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Abstract

Previous studies suggest that the temperature field in the Beaufort-Mackenzie Basin varies in response to transient geological processes and surface temperature forcings. A simple linear relationship between formation temperature and burial depth may not adequately reflect the observed temperature variation with depth. Thus a non-linear model is used to characterize the temperature-depth relationship. Temperature data from drill stem test (DST) and borehole temperature (BHT) measurements in 228 petroleum exploration wells in the Beaufort-Mackenzie Basin were analyzed and fitted to the proposed non-linear model. This report presents the non-linear model fitting and preliminary results of the data analysis.

Introduction

The late Cretaceous-Cenozoic Beaufort-Mackenzie Basin (BMB) succession of northern Canada represents a post-rift basin containing more than 14 km (46,000 ft) of deltaic and marine sediments (Dixon et al., 1992). A wealth of geological data is available for this basin from more than 250 exploration wells drilled since the 1960s. Well temperature data have been compiled and analysed as part of an ongoing study of BMB petroleum systems by the Geological Survey of Canada. Basin thermal history and geothermal structure are essential elements of basin analysis and have important implications for petroleum exploration.

A recent study of formation temperature data (Chen et al., 2008) suggests that transient geological processes and surface forcings influence the temperature field of the BMB. Thick permafrost and rapid deltaic sedimentation have suppressed near surface temperatures and heat flow in the young depocentres of the eastern Beaufort shelf. In contrast, thin permafrost and elevated temperatures (about 20°C higher on average than in the adjacent Tertiary depocentres) occur in folded and faulted strata of the west Beaufort Sea and the southwestern basin margin. In this area, contractional tectonics has led to crustal shortening and exhumation of hundreds to thousands of metres of sediment. There are numerous local high temperature anomalies in fault zones and on structural highs and Chen et al. (2008) propose that these are caused by migration of deep overpressure driven fluids within regional conduits and along fault and fracture networks.

Variation in the tectonic and depositional setting in time and space in the BMB provides conditions favouring transient geological processes that affect the basin geothermal regime~~s~~. Present day temperature profiles may reflect~~s~~ the impact~~s~~ of these geological processes by recording how they differ from the approximate linear temperature-depth relationship that is expected for a homogeneous sedimentary succession in thermal equilibrium. This study attempts to show how temperature may respond to various transient geological processes and surface forcings by using a non-linear model to fit the present day temperature-depth data. The spatial variation in model temperature distributions for various geological settings may provide important insights for basin modelling studies~~-~~(e.g. thermal history, exhumation estimation, permafrost development, etc.). This report presents non-linear model fits to the temperature data for 228 petroleum exploration wells and discusses the preliminary results of the data analysis.

Data sources

This study is based on a comprehensive data set consisting of drill-stem test (DST) and repeat formation test (RFT) results (176 wells), bottom-hole temperature (BHT) data (238 petroleum exploration wells) and shallow temperature measurements. Issler et al. (*in press*) discussed various aspects with respect to data collection, temperature data corrections and quality assessments. Hu et al. (*in prep.*) provide~~s~~ the details of data compilation and quality control for the BHT and DST data. Shallow temperature measurements were obtained from the Canadian Geothermal Data Collection project conducted from 1955 to 1980 (Judge *et al*., 1981).

Additional temperature constraints are obtained from the inferred base of permafrost interpreted from well logs and seismic check-shot or crystal cable velocities. The base of permafrost is a well-defined boundary on geophysical logs because an ice-saturated porous medium has a much higher acoustic travel velocity and formation resistivity than a water-saturated porous interval. The inferred base of the ice-bearing permafrost zone is assumed to be -1 °C as a constraint in shallow depth (Henninges *et al.*, 2005). The climate records from the last 75 years at the Inuvik station (from Environment Canada) show an annual mean temperature of –9 °C, suggesting that the temperature between the inferred base of permafrost and ground surface should not be greater than -1°C.

