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MODEL OF TERRESTRIAL THERMAL EFFECTS IN THE AREA OF THE CRUSTAL ELECTRICAL CONDUCTORS OF THE WILLISTON BASIN[1]

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ABSTRACT

Previous analysis of sub-Mesozoic sedimentary geothermal structure has shown that a north-south trending high heat flow anomaly (~80 to 100 mWm^{-2}) exists in southeastern Saskatchewan and coincides with the electrical conductivity anomaly detected by Jones and Savage on the basis of magnetotelluric (MT) studies. S_2 pyrolysis-peak studies by Price and others indicate that the heat flow anomaly extends southward through the centre of the Williston Basin in North Dakota. A numerical model that incorporates heat generation has been used to investigate the relationship between the electrical conductivity and heat flow anomalies. The preferred cause for the anomalous heat flow is enhanced heat generation in the upper crust related to mineralization. Interpretation of the heat flow anomaly in relation to the heating and thinning of the lithosphere as a result of rejuvenation when the basin was initiated is uncertain at this stage. That event may have caused redistribution of radiogenic elements and high electrical conductivity mineralization. However, the proposed high heat generation zone may have resulted from redistribution of radiogenic elements during tectonic development of the Superior-Churchill boundary zone. In this case, a zone of weakness in the lithosphere may have approximately coincided with the centre of the formed Williston Basin.

INTRODUCTION

Heat flow estimates for the Mesozoic sediments of the Williston Basin show a strong correlation with ground surface topography and hydraulic head, so the pattern of conductive heat flux from the crystalline crust and upper mantle is masked (Majorowicz et al., 1986). The observed correlation was interpreted as due to the effect of crossformational water motions in permeable lower Mesozoic aquifers. The lack of a similar correlation in heat flow through the deeper Paleozoic formations suggests less influence there from the gravity-driven hydrodynamic effect. This is probably because of much lower crossformational fluid velocities in the deeper formations, and so heat flow in these formations is more directly related to the deep heat flow from the crystalline crust and upper mantle (Majorowicz et al., 1986, 1988).

An elongated heat flow anomaly was found in southern Saskatchewan from heat flow estimates in Paleozoic strata (Majorowicz et al., 1986), and there is evidence that it extends into North Dakota (Figure 1). Price et al. (1986) reported the presence of a geothermal anomaly across the centre of the Williston Basin along the Nesson anticline and to the southwest. He based his conclusions on S_2 pyrolysis-peak studies in the Mississippian-Upper Devonian Bakken shales and suggested that the high paleoheat flows that he found were due to an aborted late Cretaceous-Paleocene rift event.

Analysis of the Williston Basin subsidence by Ahern and Mrkvicka (1984) places the timing of emplacement of the hot body in the lithosphere at approximately 400 million years ago. In order to explain subsidence of the centre of the basin, the transition of the mafic or subcrustal body that underwent transformation to eclogite was considered by Fowler and Nisbet (1985).

Few data for the existence of the thermal anomaly from deep wells in North Dakota are available. Nathenson and Guffanti (1988) reported high geothermal gradients (40 mKm^{-1} to 45 mKm^{-1}) in the eastern part of North Dakota coinciding with the S_2 pyrolysis anomaly. However, the gradient estimates by Nathenson and Guffanti (1988) are from wells in the U.S.A. at depth intervals 0.6 km to 2 km. In the case of the Williston Basin, the sediments in the depth interval are mostly clastic with a high percentage of low-conductivity shales. Similar gradients would imply heat flows from 70 to 90 mWm^{-2}, if thermal conductivities of 1.8 ± 0.2 to 2.0 ± 0.2 Wm^{-1}K^{-1} for the Mesozoic sediments in the Williston Basin are assumed (Majorowicz et al., 1986, Figure 6a). Reservoirs within Paleozoic sediments in the Williston Basin are hot (Price, 1980). As an example, the Alexandra field in North Dakota produces

