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# CONVECTIVE VERSUS CONDUCTIVE HEAT FLOW IN THE CENTRAL ALBERTA PART OF THE WESTERN CANADA SEDIMENTARY BASIN

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A detailed study of the hydrogeological and geothermal regimes in the Phanerozoic sequence of the Western Canada Sedimentary Basin was carried out for the Swan Hills and Cold Lake areas in central Alberta. The study was based on the examination, processing and interpretation of information from 6276 wells distributed over a total area of 39,500 km². The information processed refers to stratigraphic picks, chemistry of formation waters, drillstem tests and bottom hole temperatures. As a result, every stratigraphic unit is defined in terms of geometry and lithology, and characterized by appropriate hydraulic and thermal parameters. A sequence of eight major aquifer groups separated by eight aquitards and two aquicludes was indentified. The fluid flow in the Paleozoic aquifers in mainly horizontal and regional in nature, being driven by the difference in hydraulic potential between the high areas in the foothills and the lowland areas in the prairies. The fluid flow in the Cretaceous aquifers is of regional to intermediate type, with a significant downward component. The fluid flow in the aquitards is vertical. The very low permeability of the strata is reflected in flow velocities on the order of magnitude of 1 cm/a and less. Dimensional analysis of heat transport processes in each hydrostratigraphic unit shows that convective heat transfer is negligible with respect to conductive heat transfer. The respective values of Peclet number for heat flow in porous media area are less than $10^{-2}$. In the Swan Hills and Cold Lakes areas the flow of the terrestrial heat flux from the crystalline Precambrian basement of the sedimentary basin to the atmosphere is controlled by the geometry and the changes in the thermal properties of the formations in the basin. The geothermal gradients for individual layers vary from 17 mK/m for sandstone units to 42 mK/m for shales. The integral geothermal gradient of the entire sedimentary column varies between 22 mK/m and 36 mK/m. The areal distribution of the integral geothermal gradient shows a strong correlation with stratigraphy and lithology.

Um estudo detalhado dos regimes hidrogeológico e geotérmico na seqüência fanerozóica da bacia sedimentar do oeste do Canadá foi feito para as áreas de Swan Hills e Cold Lake na região central de Alberta. O estudo foi baseado no exame, processamento e interpretação da informação proveniente de 6276 poços distribuídos em uma área total de 39.500 km². A informação processada refere-se a dados estratigráficos, química das águas intersticiais, testes de formação e temperatura de fundo de poço. Como resultado, cada unidade estratigráfica é definida em termos geométricos e litológicos, e caracterizadas por parâmetros hidráulicos e térmicos apropriados. Uma seqüência de oito grupos de aquíferos separados por oito aquitardos e dois aqüidutos foram identificados. O fluxo de fluídos nos aqüíferos paleozóicos é principalmente de natureza regional e horizontal, sendo induzido por diferenças no nível peizométrico entre áreas de topografia elevada e áreas mais baixas das pradarias. O fluxo de fluídos nos aquíferos cretáceos é do tipo regional a intermediário, com uma componente descendente significativa. O fluxo de fluídos nos aquitardos é vertical. A permeabilidade muito baixa dos estratos é refletida nas velocidades de fluxo com ordem de magnitude de 1 (um) centímetro por ano e inferiores. A análise dimensional dos processos de transporte de calor em cada unidade hidroestratigráfica mostra que a transferência de calor por convecção é desprezível em relação à transferência de calor por condução. Os valores respectivos do número de Peclet para o fluxo de calor em meios porosos são inferiores a $10^{-2}$. Nas áreas de Swan Hills e Cold Lake o fluxo de calor terrestre do embasamento cristalino pré-cambriano da bacia sedimentar para a atmosfera é controlada pela geometria e pelas variações nas propriedades térmicas dos diferentes sedimentos da bacia. Os gradientes geotérmicos das diferentes camadas variam entre 17 mK/m nas unidades compostas por arenitos a 42 mK/m nos folhelhos. O gradiente geotérmico integral para toda a coluna sedimentar varia entre 22 mK/m e 36 mK/m. A distribuição superficial do gradiente geotérmico integral mostra uma forte correlação com a estratigrafia e a litologia.

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## INTRODUCTION

Sedimentary basins are of special concern in terrestrial heat flow studies for many reasons, some of them related to energy resources. These basins could be rich in hydrocarbons, as is the case for the Western Canada Sedimentary Basin. Temperature conditions are crucial in hydrocarbon maturation, which controls oil and gas formation and destruction processes, and the grade of coal deposits. Furthermore, geological observations in many areas indicate that hydrocarbon occurrences are associated with temperature anomalies. On the other hand, paleo- and actual fluid flow conditions play a role in the migration of the hydrocarbons.

Due to the existence of water in all sedimentary strata, low temperature geothermal energy can be exploited whenever the potential exists and the economic considerations justify it. When the hydrogeological conditions permit, the extraction of geothermal energy is obtained by pumping hot water from deep formations. In other cases, water has to be injected, heated during a given residence time in the aquifer and pumped back. In both instances, there is need to know the hydrogeological and geothermal regimes in the sedimentary sequence.

The temperature of deep strata is important for deep waste disposal. The water-rock interaction processes may be modified by the heat dissipated in the surrounding strata by nuclear wastes. In the case of fluid wastes, this problem is compounded by the changes in the transport processes of any dissolved substance in the injected fluid caused by temperature differences between the fluid and the surroundings.

In all these cases, there is need to know the main mechanisms of heat transfer, and to assess their importance. In the Alberta part of the Western Canada Sedimentary Basin, huge deposits of hydrocarbons (gas, conventional oil, heavy oil and oil sands) are exploited currently throught the province. One of the oil sands deposits is located near Cold Lake, on the border between Alberta and Saskatchewan. Two major oil fields, the Mitsue and Swan Hills, are located in central Alberta, near a deep waste disposal site currently under construction. For both areas, shown in Fig. 1, the Basin Analysis Group of the Alberta Geological Survey, Alberta Research Council, carried out a detailed hydrogeological evaluation of the Phanerozoic sequence in order to assess the impact of oil sands in-situ recovery processes and of deep waste disposal. In addition to the fluid flow regime, the geothermal regime was also studied, and the strength of convective versus conductive heat flow was assessed. This paper presents the results of this assessment, together with the distribution of temperatures and geothermal gradients in the two areas.

