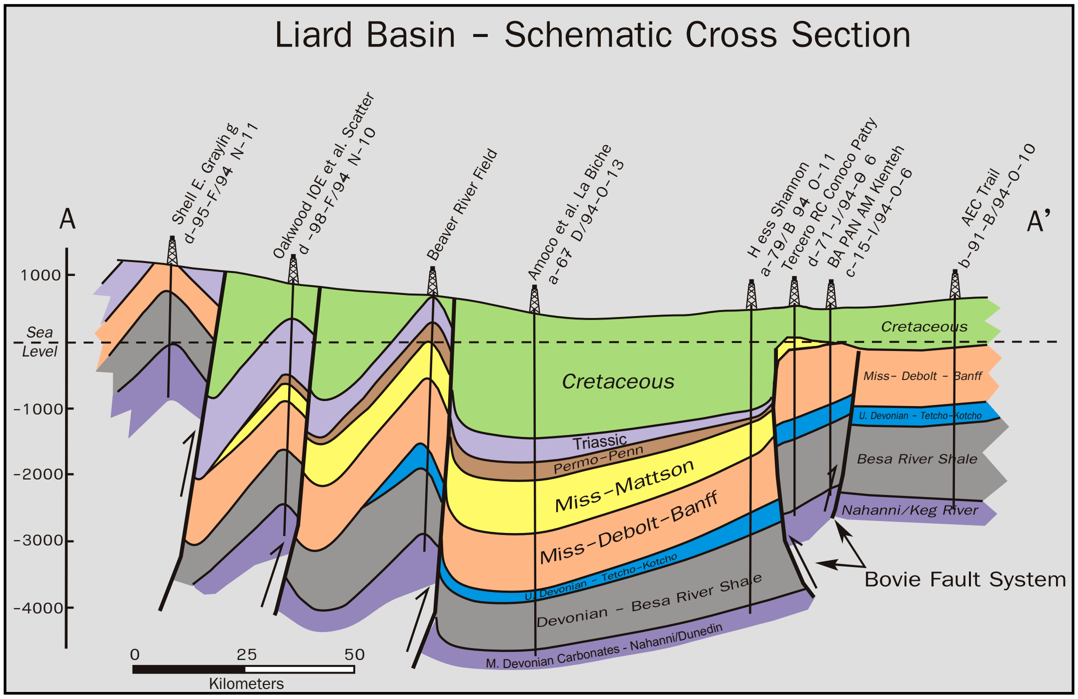
Ministry of Energy, Mines and Petroleum Resources
Oil and Gas Division
Resource Development and Geoscience Branch



Summary of Activities 2005

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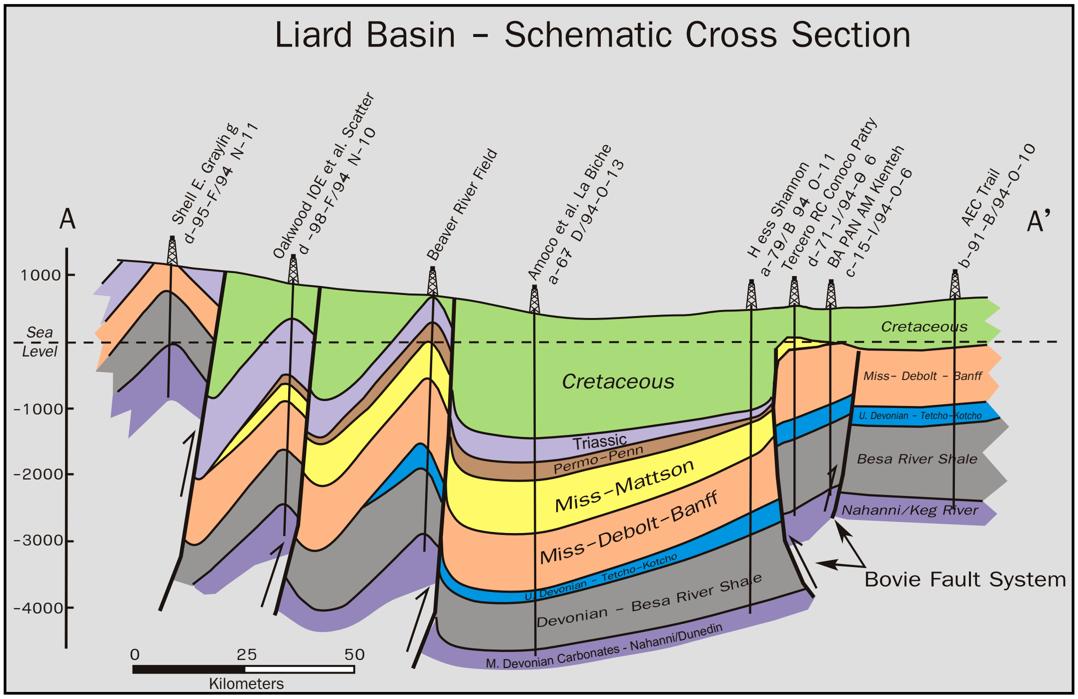

