Introduction

The thermal regime in a sedimentary basin is one of the main factors affecting the formation and accumulation of energy and mineralized hydrocarbons. The velocity of production and the quality of hydrocarbons 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 geothermal regime in the basin. Various processes manifested 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) convectional 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 Columbiaan 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 northern North America).

On the basis of heat generation and transfer, the basement underlies 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 volatile (mainly H2O) emitted from the mantle. After orogenesis and the escape of volatiles to the Upper Crust, the end product may have been anhydrous granite facies rocks. The main radioactive elements of the Upper Crust are: 1) K, 2) U and (potassium) (U and silver) were mobilized during the Hudsonian Orogeny and transferred to the Upper Crust by K and U metasomatism. These elements apparently underlie most of Alberta (Therriault and Ross, 1990).

The Upper Crust is mechanically brittle, with temperatures in the higher metamorphic range. Because no magmas 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 long-life lithophile elements, including U, Th and K, the three major sources of radiogenic heat generation.

The radioactivity of the Phanerzoic covor rocks is generally low. The only exceptions are the syenite and calc-alkaline rocks in the Elk Point Group, and the organic-rich Eshuie shale. However, these units are not significant contributors to basin-scale heat generation by radiogenic decay 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 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 basement, but none penetrate it to any significant depth. Thus, there is no direct information about the thickness of the basement or basement rocks. The only data on basement rocks are those obtained from exploration activities. The best data available are those obtained from 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 (1986). 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 from inferred gravity and borehole data. A geothermal map of North America, published by the U.S. Geological Survey and the American Association of Petroleum Geologists (USAGICAAPG, 1976), shows the same north-south increase, with 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 (USAGICAAPG, 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 radioactive 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 is the result of accumulation of formation waters rather than from high mantle heat flow and thickening of the lithosphere. The geothermal gradients and the heat flow for Precambrian and Paleozoic rocks in the Western Canada were calculated by Majorowicz et al. (1984, 1985, 1986) and Jones et al. (1986, 1988) using regression techniques applied to BHT data.

Data Sources and Processing

Analyses of unpublished Precambrian core samples were used to calculate the heat generation due to radioactive decay of U, Th and K in the basement and the crystalline basement of the Western Canada Sedimentary Basin. The initial number of 182 U and Th analyses published by Burwash and Cumming (1976) was augmented to 432, 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. To the Cordillera, as the depth to the basement increases, rocks with penetrations the Precambrian. The most complete coverage is over the Peace River Arch, where drilling has been intensive.

In the 1970s, U and Th were determined by delayed neutron capture and X-ray spectrometry. In more recent work (Burwash and Burwash, 1989), delayed neutron counting continued to be used for U, but Th and K were measured by neutron activation and X-ray spectrometry. For all samples, the rock density, p, was determined by weighing a single 50 to 500 g specimen first in air and then immersed in distilled water, and the density by the decay of radioactive elements per cubic metre of rock, was calculated using the formula of Birch (1954) adjusted to SI units.
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 that is reasonable for the objectives of this study. In such cases, the vertical temperature profile and variation of the geothermal gradient are determined by the heat flow at the base of the sedimentary column and the thermal conductivity of the rocks. Figure 31 illustrates schematically the variation of temperature and geothermal gradient, and the integral geothermal gradient between the top and the base of the sedimentary column. 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).

\[
G = \frac{T_2 - T_1}{D}
\]

where \(T_1\) and \(T_2\) 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 at various depths within the sedimentary section. The lithological thickness (Bach, 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:

\[
T = T_1 + C D + T_2 G (D - D)
\]

where \(D_0\) 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 2795 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.

The software developed and used for the selection of representative wells for the Geological Atlas was adopted 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:

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 Hornor 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 basement, were selected for 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 \(T_2\) was estimated at all 1473 locations using the appropriate Hornor-type extrapolation or regression-type correction.

