THERMAL MATURITY IN THE CENTRAL WHITEHORSE TROUGH, NORTHWEST BRITISH COLUMBIA

By J.M. English[1], M. Fowler[2], S.T. Johnston[1], M.G. Mihalynuk[3] and K.L. Wight[1]

KEYWORDS: Whitehorse Trough, Laberge Group, Sinwa Formation, Atlin Lake, Tulsequah, regional geology, organic maturation, programmed pyrolysis, vitrinite reflectance.

INTRODUCTION

The Whitehorse Trough is an early Mesozoic marine sedimentary basin, which extends from southern Yukon to Dease Lake in British Columbia. Early studies recognised the potential of the low-grade sedimentary rocks of the Whitehorse Trough to host hydrocarbon accumulations (e.g. Gilmore, 1985; Hannigan et al., 1995; National Energy Board, 2001). These assessments were based on data from samples collected in southern Yukon (Gilmore, 1985; National Energy Board, 2001), and indicate that the region is gas-prone. It is not known if potential hydrocarbon traps were filled and preserved, as none have been drilled. Structural complexity decreases and metamorphic grade is lower in the British Columbia portion of the Whitehorse Trough. On the basis of flat-lying Eocene volcanic rocks of the Sloko Group, no widespread deformation post-dates Early Eocene time (Mihalynuk, 1999). Undeformed Middle Jurassic plutons that intrude structures within the Whitehorse Trough in British Columbia constrain deformation to between about 174 and 172 Ma (the age of youngest deformed strata and oldest cross-cutting plutons, respectively; e.g. Mihalynuk et al., 1999; Mihalynuk et al., in press). Such a simple deformational history limits the possibility of post-generation hydrocarbon escape. Previous assessments of source rock potential in British Columbia were based on extrapolation of data from the Yukon portion of the Whitehorse Trough. The objective of this paper is to determine the level of organic maturation and source rock potential in this portion of the Whitehorse Trough.

GEOLOGICAL BACKGROUND

The Whitehorse Trough is an elongate arc-marginal sedimentary basin, and is believed to represent submarine-fan deposition in a forearc basin that received detritus from the Upper Triassic Stuhini and Lower Jurassic Hazelton magmatic arcs to the west and southwest during Upper Triassic to Middle Jurassic time (e.g. Tempelman-Kluit, 1979; Dickie and Hein, 1995; Hart et al., 1995; Johannson et al., 1997; Figure 1); the Stuhini Group is known as the Lewes River Group in Yukon (Wheeler, 1961). The Whitehorse Trough is juxtaposed along the Nahlin Fault with oceanic crustal rocks to the northeast, including thick platformal carbonate and argillaceous chert successions of the northern Cache Creek terrane. The Laberge Group of the Whitehorse Trough ranges in age from Lower Sinemurian to Middle Bajocian; proximal conglomeratic strata onlap onto Upper Triassic volcanic and carbonate rocks of the Stuhini Group to the south and southwest (e.g. Souther, 1971; Monger et al., 1991). Whitehorse Trough strata within the study area include carbonate rocks of the Upper Triassic Sinwa Formation, and interbedded sandstone, siltstone and argillite of the Lower Jurassic Inklin Formation.

Contraction of the Whitehorse Trough occurred in the Middle Jurassic when the Cache Creek terrane was emplaced over it during an accretionary event (e.g. Thorstad and Gabrielse, 1986; Mihalynuk, 1999). The timing of this deformational event is constrained by the age of the youngest blueschist in the Cache Creek terrane (French Range, ~174 Ma: Mihalynuk et al., in press), and the age of the oldest post-deformational stitching intrusions (~172 Ma: Mihalynuk et al., 1992; Mihalynuk et al., 2003; Bath, 2003). A Middle Jurassic southwest-vergent fold and thrust belt is developed in the Whitehorse Trough that includes the regional-scale King Salmon Thrust. During this deformation, the Cache Creek terrane was thrust westward over the Whitehorse Trough and the Stikine arc. During Bajocian time, chert-pebble conglomerates derived from the Cache Creek terrane were deposited across the Whitehorse Trough and the more southerly Middle-Upper Jurassic Bowser Basin (Ricketts et al., 1992; Mihalynuk et al., in press).

