Indications for Effective Petroleum Systems in Bowser and Sustut Basins, North-Central British Columbia

By K.G. Osadetz[1], C.A. Evenchick[2], F. Ferri[3], L.D. Stasiuk[1] and N.S F.Wilson[1]

KEYWORDS: Bowser Basin, Sustut Basin, Bowser Lake Group, Sustut Group, Skeena Group, hydrocarbons, petroleum, oil, gas, thermal maturity, organic.

ABSTRACT

Field work in the Bowser and Sustut basins has found 'live" oil stains in Bowser Lake Group sedimentary rocks. This provides direct evidence that there is an effective petroleum system in the Bowser Lake Group, specifically, and in the Bowser and Sustut basins, generally. Other, anecdotal evidence suggests that natural gas is seeping from sub-Bowser Lake Group rocks, suggesting that they may also be targets for petroleum exploration. These conclusions are consistent with revised models of thermal maturity in Bowser and Sustut basins, that illustrate large lateral and stratigraphic variations in organic and thermal maturity. As a result of these developments existing petroleum assessments need to be expanded to capture both the reduced play level risks in Bowser Lake Group plays and to add the potential of lower rocks, the latter of which are not currently attributed any petroleum potential. Much additional work is needed to improve the characterization of petroleum potential in the Bowser and Sustut basins.

INTRODUCTION

Indications for an effective petroleum system provide positive evidence for the generation, migration, entrapment and preservation of hydrocarbons in sedimentary basins. This study examines new evidence for an effective petroleum system in the Bowser and Sustut basins of north-central British Columbia. Previous studies indicated that the highest stratigraphic levels of the Bowser Basin succession contain anthracite and semi-anthracite coals. This led many to infer that the stratigraphically lower parts of the Bowser Basin had little petroleum potential, as Hilt's law commonly follows stratigraphic position, with maturity increasing down section. A geographically more comprehensive study of thermal maturity indicated that the initial pessimistic view of petroleum potential was incorrectly founded because of large lateral and stratigraphic variations in thermal maturity (Evenchick *et al.*, 2002).

Subsequent field work this summer tested the re-evaluation of the thermal history and its implications for the petroleum potential of Bowser Basin. Indications for an active petroleum system, manifest as both observed stains of "live" petroleum in Bowser Lake Group sediments and anecdotal indications for active petroleum seepages, are clear indications of effective petroleum systems for both natural gas and crude oil. These observations are consistent with the more optimistic assessment of thermal maturity variations.

SETTING

The Bowser and Sustut basins are located in the Intermontane Belt of north-central British Columbia, between 55° N and 58° N latitude, and occupy an area of more than 60,000 km^2 (Figure 1). These basins lie between the metamorphic and plutonic Omineca and Coast belts (Wheeler and McFeely, 1991). Bowser and Sustut basins are vast, effectively unexplored regions, that are prospective for petroleum accumulation and development. They overlie Devonian to early Middle Jurassic strata of Stikinia, an allochthonous terrane that accreted to the western margin of North America in the Early Jurassic to early Middle Jurassic. Broadly then, the Bowser and Sustut basins are successor basins, like the Sverdrup Basin. The Sverdrup Basin contains approximately 25% of the natural gas and 10% of the crude oil reserve in Canada (Chen *et al., 2002).*

REGIONAL STRATIGRAPHIC FRAMEWORK

The region is underlain by three broad, partly overlapping, stratigraphic successions: Bowser Lake Group, Skeena Group and Sustut Group. Bowser Lake Group is the oldest, and most widespread succession. It includes upper Middle Jurassic to mid-Cretaceous clastic strata deposited in a variety of marine and nonmarine environments (*e.g.* Tipper and Richards, 1976; Evenchick *et al*., 2001). Bowser Lake Group was deposited directly on the allochthonous terrane Stikinia, and is composed primarily of clasts derived from the oceanic Cache Creek terrane, although Stikinia was a major source in the southern basin. Syntheses of Bowser Lake Group stratigraphy include those by Eisbacher (1974a; 1981), Tipper and Richards

[1]*Geological Survey of Canada, Calgary*
[2]*Geological Survey of Canada, Vancouver*
[3] *New Ventures Branch, BC Ministry of Energy and Mines*

