flow values for the strata below and above the Paleozoic top surface. This difference was attributed to significant regional-scale transport of heat by formation waters. The conclusion of these studies was that the geothermal gradient, heat flow patterns, hydraulic heads and topography are closely related, and that groundwater flow is important in determining the geothermal pattern in the Western Canada Sedimentary Basin.

Bachu (1985, 1988) and Bachu and Cao (1992) used independent hydrogeological data (rock porosity and permeability, velocity of the flow of formation waters, and aquifer thickness) to show, through dimensional analysis, that the flow of formation waters is too weak to influence significantly the regional-scale geothermal pattern in Alberta. Accordingly, the geothermal regime in a conduction-dominated system is controlled by the heat flow from the basement and by the geometry and lithology of the sedimentary rocks. Bachu (1988) concluded that the geothermal pattern is determined at the large basin scale (10^2 - 10^3 km) by large-scale basement tectonic features; at the intermediate scale by small-scale basement features and by the lithology of the sedimentary rocks; and at the local scale (10^1 km) by topography and groundwater flow.

The observed pattern of the geothermal regime in the Western Canada Sedimentary Basin has thus been interpreted in two ways with respect to the importance of groundwater flow in controlling the temperature field. One interpretation is that the flow of formation waters causes a significant distortion of the thermal field on a basin-wide scale, and the other is that the transport of terrestrial heat is controlled almost entirely by conduction, with minor local hydrogeological effects. Given the scale of the subject area and the resolution of the available information, no definitive answer is yet possible with regard to the role of groundwater in controlling the geothermal regime in the basin.

Data Sources and Processing

Analyses of unweathered Precambrian core samples were used to calculate the heat generation due to radioactive decay of U, Th and K present in the crystalline basement underneath the Western Canada Sedimentary Basin. The initial number of 182 U and Th analyses published by Burwash and Cumming (1976) was augmented to 424, with most of the new information coming from oil wells in Alberta (Burwash and Burwash, 1989) and smaller suites from Saskatchewan and Manitoba. In addition, test drilling for the Slave River Hydroelectric Project has supplied 12 cores from northeastern Alberta where no cores were previously available because of a prohibition on drilling in Wood Buffalo National Park. There is limited well control in western Saskatchewan north of Swift Current. Toward the Cordillera, as the depth to the basement increases, few wells have penetrated the Precambrian. The most complete coverage is over the Peace River Arch, where drilling has been extensive.

In the 1970s, U and Th were determined by delayed neutron counting and K by X-Ray Fluorecence (XRF) analysis. In more recent work (Burwash and Burwash, 1989), delayed neutron counting continued to be used for U, but Th and K were measured by Instrumental Neutron Activation Analysis (INAA). For all samples, the rock density, ρ, was determined by weighing a single 50 to 500 g specimen first in air and then immersed in distilled water at 20°C. The amount of heat, *A*, produced by the decay of radioactive elements per cubic metre of rock, was calculated using the formula of Birch (1954) converted to SI units:

$$A = 0.1325\rho\,(0.718\,C_U + 0.193C_{Th} + 0.262C_K)$$

where A is given in $\mu W/m^3$ or heat generation units (HGU), ρ in g/cm^3, C_U and C_{Th} are U and Th concentrations in ppm, respectively, and C_K is the concentration of K in weight percent. Replicate analyses and comparison with standard samples analyzed by other methods (Burwash and Krupicka, 1969; Burwash and Cumming, 1976) suggest that the calculated A values are accurate within 5 percent.

The temperature distribution at the base of the sedimentary rocks of the Western Canada Sedimentary Basin was determined on the basis of bottom hole temperature data. The BHT measurements do not represent the true formation temperature because of the disturbance produced by drilling. When more than one BHT is recorded at a location, it is possible to estimate the formation temperature using the Horner method if the time of measurement is given (Chapman et al., 1984). In some cases, although there are multiple BHT measurements in a well, all record the same value, which makes them questionable, or the time of measurement is not recorded, which makes the BHT data useless. When only one BHT is recorded, whether the time is given or not, the formation temperature can be estimated by using regression-type analysis of the temperature correction with depth and time, or with depth only, respectively (Willett and Chapman, 1986).

The heat flow in the sedimentary column is vertically uniform if there are no significant lateral variations in the thermal conductivity of the rocks, as is the case of the Western Canada Sedimentary Basin, and if the effect of groundwater flow is negligible, an assumption still the object of debate. In this case, the vertical temperature profile and variation of the geothermal gradient are determined by the heat flow at the base of the sedimentary column and by the thermal conductivity of the rocks. Figure 30.1 illustrates schematically the variation of temperature and geothermal gradient, and the integral geothermal gradient between the top and the base of the sedimentary succession. The integral geothermal gradient (G) is calculated as the ratio of the temperature difference between the bottom and the top (surface) of the sedimentary column, to the total depth (or thickness):

$$G = (T_B - T_S)/D$$

where T_B and T_S are the temperatures at the bottom and surface of the sedimentary column, respectively, and D is depth. This geothermal gradient represents the average of the geothermal gradients in all the units in the sedimentary column weighted by lithological thickness (Bachu, 1985). The temperature, T, can be estimated at any point in the basin if the integral geothermal gradient, the depth, and either the temperature at the base or at the surface of the sedimentary column are known. The formula is:

$$T = T_S + GD \equiv T_B - G\,(D_B - D)$$

where D_B is the depth to the top of the Precambrian. In the above relations the temperatures are expressed in °C, depths in m, and geothermal gradient in °C/m. It is emphasized that the temperature, T, is an estimate, probably accurate within a few degrees Celsius of the true temperature.