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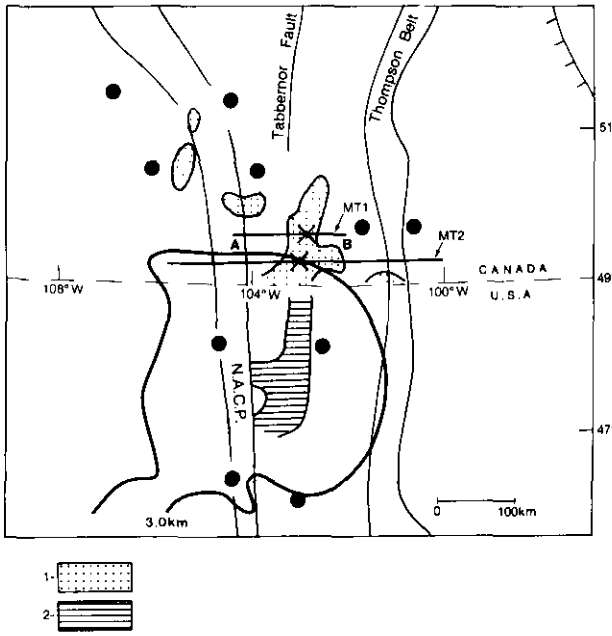

Fig. 1. The location of the heat flow anomaly in the Williston Basin: **1** - as defined by Majorowicz et al. (1986) in Canada; **2** - in the United States after Price et al. (1986). The North American Central Plains (NACP) conductive body was mapped by Alabi et al. (1975). The magnetometer stations of Alabi et al. (1978) are shown by dots. The Thompson Belt and the Tabbernor Fault are mapped after Green et al. (1985). The 3-km isoline of the Phanerozoic sediments in the Williston Basin is shown. Profile AB, used for the model calculations, coincides with the MT profile (MT1) of Rankin (Pers. comm.). The profile of Jones and Savage (1986) is marked as MT2. The MT anomaly maxima are marked by crosses.

crude oil from the Ordovician Red River Formation at a depth of 4.15 km at 182°C, which implies a temperature gradient of 43 mKm^{-1} if the surface temperature is 5°C. Sediment thermal conductivities for the Great Plains of 2.2 $Wm^{-1}K^{-1}$ have been reported by Nathenson and Guffanti (1988) and an average heat conductivity of 2.4 ± 0.2 $Wm^{-1}K^{-1}$ was estimated from net rock analysis and average rock conductivities in the southern Canadian Prairies Basin by Majorowicz and Jessop (1981). Therefore, a heat flow value of approximately 90 to 100 mWm^{-2} ± 20 mWm^{-2} is estimated for the Alexandra field, and this is similar to the heat flow in the anomalous heat flow zone in Canada (Figure 1).

The southern Saskatchewan heat flow anomaly coincides with an electrical conductivity anomaly observed from magnetotelluric (MT) studies (Jones and Savage, 1986; Rankin and Pascal, Pers. comm., 1986).

The present work investigates the relationship between the thermal and electrical anomalies and their possible causes.

THE HEAT FLOW AND ELECTRICAL ANOMALIES

The position of the southern Saskatchewan heat flow anomaly (Majorowicz et al., 1986), together with the geothermal gradient anomaly in North Dakota postulated by Price et al. (1986), on the basis of S_2 pyrolysis studies, is shown in Figure 1. The anomaly lies east of the North American Central Plains (NACP) electrical conductivity anomaly as delineated by Alabi et al. (1975). The NACP was originally defined as an elongated feature that joins a high electrical conductivity zone north of the southern Rockies (Camfield et al., 1971) to the conductive structures on the exposed shield within the Reindeer-South Indian Lakes remanent back-arc basin in northeastern Saskatchewan and northwestern Manitoba (Green et al., 1985; Handa and Camfield, 1984).

Two recent MT studies along east-west profiles in southern Saskatchewan and Manitoba by Jones and Savage (1986) and Rankin and Pascal (Pers. comm., 1986) indicated the existence of an anticlinal, high electrical conductivity body in the upper crust with its top at approximately 8 km depth but lying east of the previously defined NACP anomaly. As a result of their work, Jones and Savage (1986) and Rankin and Pascal (Pers. comm., 1986) suggested that the NACP anomaly lies approximately 75 to 90 km east of where it was originally located. The location of the MT anomaly closely coincides with the location of the southern Saskatchewan heat flow anomaly (Majorowicz et al., 1986, 1988). Their relation to the NACP electrical conductor was questioned by the results of MT studies of Maidens and Paulson (1988). However, in a recent letter Jones (1988) argues that the interpretation of Maidens and Paulson (1988) is in error and that there is only one major N-S striking conductivity anomaly west of the Thompson belt.

Anomalous basement structures and related features above them in the sedimentary cover are present in the region where the heat flow and MT anomalies occur (Majorowicz et al., 1988). High heat flow could be caused either by high heat generation related to mineralization or high heat conduction related to saline brine in motion. Either of these sources could also cause the MT anomaly.