Liard Basin – Schematic Cross Section

Summary of Activities 2005

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The Liard Basin, a sub-basin of the Western Canada Sedimentary Basin (WCSB), straddles the Northwest and Yukon Territories boundary with the Province of British Columbia. The basin contains over five kilometres of sedimentary strata of Cambrian through Upper Cretaceous age. The western side of the Liard Basin is referred to as the Liard Fold and Thrust Belt and the east boundary is defined by the Bovie Fault system. Exploration within the basin began in the 1950s with the first well drilled in the Liard Fold and Thrust Belt at the Toad River Anticline. For more information, see article by Walsh *et al*., (this volume).

In referencing articles within this publication, please use the format in the following example:

Ferri, F. and Boddy, M. (2005): Geochemistry of Early to Middle Jurassic Organic-Rich Shales, Intermontane Basins, British Columbia; in Summary of Activities 2005, BC Ministry of Energy and Mines, pages 132-151.

FOREWORD

Increasing energy production from conventional and unconventional resources has positioned the province of British Columbia as one of Canada's energy leaders. The goals and strategies set out by the Ministry of Energy and Mines play a significant role as energy continues to generate wealth. The Ministry is the steward of energy and mineral resources and is mandated to protect the public interest in development of these resources and ensure that the benefits of these developments are maximized for all residents of the province.

One of the Ministry's key objectives is to provide a strong, competitive oil and gas sector while working with governments, First Nations and communities. Further implementation and refinement of the Ministry's Oil and Gas Development Strategy has been the main catalyst for increased capital investment in British Columbia's oil and gas sector. The annual dollar amount of oil and gas industry capital investment in British Columbia is expected to reach $4 billion in 2005.

The Resource Development and Geoscience Branch within the Oil and Gas Division, serves as the lead unit within the Ministry in supplying petroleum geoscience information and knowledge to the province. It conducts ongoing energy-related projects that encompass a wide variety of studies, papers, and articles that summarize geoscience and resource development activity. This second volume of the "Summary of Activities" is the result of work completed by Branch staff; they have contributed the majority of the articles enclosed.

Geoscientists from the Geological Survey of Canada and the Alberta Geological Survey, have authored and co-authored articles on the Skeena and Bowser Lake Groups and highlighted results from surficial geology mapping. University research projects also play an important role in this volume. Contributions by the University of Alberta, University of Calgary, University of Regina, University of Victoria, and Simon Fraser University are presented here.

Some of the highlights in this volume include papers on the following:

- Exploration in the Middle Devonian Liard Basin
- Aggregate and surficial geology mapping in northeast British Columbia
- Bedrock topography mapping program and shallow gas in northeast British Columbia
- Implementation of geomatics technology for aggregate exploration in northeast British Columbia
- Bowser Lake Group stratigraphy and its relationship to the overlying Cretaceous Skeena Group
- Cumulative coal thickness and coalbed gas potential in the Comox Coal Basin on Vancouver Island

The Resource Development and Geoscience Branch continues to publish numerous open files, studies, special papers and other products, which recently included an analysis of shale gas potential in British Columbia. The Branch also continues to make improvements and add new information to its website at www.em.gov.bc.ca/oil&gas.

I thank all the authors for their contributions, dedication and perseverance; they have made this second volume another success. Lastly, these are exciting times for geoscience and its vital contributions to society. This volume contributes to our outreach efforts and documents important new findings.