The well database used for the Geological Atlas of the Western Canada Sedimentary Basin records 4069 wells reaching the Precambrian basement, of which 3793 have associated BHT measurements. These wells are unevenly distributed across the basin, with a high density in the northern, shallower parts of the basin (Peace River, Red Earth areas), and sparse in the southwestern, deeper parts. In keeping with the methodology and the scale of the Atlas, it was decided to select one well per township for the computation of the temperature at the base of the sedimentary column and of the integral geothermal gradient.

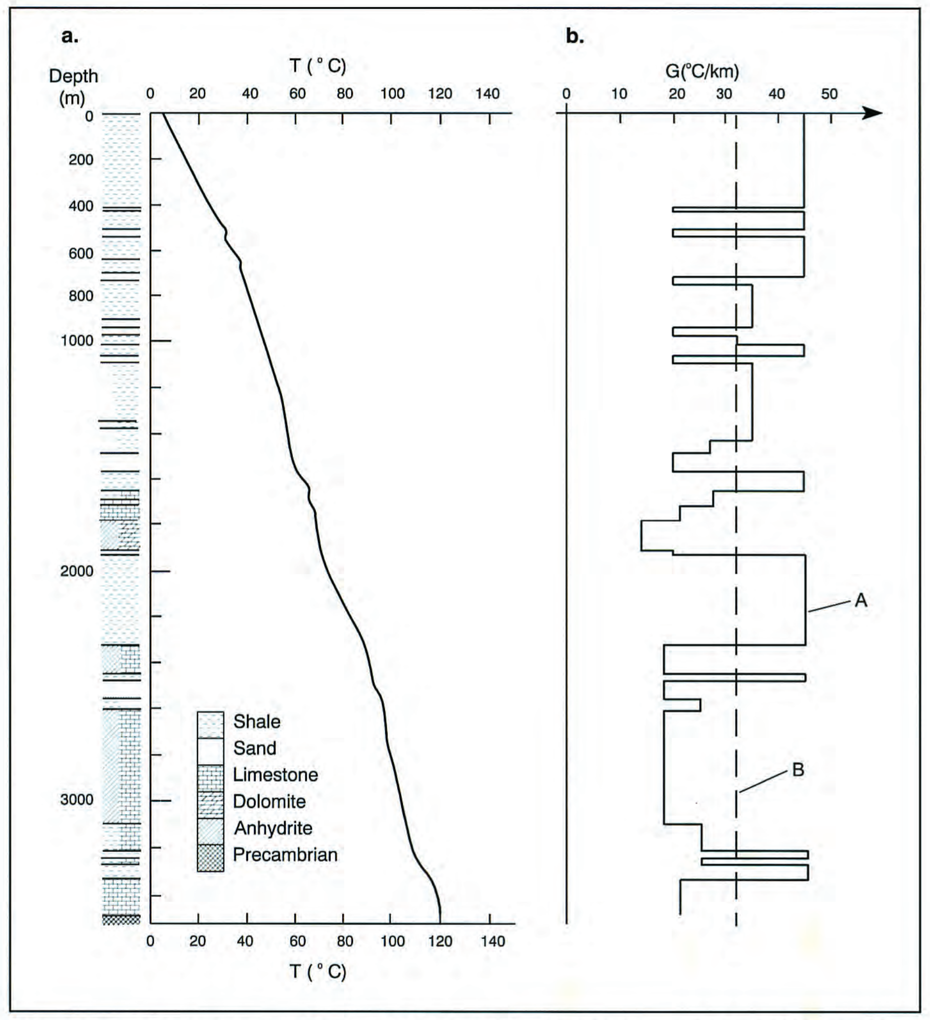

Figure 30.1 Variation with depth of calculated: **a.** temperature; and **b.** geothermal gradient (A), and integral geothermal gradient (B) for a well in the Peace River Arch area.

The software developed and used for the selection of representative wells for the Geological Atlas was adapted for the selection of the wells with BHT data used in the study of the geothermal regime. The criteria used for sample selection, in order of importance, are:

1. the well must have reached the Precambrian basement and have BHT data;
2. one well per township;
3. the well must have multiple BHT data, with the best linear approximation on a Horner plot;
4. preferably, the well has been analyzed for U, Th and K.

As a result of this selection process, 1473 wells with BHT data at the top of the Precambrian were retained for the analysis of the geothermal regime in the Western Canada Sedimentary Basin. The automatic selection was checked manually against the rejected wells, to make sure that in each township the well with the best BHT data was selected. Of the 1473 wells selected, 1086 record multiple BHTs with the associated time of measurement, another 162 wells record only one BHT with the associated time, and the remaining 225 record only the temperature, with no time given. The temperature at the bottom of the sedimentary column (T_B) was estimated at all 1473 locations using the appropriate Horner-type extrapolation or regression-type correction.