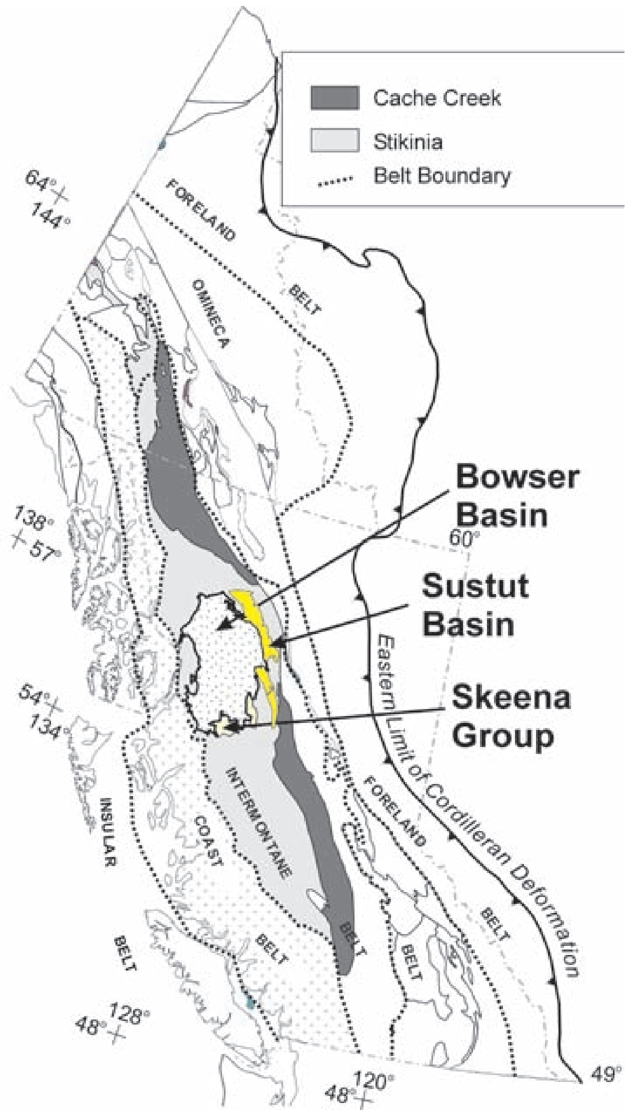

Figure 1. Location mapping showing the tectono-stratigraphic terranes and morphogeological belts of the Canadian Cordillera and the location of the Bowser and Sustut basins that are the subject of this study. Modified after Wheeler and McFeely, 1991. Locations of samples and observations are related explicitly in the text using UTM co-ordinates.

(1976), Bustin and Moffat (1983), Koo (1986), Moffat *et al.* (1988), Cookenboo and Bustin (1989), MacLeod and Hills (1990), Green (1992), Evenchick *et al.* (1992), Cookenboo (1993), Ricketts and Evenchick (1999), Evenchick (2001), Evenchick *et al*. (2000), Evenchick *et al.* (2001).

The Bowser Lake Group is divided into several lithofacies assemblages defined using lithologies, successions, and sedimentary structures. Each is interpreted to represent a dominant depositional environment in submarine fan, slope, shallow marine shelf, deltaic, and fluvial environments. This framework has been integrated with a comprehensive fossil database, permitting the regional interpretation of Bowser Basin depositional history (Evenchick, 2001; Evenchick *et al*., 2001). Mapped at reconnaissance scale, the distinctive lithofacies assemblages provide a major improvement that enhances petroleum system analysis, facilitates the search for reservoirs and traps, and identifies regions suitable for advanced geophysical prospect generation.

The Lower to mid- Cretaceous Skeena Group occurs south of the Bowser Basin. Its stratigraphic relationship to Bowser Lake Group is not clear. Skeena Group sediments were deposited in a range of marine to nonmarine environments, which locally included a volcanic provenance (Tipper and Richards, 1976; Bassett and Kleinspehn, 1997; Haggart *et al*., 1998). Mid-Cretaceous to Upper Cretaceous Sustut Group rocks occur along the northeast side of the Bowser Basin. Sustut sediments were deposited in fluvial and lacustrine environments, with possibly minor marine influence. On the southwest side of the Sustut Basin, these strata overlie deformed Bowser Lake Group and Stikine Terrane strata whereas to the northeast they overlie Stikine Terrane strata (Eisbacher, 1974b; Bustin and McKenzie, 1989; Evenchick *et al.*, 2001).