Derek Brown
Executive Director,
Resource Development and Geoscience Branch
Ministry of Energy and Mines

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STRATIGRAPHY AND RESERVOIR ASSESSMENT OF PRE-GIVETIAN STRATA IN NORTHEASTERN BRITISH COLUMBIA

Ayse Ibrahimbas[1] and Warren Walsh[2]

ABSTRACT

Northeastern British Columbia's conventional undiscovered hydrocarbon resource is estimated at 30 trillion cubic feet (Tcf), the majority of which is expected to be present in high-risk deep stratigraphic and foothills plays. In northeastern British Columbia, lower Paleozoic strata record the platform to basinal transition of a passive margin miogeocline. However, only limited data are available in the subsurface; the purpose of this study is to examine and correlate the subsurface data with existing surface studies and assess the reservoir potential of these strata.

Exposures of basinal shales of the Road River Group to platform and shelf carbonates of the Kechika, Skoki, Nonda, Muncho-McConnell, Stone, and Dunedin Formations are present in the Cordillera. In the subsurface, platform carbonates present in the westernmost part of the basin are correlative with a much thinner and discontinuous succession of carbonates and evaporates. Periodic influx of clastics, mostly sourced from the Peace River Arch (PRA), into the basin are observed as mature quartzose sediments either mixed in carbonates or deposited as sandstone sheets, as in Cambrian sandstones and Wokkpash Formation.

Potential reservoir zones exist in dolomite units of Middle to Lower Devonian Lower Keg River-Chinchaga, Dunedin, and Stone Formations and in quartz arenites of the Wokkpash Formation. Textures observed in dolomites of the Chinchaga, Stone, and Dunedin Formations are dominated by micro- to cryptocrystalline anhedral to euhedral crystals with little, if any, intercrystalline porosity. However, large saddle dolomite crystals, possibly filling vuggy or fracture porosity, offer potential for reservoir development. Drill Stem Tests (DSTs) show low to high permeabilities, with gas recoveries from these zones. Quartz arenites of Wokkpash Formation contain mature sandstones with carbonate cement. No intercrystalline porosity is observed in thin sections; however, microfractures may provide some porosity and permeability. Limited DST measurements from this unit show low to average permeability with some fluid recovery. This unit may have fractured-reservoir potential, depending on the density of the open fractures and the fracture patterns in a suitable trap setting.

KEYWORDS: Subsurface Lower Paleozoic Stratigraphy, Northeastern British Columbia, Reservoir Assessment, Wokkpash Sandstone

INTRODUCTION

Increase in the demand for and the declining production of the known hydrocarbon plays in Western Canada Sedimentary Basin (WCSB) has caused not only an increase in exploration studies but also a need for reassessment of the available wells and plays. Deep stratigraphic and foothills plays hold great potential for future gas supply, which to date has been explored very little in northeastern British Columbia. Due to current and expected increase in demand, previously subeconomic reservoirs, determined from DSTs and production tests, are now in need of re-evaluation with the aid of improved seismic and drilling techniques,.

The main objective of this study is to correlate pre-Keg River–Chinchaga strata in northeastern British Columbia. These subsurface correlations are based on 65 wells that penetrate the Lower Paleozoic strata and are tied to paleogeography and outcrop studies done previously by other authors (Taylor and Stott, 1999; Ferri *et al.*, 1999; Pyle and Barnes, 2000, Taylor and Stott, 1973; Fritz, 1980C; Gabrielse, 1981; Taylor *et al.*, 1979; Thomson, 1989) (Figure 1). A stratigraphic framework is constructed for the Lower Paleozoic using cross-section correlations and literature data.

The second objective of this study is an assessment of hydrocarbon potential in pre-Keg River–Chinchaga strata. A detailed study is done using drill cutting sample descriptions, thin section descriptions, DST results, and well-site reports.

This study addresses the following issues:

- regional subsurface correlation of pre-Keg River–Chinchaga strata,
- correlation of this strata with the outcrop equivalents,
- geologic setting and major paleogeographic elements,