The surface temperature (T_S) was estimated from air temperature measurements at 558 climatic stations across Western Canada (Environment Canada, 1982a, b). Dimensional analysis showed that diurnal and seasonal temperature variations propagate into the ground only a few centimetres and metres, respectively (Bachu, 1985), and can be neglected. Thus, the surface temperature was calculated as the annual average of the multiannual monthly averages of ground surface temperatures. The latter were obtained from the corresponding air-temperature averages after applying a correction to take into account the freezing of the ground surface during winter when the air temperature drops below 0°C. A computer-generated map of the multiannual ground surface temperature across Western Canada was obtained this way, with values in the 5 to 7°C range, similar to results obtained previously for mean annual soil temperature at 150 cm depth (Loveseth and Pfeffer, 1988). The surface temperature (T_S) at each location corresponding to the 1473 wells with bottom temperatures was calculated by automatic interpolation in the ground surface temperature map. Finally, the integral geothermal gradient (G) was calculated at each location according to its definition.

The basement heat flow (Q) was estimated based on the integral geothermal gradient (G) and the well effective thermal conductivity λ_{eff} according to:

$$Q = \lambda_{eff}\,G$$

The well effective thermal conductivity can be calculated if the lithology, porosity and corresponding rock thermal conductivity are known. A search through the electronic database of Canadian Stratigraphic Services Ltd. (CANSTRAT) indicated the existence of net-rock analyses at 759 of the 1473 wells for which the integral geothermal gradient was determined. Normally, the information about the upper portion of wells in the CANSTRAT database is missing for various reasons, the most common being well casing and core absence. Thus, the detailed CANSTRAT lithological analysis has to be supplemented with information from well logs. Only 504 of the initial 759 CANSTRAT wells have enough coverage in depth (from the Precambrian basement to at least above the top of the Mannville Group) to allow for a meaningful and realistic supplementing of porosity and lithology information. The thermal conductivity for each analyzed interval was calculated based on measured and literature values (Beach et al., 1987; Brigaud et al., 1990; Horai, 1971) corrected for the effects of porosity and temperature (Brigaud et al., 1990), using the geometric average for the mixture of various rock types and water (Bachu, 1991; Brigaud et al., 1990). The well effective thermal conductivity was calculated using the series model (harmonic average) appropriate for a layered sequence. Finally, the basement heat flow was calculated using integral geothermal gradients corrected for glaciation effects (Jessop, 1990) and heat generation in the sedimentary strata (Rybach, 1988). After elimination of a few outlier values, 487 heat flow values were used in the analysis. A detailed description of the methodology used in calculating the basement heat flow is given in Bachu (1993).

Computer-generated maps were produced for the distributions of heat generation (A), heat flow (Q) and temperature (T) at the base of the sedimentary column (top of Precambrian), and the integral geothermal gradient (G), using the same software used for the draft geological maps of this Atlas. It should be pointed out here that the maps are as reliable as the data distributions allow. In areas of high data density, such as northern Alberta, the maps are more reliable than in areas of sparse data distribution, where single anomalous points exert a disproportionate influence. Nevertheless, the maps are representative for the currently available information. The corroboration of basement tectonics by features observed on the different maps increases the reliability of the distribution maps to be presented.

Geothermal Regime

Heat Generation

Statistical analyses of composite samples from the exposed Canadian Shield (Eade and Fahrig, 1971) indicate that the concentration of radioactive elements varies widely between the various tectonic provinces. The average heat-generation values are low for the Archean Superior and Slave provinces and high for the Proterozoic Churchill and Bear provinces. Analyzed core samples from the basement of the Western Canada Sedimentary Basin represent three and possibly all four of the tectonic provinces listed by Eade and Fahrig (1971). Figure 30.2 shows the geological provinces and the major structural features of the exposed Canadian Shield, and their inferred extensions beneath the Western Canada Sedimentary Basin. The high variability of the heat generation at the top of the Precambrian is related to the variability identified for the exposed shield. The heat generation map (Fig. 30.2) can be separated into eight regions, from northwest to southeast.