REGIONAL STRUCTURAL FRAMEWORK

Strata of Stikinia and the three overlying successions are folded and thrust faulted in contractional structures of the Skeena Fold Belt, a thin-skinned fold and thrust belt of Cretaceous age (Evenchick, 1991a). The dominant structures are open to close folds hundreds of metres to kilometer-scale wavelengths. Larger wavelength folds are associated with structural culminations of competent volcanic rocks of Stikinia. The dominant fold trend is northwest, but domains of northeast trending structures occur locally on the west side of the fold belt. Large-scale features of the fold belt are presented by Evenchick (1991a,b; 2001). Structural studies of more restricted areas include those by Moffat and Bustin (1993), and Bone (2002).

First order characteristics of the fold belt are (Evenchick, 1991a,b; 2001):

1. Folds in most of the belt trend northwest, are close to tight, and upright to inclined to the northeast;
2 Thrust faults are present, but difficult to recognize because Bowser Lake Group lacks distinctive regional stratigraphic markers;
3. Contractional structures affect underlying volcanic, clastic, and carbonate successions of Stikinia; the fold belt accommodated a minimum of 44% horizontal shortening;
4. It terminates to the northeast in a triangle zone within Sustut Group; and it is rooted in the Coast Belt to the west.

The scale of folds is controlled by the proximity to mechanically strong volcanic units in the Stikine Terrane. The relationships between structures and stratigraphic units indicate that orogenic shortening began prior to Albian (mid-Cretaceous) time, and continued into the

Maastrichtian (latest Cretaceous) or later (Evenchick, 1991a; 2001). Provenance and basin analysis link Sustut Basin subsidence to Skeena Fold Belt formation (Eisbacher, 1974b). Sustut Group and Devils Claw Formation are both inferred to be synorogenic deposits linked to Skeena Fold Belt deformation (Evenchick, 2001). The revised structural model, especially the identification of a triangle zone, has important implications for a revised petroleum assessment.

PREVIOUS WORK

PREVIOUS ASSESSMENT OF PETROLEUM POTENTIAL

Bowser and Sustut basins were assessed using a probabilistic play-based volumetric method (Hannigan *et al.,* 1995; Canadian Gas Potential Committee, 2001). The method (Lee, 1993) employs distributions of potential petroleum field parameters, constrained by available data, to calculate a conditional petroleum accumulation size distribution. By estimating both the number of potential prospects and the prospect-level risk it is possible to infer the likely number of petroleum accumulations to be found. This is used to produce a set of distributions that describe the probability of pool size for a pool of a given size rank. The play-level risk modifies the calculated total play potential. Because of the very large size of the basin and its untested structures, the basin was attributed a significant undiscovered potential, although this was significantly affected by play-level risks. Resource potentials were calculated for five anticlinal plays (Hannigan *et al*., 1995).

Skeena Group gas play has a mean in-place natural gas potential of 7.19 x 1010 m^3 (2.54 TCF - trillion cubic feet). The median largest field size is 1.47 x 1010 m^3 (519 BCF - billion cubic feet) in place. It is expected that about 19 Skeena Group gas fields will be found. Skeena Group oil play has a mean in-place potential of 2.01 x 108 m^3 or 1264 million barrels. The largest Skeena Group oil field is estimated to be between 1.00 x 107 m^3 and 1.42 x 108 m^3 or 63.1 to 893.3 million barrels. The expected number of Skeena Group oil fields is 16. Bowser Lake Group gas play has a total mean in-place gas potential of 5.78 x 1010 m^3 or 2.0 TCF. The median largest undiscovered field size (in-place) is 1.80 x 1010 m^3 (637 BCF). The assessment identified significant play level risks, especially for the preservation of Bowser Lake Group reservoirs. If gas fields exist in Bowser Lake Group then the expected number of fields is 173. No oil potential was assigned to Bowser Lake Group plays, because of the now-outdated thermal maturity model that prevailed at the time of the assessment. Sustut Group gas play is among the most attractive, despite significant concerns including the relative timing of trap formation to hydrocarbon generation. The mean in-place play potential is 5.27 x 1010 m^3 or 1.86 TCF of gas. The median largest Sustut Group field size is 1.24 x 1010 m^3 (438 BCF). The expected number of Sustut Group gas fields is 14. Sustut Group structural oil play has play parameters and risks similar to its gas play. The mean in-place Sustut oil potential is 1.84 x 108 m^3 (1158 million barrels) and the median largest field size is 4.17 x 107 m^3 or 262 million barrels. The expected number of oil fields in the Sustut Group is 14.