## DATA COLLECTION AND PROCESSING

The Swan Hills study area, covering 15,760 km², is bordered in the northwest by the Lesser Slave Lake, and in the east by the northward-flowing Athabasca River (Fig. 2a). The ground elevation, with an average of 790 m, varies between 530 m in the northeast on the Athbasca River and 1340 m in the hills of the west-central part. The Cold Lake study area (Fig. 2b) extends west of Cold Lake and north of the NorthSaskatchewan River, representing an area of 23,700 km² with an average ground elevation of about 620 m. Due to the general southwestward dipping of the Precambrian platform, the thickness of the sedimentary column increases from northeast of southwest, from about 1 km to 2 km in the Cold Lake area, and from about 2 km to 3.4 km in the Swan Hills area.

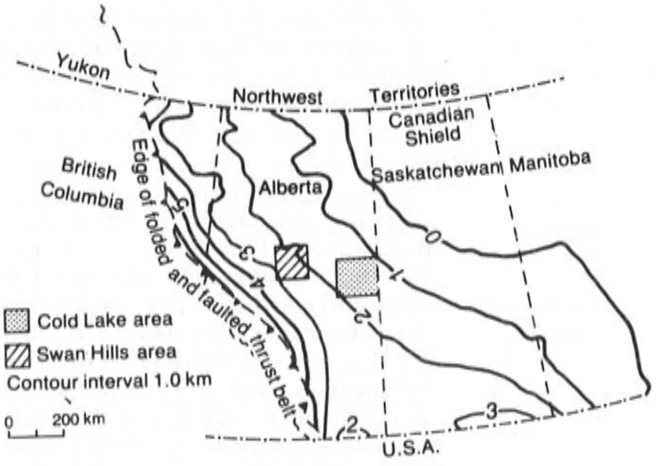

**Figure 1** — Location of the Swan Hills and Cold Lake areas.

Given the existence of hydrocarbons, there is a lot of drilling activity in both areas. The Energy Resources Conservations Board (ERCB) well data base provided information updated to 1983 about well longs, core and drillstem tests at about 3100 wells drilled in the Cold Lake area and 3276 wells drilled in the Swan Hills area. This information was transferred into a custom-designed data base at the Alberta Research Council, and additional data about drillstem tests (DST), chemistry of formation waters and bottom hole temperatures (BHT) were added manually. Given the amount and the distribution of the data available, all processing was done automatically using specially designed software. Human intervention was needed only to check and correct some data and interpret the results. A detailed description of the techniques used to process all this information is given in Bachu et al. (1986); only the main concepts of data processing are presented subsequently.

The stratigraphic picks at the wells in the area were sorted by formations and transformed into top surfaces defined by values at nodes in regular grids, based on the principles defined by Jones & Johnson (1983).

Special software was used to cull, manipulate and statiscallly analyse the chemistry data, based on the criteria and methods presented by Hitchon (1985).

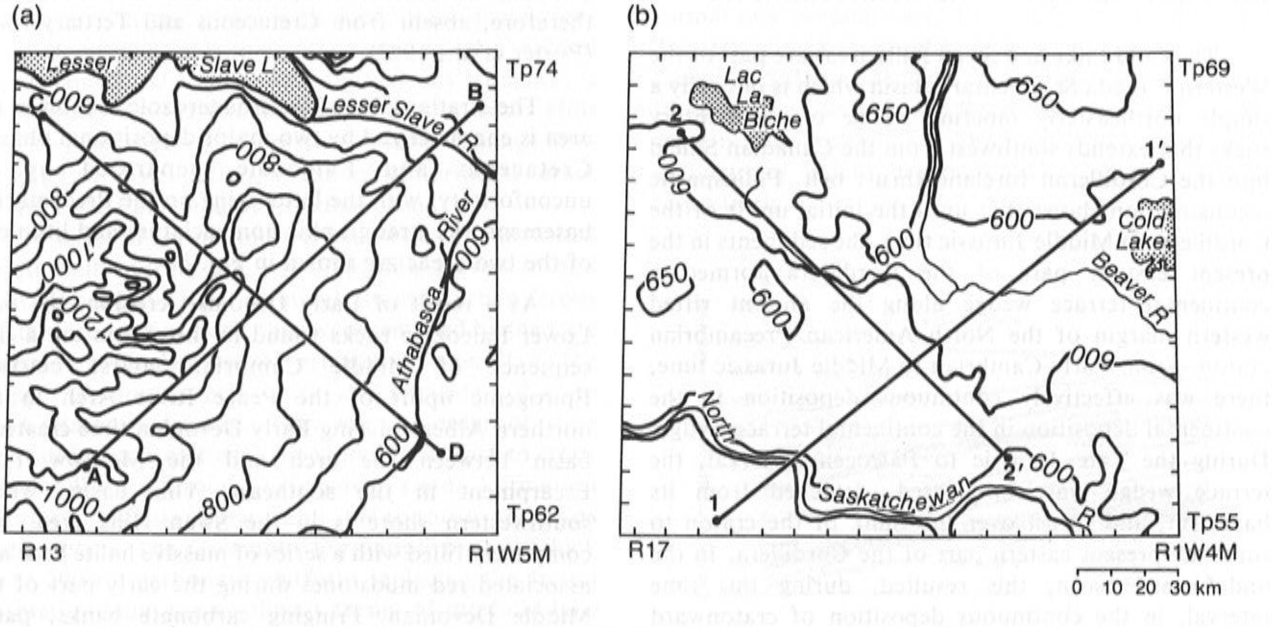

Figure 2 — Topography and hydrostatigraphy of (a) the Swan Hills area; and (b) the Cold Lake area.

Incomplete and obviously erroneous analyses were removed. Questionable quality samples coming from holding tanks or produced by bailing were rejected Samples contaminated with drilling fluid or mud filtrate water, or by the use of KCl muds, acid washed, or washes from cement jobs, were also eliminated. The flowing components were reported for the retained formation water analyses: total dissolved solids, Cl, Ca, Mg, Br, I, $HCO_3$, $CO_3$, $SO_4$, density and resistivity.

The drillstem tests were interpreted using a semilog technique for shut-in analysis, or a type-curve matching technique for flow period analysis (Bachu & Sauveplane, 1984). This provided information about the formation pressure at the recorder depth and about permeability. Core analyses were used to provide additional information about permeabity and porosity. The hydraulic heads and the hydraulic conductivities were derived from pressures and permeabilities, respectively, by taking into account the appropriate water density as resulting from the chemistry of formations waters. The water density reported in chemical analyses for laboratory conditions was adjusted for variations due to temperature increase with depth.