1. Northwest Alberta, northeast British Columbia, and adjacent Northwest Territories
   High heat-generation values reflect the southern extension of the Great Bear Magmatic Arc, equivalent to the Bear Province. The lithology of a number of samples in this area suggests the presence of a Proterozoic magmatic arc.
2. Great Slave Lake Shear Zone
   This major transcurrent fault zone is clearly visible on regional aeromagnetic maps (Ross et al., *this volume*, Chapter 4). Heat generation values are low along the shear zone because of loss of radioactive elements during shearing, the incorporation of slices of Archean crust, or the infaulting of Proterozoic clastic sedimentary rocks. At various points along the shear zone there is evidence of all three possibilities (Burwash et al., *this volume*, Chapter 5).
3. Peace River Arch
   The complex pattern of contours reflects the closer well spacing and the variation of heat generation values through one order of magnitude. A broad band of above-average values extends across the width of Alberta between 55 and 59°N.
4. Edmonton Anomaly
   The alignment of four samples of leucocratic biotite granite/adamellite with high U and Th contents (Burwash, 1979) indicates a linear heat generation anomaly striking northeast from the city of Edmonton. This anomaly corresponds very closely to the negative Bouguer anomaly defined by Burwash and Culbert (1976) as the Edmonton-Kasba Lake trend.
5. Southern Alberta
   An extensive tract of Alberta south of 52°N is characterized by low heat-generation values. Although it was subjected to a Hudsonian thermal overprint (1800Ma), the chemical composition of this crustal segment reflects its Archean time of crystallization (Ross et al., 1991). Part of this low U and Th crust is a northward extension of the Wyoming craton.
6. Southwestern Saskatchewan
   Basement cores collected in the vicinity of Swift Current, Saskatchewan, have anomalously high U and Th contents, reflecting highly differentiated magmas enriched in SiO_2, K_2O, U and Th. These magmas have produced the source rock for commercial helium production (Burwash and Cumming, 1976).
7. Trans-Hudson Orogen
   The arcuate patterns of lithotectonic domains that form the Trans-Hudson Orogen on the exposed Shield are not apparent on the contour map of heat generation. The lithological heterogeneity of the Cree Lake and La Ronge belts and the limited number of core samples are probable reasons.
8. Southwestern Manitoba-southeastern Saskatchewan
   The boundary between the Superior and Churchill provinces, as defined by Peterman (1962) and recently revised by McGregor (Burwash et al., *this volume*, Chapter 5), separates a broad area of low heat-generation values in southern Manitoba from higher values to the west. In the Archean granite-greenstone terrane of the western Superior Province, plagioclase usually

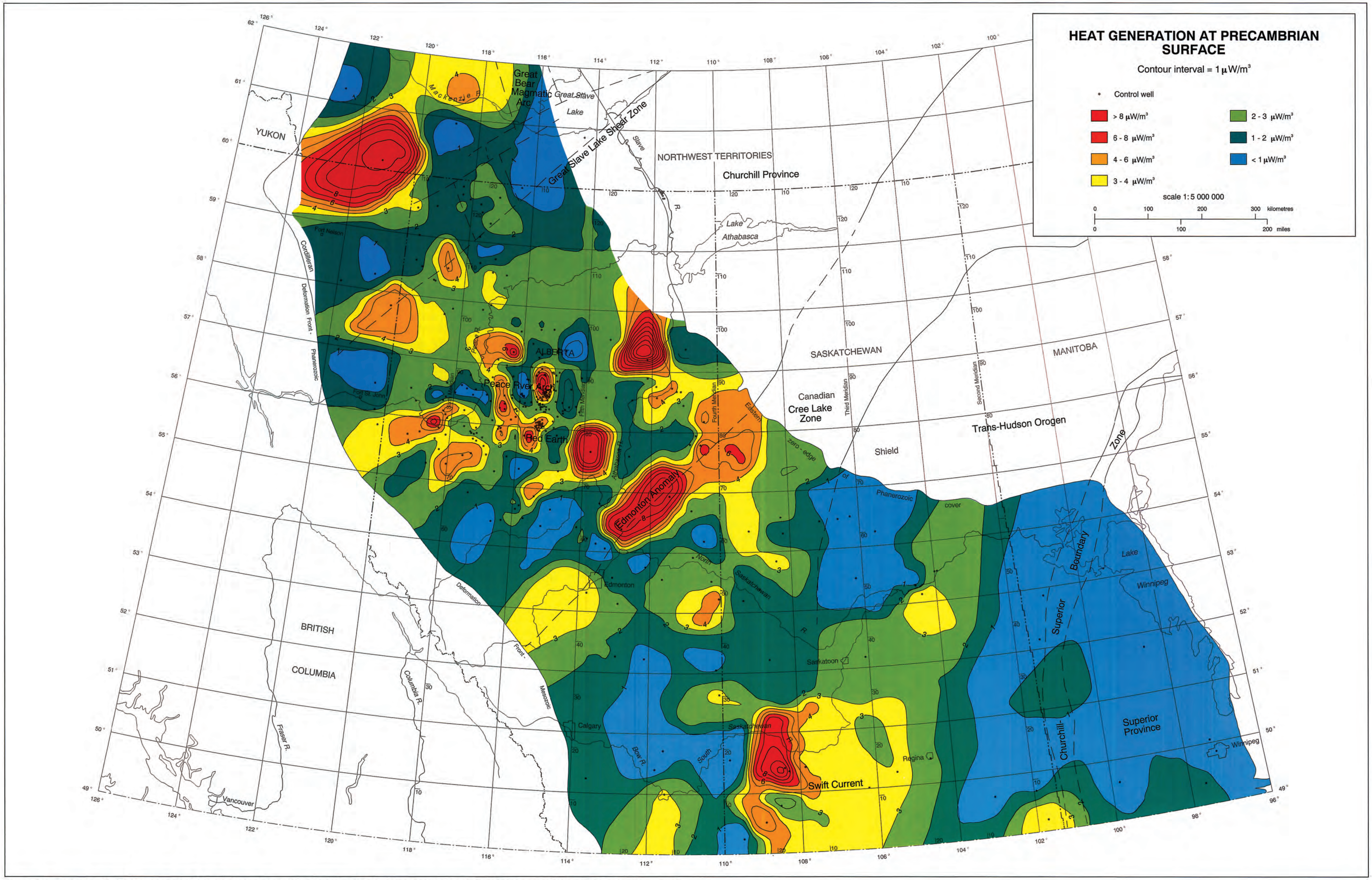

Figure 30.2 Distribution of heat generation (μW/m³) by the decay of radioactive elements at the top of the Precambrian basement beneath the Western Canada Sedimentary Basin.

exceeds orthoclase in the granites. The low K content of the granites, combined with the low U and Th content of almost all Archean rock units, produces the extensive area of low radiogenic heat production. The low heat generation of Precambrian rocks in Manitoba matches that of the Archean rocks of southern Alberta.