There are notable high temperature readings in a number of wells at shallow depth within the permafrost zone. The reason for this is unclear but these anomalies are unlikely to represent the true formation temperature. They may be the result~~s~~ of disequilibrium between the warm mud fluid and the cold formation. Also, for BHT measurements, maximum recording thermometers are used and it is important that they be properly reset at the appropriate low initial temperature prior to the start of logging operations. The temperature data points were plotted against depth in each well for visual inspection prior to further analysis to ensure data quality; poor quality data were removed to avoid distorting temperature trends.

Method

A temperature profile is controlled primarily by deep heat flux, thermal conductivity of the rocks, and relevant shallow boundary conditions. For stacked sedimentary layers of variable thickness, l_i and conductivity, λ_i, the temperature at a given depth, T_y, can be calculated using the steady state Fourier's law that describes the relation between the thermal conductivity and thermal gradient (e.g. Allen and Allen, 2005):

$$T_y = T_0 + q\sum_{i=1}^{n} \frac{l_i}{\lambda_i} \qquad (1)$$

where T_0 is the surface temperature and q is heat flow with $\sum l_i = y$. The ratio $c=q/\lambda$ is the geothermal gradient. For a homogenous case, the equation simplifies:

$$T_y = T_0 + cy \qquad (2)$$

Eq. (2) is used commonly to approximate temperature-depth relationships. It may not be adequate where thermal disequilibrium prevails in a geologically active setting. ~~That~~ Thermal disequilibrium can result from surface temperature changes and transient geological processes~~,~~ such as exhumation and subsurface fluid flow.

To study individual temperature profiles and possible responses to variations in transient geological processes and surface forcings, a non-linear model, defined in Eq. (3), is used for this study:

$$T_y = T_0 + cy^{\beta} \qquad (3)$$

where β is a power coefficient to be determined by data. The power coefficient β is a shape parameter that indicates the vertical variation of the temperature. The use of a power function is because of its flexibility. When β=1, it reverts to Eq. (2), representing a linear relationship between the burial depth and temperature. When $\beta<1$, the temperature-depth profile is convex (elevated near surface temperatures), a shape that is typical for rapidly exhumed areas or areas that are affected by warm fluid discharge (e.g. Allen and Allen, 2005). If $\beta>1$, the temperature-depth profile is concave (suppressed near surface temperatures)~~,~~ which is typical for areas with meteoric water recharge or rapid sedimentation. With the power coefficient varying from >1 to <1, the temperature-depth curve moves from a concave to convex in shape, representing a transition from a suppressed temperature regime to an elevated one.

Figure 1 shows three types of idealized temperature/gradient profiles and their relationship modelled by Eq. (3). For the convex profile, temperature gradient decreases with increasing depth whereas it increases with increasing depth for the concave profile.

Results and discussion

Figure 2 is a regional geological map of the Beaufort-Mackenzie basin, showing the regional geological setting and well locations of the temperature profiles. The detailed tectonic setting and definition of various thermal regimes are referred to in Lane and Dietrich (1995) and Chen et al. (2008).

Figure 3 shows various styles of temperature profiles found in the study area. The four types of typical temperature profiles include convex (3a), concave (3b), linear (3c) and dog-leg (3d). The dog-leg profile is regarded as a variant of the convex profile with higher rate of temperature increase in the deep interval, and will not discussed further in this report.

Examples of convex temperature profiles are shown for the Ellice O-14 and Minuk I-53 wells that are located in exhumed and deformed strata in the western part of the study area near Ellice Island (Figure 4). Examples of concave temperature profiles are shown for the Arluk E-90 and Uviluk P-66 wells (Figure 5) situated in rapidly deposited sediments of the central and eastern outer Beaufort Shelf (Figure 2). A linear temperature profile is illustrated for the Unipkat I-22 well (Figure 6) on Richards Island (Figure 2).

The pointwise temperature gradients plotted in figures 4 to 6 are derived from the temperature difference between any pair of temperature points divided by their distance (difference in depth). The reliability of such gradients varies depending on the quality of the temperature measurements as well as the distance of the paired data points. Larger depth differences give smoother gradients if temperature errors are constant. In other words, long distance data pairs provide average estimate whereas shorter ones provide local gradients. If the distance is too short, any error in the temperature measurement will compromise the gradient estimation.