Revised stratigraphic and structural frameworks are key elements in improved calculations of Bowser and Sustut basin petroleum potential. Primary among these are division of the Bowser Lake Group into a number of lithofacies assemblages so that stratigraphic components of entrapment may be considered, and the revision of the structurally defined plays to consider a foreland fold and thrust belt that includes a frontal triangle zone. It is believed that the existing assessments (Hannigan *et al*., 1995; CGPC, 2001) have underestimated the petroleum potential because of perceptions that observed levels of thermal maturity in some of the highest stratigraphic levels were unfavorable for both the diagenesis of reservoirs (a play-level risk) and the function of the petroleum systems. Changes in the description of organic maturity history have had a profound impact on how the petroleum resource potential of the basin is perceived and risked.

REVISED THERMAL MATURITY MODEL

Petroleum resource potentials of these basins must be re-assessed using new stratigraphic and tectonic models which consider the physical environment, primarily temperature, and temporal relationships between hydrocarbon generation, migration, entrapment, and preservation. The first widespread thermal maturity data set for the Bowser and Sustut basins illustrates that large regions have sufficiently low organic maturity levels, that the generation and preservation of hydrocarbons and the diagenetic history of reservoirs are favourable for the formation and preservation of a significant petroleum resource (Evenchick *et al.,* 2002). These results are a substantial change from the previous view that the high thermal maturity of some of the highest Bowser strata is a negative indication for hydrocarbon potential in all stratigraphic levels and regions of the basin. Although parts of the study area are at very high thermal maturity levels, there are clear regional variations in the thermal maturity of outcrops such that even the lowest stratigraphic units are marginally to fully mature in select regions of the basin.

The presence of type 2 migrabitumen, identified in the thermal maturity study, is a positive indication for the generation and migration of liquid petroleum within the Bowser Basin. Together the revised patterns and levels of thermal maturity, combined with positive indications for the generation and migration of liquid petroleum, provides a much more positive indication for petroleum system function and petroleum preservation than was held previously. The preliminary thermal maturity data show a number of first-order patterns not previously recognized.

1) The highest levels of thermal maturity (Ro max > 2.5%) underlie a broad area and cross a wide range of stratigraphic units. This region coincides approximately with a broad aeromagnetic high. The high thermal maturity and aeromagnetic anomaly are possibly a result of bur-

ied Late Cretaceous and/or Tertiary plutons similar to those that outcrop in the southeast-most part of the study area. In this interpretation the plutons are the source of increased heat flow.

2) The northwest limit of the region described above coincides with areas of highest thermal maturity reported by Bustin and Moffat (1983). Although we recognize the same general pattern of reduced thermal maturity to the northwest, as noted by Bustin and Moffat (1983), in several areas, we observe and report lower thermal maturity than Bustin and Moffat (1983). This difference will be addressed in future analyses.
3) Significant portions of the northwest and western Bowser Basin are within the range of Ro max values compatible with oil and gas preservation. These regions were not previously recognized, and the lower thermal maturation than assumed indicates a greater possibility for oil and gas generation and preservation, and reduced exploration risk.
4) A broad band of strata in the northeast Bowser Basin and southwest Sustut Basin, coinciding with the roof of the triangle zone and regions structurally below the roof, reached peak thermal maturity in the main stage of oil generation. These relationships are highly favourable for a potential triangle zone play.
5) Northeast of the triangle zone, samples in the Sustut Group are consistently in the main stages of hydrocarbon generation. Although data are sparse, they are widespread in a large area of favourable stratigraphic and structural traps, and suggest reduced play-level risk. The combination of thermal maturity and structural position in the triangle zone are most favourable revisions of the geological parameters constraining petroleum potential. Not only was the triangle zone play not explicitly considered in the previous assessments (Hannigan *et al*., 1995; CGPC, 2001), but it presents a clear analogue to some of the most prospective and productive settings in the thrust and fold belt of the Foreland Belt of the southern Canadian Cordillera (Stockmal *et al*., 2001).