Enhanced heat generation associated with mineralization in the mid-upper crust could explain the high heat flow (Majorowicz et al., 1986) and related electrical conductivity anomaly (Jones and Savage, 1986). Jones and Majorowicz (1987) stated that, although a number of high heat generation zones exist in the basement of the western Canadian sedimentary basin, the area between 100° W and 104° W in southern Saskatchewan exhibits near-normal heat generation at the Precambrian basement surface. Therefore, a high heat generation zone is suggested to exist at larger depths below the crystalline basement top which is coincident with the high electrical conductivity zone.

Interconnection of fractures with saline brine in the fault zone may also contribute to high apparent thermal conductivity and be a second cause for the high heat flow observed in the area.

A heat flow anomaly in the mantle has been rejected since it would have caused a widespread heat flow anomaly in the subsurface, contrary to the observed pattern. Also, there is no evidence of the change in the sedimentation rate in the recent geological history which would have been related to cooling of the subcrustal body in the anomalous mantle heat flow zone.

Two possible causes for the coincident heat flow/electrical conductivity anomalies, i.e., enhanced heat generation associated with mineralization of the mid-upper crust and enhanced thermal conductivity/electrical conductivity caused by the moving brine, were investigated using a numerical model.

THE MODELS AND DISCUSSION

The two-dimensional numerical finite-difference method (Jones and Ertman, 1985) for solving the conduction equation with source term has been used to investigate the possible character of the thermal regime associated with an anomalous mid-upper crustal structure. The equation is:

$$\rho c \frac{\partial T}{\partial t} = \nabla(K \nabla T) + A \ ,$$

where t is time, ρ is density, c is specific heat, T is temperature, K is thermal conductivity, and A is the heat source term.

The shape of the computed anomalous structure is based on the interpretation of MT results by Jones and Savage (1986) and Rankin and Pascal (Pers. comm., 1986). The anticlinal structure with high electrical conductivity was assigned either anomalous heat generation or anomalous thermal conductivity values. These two sources of the observed heat flow anomaly need not be competing at all. However, allowing for both an anomalous A and K distribution in the electrical conductor would require additional information not available at present. Therefore, two independent causes are considered in this paper. Initially, the structure was considered to have uniform properties throughout, but the fit of heat flow values calculated from this suite of models to the heat flow estimates from the borehole data was poor. Subsequently, the anticlinal structure was divided into blocks of different anomalous heat generation ΔA or different thermal conductivity K.

A close fit to the observed values was obtained for two models as shown in Figure 2a, b. One model requires anomalous heat generation in the mid-upper crystalline crust $\Delta A = 4 \mu Wm^{-3}$. Heat generation for the Precambrian basement rocks can vary from $0.1 \mu Wm^{-3}$ to $14.0 \mu Wm^{-3}$ (Beach et al., 1987). In most classical heat-generation models heat generation decreases with depth. However, the zone where anomalous electrical and thermal features occur in the Williston Basin can be related to the widespread redistribution of radiogenic elements from the oceanic sediments into overriding Superior crust in the Superior-Churchill boundary zone (Drury, 1985). Further evidence for such a possibility comes from the superdeep borehole on the Kola Peninsula, where rocks of low heat production overlie a geologically distinct formation with much higher radioactivity (Lister, 1987).

However, the belief that the Superior crust overrode the Churchill crust during the Hudsonian orogeny given by Drury (1985) differs from others (see Green et al., 1985 for the review) who concluded on the basis of geological and geophysical evidence that the Superior craton was thrust beneath terranes now represented by the so-called Churchill Province.

Anomalous thermal conductivity is a second possibility, as illustrated in Figure 2b. The temperatures reach almost 500°C in the eastern part of the structure in this particular model. This zone with high heat flow lies within an area of low magnetic field strength and immediately west of a region of rapid change in magnetic field, as shown in the magnetic map and its tectonic interpretation by Green et al. (1979) and Green et al. (1985) (see Majorowicz et al., 1988, Figure 2). This may be a result of high temperatures that approach the Curie point. If high heat conduction exists, joined fractures within the mid-upper crust would be necessary to allow fluid convection to enhance the heat transfer.