Figure 7 is a map view of the geographic distribution of the fitted concave, convex and linear temperature profiles for the BMB. The appendix contains plots showing temperature data with superimposed non-linear model fits and calculated temperature gradients for the 228 BMB wells used in Figure 7. The three distinct groups of temperature profiles appear to occur in different temperature regimes (Figure 7).

Geographically, the convex temperature profiles prevail in the western Canadian Beaufort Sea and the southwest basin margin onshore in a contractional tectonic setting, where Eocene and late Miocene compression resulted in about 20 km of crustal shortening (Lane and Dietrich, 1995) and the removal of a few hundreds to thousands of metres of Tertiary strata (Majorowicz and Dietrich, 1989; Chen et al., in preparation). In contrast, the concave profiles dominate in eastern and northern parts of the BMB where rapid sedimentation in a deltaic setting has accumulated a thick Tertiary succession in the Eocene-Pliocene depocentres. The convex and concave profiles co-exist in the Tuktoyaktuk Peninsula along the southeastern basin margin where the Eskimo ŁLakes fault zone (ELFZ) (Figure 2) served as the Late Jurassic - Early Cretaceous rifted margin. This may indicate the co-existence of meteoric water recharge and discharge of deep warm fluids migrated from overpressured deep intervals to fault blocks within the ELFZ.

Straight line temperature profiles are scattered across the basin, predominantly around Richards Island and far north in the offshore areas, with a few occurrences Tuktoyaktuk Peninsula. It is possible that well successions with linear temperature profiles are closer to thermal equilibrium. However, the degree to which temperature profiles exhibit curvature is a function of the number of data points and the quality of the data. Future thermal modelling will help to address questions concerning the thermal regime of the BMB.

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Appendix

Appendix A. Temperature vs. depth plots of the 228 wells with non-linear fittings (left) and temperature gradient vs. depth plots of the wells (right). The geothermal gradients are estimated from every pairs of data available for each well. See text for details on explanation.

Figure Captions

Figure 1. Models of temperature profiles defined by a power law function (Eq. 3), allowing a linear relationship between temperature and depth being modified by surface forcing and transient geological processes in this study (1a). Corresponding temperature gradient profiles of the three typical types of temperature profiles (1b).

Figure 2. A map showing location of the study area and regional geological settings (fault patterns are from Lane and Dietrich, 1995). See Chen et al. 2008 for details of the geological setting of the study area.

Figure 3. Different styles of temperature profiles observed in BMB: convex (a), concave (b), linear (c) and dog-leg profile (d). Geographic distribution of different styles are shown in Figure 7.

Figure 4. Example of convex-shaped temperature profiles and corresponding geothermal gradient profiles for the Ellice O-14 and Minuk I-53 wells in the western Beaufort region.

Figure 5. Example of concave-shaped temperature profiles and geothermal gradient characteristics for the Arluk E-90 and Uviluk P-66 wells in the northern and eastern regions of the outer Beaufort shelf.

Figure 6. Example of a–linear temperature-depth profile and geothermal gradient characteristics for the Unipkat I-22 well.

Figure 7. Geographic distribution of the three distinct temperature profile styles in the study area. The convex temperature profile prevails in the contractional setting in the southwest where exhumation has removed large amount of overburden and where permafrost is thin or absent. The–concave temperature profiles are predominant in the north and northeast, where rapid deposition in a cold arctic delta may have caused thermal disequilibrium. Mixed–convex and concave temperature profiles may indicate a complex hydrodynamic situation. The co-occurrence of discharge of–upwelling deep

warm fluids and recharge of meteoric water from the cold arctic surface along the fault zone and the structural partitioning of the rifted margin may be conducive to the occurrence of both types of temperature profiles. Straight line temperature profiles are scattered across the basin, predominantly around–Richards Island and north in the offshore areas, with a few occurrences Tuktoyaktuk Peninsula, representing perhaps a thermal status closer to equilibrium.