THERMAL MATURITY IN THE CENTRAL WHITEHORSE TROUGH

Systematic sample collection for programmed pyrolysis was undertaken in the central Whitehorse Trough in order to assess the level of organic maturation and source rock potential of this basin. Programmed pyrolysis of whole rock using the Rock-Eval 6 system provides information on the type, maturity and quantity of associated organic matter (Behar et al., 2001; Lafargue,

[1] *University of Victoria*
[2] *Geological Survey of Canada (Calgary)*
[3] *B.C. Ministry of Energy and Mines*

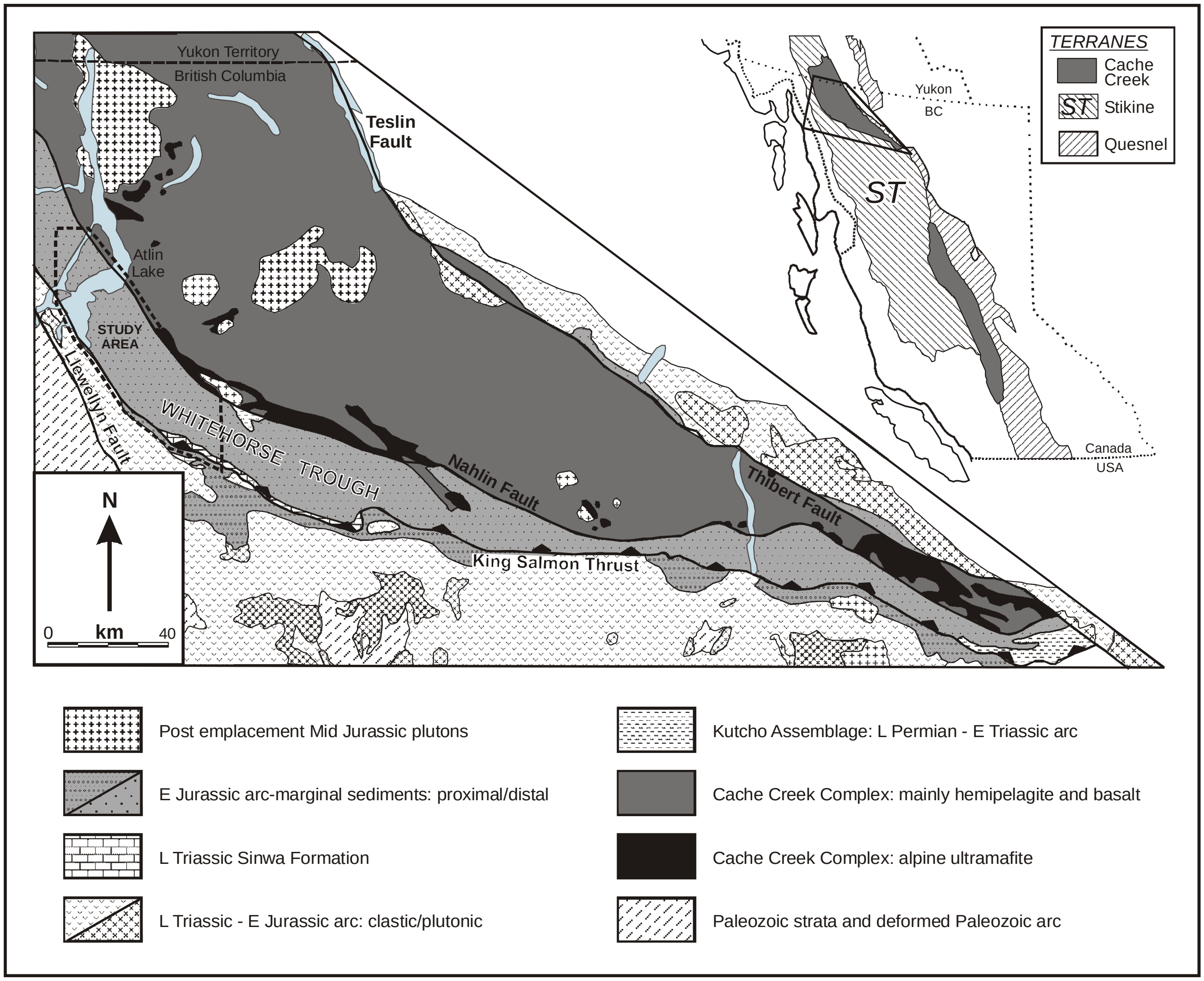

Figure 1. Map of British Columbia showing the distribution of the primary components of the Intermontane belt in the northern Canadian Cordillera (top right) and a regional geologic map (main). This geology map does not include post-Middle Jurassic rock units. The central Whitehorse Trough study area is outlined by a dashed box.

