GEOLOGICAL SURVEY OF CANADA
OPEN FILE 6407

An empirical relation between present temperature and vitrinite reflectance for Cenozoic strata of the Beaufort-Mackenzie Basin, Canada

Z. Chen, D.R. Issler and L.D. Stasiuk

2010

Natural Resources Canada   Ressources naturelles Canada

GEOLOGICAL SURVEY OF CANADA
OPEN FILE 6407

An empirical relation between present temperature and vitrinite reflectance for Cenozoic strata of the Beaufort-Mackenzie Basin, Canada

Z. Chen, D. R. Issler and L. D. Stasiuk

2010

This publication is available from the Geological Survey of Canada Bookstore
(http://gsc.nrcan.gc.ca/bookstore_e.php).
It can also be downloaded free of charge from GeoPub
(http://geopub.rncan.gc.ca/).

Z. Chen, D. R. Issler and L. D. Stasiuk, 2010. An empirical relation between present temperature and vitrinite reflectance for Cenozoic strata of the Beaufort-Mackenzie Basin, Canada; Geological Survey of Canada, Open File 6407, 14 p.

Open files are products that have not gone through the GSC formal publication process.

Table of Contents

Summary
Percent vitrinite reflectance in oil (%VRo) and present temperature (T) data from selected petroleum exploration wells are analyzed and used to establish an empirical %VRo-T relationship for the Beaufort-Mackenzie Basin. This report describes the derivation of the empirical relationship and illustrates how it can be used to estimate the magnitude of sediment exhumation and assess whether sediments are currently at maximum temperature.

Introduction

Thermal maturity and burial history information are required for understanding petroleum systems and evaluating petroleum resource potential. Percent vitrinite reflectance in oil (%VRo) is a commonly used thermal indicator for estimating the maturity of organic matter and is a key parameter for constraining thermal models of petroleum generation. %VRo-depth gradients can be also used to estimate the thickness of missing (eroded or structurally removed) strata in exhumed sedimentary successions and the quality of results can be assessed by comparing %VRo data with present temperatures. There are published empirical relationships between %VRo and temperature for a number of basins (e.g. Barker and Pawlewicz, 1986; Middleton, 1982; Price, 1983) but these do not have universal application because temperature is not the only variable affecting thermal maturity and heating rate, pore pressure and pore fluid types also affect the %VRo-T relationship (e.g., Hao *et al*., 1992; Huang, 1996). Therefore, it is preferable to develop a basin specific empirical relationship.

Present temperature and %VRo data from selected exploration wells in the Beaufort-Mackenzie region are analyzed here and an empirical relationship between these two variables is established. We demonstrate two useful applications of this empirical relationship with general implications for basin analysis and petroleum exploration: a) estimation of the magnitude of exhumation of the Cretaceous-Cenozoic stratigraphic succession; and b) validation of temperature profiles in areas that are considered to be at maximum temperature conditions.

Data sources

Vitrinite reflectance data were collected from various sources for 92 petroleum exploration wells from the Beaufort-Mackenzie region as part of a government-industry research project on petroleum systems. The data used for this study are from well history reports, Geological Survey of Canada (GSC) internal data sets and data collections commissioned by GSC projects (e.g. Stasiuk *et al*., 2005, 2009). There are inconsistencies within this mixed data set. For examples, there is a large spread in %VRo values for the same wells in some cases and incompatibilities between measured %VRo levels and other paleotemperature indices such as the degree of apatite fission track annealing and Rock-Eval Tmax in other cases. For some wells, it was not possible to find burial history models that provided a reasonable match between calculated and measured %VRo values. Different data sources (measured by various petrologists and laboratories for the same wells) may contribute to these inconsistencies in some degree. In an attempt to overcome these problems and standardize the %VRo data, priority wells were selected for reanalysis (e.g. Stasiuk *et al*., 2005) and new data acquisition (e.g. Stasiuk *et al*., 2009) by the GSC.