INDICATIONS FOR EFFECTIVE PETROLEUM SYSTEMS

OIL STAINS

A sample of an ammonite in a very fine grained chert arenite was collected from Muskaboo Creek assemblage marine succession at the "Tsatia Mountain" reference section , 02-OE-36 (NAD 27, UTM Zone V E442468 N6380068), during 2002 fieldwork. The sample was notable because material, initially suspected to be pyrobitumen, occurred as a cast in an anatomical sinus of the fossil. Subsequent and more careful examination indicates that the cast material is calcite blackened by numerous primary and secondary petroleum fluid inclusions. Petrographically these fluid inclusions are composed of a sky-blue fluorescing "live" oil (Figure 2). Some fluid inclusions in this material may also contain petroleum condensate. These

(a)
(b)
(c)

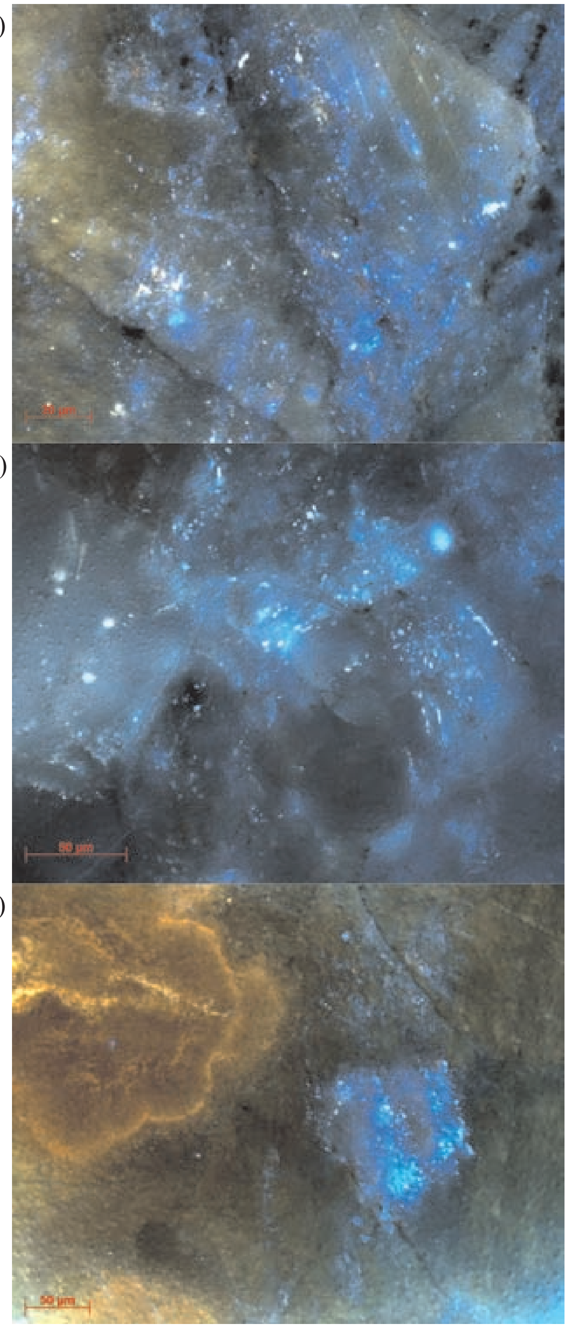

Figure 2. Photomicrographs of petroleum fluid inclusions from Muskaboo Creek Assemblage Rocks, Bowser Lake Group, at the "Tsatia Mountain" reference section , (NAD 27, UTM Zone V E442468 N6380068). Sample field number 02-OE-36; and GSC Calgary Collection Number C-428547. Organic Petrology Pellet Number 575/02, calcite 'vein' filling material in an ammonite fossil, Figure 2a, (top) and 2b, (middle) and 2c, (bottom). Abundant blue fluorescing crude oil inclusions, predominantly in coarse grained calcite, occur as both primary fluid inclusions and within micro-fractures within the calcite. Also present is an orange fluorescing fine grained botryoidal carbonate that may be fossil infill. The fluid inclusions are two-phase hydrocarbon fluid inclusions that might be suitable for the determination of homogenization temperatures. In colour the petroleum fluid inclusions are both bright yellow and blue, in black and white both populations of petroleum fluid inclusions are white. Scales as indicated.