The temperature data were obtained from ERCB data files, as well as from DST reports. Most of the data were collected by producing companies under unknown and uncontrolled conditions. The data were gathered by a number of different individuals, using a variety of tools and techniques. The raw BHT data have a systematic error that may be depth dependent (Chapman et al., 1984), and questions concerning the accuracy of the data must arise. However, no realistic attempt at error analysis could be made in the absence of information on temperature recovery with time after cessation of circulation. Therefore, it is assumed that the data are representing the real temperature. Whenever there were values measured at different times since circulation ceased, the last value was retained. Furthermore, when at the same location temperatures were measured at successive depths, they were checked in terms of consistency, i.e. inversions of temperature and abrupt changes in the local thermal gradient were singled out and checked. Thermal properties of the rocks and the fluids are not commonly measured, and literature values were used in the study (Majorowicz & Jessop, 1981).

At the end of the screening and checking process about 2030 formations water analyses, 4300 temperature data, 2100 drillstem tests and 5000 core analyses were retained, which represent approximately 40 percent of the initial data base for both areas. All the point data, represented by a value (e.g. temperature, permeability) associated with a particular location, were sorted by formation using an automatic procedure for interpolation through the three-dimensional stratigraphic structure defined by the grids of top surfaces. The data distributions for flow variables with continuous variation, such as temperature and hydraulic heads, were converted into regular grid distributions using the kriging method (Yeh et al., 1983) and analysed for trends. The data distributions for parameters which depend on the solid matrix, such as permeability and porosity, were analysed statistically. Literature values were used for the parametes of formations where no data were available. In the end, every stratigraphic unit in the sedimentary sequence was characterized by appropriate hydraulic and thermal parameters. The potentiometric and temperature fields were also defined, allowing for the corresponding analysis of flow processes.

## GENERAL GEOLOGY AND STRATIGRAPHY

The Cold Lake and Swan Hills areas are part of the Western Canada Sedimentary Basin which is basically a simple northeasterly tapering wedge of sedimentary rocks that extends southwest from the Canadian Shield into the Cordilleran foreland thrust belt. Palinspastic reconstruction shows that until the initial uplift of the Cordillera, in Middle Jurassic time, the sediments in the present eastern part of the Cordillera formed a continental terrace wedge along the ancient rifted western margin of the North American Precambrian craton. From Early Cambrian to Middle Jurassic time, there was effectively continuous deposition in the continental deposition in the continental terrace wedge. During the Late Jurassic to Paleocene interval, the terrace wedge was compressed, detached from its basement, and thrust over the flank of the craton to form the present eastern part of the Cordillera. In the undeformed basin, this resulted, during this time interval, in the continuous deposition of cratonward (eastward) prograding clastic detritus shed by the evolving Cordillera. Evaporites and carbonates are, therefore, absent from Cretaceous and Tertiary rocks (Porter et al., 1982).

The stratigraphy of the Phanerozoic section in the area is characterized by two major depositional phases, Cretaceous and Paleozoic, separated by an unconformity, with the latter lying on the Precambrian basement. the stratigraphic nomenclature and lithology of the two areas are shown in Fig. 3.

As a result of Early Devonian erosion, the only Lower Paleozoic rocks found in the region are a thin sequence of Middle Cambrian coarse clastics. Epirogenic uplift of the Peace River Arch in the northern Alberta during Early Devonian time created a basin between the arch and the Meadow Lake Escarpment in the southeast. This basin, whose southwestern shore is in the Swan Hills area, was completely filled with a series of massive halite beds and associated red mudstones during the early part of the Middle Devonian. Fringing carbonate banks, patch reefs and thin carbonate beds, laid down under open

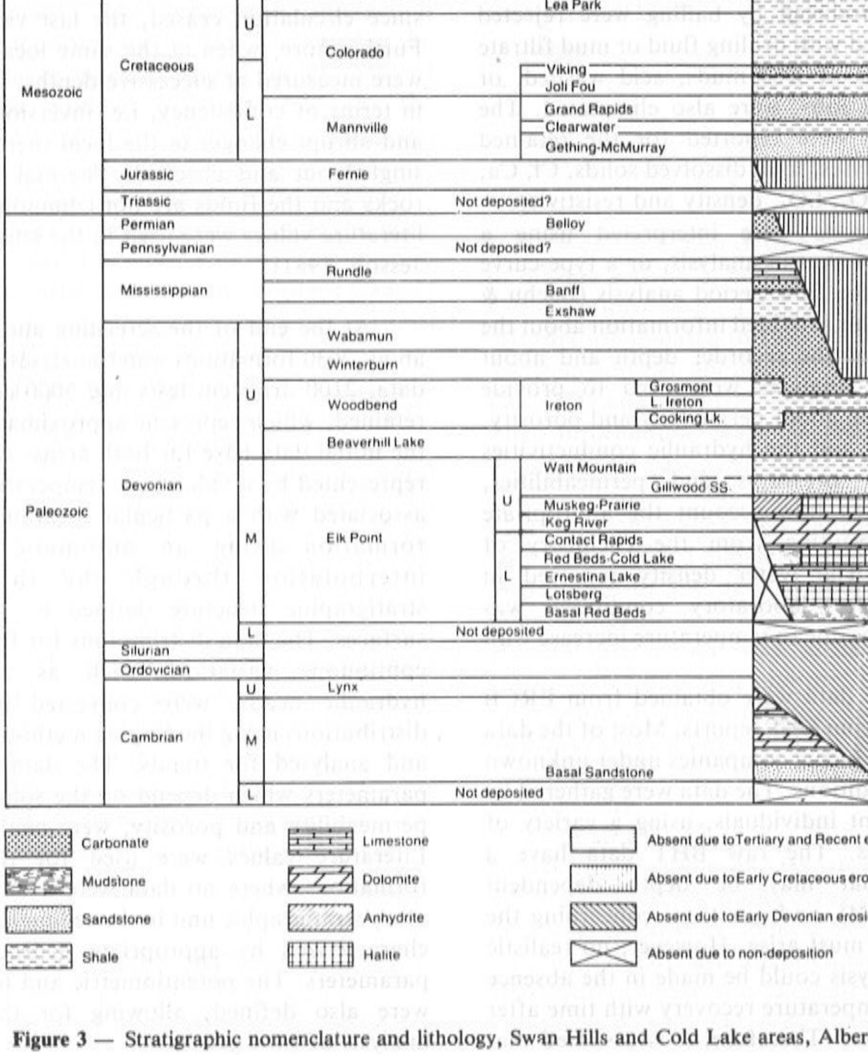

**Figure 3 — Stratigraphic nomenclature and lithology, Swan Hills and Cold Lake areas, Alberta.**

marine conditions, overlay the halite beds and red mudstones. In the Swan HIlls area, these formations were deposited onlapping the top of the eroded Cambrian. Overlying conformably all this sequence, is the Muskeg Formation (anhydrite) in the Swan Hills area, which exhibits an eastward facies change into Prairie Evaporite (halite), absent in the northeast corner of the Cold Lake area due to dissolution.