A subset of thirteen wells with good quality %VRo data were selected to establish an empirical relationship between %VRo and temperature. Corresponding temperature data are from a larger compilation of corrected bottom-hole temperature (BHT) and drillstem test (DST) temperature data for 251 exploration wells in the Beaufort-Mackenzie Basin (Hu *et al*., in press and Issler *et al*., in press). A temperature-depth trend was constructed from the pointwise temperature data for each well and used to interpolate a present day temperature value for each %VRo measurement.

Method

Thermal alternation of organic matters can be approximated by the result of a set of parallel first-order reactions. The temperature dependency of decomposition rate of organic matter is assumed to follow Arrhenius' law (e.g. Whelan and Farrington, 1992):

$$k_i = A_i \exp\{-E_i / RT\} \qquad (1)$$

where k_i is the reaction rate, A_i a proportional constant or frequency factor, E_i the activation energy for the i^{th} reaction, R is the ideal gas constant, and T is the temperature.

Using *%VRo* as the thermal alternation indicator, an empirical relation between temperature and vitrinite reflectance can be written as:

$$\ln(\%VR_o) = a + bT \qquad (2)$$

where a and b are constants to be determined by %VRo and temperature data. When both %VRo and T data are available from the same wells in areas currently at maximum burial and temperature conditions, an empirical relation of the two variables can established.

Several published empirical models based on equation (2) have been calibrated using data collected from different basins or obtained from laboratory experiments (e.g., Barker and Pawlewicz, 1986; Stasiuk 2002; Corcoran and Dore, 2005). However, the empirical relation in Eq. (2) is case sensitive because thermal alteration of organic matter is not only a function of temperature, but also time and other factors, such as type of organic matter as indicated by A_i and E_i in Eq. (1). From Eq. (1), it is also obvious that the thermal alteration of organic matter is an integration of reaction rates from the time immediately after the deposition of the organic material to the time that maximum burial depth (assuming this coincides with the maximum temperature) is reached. Therefore, %VRo is also a function of heating time. Laboratory experiments and case studies confirm this and also suggest that other factors, such as heating rate, pore pressure and pore fluid types also affect the %VRo-T relationship (Hao et al., 1992; Morrow and Issler, 1993; Huang, 1996; Corcoran and Dore, 2005). Thus, the %VRo-T relation requires a basin specific calibration. This is particularly true for the Beaufort-Mackenzie Basin where rapid Cenozoic burial and associated rapid heating has resulted in low thermal maturity and a deep oil window (e.g. Issler and Snowdon, 1990).

Data analysis and Results

The Cretaceous – Cenozoic Beaufort-Mackenzie Basin has a complicated tectonic history with a rifted margin in the east and foreland basin setting in the west (Figure 1). In the west and southwest, contractional tectonics has led to about 20 km of crustal shortening (Lane and Dietrich, 1995). The resulting uplift and erosion removed a few hundreds to thousands of metres of strata (Majorowicz and Dietrich, 1989; Chen *et al.*, in preparation). In contrast, rapid Late Cretaceous-Cenozoic deltaic sedimentation resulted in a thick (> 10 km) sedimentary succession in the north and east along the rifted margin (Dixon et al., 1992).

All thirteen wells selected for this study are from the central basin area near the Tarsiut-Amauligak Fault Zone on the Beaufort Shelf and the Taglu Fault Zone on Richards Island (Figure 1 and Table 1). The thickness of permafrost in this area ranges from 500-700 metres (Issler *et al.*, in press) and the geothermal gradient varies from 20°C/km to

30°C/km in shallow depth (Chen *et al*., 2008). The typical temperature profile (temperature variation with depth) has a concave shape (Figure 2), showing an increasing trend of temperature gradient downward with depth. Such a profile could be related to heat flow suppression in response to rapid sediment burial and near surface cooling due to presence of thick permafrost. However, the impacts from heat flow suppression and near surface forcing vary spatially depending on depositional settings and thickness of permafrost. Furthermore, local high temperature anomalies may occur on structural highs and in fault zones, causing deviation from a normal temperature-depth relationship and showing abrupt variation in geothermal gradient. As a result, a combination of all types of temperature profiles fits well with a linear temperature-depth model (Figure 3).