et al., 1998). Aliquots of sediment samples were dried and powdered for Rock-Eval/TOC analysis at the Geological Survey of Canada Calgary (GSCC). A Vinci Technologies Rock-Eval 6 instrument was used. Duplicate analyses of samples were carried out to test reproducibility of data. Each sample of about 100 mg of finely ground source rock is put in a furnace at 300°C, raised to 850°C, and then allowed to cool. The hydrocarbons liberated during heating are analysed by a flame ionisation detector, which separates the components into two parameters (Figure 2). The first peak, denoted S_1 (mg $_{HC}$/g $_{rock}$), indicates ’free bitumen’ already in the sample.The second peak, denoted S_2 (mg $_{HC}$/g $_{rock}$), results from thermal breakdown of kerogen. The Rock-Eval 6 S_3 parameter (mg $_{CO2}$/g or $_{CO}$/g $_{rock}$) represents the oxygen-bearing compounds released at the same time as the S_1 peak added to that obtained between 300° and 400° as measured by an infra-red cell. The temperature corresponding to the maximum of the S_2 peak (T_{max}) is an indicator of source rock maturity, although this value is only reliable when S_2 > 0.2 (Peters, 1986), and is also affected by organic matter type. An indication of source rock richness is given by the sum of the first two peaks (S_1 + S_2). Other determined parameters include the Hydrogen Index

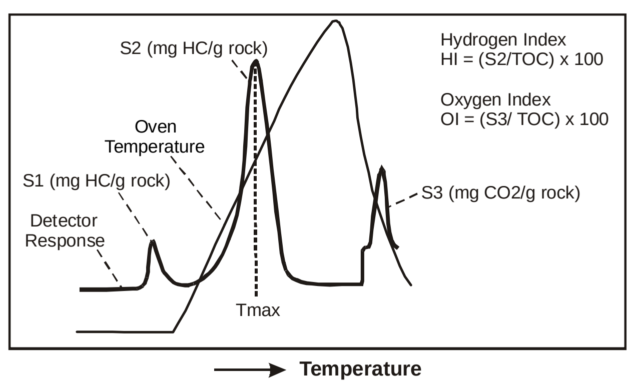

Figure 2. Schematic pyrogram illustrating the liberation of hydrocarbon during heating of the rock sample. Determined parameters include S_1, S_2, S_3, T_{max}, and the hydrogen and oxygen indices.

(S_2/TOC) and the Oxygen Index (S_3/TOC); these parameters are used to determine the type of organic matter present in a low maturity potential source rock.

The complete Rock-Eval pyrolysis dataset may be obtained at the BCGS website (Fowler, 2004). Source rocks with total organic carbon (TOC) contents of 0-0.5%, 0.5-1%, 1-2%, and > 2% are considered poor, fair, good, and very good, respectively (Peters, 1986). Using this classification, most samples, including all samples from the Sinwa Formation, are classified as poor to fair source rocks, with 22% classified as good, and 8% classified as very good (Figure 3). The good and very good source rocks within the Inklin Formation appear to occur dominantly in Pliensbachian successions.