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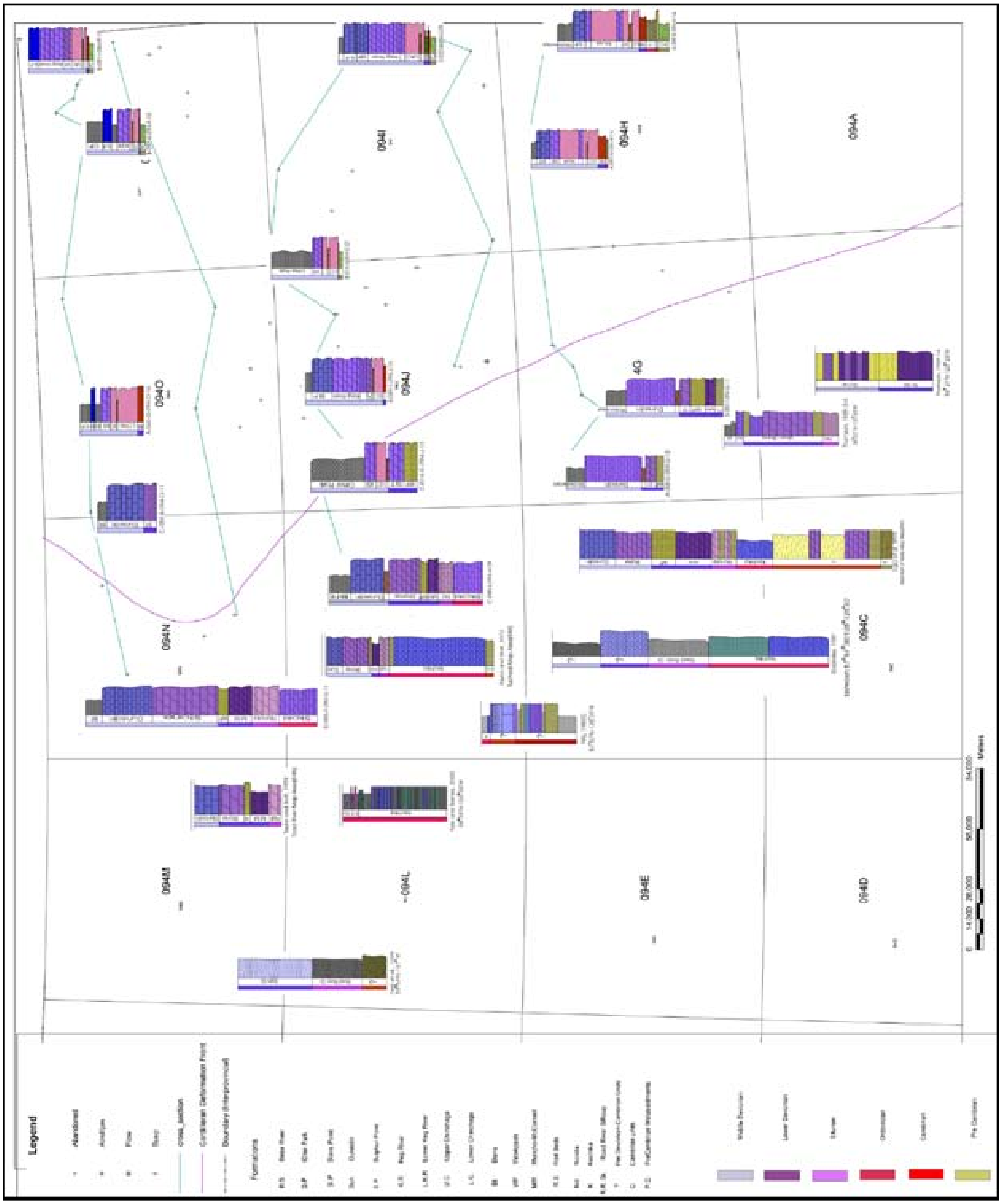

Figure 1. Map showing the previous studies by Taylor and Stott, 1999; Ferri et al., 1999; Pyle and Barnes, 2000, Taylor and Stott, 1973; Fritz, 1980C; Gabrielse, 1981; Taylor et al., 1979; Thomson, 1989.

- a top database of the 65 wells penetrating this interval,
- thin-section study for both correlation of the units and reservoir quality assessment, and
- assessment of potential reservoir units.

GEOLOGIC SETTING AND PALEOGEOGRAPHY

During the Lower Paleozoic, deposition within the WCSB occurred in a miogeocline on the passive margin of western North America. This miogeocline formed as a result of Late Proterozoic rifting, hosting Uppermost Proterozoic to Lower Devonian rocks with distinct periods of rifting and extension. This resulted in complex paleogeography and the depositional fabric variation observed in Lower Paleozoic rocks. The southern Canadian Cordillera, including the study area, is named the Southern Cordilleran Upper Plate Zone by Cecile et al. (1997) and has characteristics of an upper plate margin in an asymmetric rift setting, as described by Lister et al. (1991). The upper plate margin is defined by a narrow continental shelf with continentward crustal highs produced by steeply dipping extensional faults. These abrupt variations in the basement structure affect the depositional setting.