Vitrinite reflectance measurements show a large spread and lack an obvious trend of increasing thermal alteration with depth in shallow parts (< 2000 m) of the basin. One of the primary reasons for this is that recycling of previously deposited, thermally altered organic matter is pervasive in this deltaic environment. In particular, extensive recycling is a characteristic of the Plio-Pleistocene Iperk Sequence and is well documented by fossil evidence and elevated Rock-Eval Tmax values. Furthermore, thermal alteration cannot begin effectively in the present shallow burial zone (<2000 m, depth varying depending on the depth to base of permafrost and geothermal gradient) where the formation temperature is lower than the temperature at which the organic matter formed and was deposited. At greater depths and higher temperatures, %VRo values increase systematically with depth as expected. Figure 4 shows typical %VRo profiles (including anomalous values) for the central and northeastern parts of the basin. Figure 5 shows the general trend of increasing thermal maturity with depth for the study area based on representative %VRo data (excluding anomalous values due to recycling, caving, change in organic type, etc.) from the thirteen study wells.

Figure 6 shows the relationship between present day temperature and %VRo in the study area. A least squares fit of the data points to Eq. (2) gives estimates for the parameters, a=-1.6236 and b=0.0093 with correlation coefficient of 0.91, representing the empirical T-%VRo relationship for this basin. Other published empirical relationships based on different data sets are also plotted in figure 6 for comparison. The Beaufort-Mackenzie T-%VRo relationship requires higher temperatures than the Barker and Pawlewicz (1986) relationship to achieve equivalent %VRo values. This may in part reflect the relatively short heating times related to rapid burial of the Beaufort-Mackenzie Cenozoic successions. However, the Barker and Pawlewicz (1986) T-%VRo relationship may also be biased to lower temperatures because they included uncorrected bottomhole temperatures in their estimates of maximum paleotemperature. Figure 7 displays the measured temperature profile from the Amauligak J-44 well and the inferred temperature profile from %VRo data, showing a good fit of the measured and inferred temperatures using the Beaufort-Mackenzie T-%VRo relationship.

Discussion

There are several applications of the established empirical T-%VRo relationship in basin analysis and petroleum exploration. One of the important applications is to estimate the thickness of missing strata in variably exhumed stratigraphic successions (e.g. Corcoran and Dore, 2005). By converting %VRo measurements to equivalent paleo–temperature values and assuming a time-invariant geothermal gradient, the difference between the inferred paleotemperature-depth trend and the present temperature-depth trend gives an estimate of the magnitude of exhumation. Figure 8 is an example of the estimated magnitude of exhumation for the Adgo J-27 well, where about 1500 metres of Tertiary strata are inferred to have been removed during Late Miocene-Early Pliocene erosion.

A recent study by Chen *et al*. (2008) indicates that structural highs and active fault zones in the Beaufort-Mackenzie Basin are associated with higher than average temperatures. The T-%VRo relationship can be used to validate such high temperature anomalies by comparing measured formation temperatures with %VRo values converted temperatures. For example, there is an abrupt increase in temperature below the base of permafrost (assuming -1°C at the base of permafrost based on Henninges, *et al*. 2005) in the Amauligak F-24 well (Figure 9). The base of permafrost is interpreted using well logs (indicated by high sonic velocity and high resistivity) and is consistent with the temperature recorded a few tens of metres below its base. The temperature increases by more than 20°C within a 500 metre interval beneath the permafrost, suggesting a geothermal gradient of >40°C/km, which is far greater than the common temperature gradient of 20-25°C/km at this depth in this part of basin. The %VRo converted temperatures are consistent with the measured temperatures, suggesting that measured temperatures are representative of true formation temperatures and that these represent maximum thermal conditions. The implication is that this is a persistent rather than transient thermal anomaly.