The existence of such a fractured zone in the upper crust is speculative. Seismic reflection data from many sites in Europe and North America show that the uppermost 10 to 15 km of the Earth's continental crust differs from the lower crust. The upper crust is transparent and the lower crust is reflective. Gough (1986) has interpreted these differing characteristics and has suggested that the entire crust contains saline water, but it is in separated cavities in the compressively stressed rocks of the upper crust, whereas in the lower crust it forms an interconnected film on crystal surfaces. However, these characteristics now seem to be associated with recently extended crustal structures and are not a general characteristic of continental crust. The Precambrian crust beneath the Williston Basin is distinguished by being relatively reflective in the upper crust (Green et al., 1985).

The presence of a low-velocity layer has been reported from crustal seismic studies in the Williston Basin (Morel-a-L'Huissier et al., 1987), but any correlation between it and the NACP geomagnetic anomaly is unclear (Kanasewich et al., 1987).

Broadside refraction data support the presence of a north-south velocity discontinuity or fault zone east of longitude 103° W at latitude 50° N (Kanasewich et al., 1987). This coincides with the location of the heat flow and MT electrical conductivity anomalies. Southward extension of the Tabbernor Fault zone towards the anomalous zone under the Williston Basin as suggested by Green et al. (1985), Kanasewich et al. (1987) and Majorowicz et al. (1988) may occur.

Whether or not the zone is accompanied by interconnected fractures in the upper crystalline crust that allow saline water flow is a question that has to be investigated. The stress field in the crust as proposed by Gough (1986) would not allow for existing fractures to be open and interconnected in the upper crust except for large, frequently active faults. Most fractures will be held closed by horizontal compression or will fill with minerals such as quartz or epidote. There is no strong seismological evidence for