A series of formations were subsequently deposited conformally during the rest of Middle Devonian and early Upper Devonian. Although Lower Carboniferous strata were once present, they were removed by the Late Paleozoic to Early Mesozoic erosion. As a result, all the Upper Devonian rock units are truncated due to pre-Cretaceous erosion. They are, in order of their deposition, and of their truncation from east to west: Beaverhill Lake Group (carbonates), Ireton Formation (shales), Winterburn and Wabamun Groups (carbonates). The Grosmont Formation forms a thick (over 200 m) carbonate platform replacing the Ireton Formation from the northwest corner of the Cold lake area to the northeast corner of the Swan Hills area, and extending far north.

The Mississippian part of the sequence occurs as deeply bevelled series of west-dipping subscrops. The basal Exshaw Formation is a thin upward-coarsening bituminous shale. The overlying Banff Formation is an interbedded shale-to-carbonate sequence which indicates continued transgression and greater shelf circulation. This trend was maintained, as shown by the largely limestone succession of the overlying Rundle Group. Regression of Mississippian seas back to the narrowing Cordilleran basin was accompanied by a wesward tilt of the craton margin (Porter et al., 1982). This emergence and mild relief triggered extensive erosion which stripped back the Mississippian strata to their present subcrop pattern.

In the study area, the Pennsylvanian was a period of subaerial erosion, the original Permian cover (Belloy Formation) being almost completely removed by further erosion in the early Triassic Period; Upper Triassic beds were probably not deposited, and the original Lower Jurassic cover (Fernie Group) was almost completely removed by pre-Cretaceous erosion. Northeast of the up-dip erosional edges of Triassic and Lower Jurassic strata, Lower Cretaceous units rest on southwest dipping Mississippian carbonates, and on the Wabamun, Winterburn, Woodbend and Beaverhill Lake Groups, thus creating approximately a 200 Ma gap in the local stratigraphic record.

Throughout the Cretaceous there was continuous, conformable deposition of eastward-thinning clastic wedges that interfinger with westward-thinning marine shaley intervals associated with the fluctuating Western Interior Seaway. Cretaceous strata in the Alberta plains are devided, in upward order, into the Mannville, Colorado and Post-Colorado Groups.

Because of the mild regional dip (5 to 10 m/Km) and low relative relief, the modern erosion level truncates the sedimentary fill of the basin over a relatively narrow stratigraphic range. Upper Cretaceous formations predominate, the exception being Lower Tertiary strata over the highest plains and outer foothills. Surficial deposits of glacial origin overlie the Phanerozoic sequence. Regional dip and strike crosssection through the Swan Hills and Cold Lake sedimentary blocks are presented in Figs. 4 and 5, respectively.

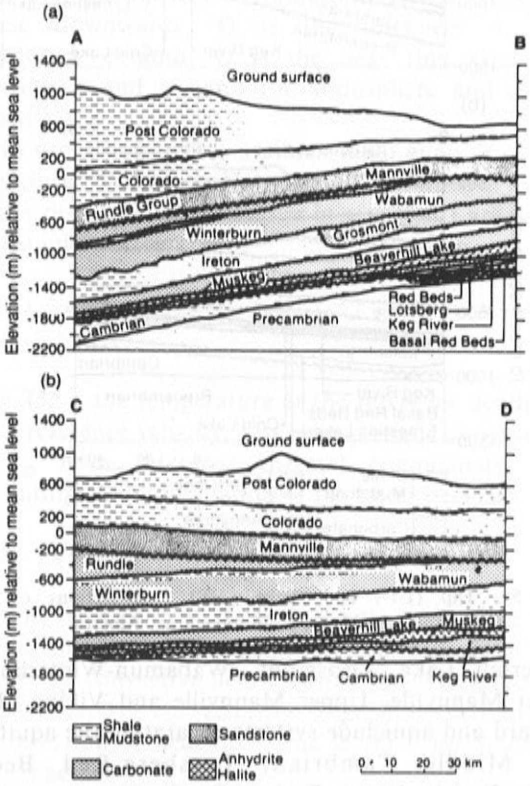

**Figure 4** — Dip (A-B) and strike (C-D) cross-sections of the sedimentary block, Swan Hills area, Alberta

## ANALYSIS OF FLUID FLOW

In sedimentary basins there is a fluid continuum throughout their entire thickness, with the possible exception of evaporite beds which may act as aquicludes. The movement of fluids in the subsurface environment is three-dimensional in nature, and usually very complex. The flow in aquifers is mainly horizontal, driven generally by gravity forces, while the flow in aquitards is vertical (Bear, 1972). Moreover, the fluid flow in aquifers may be part of a local, intermediate, or regional system (Toth, 1980), with implications on all transport phenomena related to convection, including heat transfer. By analysing the geometry, lithology and hydraulic properties of the stratigraphic units in the Cold Lake and Swan Hills areas, eight aquifer systems separated by eight aquitards and/or aquicludes were differentiated above the Precambrian basement. A hydrostratigraphic unit is defined as one or more rocks units in contact, which have similar characteristics with respect to fluid flow.