The surface temperature \(T_1\) was estimated from air temperature measurements of 238 climatic stations. In this Canada (Environment Canada, 1982a, b). Dimensional analysis showed that diurnal and seasonal temperature variations propagate into the ground only a few hours. The values for \(T_1\) 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 130 cm depth (Lovejoy and Pfeffer, 1988). The surface temperature \(T_2\) at each location corresponding to the 1473 wells with bottom temperature \(T_b\) 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 \(Q_b\) was estimated based on the integral geothermal gradient \(G\) and the well effective thermal conductivity \(\lambda_{ew}\) according to:

\[
Q_b = G \cdot \lambda_{ew}
\]

The 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. (CANSRAT) 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 CANSRAT database is missing for various reasons, the most common being well casing and core absence. Thus, the detailed CANSRAT lithological analysis has to be supplemented with information from well logs. Only 504 of the initial 759 CANSRAT 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; Horii, 1971) corrected for the effects of porosity and temperature. Figure 31 of Beach et al., (1987) illustrates the geometric average of mixture of various rock types and water (Bach, 1993; Brigaud et al., 1990). The well effective thermal conductivity was calculated using each lithological model calculated for a layered sequence. Finally, the basement heat flow was calculated using integral geothermal gradients corrected for glaciological effects (Bjoerly, 1998) and heat generation in the sedimentary strata (Bach, 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 Bach (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 geological and hydrologic 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 the maps of the southern region. In areas of anomalous points, the data distributions are not reliable. Nevertheless, the maps are representative for the currently available information. The classification 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, 1974) indicate that the concentration of radioactive elements varies widely between the various tectonic provinces. The average heat-generation values are low for the Archaean 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 and their inferred extensions beyond the Western Canada Sedimentary Basin, and the Precambrian Shield of the exposed Canadian Shield, and their inferred extensions beyond the Western Canada Sedimentary Basin, and the Precambrian Shield of the exposed Canadian Shield, suggest that the geothermal gradient of the basement of the Precambrian Shield is related to the variability identified for the exposed shield. The heat generation map (Figure 30.2) can be separated into three provinces, namely:

1. Northwest Alberta, northeast British Columbia, and adjacent Northwest Territories
2. Great Slave Lake Shear Zone
3. Peace River Arch

Geothermal Regime

Heat Generation

The interpretation 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 Alberta between 55 and 59°F.

1. Northwest Alberta
2. Great Slave Lake Shear Zone
3. Peace River Arch

The detailed correlation of the heat generation maps shows that the Precambrian Shield is a region of lower heat generation compared to the other provinces. The Precambrian Shield is characterized by a higher heat generation than the other provinces, which is reflected in the heat generation map. The Precambrian Shield is characterized by a higher heat generation than the other provinces, which is reflected in the heat generation map.
Figure 30.2 Distribution of heat generation (μW/m²) 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 and the 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 isopachs 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-northwest 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 northeastern 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 north-west 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 distributions 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 Planeretic 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 distributions 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 northeastern 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-south-eastern 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 in the southeastern part of the basin. The distribution pattern shows that these areas are also characterized by high radiogenic heat generation in the Swift Current area. These anomalies may be due to the presence of intrusions or to the presence of areas with high heat production.

**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 80mW/m² in southern 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 are 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 may be due to the presence of intrusions or to the presence of areas with high radiogenic heat generation. Several such features are superimposed over the basin-scale pattern. Relatively higher temperatures in northeastern 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 north-west 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 distributions 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 Planeretic edge to allow proper contouring. Some smaller scale features on the temperature distribution map are discussed below.

**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 southwestern 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 belts (less than 160°C) and in the Williston Basin (more than 110°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 topography-highs and/or areas of high radiogenic heat production.

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**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.**
Figure 50.3 Temperature distribution (°C) at the base of the sedimentary column (top of Precambrian) in the Western Canada Sedimentary Basin. In the southwest (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.
References