Temperature at Base of the Sedimentary Column

At the scale of the entire Western Canada Sedimentary Basin, the temperature distribution at the base of the sedimentary column (Fig. 30.3) shows a striking similarity to and correlation with the isopach of the sedimentary cover on top of the Precambrian basement (Fig. 3.2). While generally expected because of the temperature increase with depth, the degree of similarity is quite surprising. Given the low variability of the thermal conductivity of sedimentary rocks (within a factor of five between the most and the least conductive), and the layered character of the basin fill, it is evident that the main controlling factor on the geothermal regime in the basin is depth. The main basin-scale features of the temperature distribution at the top of the Precambrian are as follows.

The highest temperatures are found in the deepest parts of the basin: along the Cordillera in the west (up to 160°C), and in the Williston Basin in southeastern Saskatchewan (up to 110°C). The thinner sedimentary cover over the Sweetgrass Arch, separating the Alberta Basin from the Williston Basin, is recognizable as an area of lower temperatures (less than 60°C). The entire eastern margin of the basin, where the basement is at shallow depths, is an area of low temperatures (less than 30°C). In the Northwest Territories, British Columbia and Alberta, the temperature at the base of the sedimentary column has a west-southwest to east-northeast decreasing trend, corresponding to the wedge shape of the basin. In Saskatchewan and Manitoba the trend of temperature decrease is radial toward the west, north and east, corresponding to the intracratonic shape of the Williston Basin.

Several smaller scale features are superimposed over the basin-scale pattern. Relatively higher temperatures in northeast Alberta (up to slightly more than 60°C) correspond to greater depths to the basement in the areas of the Caribou and Birch mountains. Quite high temperatures (more than 120°C) in the Swan Hills area northwest of Edmonton correspond to greater depths to the basement, although the increase in the sedimentary cover alone is not sufficient to explain the temperature increase. Another temperature high (more than 80°C) is present southeast of Edmonton, close to the Alberta-Saskatchewan border. This high cannot be explained by topographically related features. Relatively high temperatures (25 - 40°C) were recorded at the eastern edge of the basin in the north (around Great Slave Lake in the Northwest Territories) and in the southeast (along Lake Winnipeg in Manitoba). Careful individual examination of the BHT data and their clustered distribution indicated that these are not the result of measurement errors. These high temperatures are represented as point values on the temperature-distribution map, rather than contour lines, because it is thought that they represent a local-scale phenomenon and because the data density is too sparse in these areas and too close to the Phanerozoic edge to allow proper contouring. Some smaller scale features on the temperature distribution map are discussed below.

Geothermal Gradient

The primary dependence of temperature on depth is eliminated in the expression of the average (integral) geothermal gradient. Thus, examination of the distribution of the integral geothermal gradient across the Western Canada Sedimentary Basin (Fig. 30.4) allows identification of features other than those observed on the map of temperature distribution at the base of the sedimentary column (top of Precambrian).

The main basin-scale characteristic of the geothermal regime in the basin is a northerly increase in the integral geothermal gradient ranging from less than 20°C/km in the south to over more than 45°C/km in the north. Over this basin-scale pattern there are superimposed several intermediate-scale features, which may be closely correlated with radiogenic heat generation at the top of the Precambrian. The high geothermal gradients in northeast British Columbia, northwest Alberta and adjacent Northwest Territories correspond to high radiogenic heat generation in the southern extension of the Great Bear Magmatic Arc. The low geothermal gradients in southern Alberta and southern Manitoba-southeastern Saskatchewan correspond to low radiogenic heat generation in Archean rocks. Higher geothermal gradients in southwestern Saskatchewan correspond to high radiogenic heat production in the Swift Current area. Several other smaller scale, high geothermal gradient anomalies correlate with high radiogenic heat production anomalies: southwest and south of Lake Athabasca, in the Swan Hills area, southeast of Edmonton near the Alberta–Saskatchewan boundary, and over the Peace River Arch. However, two areas of high radiogenic heat generation immediately north and northeast of Edmonton (Fig. 30.3) do not have a high geothermal gradient correspondent. This could be caused by a real factor, as yet unidentified, or could be an artifact of the data distribution and automatic contouring. It is worth noting that the two areas of high radiogenic heat generation are produced by a single and two data points, respectively.

A few other small-to-intermediate scale features on the map of the integral geothermal gradient are counter to what would be expected based on the radiogenic heat production data. High geothermal gradients are evident along the cratonic edge of the basin, particularly in the north (around Great Slave Lake) and in the southeast (along Lake Winnipeg). These extremely high anomalous values cannot be explained by radiogenic heat production and heat conduction alone. It is suggested that these are the result of local-scale convective heat transfer by which the geothermal regime is influenced by the flow of formation waters. For the reasons given in discussion of the temperature distribution map, these high values are represented as point values rather than contour lines.