The aquifer systems, in ascending order from the Precambrian basement are: Basal Cambrian, Keg River,

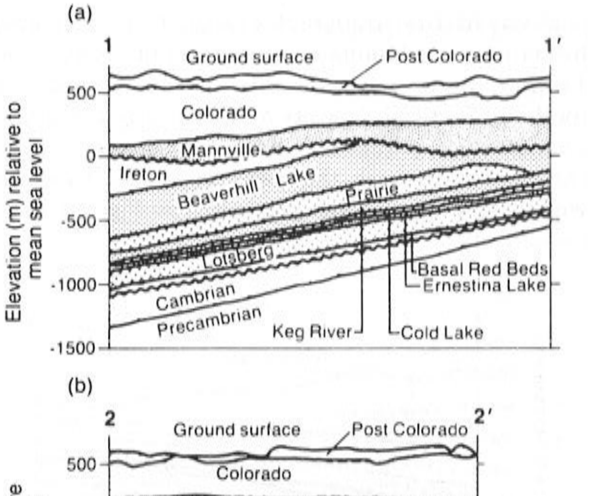

**Figure 5** — Dip (1-1') and strike (2-2') cross-sections of the sedimentary block, Cold Lake area, Alberta.

Beaverhill Lake, Grosmont, Wabamun-Winterburn, Lower Mannville, Upper Mannville and Viking. The aquitard and aquiclude systems separating the aquifers are: Middle Cambrian, Lotsberg-Red Beds, MuskegPrairie, Ireton, Exshaw-Banff, Clearwater, Joli Fou and Post-Viking. The fluid flow in the regional aquifer systems is mainly horizontal, being gravity driven by the potential difference between the highs in the Foothills Belt in southwestern Alberta, and the lows at the Precambrian Shield in northeast Alberta. The fluid flow in the Cambrian and Paleozoic aquifers is of basin-wide regional type, while the flow in the Cretaceous aquifers is of intermediate type with a strong downward component. Local fluid flow is present only in the shallow Tertiary and Quaternary aquifers. The hydraulic head in the aquifers varies generally between 300 and 600 mm. The horizontal hydraulic gradients of the flow in aquifers are of the order of magnitude $10^{-4}$. with local values up to $10^{-3}$, while the hydraulic gradients of the vertical flow in aquitards is of the order of magnitude $10^{-1}$—$10^{0}$.

In order to complete the quantitative flow picture, it is necessary to know the values and distribution of two hydraulic characteristics of the porous media: the porosity n and the hydraulic conductivity K. In Table 1 are shown average values of these parameters by hydrostratigraphic units. It should be added that the variation of hydraulic conductivity values is generally one order magnitude on each side of the average. Based on the potentiometric surfaces and distributions of hydraulic parameters, it is possible to compute the Darcy velocity of the fluid flow in each aquiffer by taking the product between the hydraulic gradient and hydraulic conductivity. Local velocities in aquifers vary in the range $10^{-2}$. to $10^{2}$ cm/a, with a characteristic order of magnitude of 1 cm/a.

The characterization of the aquitards is more difficult, due to lack of data. The permeability is usually so low that it is not possible to perform any drillstem tests. However, some estimations can be made by taking an integral approach. The density of formation waters can be taken as the average of the characteristic densities in the aquifers above and below each aquitard. The fluid flow in aquitards is vertical, being driven by the difference between the potentiometric surfaces of the adjacent aquifers. For a given area, the total discharge through an aquitard can be computed by applying an integral mass procedure. In this case, the

**Table 1** – Representative values of the parameters characterizing the flow of formation waters in the Swan Hills and Cold Lake areas, Alberta

| Hydrostratigraphic System | Average Thickness (m) | | Formation Water Density (kg/m$^3$) | | Porosity | | Hydraulic Conductivity (m/sec) | | Characteristic Velocity (m/sec) | |
|---|---|---|---|---|---|---|---|---|---|---|
| | a | b | a | b | a | b | a | b | a | b |
| Post-Viking | 794 | 314 | 1020 | 1025 | n.a. | 0.29 | n.a. | n.a. | $2.1x10^{-13}$ | $1.9x10^{-13}$ |
| Viking | 19 | 9 | 1020 | 1026 | 0.15 | 0.23 | $1.5x10^{-7}$ | $6.1x10^{-7}$ | $0.6x10^{-10}$ | $0.1x10^{-10}$ |
| Upper Mannville | 152 | 86 | 1020 | 1026 | 0.15 | 0.33 | $2.0x10^{-7}$ | $1.2x10^{-5}$ | $2.0x10^{-10}$ | $0.3x10^{-10}$ |
| Clearwater | 34 | 4 | 1030 | 1025 | n.a. | n.a. | n.a. | n.a. | $3.2x10^{-13}$ | $2.0x10^{-13}$ |
| Lower Mannville | 194 | 44 | 1035 | 1025 | 0.16 | 0.34 | $0.1x10^{-7}$ | $2.2x10^{-5}$ | $0.2x10^{-10}$ | $1.6x10^{-10}$ |
| Wabamun-Winterburn | 381 | 8 | 1070 | 1025 | 0.15 | 0.11 | $1.7x10^{-7}$ | $1.0x10^{-6}$ | $1.9x10^{-10}$ | $1.6x10^{-10}$ |
| Grosmont | 150 | 68 | n.a. | 1020 | 0.07 | 0.12 | $8.1x10^{-7}$ | $7.5x10^{-7}$ | $1.4x10^{-10}$ | $1.6x10^{-10}$ |
| Ireton | 298 | 113 | 1100 | 1040 | n.a. | n.a. | n.a. | n.a. | $1.6x10^{-14}$ | $0.6x10^{-14}$ |
| Beaverhill Lake | 191 | 240 | 1140 | 1050 | 0.07 | 0.13 | $1.1x10^{-7}$ | $1.5x10^{-7}$ | $1.1x10^{-10}$ | $0.9x10^{-10}$ |
| Muskeg-Prairie | 80 | 124 | 1170 | – | 0.06 | 0.0 | n.a. | – | $1.5x10^{-13}$ | – |
| Keg River | 48 | 36 | 1200 | 1180 | 0.10 | 0.02 | $1.4x10^{-7}$ | $1.6x10^{-7}$ | $1.3x10^{-10}$ | $0.2x10^{-10}$ |
| Middle Cambrian | 156 | n.a. | 1170 | 1180 | n.a. | n.a. | n.a. | n.a. | $0.7x10^{-14}$ | n.a. |
| Basal Cambrian | 24 | 64 | 1170 | 1180 | 0.10 | 0.18 | $3.0x10^{-7}$ | $8.1x10^{-7}$ | $3.6x10^{-10}$ | $4.8x10^{-10}$ |

a – Swan Hills area; b – Cold Lake area

Note: the fluid flow is mainly horizontal in aquifers and vertical in aquitards characteristic velocity is obtained by dividing the total discharge by the area. The characteristics of the fluid flow in aquifers and aquitards are presented in Table 1 for both study areas. As for the Lotsberg-Red Beds and Prairie aquicludes, there is no fluid flow through these thick halite beds.