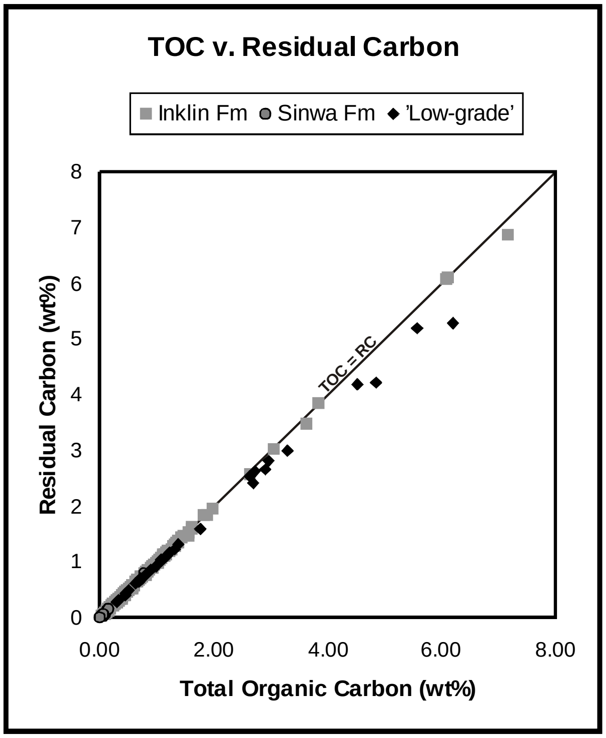

Figure 3. Plot of total organic carbon (TOC) versus residual carbon for samples from the central Whitehorse Trough. 'Low-grade' samples form a subset of the Inklin Formation samples, for which $S_2 > 0.2$ and $T_{max} < 480\ ^{\circ}C$.

However, most authors now believe that a TOC content of greater than 1% and likely a minimum of 2% is needed for the generation and expulsion of liquid hydrocarbons (Hunt, 1996; Meyer and Nederlof, 1984; Peters and Moldowan, 1993; Thomas and Clouse, 1990). Thus, few of the Whitehorse Trough samples are likely to have been oil-prone source rocks. TOC is almost equal to residual carbon in the majority of samples (Figure 3), indicating that there is little generative potential left in these rocks. Therefore, depending on organic matter type in these samples originally, they may have had much higher initial TOC contents. Consequently, samples presently having a TOC content of at least 1% could have been hydrocarbon source rocks assuming they originally contain oil-prone Type I or II organic matter.

The organic matter type in a source rock can be determined by plotting Hydrogen Index against the Oxygen Index (Espitalié et al., 1977; Figure 4). None of the potential source rocks sampled in the central Whitehorse Trough are oil prone; the majority are inert (low Hydrogen Index) due to the lack of generative potential, while the rest are gas prone (Figure 4). The lack of generative potential is mostly a function of high thermal maturity. From a spatial standpoint, samples that are gas prone and have generative potential are from the northeastern flank of the central Whitehorse Trough. This belt of rock is interpreted to represent the structurally and stratigraphically highest units within the Laberge Group in this region, and is interpreted to continue northeast beneath the structurally overlying Cache Creek Terrane.

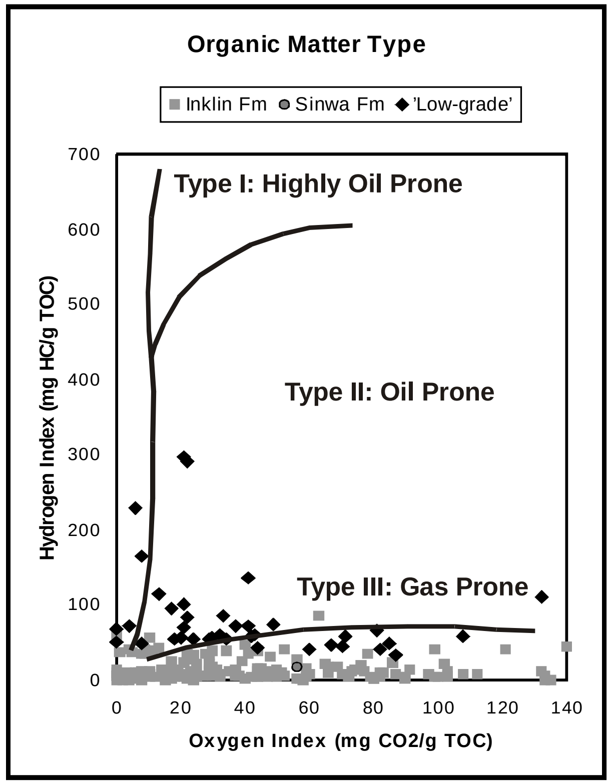

Figure 4. Plot of hydrogen index versus oxygen index for samples from the central Whitehorse Trough. 'Low-grade' samples form a subset of the Inklin Formation samples, for which $S_2 > 0.2$ and $T_{max} < 480\ ^{\circ}C$. The organic matter type in a source rock can be determined from this plot (Espitalié et al., 1977).