The major paleogeographic elements in northeastern British Columbia during the Lower Paleozoic were the Kechika Trough, representing deep marine deposition, and adjacent MacDonald Platform carbonates, defined as a Continental Shelf province (Figure 2). The cratonic platform to the east has thin, shallow- to restricted-marine sediments (Cecile et al., 1997; Morrow and Geldsetzer, 1988). Lower Paleozoic sedimentation was also affected by paleotopographic highs such as the Peace River Arch, the MacDonald High, and the Tathlina High. The Liard Line and Great Slave Lake Shear Zone are northeast-trending basement lineaments, which also affected the Lower Paleozoic paleogeography (Cecile et al., 1997).

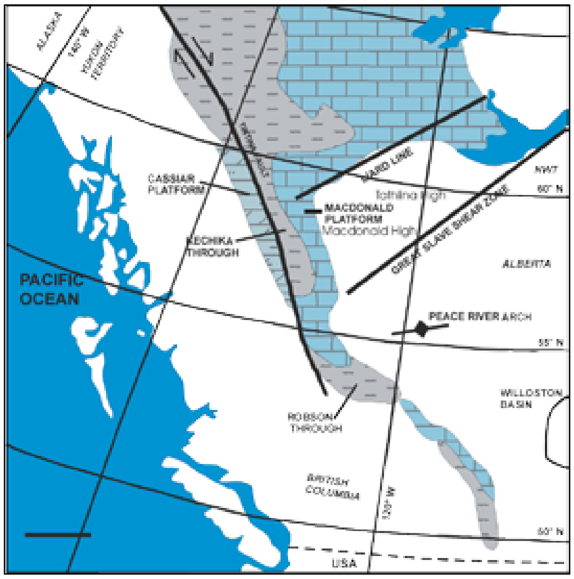

Figure 2. Map of the lower Paleozoic palegeography with the major depositional and the structural elements (Modified from Cecile et al., 1997)

STRATIGRAPHY

Stratigraphic studies on Lower Paleozoic strata of northeastern British Columbia have been done since the late 1960s, mostly as surface studies for individual map areas (Ferri et al., 1999; Fritz, 1980; Gabrielse, 1981; Pyle and Barnes, 2000; Taylor et al., 1979; Taylor and Stott, 1973, 1999; Thomson, 1989; Cecile and Norford, 1979). Pugh (1973) completed a detailed study of the subsurface of Lower Paleozoic stratigraphy in northern and central Alberta, in which he defined the nomenclature used in more recent studies. Hein and McMechan (1994), Meijer Drees (1994), and Slind et al. (1994) have compiled available subsurface studies and demonstrated the stratigraphic rela-

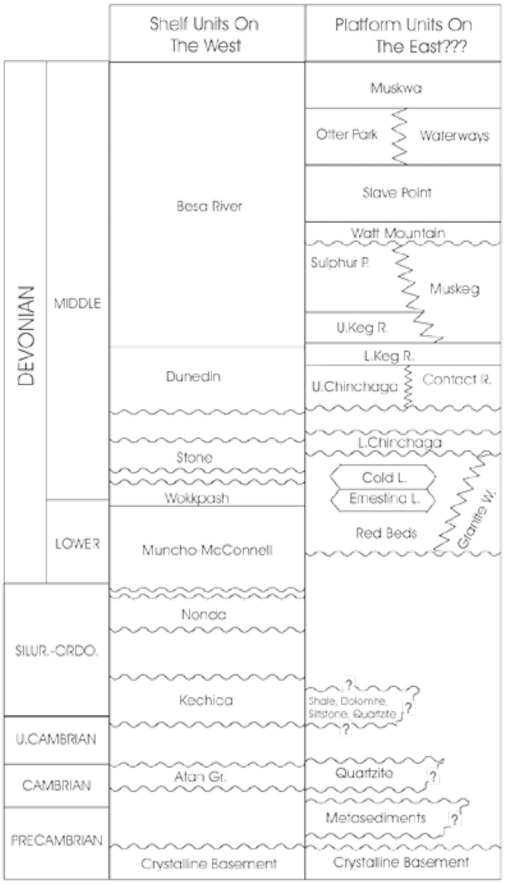

Figure 3. Generalized stratigraphic chart for this study for the Precambrian and Lower Paleozoic in northeastern British Columbia. (Also compiled from Slind et al., 1994; Hein and McMechan, 1994; Meijer Drees, 1994). Time intervals, unit thicknesses, and erosional or depositional effects are not shown to scale.

tionships of the Lower Paleozoic units in a regional sense within the WCSB. The nomenclature used for this study is based on their work (Figure 3).