As a general remark, the fluid flow in the Swan Hills and Cold Lake .areas of the Western Canada Sedimentary Basin is very complex in nature, due to the stratigraphic and lithologic complexity of the sediments, and is characterized by very low velocities of the order of 1 cm/a. There is no homogeneous unidirectional fluid flow through the entire column of the sedimentary sequence, but a complicated pattern of horizontal flow in aquifers and vertical flow in aquitards and some aquifers.

## ANALYSIS OF HEAT FLOW

The geothermal structure in a sedimentary basin is governed mainly by the transport to the surface of heat that flow upward from the subcontinental mantle and of heat that is generated internally by the decay of radioactive isotopes in the rocks. The main mechanisms of heat transfer are conduction and convection by a moving fluid.

On a geological time scale, the loss to the atmosphere of the Earth's internal heat is an unsteady process due to variations in the Earth's heat flux. On the human time scale, however, the Earth's heat flux may be considered constant. The only direct variation with time are introduced at the sedimentary basin by the diurnal and annual changes of temperature at the surface, changes which propagate in the system with an amplitude that decreases exponentially with depth. The characteristic depth of penetration for the daily temperature variations is of the order of centimetres, while for the annual temperature variations is of the order of metres (Bunterbarth, 1984). Taking into account that the depth of the sedimentary basin varies between 1 km in Cold Lake area and 3.4 km in the Swan Hills area, it follows that the temperature variations at the surface can be neglected, and the heat transfer processes can be considered steady.

The effect of radioactivity in the sediments on the heat transfer processes in the Western Canada Sedimentary Basin is negligible (Majorowicz et al., 1984). Assuming that the Fourier Law of heat conduction is valid, the partial differential equation for steady-state heat transfer in a porous medium without heat sources can be written as:

$$\nabla.\lambda_m \nabla T - n \varrho_f c_f v . \nabla T = 0 \tag{1}$$

where T is temperature, v is the fluid velocity, n is the porosity of the medium, $\varrho$ is density, and c is the specific heat. The thermal conductivity of the saturated porous medium, $\lambda_m$, is defined by (Cheng, 1978):

$$\lambda_m = n\lambda_f + (1-m)\lambda_s \tag{2}$$

In the above equations, the subscripts f and s refer to the fluid and solid phases, respectively.

The boundary conditions that define the heat flow together with equation 1 are:

at surface: $T = T_a$ at $z = 0$ (3)
at the base of the basin: $Q = Q_c$ at $z = D$ (4)

where z is the vertical coordinate measured from the surface downwards, D is the thickness of the sedimentary column, Q is the heat flux, and the subscripts a and c stand for atmosphere and crust, respectively.

In order to perform a dimensional analysis of the importance of convective versus conductive heat transfer processes, the variables in equation 1 are made dimensionless as follows:

$$(X,Y,Z,) = (x,y,z)/L; \quad \theta = (T - T_a)/\Delta T, \Delta T = T_D - a; \quad V = v/v_o; \quad \Lambda = \lambda/\lambda_o \tag{5}$$

where TD is the temperature at the reference depth D, $v_o$ is a reference velocity, L is characteristic dimension, and $\lambda_o$ is a reference thermal conductivity. By substituting (5) into equation 1, the latter becomes:

$$\nabla.\Lambda\nabla\theta = \mathrm{Pe} V.\nabla\theta \tag{6}$$

where $\mathrm{Pe} = n\,\varrho_f\,c_f\,v_o\,L/\lambda_o$ is the Peclet number for heat transfer in porous media, and is a measure of the intensity of convective heat transfer versus conductive heat transfer. The characteristic length L is taken in the main direction of heat flow, and in this case becomes the thickness d.

Given the variability of the sediments in terms of stratigraphy, lithology and hydraulic and thermal properties, and especially due to the complexity of the fluid flow pattern, the analysis of convective versus conductive heat flow has to be performed by hydrostratigraphic units, and not for the entire sedimentary column taken as a single layer with averaged properties. The order of magnitude of the Peclet number is presented in Table 2 for the aquifer and aquitard systems identified in the Swan Hills and Cold Lakes areas of central Alberta. The average thermal conductivity of the sediments in Alberta is $\lambda_o$ = 2.5 W/mK (Majorowicz & Jessop, 1981). As can be seen in Table 2, the strength of convective heat transfer in the Swan Hills and Cold Lake areas of the western Canada sedimentary basin is at least two orders of magnitude less than the strength of conductivity heat transfer, and as such can be neglected.

The main mechanism for heat transfer from the basement to the atmosphere is thermal conduction through the sedimentary column. Mathematically, this can be expressed as the unidimensional steady-state conduction equation for a multilayered structure of infinite lateral extent:

$$d/dz(\lambda(z)dT/dz) = 0 \tag{7}$$

**Table 2** – Order of magnitude of Peclet number and geothermal gradients in the hydrostratigraphic sequence in the Swan Hills and Cold Lake areas, Alberta.

| Hydrostratigraphic System | Order of Magnitude of Pe | | Geothermal Gradient (mK/m) | |
|---|---|---|---|---|
| | a | b | a | b |
| Post Viking | $2x10^{-4}$ | $5x10^{-5}$ | n.a. | 42.2 |
| Viking | $2x10^{-4}$ | $3x10^{-5}$ | 20.1 | 19.7 |
| Upper Mannville | $5x10^{-3}$ | $1x10^{-3}$ | 20.0 | 19.0 |
| Clearwater | $1x10^{-5}$ | $1x10^{-6}$ | n.a. | n.a. |
| Lower Mannville | $5x10^{-3}$ | $3x10^{-3}$ | 17.3 | 17.0 |
| Wabamun-Winterburn | $1x10^{-2}$ | $2x10^{-3}$ | 17.3 | 17.0 |
| Grosmont | $2x10^{-3}$ | $1x10^{-3}$ | 15.1 | 16.5 |
| Ireton | $3x10^{-6}$ | $5x10^{-7}$ | 40.9 | 40.1 |
| Beaverhill Lake | $2x10^{-3}$ | $5x10^{-4}$ | 18.1 | 18.5 |
| Muskeg-Prairie | $1x10^{-6}$ | 0.0 | 27.9 | n.a. |
| Keg River | $5x10^{-4}$ | $2x10^{-6}$ | 25.6 | n.a. |
| Middle Cambrian | $5x10^{-7}$ | n.a. | 30.2 | n.a. |
| Basal Cambrian | $1x10^{-3}$ | $5x10^{-2}$ | n.a. | n.a. |

a – Swan Hills area
b – Cold Lake area

with the boundary conditions (3) and (4).