T_{max} can be used as an indicator of thermal maturation as long as $S_2 > 0.2$. Unfortunately, for the majority of samples, this qualifier rules out the interpretation of the pyrolysis data for maturation purposes. Once again, qualifying samples tend to come from the northeastern flank of the Whitehorse Trough, and these samples are within the oil and gas windows (Figure 5). Although, T_{max} values of samples with S_2 <

0.2 must be viewed cautiously, it can be graphically shown that most samples from the southwestern flank of the Whitehorse Trough are overmature (Figure 5). Distribution of mature and overmature areas of the central Whitehorse Trough can been seen by contouring T_{max} values (Figure 6), and is consistent with limited available vitrinite reflectance data (Table 1).

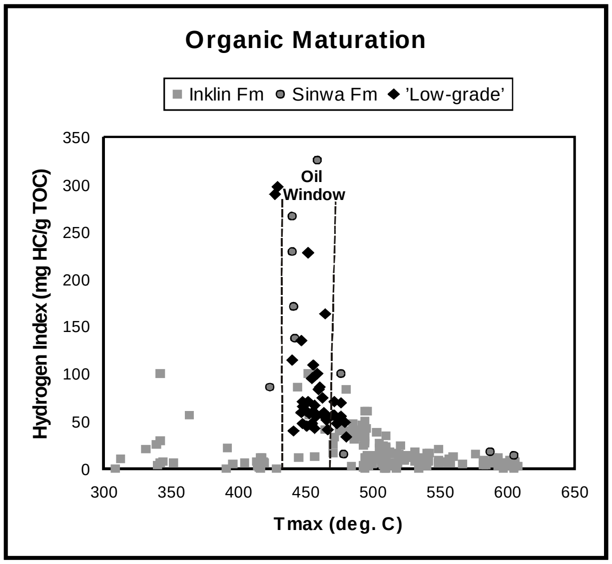

Figure 5. Plot of hydrogen index versus T_{max} for samples from the central Whitehorse Trough. 'Low-grade' samples form a subset of the Inklin Formation samples, for which S_2 > 0.2 and T_{max} < 480 °C. Due to low S_2 values, T_{max} values for the majority of other Inklin Formation samples are suspect and are dominantly overmature.

The vitrinite reflectance values suggest that potential source rocks along the northeastern flank of the central Whitehorse Trough are almost immature. If these vitrinite reflectance data are accurate, this may imply that there was even little hydrocarbon potential in the basin originally as these 'low maturity' samples have low Hydrogen Index values. Higher levels of organic maturation along the southwestern flank of the central Whitehorse Trough may reflect increased structural burial of these strata or contact metamorphism during Eocene magmatism.

SUMMARY

The Whitehorse Trough is an early Mesozoic marine sedimentary basin, which extends from southern Yukon to Dease Lake in British Columbia. Strata within the central Whitehorse Trough include carbonate rocks of the Upper Triassic Sinwa Formation, and interbedded sandstone, siltstone and argillite of the Lower Jurassic Inklin Formation. Programmed pyrolysis data indicate that potential source rocks in the Inklin Formation are gas-prone, and are within the oil and gas windows along the northeastern flank of the central Whitehorse Trough.

TABLE 1. VITRINITE REFLECTANCE DATA FROM THE ATLIN AREA, NW BRITISH COLUMBIA

Sample Number	Age	NAD	Easting	Northing	$R_o$max
GGAJ-92-59-2T	Late Pliensbachian	27	571625	6578475	0.6
GGAJ-92-56-T	Early Pliensbachian	27	568200	6576600	0.85
GGAJ-92-184-T	Early Pliensbachian	27	568575	6575975	0.85
GGAJ-92-119-T	Late Sinemurian	27	566725	6559450	1.45
GGAJ-92-177-T	Early Sinemurian	27	562950	6576175	1.54
GGAJ-92-45-T	Early? Sinemurian	27	566300	6574850	1.62
ABA02-13-1	na	83	602818	6543186	1.45
FCO02-1-2c	na	83	605002	6540947	2.36
JEN02-5-7	na	83	588036	6557555	0.85
JEN02-6-2a	na	83	588883	6557054	0.98
JEN02-19-9e	na	83	590287	6547881	1.87
LLE02-10-7	na	83	586892	6546875	1.79
MMI02-6-1-1	na	83	588017	6552900	1.07
MMI02-7-5-2	na	83	588090	6551600	1.65
MMI02-19-4-6	na	83	593505	6549108	2.05
MMI02-20-6	na	83	593040	6546960	1.79
ORO02-6-1c	na	83	589770	6555472	0.92
STJ02-3-3a	na	83	591257	6553403	1.05