Acknowledgements
This work was supported with funding from the Program for Energy Research and Development (PERD) and the Beaufort-Mackenzie consortium of oil companies (BP Canada Energy Company, Chevron Canada Limited, ConocoPhillips Canada Resources Corporation, Imperial Oil Resources Ventures Limited, MGM Energy Corporation and Shell Exploration and Production Company) under the Earth Sciences Sector (ESS) Geo-Mapping for Energy and Minerals Program and the former ESS Secure Canadian Energy Supply Program. The authors thank Kezhen Hu (GSC Calgary) for compiling the vitrinite reflectance and temperature data used in this study. The internal reviewer, Dr. David Morrow of the Geological Survey of Canada, is thanked for his helpful comments and suggestion.

References

Barker, C. E. and Pawlewicz, M. J., 1986. The correlation of vitrinite reflectance with maximum temperature in humic organic matter. In: Buntebarth, G. and Stegena, L., Editors, 1986. Paleogeothermics – evaluation of geothermal conditions in the geologic past, Springer-Verlag, New York, pp. 79–94.

Chen, Z., Osadetz, K. G., Issler, D. R., Grasby, S. E., 2008. Hydrocarbon Migration Detected by Regional Temperature Field Variations, Beaufort-Mackenzie Basin, Canada. AAPG Bulletin. V. 92 (12), p.1639-1653.

Chen, Z. et al., (in preparation), Exhumation estimations of Cretaceous-Tertiary succession and their geological controls, Beaufort-Mackenzie Basin, Canada.

Corcoran, D. V. and Dore, A. G., 2005. A review of techniques for the estimation of magnitude and timing of exhumation in offshore basins, Earth Science Reviews, v. 72, p.129-168.

Dixon, J., J. Dietrich, and D. H. McNeil, 1992. Jurassic to Pleistocene sequence stratigraphy of the Beaufort - Mackenzie Delta and Banks Island areas, Northwest Canada: Geological Survey of Canada, Bulletin 407, 90p.

Henninges, J., Chrotter, J., Erbas, K. and Huenges, E., 2005, Temperature field of the Mallik gas hydrate occurrence – implications on phase changes and thermal properties. In: Scientific Results from the Mallik 2002 Gas Hydrate Production Research Well Program, Mackenzie Delta, Northwest Territories, Canada; Dallimore, S R; Collett, T S. Eds., *Geological Survey of Canada, Bulletin*. 585: Paper 50.

Hao, F., and J. Chen, 1992, The cause and mechanism of vitrinite reflectance anomalies: Journal of Petroleum Geology, v. 15, p. 419-434.

Hu, K., (in press), Temperature data compilation and correction for the Beaufort-Mackenzie Basin, GSC Open File #6057.

Huang, W., 1996. Experimental study of vitrinite maturity: effects of temperature, time, pressure water, and hydrogen index, Organic Geochemistry, v.24 (2), p.233-241.

Issler, D. R., K., Hu, L. S. Lane and J. R. Dietrich, (*in press*), GIS Compilations of Depth to Overpressure, Permafrost Distribution, Geothermal Gradient, and Regional Geology, Beaufort-Mackenzie Basin, Northern Canada: Geological Survey of Canada, Open File 5689.

Issler, D.R. and Snowdon, L.R. 1990. Hydrocarbon generation kinetics and thermal modelling, Beaufort-Mackenzie Basin. Bulletin of Canadian petroleum Geology, v. 38, no. 1, p. 1-16.

Lane, S. L. and J. R. Dietrich, 1995, Tertiary structural evolution of the Beaufort Sea-Mackenzie Delta region, Arctic Canada: Bulletin of Canadian Petroleum Geology, v. 43 (3), p. 293-314.

Majorowicz, J. A. and J. R. Dietrich, 1989. Comparison of the geothermal and organic maturation gradients of the central and southwestern Beaufort-Mackenzie Basin, Yukon and Northwest Territories: in Current Research, Paper 89-1G, p.63-67.

Middleton, M. F. 1982. Tectonic history from vitrinite reflectance. Geophysical Journal of the Royal Astronomical Society, v. 62, p. 121-132.