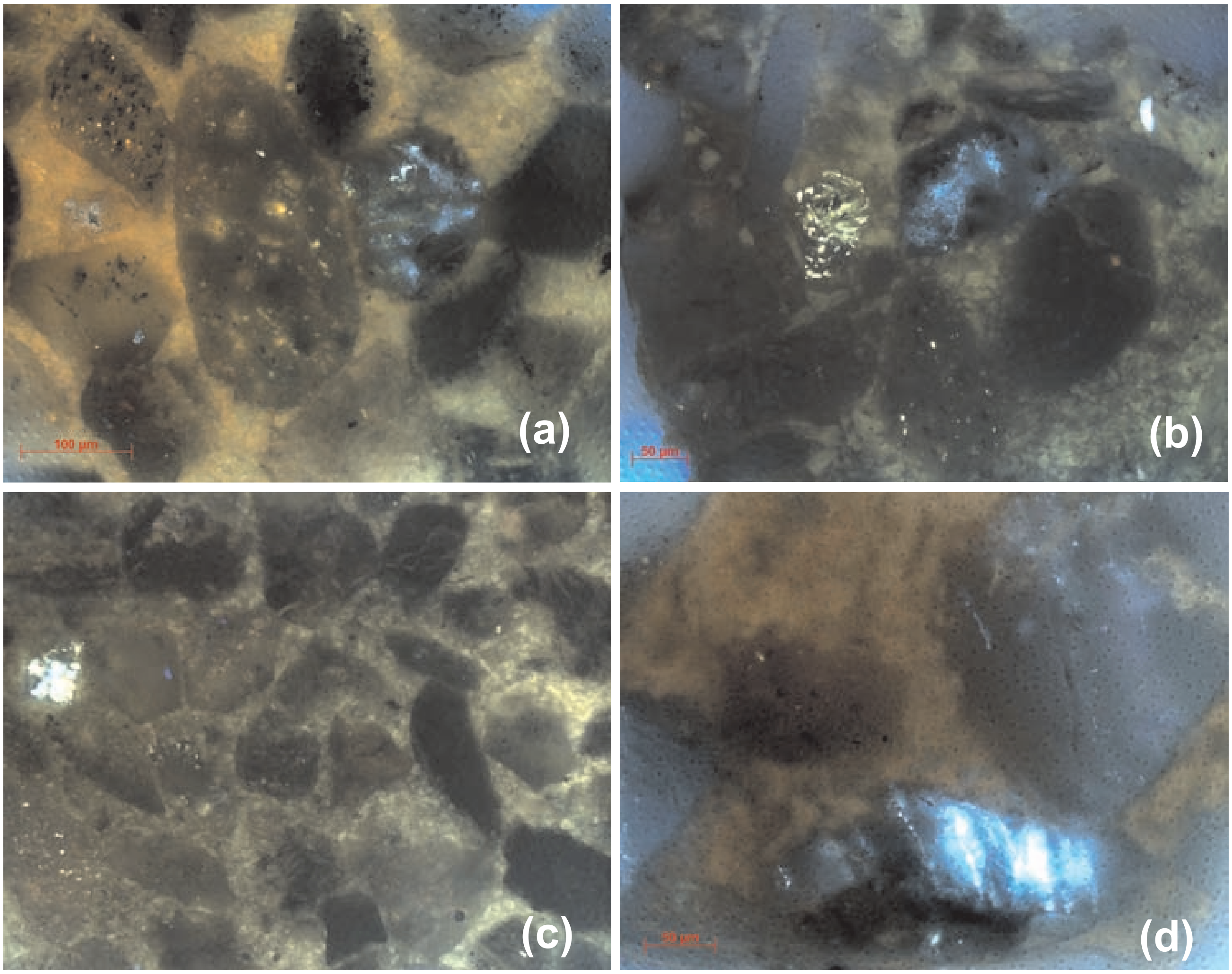

Figure 3. Photomicrographs of petroleum fluid inclusions from Muskaboo Creek Assemblage Rocks, Bowser Lake Group, at the "Tsatia Mountain" reference section , (NAD 27, UTM Zone V E442468 N6380068). Sample field number 02-OE-36; and GSC Calgary Collection Number C-428547. Organic Petrology Pellet Number 576/02, Muskaboo Creek Assemblage chert arenite, Figure 3a) and 3b) (top row, left to right) and 3c) and 3d) (bottom row, left to right) Abundant orange to yellow to white yellow crude oil inclusions within microfractured grains that occur with sparse blue fluorescing crude oils and condensate fluid inclusions. These petroleum fluid inclusions appear to be restricted to the mineral grains and do not occur in the fine-grained matrix and inter-particle regions. In colour the petroleum fluid inclusions are both bright yellow and blue, in black and white both populations of petroleum fluid inclusions are white. Scales as indicated.

petrographic characteristics indicate a petroleum composition consistent with an unaltered, low density, high thermal maturity crude oil, >45^{o} API. The occurrence mode and its position in the paragenetic sequence indicates that the oil in these petroleum fluid inclusions resulted from an indisputable secondary migration of petroleum into the fossil.

In addition, and quite unexpectedly, a large number of detrital chert grains from the host rock also contain fluorescing inclusions of "live" petroleum. The fluid inclusions have two dominant sets of petrographic characteristics and compositions whose mode of occurrence is similar. Typically the petroleum fluid inclusions occur as sub-parallel fine, linear to planar inclusions within individual grains, possibly following original bedding laminations, which are chaotically oriented within the chert arenite rock mass. The two sets of petroleum fluid inclusions contain distinctively different petroleum compositions. One set is composed of yellow to green fluorescing petroleum. This represents an inferred unaltered medium density petroleum of moderate thermal maturity, 30-35^{o} API. The other set is composed of sky blue fluorescing petroleum. This set is inferred to be compositionally similar to the petroleum in the ammonite cast filling material. It too is inferred to be composed of an unaltered, low density, high thermal maturity crude oil, >45^{o} API. The siliceous matrix of the sandstone does not appear to have petroleum fluid inclusions.