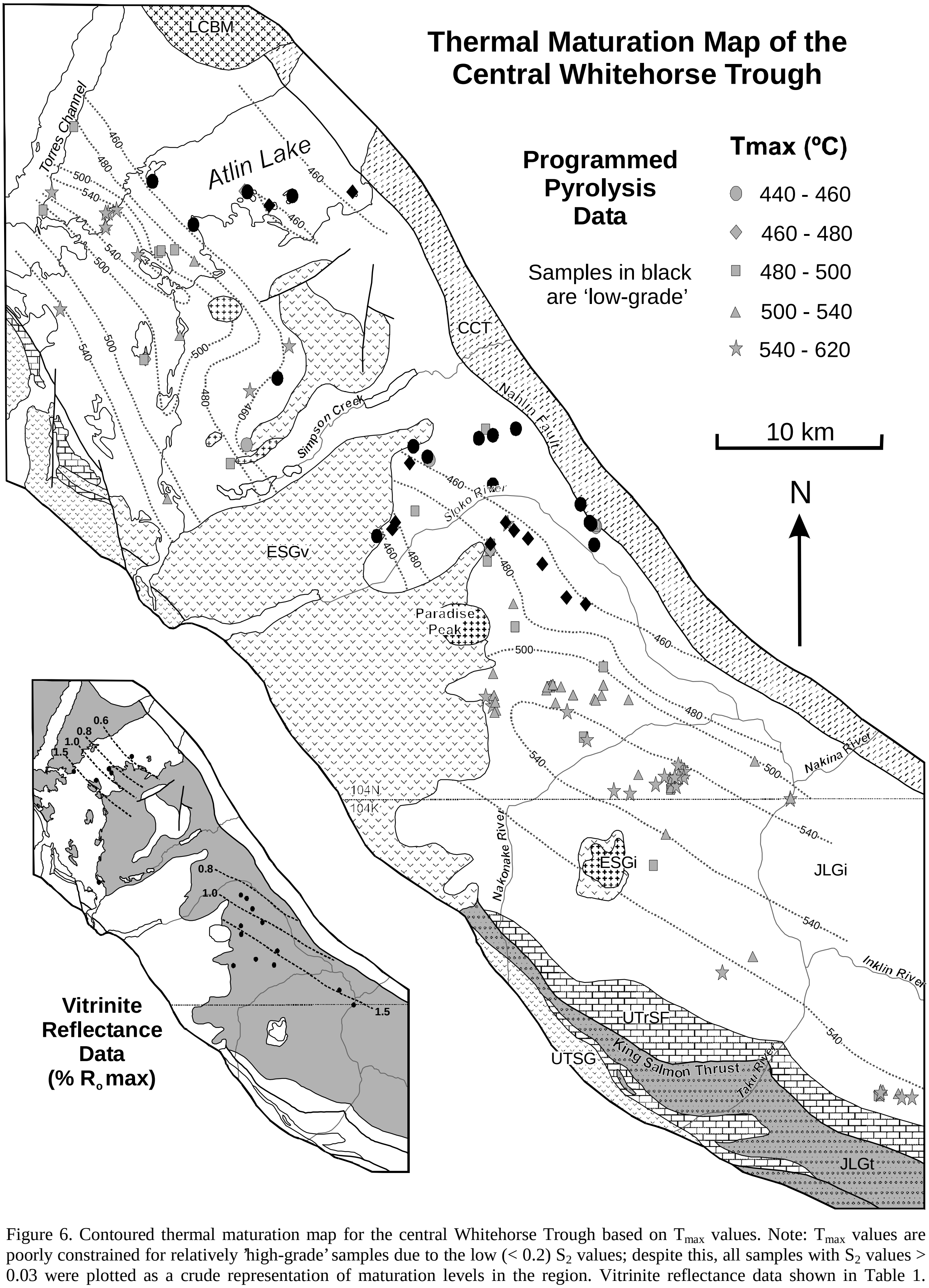

Figure 6. Contoured thermal maturation map for the central Whitehorse Trough based on T_{max} values. Note: T_{max} values are poorly constrained for relatively 'high-grade' samples due to the low (< 0.2) S_2 values; despite this, all samples with S_2 values > 0.03 were plotted as a crude representation of maturation levels in the region. Vitrinite reflectance data shown in Table 1. Abbreviations: CCT – Cache Creek terrane; ESGi – Eocene Sloko Group intrusions; ESGv – Eocene Sloko Group volcanics; JLGi – Jurassic Laberge Group Inklin Formation; JLGt – Jurassic Laberge Group Takwahoni Formation; LCBM – Late Cretaceous Birch Mountain pluton; UTrSF – Upper Triassic Sinwa Formation; UTSG – Upper Triassic Stuhini Group.