Morrow, D. W. and Issler, D. R. 1993. Calculation of vitrinite reflectance from thermal histories: a comparison of some methods. American Association of Petroleum Geologists Bulletin, v. 77, no. 4, p. 610-624.

Price, L. C. 1983. Geologic time as a parameter in organic metamorphism and vitrinite reflectance as an absolute paleogeothermometer. Journal of Petroleum Geology, v. 6, p. 5-38.

Stasiuk L.D., M.G. Fowler, L.R. Snowdon, M. Tomica, J. Potter and G. Addison, 2002, Regional Thermal Maturity Evaluation of Devonian-Mississippian Source Rock Strata in the Western Canada Sedimentary Basin: Implications for Thermal History and Petroleum Exploration, Canadian Society of Petroleum Geologist 2002 Convention, June 3-5, 2002, Calgary, Alberta, Canada.

Stasiuk, L. D., D. R., Issler, M. Tomica, and J. Potter, 2005. Re-evaluation of thermal maturation – vitrinite reflectance profiles for Cretaceous and Tertiary strata, Beaufort-Mackenzie Basin, Northwest Territories (Adlartok P-09, Amerk O-09, Edlok N-56, Ikhil K-35, Sarpik B-35, Hansen G-07 and Havik B-41): Geological Survey of Canada, Open File 4665, on CD-ROM.

Stasiuk, L. D., D. R., Issler, J. Dixon, and D. H. McNeil, 2009. Thermal maturity of Cretaceous and Tertiary strata in the Itiginkpak F-29, Napartok M-01, Kurk M-15, Tuk B-02, and Tuk M-18 wells, Beaufort-Mackenzie Basin, Northwest Territories. GSC Open File 5639.

Whelan, J. and Farrington, J. W., 1992. Organic matters: productivity, accumulation, and preservation in recent and ancient sediments, Columbia University Press, New York, p.23-24.

Figure Captions

Figure 1. Map showing the regional geological setting of the Beaufort-Mackenzie Basin and well locations of the vitrinite reflectance profiles in this study.

Figure 2. Typical temperature profile in the Cenozoic strata of the central Beaufort-Mackenzie Basin showing common features of temperature variation with depth. a) a concave temperature profile at the Kogyuk N-67 well, and b) interval geothermal gradient for the same well showing an increasing trend with depth. The pointwise temperature gradients are estimated from the temperature difference between any pair of temperature points divided by their distance (difference in depth).

Figure 3. Cross plot of temperature versus depth, showing general temperature trend with depth in this region.

Figure 4. Typical vitrinite reflectance profiles in the Cenozoic strata of the central Beaufort-Mackenzie Basin. Recycled coaly materials with relatively constant vitrinite reflectance values are commonly observed at shallow depth in this basin. Blue squares represent data points on a normal %VRo-depth trend and the red crosses may indicate data points from recycled or caved material or %VRo values from different organic material.

Figure 5. Cross-plot of measured %VRo versus depth for the thirteen study wells (anomalous data points excluded). The depths are from ground level for onshore wells and sea level for offshore wells.

Figure 6. Cross plot of temperature and vitrinite reflectance data points for thirteen wells, and the fitted empirical relationship between the two variables. Other published empirical relationships between the same variables are plotted for comparison.

Figure 7. Comparison of observed temperature data points and %VRo converted temperature points, showing a consistent temperature trend with depth (Amauligak J-44).

Figure 8. An example of using the empirical T-%VRo model for estimation of the magnitude of exhumation at Adgo J-27 well location. The Pliocene Iperk Sequence overlies directly on the Late Eocene Richards Sequence and the estimated magnitude of late Miocene erosion is about 1800 metres (1300 metres difference indicated by temperatures plus the thickness of Iperk Sequence).

Figure 9. An example of the confirmation of present maximum temperature conditions using %VRo converted temperature at Amauligak F-24. See text for interpretation.

Table Caption

Table 1. A list shows well names and location and other relevant information for the thirteen wells used this study.