From these observations we infer that the detrital chert grains themselves are carrying two different petroleums of distinctive thermal maturity. The preservation of this difference is a strong indication that the local level of thermal maturity is equal to or less than that of the yellow-green fluorescing inclusions, or less than ~0.8 vitrinite reflectance equivalent. This is consistent with the maturities reported locally from other petrographic samples (Evenchick *et al.,* 2002). It confirms that the basin contains regions of thermal maturity suitable to the generation and preservation of crude oil. When and where the petroleum fluid inclusions in the detrial chert grains originated is not yet determined. They may represent an in-situ generation of petroleum, in which case the petroleum generation would have to predate their formation as detrital grains. Alternatively, they might be composed of oils generated during multiple phases of secondary migration, or some combination of autochthonous and allocthtonous petroleum generation. The secondary stained calcite in the ammonite, the "vein filling", has a much higher thermal maturity than the sedimentary rocks it hosts, suggesting secondary migration of an oil of greater than 45^{o} API through the Bowser sediments at this locality.

The details of the diagenesis and the significance of the absence of petroleum fluid inclusions in the cement of the arenite are currently the subject of additional study. As well, it may be possible to perform a solvent extraction on the sample for the purpose of characterizing the bulk and molecular composition of the petroleum. The extent of these stains in the basin should be examined in greater detail and more petrography should be done on available samples.

ANECDOTAL INDICATIONS FOR SEEPAGES

In the course of fieldwork this season, local residents Mr. Hal and Mrs. Bunty Althaus, proprietors of the Tatogga Lake Resort, on the eastern shore of Tatogga Lake, volunteered knowledge of a persistent possible natural gas seepage adjacent to their dock. Mr. And Mrs. Althaus characterized the possible gas seep as:

- Persistent. They had been aware of the seepage in the same location for about ten years, 'ever since they had owned the place';
- Of noticeable volume. They had observed anomalous freezing and melting behaviour in the lake over the possible seepage, identical to petroleum gas seepages that one of us (Osadetz) had observed elsewhere, and;
- Flammable. Mr. Althaus recounted how he had once ignited gas from the seepage.