ACKNOWLEDGEMENTS

This research was funded by a University of Victoria Fellowship to J.E., an NSERC Discovery Grant to S.T.J., an NSERC Undergraduate Student Research Award to K.W., and by the Geological Survey of Canada and the British Columbia Ministry of Energy and Mines. Thanks to the rest of the bedrock geology mappers who worked in the Whitehorse Trough as part of this project: Fabrice Cordey, Lucinda Leonard, Adam Bath, Lee Ferreira, Jacqueline Blackwell, Fionnuala Devine, and Oliver Roenitz. Thanks to Lucinda Leonard for assistance in drafting figures. Thanks also to Norm Graham at Discovery Helicopters for logistical assistance. Figure 6 was prepared with the GMT software (Wessel and Smith, 1995).

REFERENCES

Bath, A. (2003): Atlin TGI, Part IV: Middle Jurassic granitic plutons within the Cache Creek terrane and their aureoles: Implications for terrane emplacement and deformation; in Geological Fieldwork 2002: B.C. Ministry of Energy and Mines, Paper 2003-1, pages 51-55.

Behar, F., Beaumont, V. and Penteado, H. L. D. B. (2001): Rock-Eval 6 Technology: Performances and Developments; Oil & Gas Science and Technology, Volume 56, pages 111-134.

Dickie, J. R. and Hein, F. J. (1995): Conglomeratic fan deltas and submarine fans of the Jurassic Laberge Grup, Whitehorse Trough, Yukon Territory, Canada: fore-arc sedimentation and unroofing of a volcanic island arc complex; Sedimentary Geology, Volume 98, pages 263-292.

Espitalié, J., Madec, M., Tissot, B., Mennig, J. J. and Leplat, P. (1977): Source rock characterisation method for petroleum exploration; Proceedings of the 9th Annual Offshore Technology Conference, Volume 4, pages 439-448.

Fowler, M. (2004): Rock-Eval VI analysis of samples from the central Whitehorse Trough; Energy-Resource Development and Geoscience Branch, B.C. Ministry of Energy and Mines, Petroleum Geology Open File 2004-2.

Gabrielse, H. (1998): Geology of Cry Lake and Dease Lake map areas, north-central British Columbia; Geological Survey of Canada, Bulletin 504, 147 pages.

Gilmore, R. G. (1985): Whitehorse field party; unpublished report; Petro-Canada, 16 pages.

Hannigan, P., Lee, P. J. and Osadetz, K. G. (1995): Oil and gas potential of the Bowser - Whitehorse area of British Columbia; unpublished report; *Institute of Sedimentary and Petroleum Geology*, 47 pages plus appendices.

Hart, C. J. R., Dickie, J. R., Ghosh, D. K. and Armstrong, R. L. (1995): Provenance constraints for Whitehorse Trough conglomerate: U-Pb zircon dates and initial Sr ratios of granitic clasts in Jurassic Laberge Group, Yukon Territory; in Jurassic magmatism and tectonics of the North American Cordillera, Miller, D. M. and Busby, C., Boulder, Colorado, Geological Society of America, Special Paper 299, pages 47-63.

Hunt, J. M. (1996): Petroleum Geochemistry and Geology; W.H. Freeman and Company, New York, 743 pages.

Johannson, G. G., Smith, P. L. and Gordey, S. P. (1997): Early Jurassic evolution of the northern Stikinian arc: evidence from the Laberge Group, northwestern British Columbia; *Canadian Journal of Earth Sciences*, Volume 34, pages 1030-1057.

Lafargue, E., Marquis, F. and Pillot, D. (1998): Rock-Eval 6 applications in hydrocarbon exploration, production and soils contamination studies; *Oil & Gas Science and Technology*, Volume 53, pages 421-437.