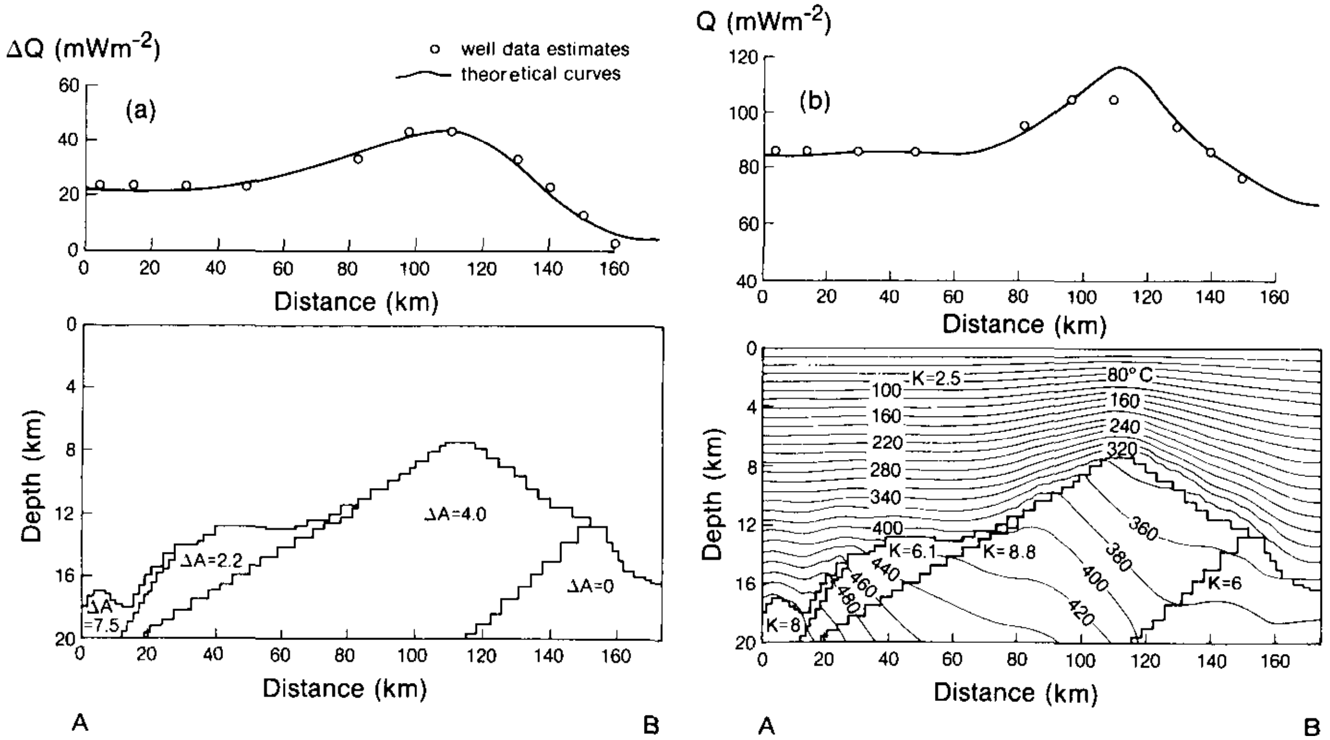

Fig. 2. Two-dimensional model of the crustal structure beneath the Williston Basin and the numerically calculated geothermal effects along profile AB indicated in Figure 1. Model (a) concerns anomalous heat generation and model (b) concerns thermal conductivity structure. a) Assumed: uniform conductivity K = 2.5 Wm^{-1}K^{-1}, anomalous heat flow into the bottom of the model Q_m = 0, density ρ = 2.76 x 10^3 kg m^{-3}, specific heat c = 1.3 x 10^{-3} J kg^{-1} K^{-1}, ΔA is the difference between heat generation in east block and that in the surrounding crust above it (in μWm^{-3}). The observed heat flow values (dots) are normalized with respect to an assumed regional heat flow of 60 mWm^{-2}. The average error of heat flow estimates is 25 percent. b) Assumed: uniform heat generation A = 1.4 μWm^{-3}, heat flow into the bottom of the model Q_m = 20 mWm^{-2}, ρ and c as in model (a), assumed conductivities K (in Wm^{-1}K^{-1}) are assigned to each block of the structure. Isotherms are in °C. For both models a 101 x 101 mesh was used, with dimension 174 km x 20 km. The upper boundary in both models was maintained at 0°C, and an initial temperature distribution of 25°C km^{-1} was used. No heat flux was permitted across the side boundaries. A time duration of 15 million years in 30 x 10^{3}y increments was allowed for the thermal field to develop.

the existence of a presently active fault zone in the anomalous heat flow area. However, earthquake activity has been reported along the NACP anomaly by Alabi, et al. (1975) but also in the Tabbernor Fault southward-extension zone under the Williston Basin (A. Green, Pers. comm., 1988).

In light of the above arguments, the possibility of a heat source in the upper crust appears to be more probable. However, the second possibility, i.e., enhanced thermal conduction, cannot be rejected. A hot spot origin of the Williston Basin was considered by Ahern and Mrkvicka (1984), but the timing of the emplacement of the hot body (mantle diapir) in the mantle beneath the thick crust was estimated to be approximately 400 Ma., and they pointed out that the thermal effects would have decayed by now (see their Figure 24). The suggestion that a rift occurred in the Williston Basin during the late Cretaceous-Paleocene time (Price et al., 1986) as a result of a thermal event is not generally supported by other data. Uplift and anomalous sedimentation patterns would be an expected consequence of such an event, but there is no evidence from seismic, gravity or stratigraphic records to support this hypothesis. It is, therefore, unlikely that a transient thermal source related to a hot body can explain the present day heat flow.

The preferred possible cause for the anomalous heat flow is enhanced heat generation in the mid-upper crust related to increased abundances of radiogenic uranium, thorium and potassium that accompanied high electrical conductivity mineralization in the anomalous zone. There are several possible causes for mineralization in the mid-upper crust. The heating and thinning of the lithosphere during the formation of the Williston Basin may rejuvenate the crust (Ahern and Dimitras, 1985), but its relation to redistribution of the mineralization in the upper crust is uncertain.

It is possible that the proposed midcrustal mineralized zone with high heat generation and anomalously high electrical conductivity may have been created much earlier from the redistribution of radiogenic and other conductive elements during Hudsonian (~1.8 Ga) tectonic development of the Superior-Churchill boundary zone that involved collision of continental fragments. The collision line passes under the centre of the Williston Basin, as do the anomalous heat flow and electrical conductivity midcrustal zones. In this case, the high heat generation, high heat flow zone would have been present in the crust in Hudsonian (Post Hudsonian) time and would have been a zone of weakness in the lithosphere that may have existed approximately coincident with the centre of the *later* formed Williston Basin.

CONCLUSIONS

Although the heat flow values calculated from the numerical models match those observed, it is clear that other models are possible. Nevertheless, these two models are consistent with the magnetotelluric results that indicate the top of the electrical conductivity to be at midcrustal depth.

Within the constraints of the geothermal and electrical observations, either model is feasible. The preferred cause for the anomalous heat flow and electrical conduction is mineralization and redistribution of radiogenic and electrical conductive elements in the crust during the tectonic collision that formed the Superior-Churchill boundary zone. However, the anomalous structure could have been also caused by Paleozoic extension and be due to anomalous thermal conductivity, which is often associated with anomalous electrical conductivity.

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