In the above equation, the variation of the thermal conductivity with depth can be approximated by a stepwise function following the geometry of the strata. Therefore, at a given location, the heat flux crossing the sedimentary basin produces a vertical temperature distribution and a geothermal gradient depending ultimately on lithology.

Given the mild regional dip, the relatively small range of topographic variations, and the general layering of the sedimentary strata, it is possible to compute the geothermal gradients $G = dT/dz$ for each unit as the slope of the regression line fitted to the temperature-versus-depth data in the respective unit. In computing the individual geothermal gradients by this method, attention was paid to the representativeness of the data sample. Care was taken to limit the areal extent of the data distributions in the case of dipping formations. As expected, the less conductive layers (shales) have a higher temperature gradient, while the more conductive ones (sandstone, carbonates) have a lower one (Table 2). Fig. 6 presents the geothermal gradient for the shaley Ireton Formation in the western parts of the Swan Hills (a) and Cold Lake (b) areas, where it is present. The heat flux in the Swan HIlls area is only slightly higher than in the Cold Lake area (Majorowicz & Jessop, 1981). It could be seen that, for approximately the same heat flux, the geothermal gradient in a relatively homogeneous formation is practically the same. The different intercept of the geothermal gradient in Ireton Formation in the Swan Hills and Cold Lake regions is due to the different overall stratigraphic and lithologic structures and to the different depth of the formation in the sedimentary sequence in the two areas (Figs. 4 and 5).

The integral geothermal gradient G defined by

$$\overline{G} = (T_D - T_a)/D \tag{8}$$

The influence of lithology on the geothermal gradients in the same area is shown in Fig. 7, where the individual gradients for a sandstone, a carbonate and a shaley anhydrite formation in the Swan Hills area are presented.
represents in fact a weighted average of the individual gradients $G_i$ in each unit in the stratigraphic sequence above the measuring point (Bachu, 1985):

$$G = \Sigma G_i \Delta z_i / \Sigma \Delta z_i \tag{9}$$

where $\Delta z_i$ is the thickness of the unit i.

In the absence of significant heat transport by convection, and assuming a relatively constant heat flux, the distribution over a given area of the integral geothermal gradient for the entire sedimentary column is influenced only by the geometry and lithology (thermal properties) of the strata. Fig. 8 presents the variation of the integral geothermal gradient in the Cold Lake, Swan Hills and the in-between areas. In computing the values of the integral geothermal gradient, an average annual temperature of $T_a = 1°C$ was considered at the top (Environment Canada, 1982), and the individual BHT value at the wells reaching the Precambrian basement were taken at the bottom.

As noted previously, some formations are not present everywhere, due to erosional and/or depositional phenomena (Figs. 3, 4 and 5). If $\overline{G}$ is the integral geothermal gradient at a point, and $\overline{G}_{-j}$ is the integral geothermal gradient at a point where the layer j of thickness $\Delta z_j$ is the absent due to erosion, or due to lateral changes in lithology, the ratio between the two is given, respectively, by (Bachu, 1985):

$$\overline{G}_{-j}/\overline{G} = 1 - (G_j/\overline{G} - 1)/(\Sigma\Delta z_i/\Delta z_j - 1) \tag{10}$$

$$\overline{G}_{-j}/\overline{G} = 1 - (G_j - G_{-j})\Delta z_j/G\Sigma\Delta z_i \tag{11}$$

where $G_j$ is the geothermal gradient in the layer j present at the reference point, and $G_{-j}$ is the geothermal gradient in the layer substituting the absent formation.

According to the relationships 10 and 11, for a given heat flux the value of the integral geothermal gradient increases when a more conductive formation is absent, or when less conductive formations are predominant in the sequence. For example, in the Swan Hills area, along the cross-section A-B (Fig. 4), 1400 m of Upper Cretaceous and Tertiary shaley sediments are absent in the northeast due to erosion. Furthermore, about 210 m of Ireton shales are replaced by Grosmont carbonates, and about 90 m of Lotsberg halite replace Middle Cambrian shales. Considering a geothermal gradient of 40 mK/m for shales, 18 mK/m for carbonates and 12 mK/m for halite, application of relationships 10 and 11 brings about an integral geothermal gradient of 25 mK/m at the point B versus 33.6 mK/m at the point A. Further to the east of the Swan Hills area, the integral geothermal gradient decreases due to the lateral facies change of shaley anhydrite (Muskeg Formation) into halite (Prairie Formation). In the western part of the Cold Lake area, the integral geothermal gradient increases due to the increase in the ratio of less conductive versus more conductive strata, increase caused by the removal through erosion of the originally thick (300 to 400 m) Wabamun and Winterburn carbonates, and by the nondeposition of the Grosmont carbonate complex (Fig. 5). In the eastern part of the Cold lake area, the thick Ireton shales (300 m) are absent due to erosion, and again the integral geothermal gradient decreases due to an increased average thermal conductivity of the sedimentary column. Finally, in the northeast corner of the Cold Lake area there is a trend to increased integral geothermal gradients due to the absence of 130 m of halite (Prairie Formation), absence caused by salt dissolution. These variations in the integral geothermal gradient, controlled by changes in the topography, geometry and lithology of the strata, are superimposed over a slight decrease in the terrestrial heat flux from the Swan Hills to the Cold Lake area (Majorowicz & Jessop, 1981).