Meyer, B. L. and Nederlof, M. H. (1984): Identification of source rocks on wire-line logs by density/resistivity and sonic transit time/resistivity crossplots; *American Association of Petroleum Geologists Bulletin*, Volume 68, pages 121-129.

Mihalynuk, M. G. (1999): Geology and mineral resources of the Tagish Lake area (NTS 104M/8, 9, 10E, 15 and 104N/12W) northwestern British Columbia; *B.C. Ministry of Energy, Mines and Petroleum Resources*, Bulletin 105, 217 pages.

Mihalynuk, M. G., Erdmer, P., Ghent, E. D., Archibald, D. A., Friedman, R. M., Cordey, F., Johannson, G. G. and Beanish, J. (1999): Age constraints for emplacement of the northern Cache Creek terrane and implications of blueschist metamorphism; *in* Geological Fieldwork 1998, *B.C. Ministry of Energy, Mines and Petroleum Resources*, Paper 1999-1, pages 127-141.

Mihalynuk, M. G., Erdmer, P., Ghent, E. D., Cordey, F., Archibald, D., Friedman, R. M. and Johannson, G. G. (in press): Subduction to obduction of coherent French Range blueschist - In less than 2.5 Myrs?; *Geological Society of America Bulletin*.

Mihalynuk, M. G., Johnston, S. T., English, J. M., Cordey, F., Villeneuve, M. E., Rui, L. and Orchard, M. J. (2003): Atlin TGI, Part II: Regional geology and mineralization of the Nakina area (NTS 104N/2W and 3); *in* Geological Fieldwork 2002, *B.C. Ministry of Energy and Mines*, Paper 2003-1, pages 9-37.

Mihalynuk, M. G., Smith, M. T., Gabites, J. E., Runkle, D. and Lefebure, D. (1992): Age of emplacement and basement character of the Cache Creek terrane as constrained by new isotopic and geochemical data; *Canadian Journal of Earth Sciences*, Volume 29, pages 2463-2477.

Monger, J. W. H., Wheeler, J. O., Tipper, H. W., Gabrielse, H., Harms, T., Struik, L. C., Campbell, R. B., Dodds, C. J., Gehrels, G. E. and O'Brien, J. (1991): Upper Devonian to Middle Jurassic assemblages - Part B. Cordilleran terranes; *in* Geology of the Cordilleran Orogen in Canada, The Geology of North America, Gabrielse, H. and Yorath, C. J., Denver, Colorado, *Geological Society of America*, pages 281-327.

National Energy Board (2001): Petroleum resource assessment of the Whitehorse Trough, Yukon Territory, Canada; *Yukon Energy Resources Branch*, 50 pages.

Peters, K. E. (1986): Guidelines for evaluating petroleum source rock using programmed pyrolysis; *The American Association of Petroleum Geologists Bulletin*, Volume 70, pages 318-329.

Peters, K. E. and Moldowan, J. M. (1993): The Biomarker Guide; Prentice-Hall, Eaglewood Cliffs, New Jersey, 363 pages.

Ricketts, B. D., Evenchick, C. A., Anderson, R. G. and Murphy, D. C. (1992): Bowser basin, northern British Columbia : Constraints on the timing of initial subsidence and Stikinia - North America terrane interactions; Geology, Volume 20, pages 1119-1122.

Souther, J. G. (1971): Geology and mineral deposits of Tulsequah map-area, British Columbia; Geological Survey of Canada, Memoir 362, 84 pages.

Tempelman-Kluit, D. J. (1979): Transported cataclasite, ophiolite and granodiorite in Yukon : evidence of arc-continent collision; Geological Survey of Canada, Paper 79-14, 27 pages.

Thomas, M. M. and Clouse, J. A. (1990): Primary migration by diffusion through kerogen: II. Hydrocarbon diffusivities in kerogen; Geochimica et Cosmochimica Acta, Volume 54, pages 2781-2792.

Thorstad, L. E. and Gabrielse, H. (1986): The Upper Triassic Kutcho Formation, Cassiar Mountains, north-central British Columbia; Geological Survey of Canada, Paper 86-16, 53 pages.

Wessel, P. and Smith, W. H. F. (1995): New version of the Generic Mapping Tools released; Eos, Volume F359.

Wheeler, J. O. (1961): Whitehorse map-area, Yukon Territory (105D); Geological Survey of Canada, Memoir 312, 156 pages.