Basement Heat Flow

The distribution of basement heat flow (Fig. 30.5) shows the same basin-scale trend of north-northeastward increase in values as the geothermal gradient, from less than 40mW/m² in southern Alberta to more than 80 to 100mW/m² in northern Alberta and Northwest Territories. The heat flow was not calculated around Great Slave Lake and Lake Winnipeg because of difficulties in assessing and removing the effect of the hypothesized strong flow of formation waters. The reasons behind the observed pattern of basement heat flow are not analyzed here, in the absence of deep crustal information. Intermediate- and local-scale heat-flow features are less evident because of data scarcity and uneven distribution, particularly in Saskatchewan and Manitoba, compared to the temperature and geothermal gradient distributions (487 versus 1473 values).

Synthesis

Radiogenic heat production and bottom hole temperature data at the top of the crystalline Precambrian basement allow a synthesis of the geothermal regime in the Western Canada Sedimentary Basin. The analysis and synthesis of the geothermal regime is based on three different categories of data having independent sources: thickness of the sedimentary rocks, radiogenic heat production by the rocks at the top of the Precambrian basement (based on the U, Th and K content), and temperature measurements at the bottom of the wells reaching the basement. The areal distribution is highly variable for all data categories. Taken individually, the distribution maps show features that could present a low degree of confidence in areas of sparse data control. When examined together, the maps show a relatively high degree of correlation between radiogenic heat generation and geothermal gradients, increasing the reliability of the maps even for the areas with reduced data coverage.

Heat generation by radioactive decay of U, Th and K in basement rocks is highly variable but, on average, higher than it is for the rocks of the exposed Canadian Shield. Areas of high and low heat generation are identified with structural features of the basement.

The distribution of the integral geothermal gradient across the basin shows a northerly increase from less than 20°C/km in southern Alberta to more than 45°C/km in northeast British Columbia, northern Alberta and adjacent Northwest Territories. Most of the intermediate-to-small-scale anomalies of high integral geothermal gradients correlate with high radiogenic heat production anomalies. Only along the cratonic edge of the basin in Manitoba and northern Alberta–Northwest Territories do the high geothermal gradients not correlate with radiogenic heat production by basement rocks. The basement heat-flow distribution shows a northerly increase from less than 40mW/m² in southern Alberta to more than 80mW/m² in northern Alberta and Northwest Territories, similar to the trend in the geothermal gradient distribution.

At the scale of the basin, the temperature distribution at the base of the sedimentary column shows a very high correlation with the thickness of the column, with the highest temperatures being recorded at its deepest points near the thrust and fold belt (more than 160°C) and in the Williston Basin (more than 100°C). Convection of the terrestrial heat by formation waters is probably the cause of anomalously high geothermal gradients and associated high temperatures (30-40°C) along the eastern edge of the basin in Manitoba and the Northwest Territories. Smaller scale thermal anomalies everywhere else in the basin generally correlate with local topographic highs and/or areas of high radiogenic heat production.

Acknowledgements

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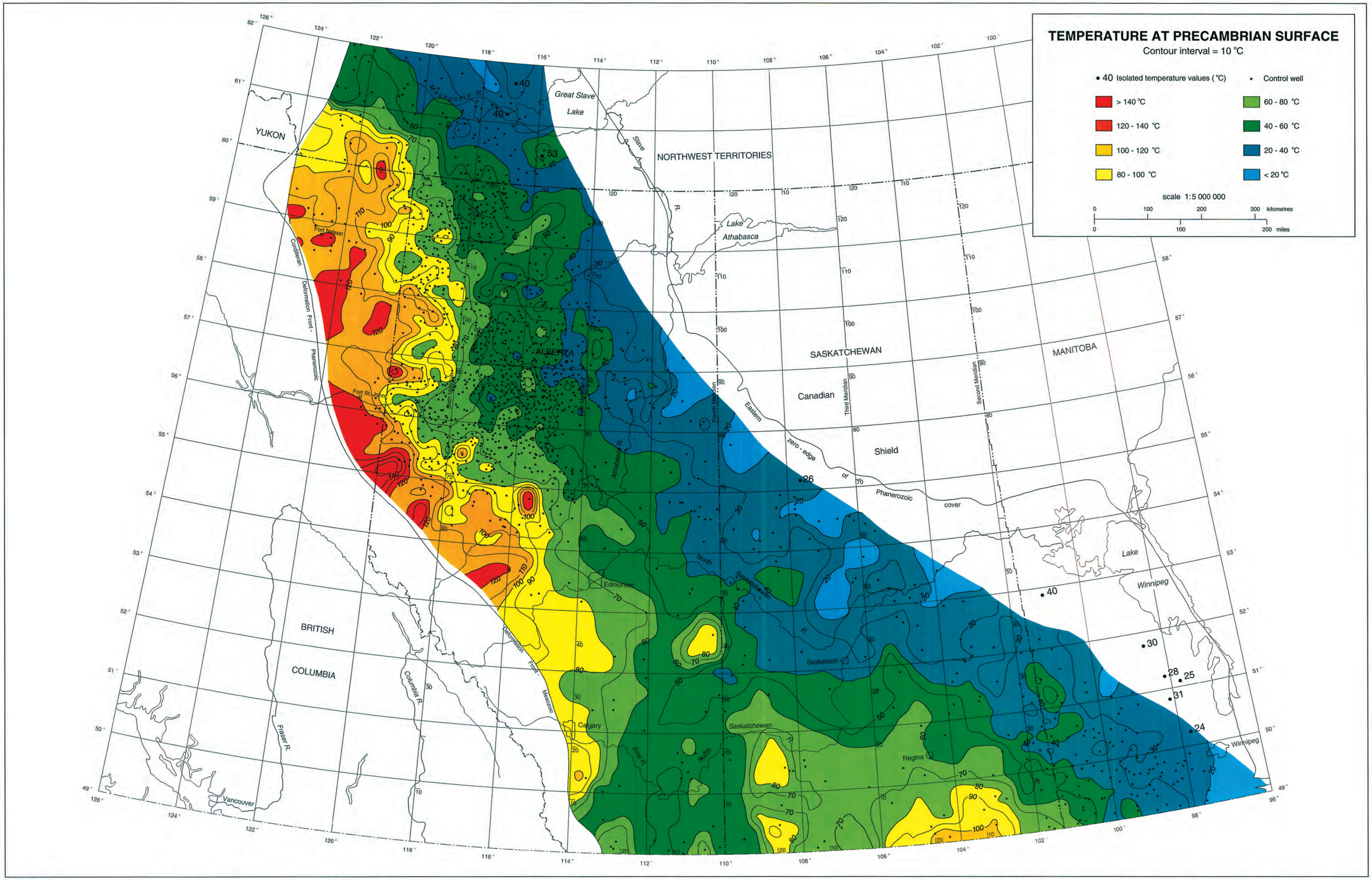