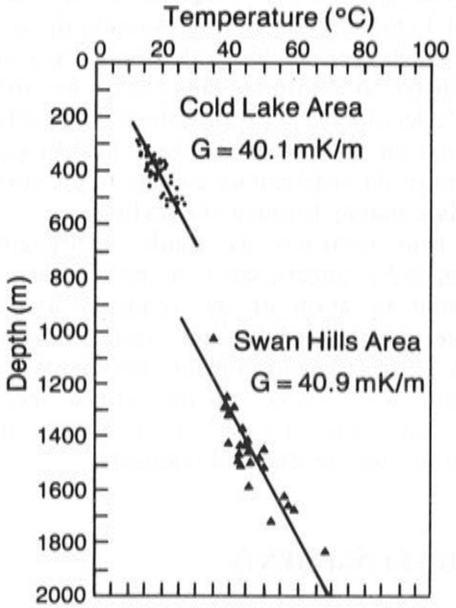

**Figure 6** — Geothermal gradient in shaley Ireton Formation, in (a) Swan Hills area; and (b) Cold Lake area.

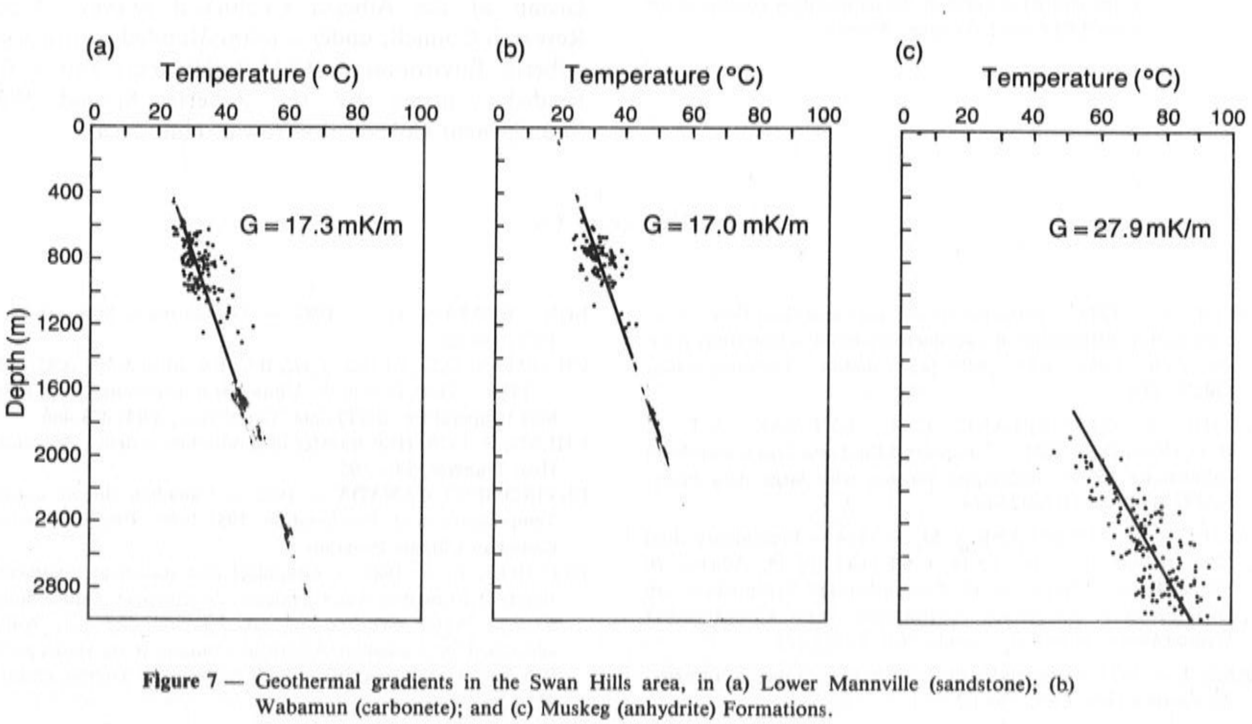

**Figure 7** — Geothermal gradients in the Swan Hills area, in (a) Lower Mannville (sandstone); (b) Wabamun (carbonete); and (c) Muskeg (anhydrite) Formations.

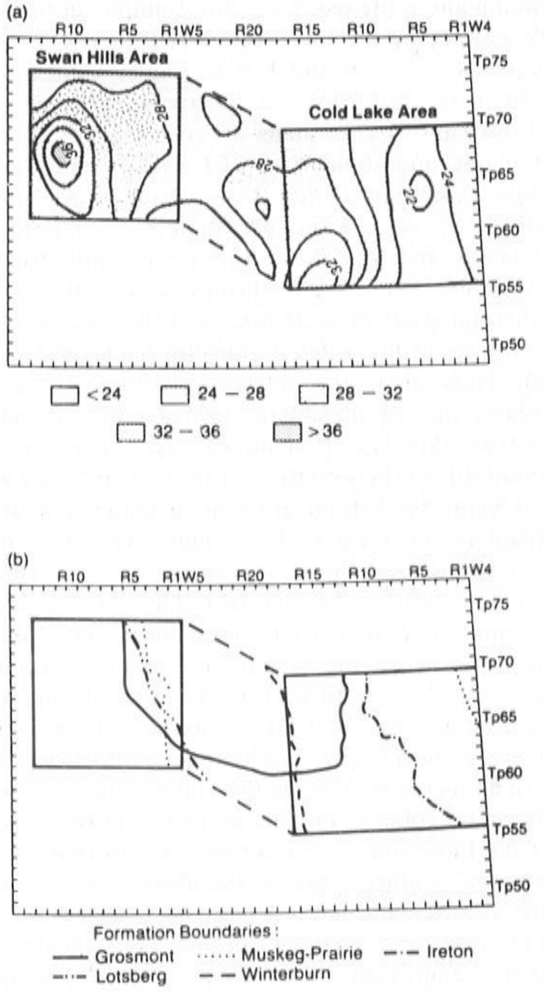

**Figure 8** — Distribution of the integral geothermal gradient (mK/m) for the entire thickness of the sedimentary column in the Swan Hills-Cold Lake area, Alberta.

## CONCLUSIONS

The main mechanisms of heat transfer in sedimentary basins are conduction and convection by moving fluids. The flow of formation water is gravity induced and controlled by the topography of the basin, as well as by stratigraphy through such characteristics as the permeability and porosity of the strata and the geometry of the aquifers, aquitards and aquicludes. A detailed hydrogeological study was carried out for the entire Phanerozoic sequence in the central Alberta part of the Western Canada Sedimentary Basin (Swan Hills and Cold Lake areas). For low permeable rocks as those found in this region, the velocity of fluid flow in aquifers is very low, on the order of 1 cm/a. At these low velocities, the convective heat transfer is negligible with respect to conductive heat transfer, as shown by values much less than unity of the Peclet number for heat transfer in porous media. Therefore, the flow of the terrestrial heat flux from the basement of the sedimentary column to the atmosphere takes place mainly through conduction.

If heat transport by fluids is negligible, the stratigraphy has direct control on the heat flow through the spatial variation of the geometry and thermal properties of the sedimentary strata. However, the changes in stratigraphy and/or lithology have to be significant with respect to the entire sedimentary column, in order to reflect in the temperature distributions and geothermal gradients.

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