The site of the possible seepage, (NAD 27, UTM Zone V E440380 N6396997 ~+825m elev.), was visited by two of us (Osadetz and Ferri) that day, but conditions on the lake, including a considerable chop, and the recovery efforts at a crashed floatplane adjacent the dock, were not conducive to successfully observing a seepage free of contamination.

The possible seepage, at this locality, occurs in a region of Hazelton or Stuhini group outcrop and the pattern of local thermal maturity is consistent with a possible natural gas seepage from these rocks. The manner in which the information was volunteered, the consistency of the recounting by both Mr. And Mrs. Althaus, and the description of anomalous freezing and melting behaviour at the site of the possible seepage were consistent with it being a natural seepage of thermogenic petroleum. Additional work, at the site of the possible seepage accompanying the early days of freezing on the Lake, and elsewhere in the vicinity, as well as additional interviews of local residents, is warranted.

DISCUSSION

The observation of "live" petroleum stains, both in "vein-filling" material and "detrial" clasts of Bowser Lake Group occur within the region where the revised thermal maturity model suggests that the Bowser Lake Group is within the main stage of petroleum generation. The different petrographic characteristics of the inclusions are a clear indication that at least some of the higher maturity, sky blue fluorescing, petroleum fluid inclusions have migrated into these rocks. When these observations are combined with the anecdotal indications for a natural gas seepage from sub-Bowser rocks at Tatogga Lake it is clear that there is an effective petroleum system, or systems, operating in the Bowser and Sustut basins of the Intermontane Belt. These observations, and the composition of the petroleum at each occurrence, are consistent with the revised thermal maturity observations and patterns reported by Evenchick *et al.* (2002). The corroboration of this much larger data set of thermal maturity indicators suggests that the general inferences of that report are correct. Together these observations reduce play level risks that were applied to the existing petroleum assessments. This suggests that the assessments should be revised to consider these new, more favourable data. The impact of such a revision can be inferred qualitatively to increase both the size and certainty of the mean petroleum resource potential in the Bowser and Sustut basins. Most important, the indications for possible gas seepage in regions of sub-Bowser Lake Group outcrops suggests that there may be petroleum potential in lower strata. These new plays need to be defined and should be used to augment the existing set of petroleum plays in subsequent reassessments of the petroleum potential of Bowser and Sustut basins.

There is a general tendency to consider regions of high thermal maturity as unfavourable for petroleum preservation and occurrence. However, data from the United States shows that petroleum potential and production remains even where rocks have been buried to very great depths and reached high temperatures (Dymond and Osadetz, 2002). In the U.S.A., 20,715 wells have been drilled to depths greater than 15,000 feet, or ~5 kms. 11,522 of these deep wells are producing petroleum wells and 5,119 of these wells are producing from the deepest formation penetrated. In 1999 more than 1.5 TCF of natural gas was produced from wells completed deeper than ~5 kms. Acknowledging the increased risk with complicated and deep burial, it is valuable to consider that the limits and margins of petroleum production from sedimentary rocks are best proved by the drill bit than by inferences and models that are often valid only in specific geographic regions.

CONCLUSIONS

Field work in the Bowser and Sustut basins has found migrated and possibly indigenous 'live' oil stains in Bowser Lake Group sedimentary rocks. This provides direct evidence that there is an effective petroleum system in the Bowser and Sustut basins. Anecdotal evidence suggests that flammable, probably petroleum, natural gas is seeping from sub-Bowser rocks near the edge of Tatogga Lake. This suggests another target for petroleum exploration. As a result of these developments, existing petroleum assessments need to be expanded to capture both the reduced play level risks in Bowser Lake Group plays and to add the potential of sub-Bowser Lake Group rocks, the latter of which are not currently attributed any petroleum potential. These conclusions are consistent with revised models of thermal maturity in Bowser and Sustut basins (Evenchick *et al*., 2002), which are much more favourable for petroleum preservation and entrapment than previous, still locally valid, models (Bustin and Moffat, 1983). Much additional work is needed to improve the characterization of petroleum potential in this region.

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