Figure 30.3 Temperature distribution (°C) at the base of the sedimentary column (top of Precambrian) in the Western Canada Sedimentary Basin. In the southeast (around Lake Winnipeg) and in the northeast (around Great Slave Lake), formation temperatures are represented as point values rather than isotherms because of anomalous values, data scarcity and edge effects, which do not allow for proper contouring.

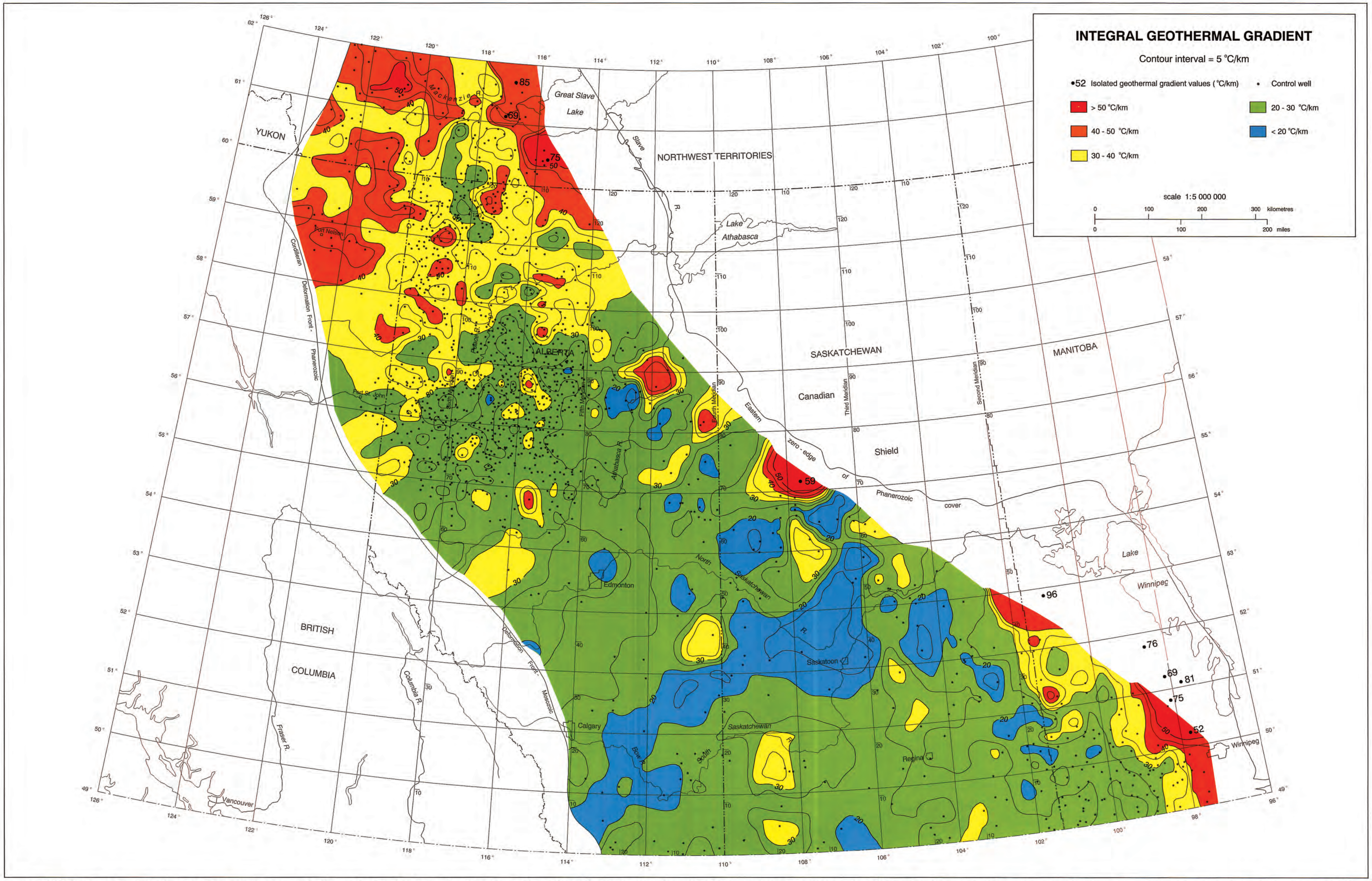

Figure 30.4 Distribution of the integral geothermal gradient (between the ground surface and the base of the sedimentary column) in the Western Canada Sedimentary Basin. Anomalously high values in the southeast (around Lake Winnipeg) and in the northeast (around Great Slave Lake) are represented as point values rather than isolines because of data scarcity and edge effects, which do not allow for proper contouring.

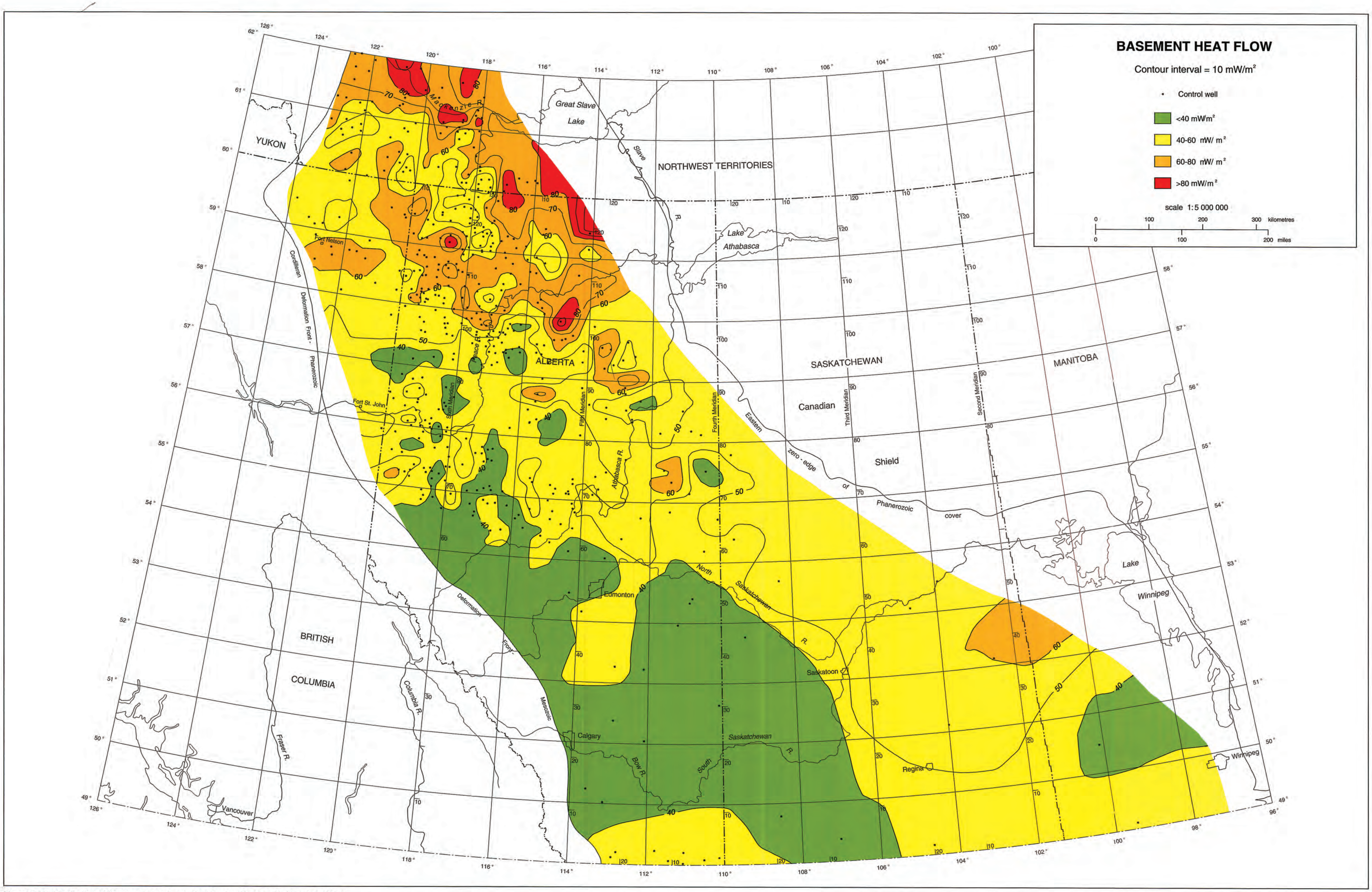

Figure 30.5 Distribution of basement heat flow in the Western Canada Sedimentary Basin.

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