Precambrian Metasediments: The oldest strata penetrated by the wells in the study area are the fine clastics of Precambrian age. The drill cutting samples of green to olive-grey coloured mudstone and siltstone with chlorite are similar to those of the Middle Proterozoic Muskwa Assemblage, as described by Taylor and Stott (1973). The wells penetrating this succession are mostly in the northeastern part of the study area, where the strata unconformably underlie Mid-Devonian evaporates (Figures 4, 5, and 6). The Muskwa assemblage is interpreted as a possible re-entrant into the ancestral North American plate that affected much of northeastern BC. Thomson (1981) suggests from the seismic-reflection data that more than 2000 m of pre-Middle Devonian strata is present, most of it as the Muskwa assemblage in the western margin of the plains in southeastern Fort Nelson Map area (94J).

Cambrian: The Cambrian strata consist of quartz arenite, which unconformably overlies Precambrian rocks. This unit is composed of mature quartz arenites, siltstones, and orthoquartzites that are correlated to the Middle Cambrian Atan Group in the northern Rocky Mountains and the quartzites of the Gog Group in the south (Taylor and Stott, 1973; Hein and McMechan, 1994).

The sandstones are fine- to medium-grained and fairly well sorted. The diagenetic minerals include syntaxial quartz overgrowths, pore-filling carbonate cement, and pyrite cement, especially in the siltstones (Figure 7).

In well BRC HTR ET AL RING a-49-B/94-H-16 (Figure 8), a 12 m zone of red beds composed of poorly sorted floating quartz grains in a hematite-bearing matrix underlies the sandstones and unconformably overlies the Precambrian strata. A few highly corroded feldspar grains are also visible; however, there are no other lithic fragments present. These sediments are probably more distal equivalents of the red fanglomerate deposits of the Atan Group described by Taylor and Stott (1973). Gehrels and Ross (1998) suggest a large region of the northwestern Canadian Shield for provenance of these sandstones because of the broad range in age of the detrital zircons sampled. The high maturity of these sandstones may also be due to recycling of detritus from older units.

Upper Cambrian(?), Silurian, and Ordovician: The strata overlying the Cambrian quartzites in the east are grey-green waxy shales interbedded with siltstones and dolomites, as described from drill-cutting samples. The strata lie between the Lower to Lower Middle Devonian Red Beds and the Cambrian quartzites. When using the cross sections and the petrophysical logs, they may be correlated with either the fine-grained clastics of the Mount White and the Earlie Formations overlying the Gog Group (Slind *et al.*, 1994) or with remnants of the Silurian-Ordovician strata (Figures 8 and 9). These strata are penetrated by only two wells in the southeast of the study area and are absent in the west, suggesting that they are not continuous but rather locally deposited or preserved.

In the west, limestones of the Kechika Formation, dolomites of the Nonda Formation, and the base of the Muncho-McConnell Formation all are correlated to Ordovician-Silurian strata deposited in the platform setting (Figure 3). There are only a few wells further northwest that penetrate the Nonda and Skoki Formations, indicating the eastern subsurface edge of the platform (Figures 4 and 5).

Lower and Lower-Middle Devonian: Lower-Middle Devonian strata on the platform are represented by red beds of interbedded shale, siltstone, and dolostone, along with dolomites and anhydrites of the Ernestina Lake Formation, and finally locally thin salt beds of the Cold Lake Formation. At the northern margin of their area of preservation, the lower Paleozoic rocks form the erosional escarpment of Meadow Lake, which was the limit of a Middle Devonian sea within which the lower Elk Point evaporites were deposited along the margins of the basin (Meijer Drees, 1986). The base of these units coincides with the pre-Devonian erosional unconformity.

In the west, the Wokkpash Formation, quartzites of the regressive phase of the Muncho-McConnell Formation, and the unconformably overlying sandy and silty dolomites of the Stone Formation represent the Lower and Lower-Middle Devonian. The Wokkpash Formation, which conformably overlies the Muncho-McConnell, is a succession of nearshore dolomitic quartz arenite (Figures 8 and 9). The unit is extensively correlated in the subsurface of the study area, with thicknesses up to 100 m in the well logs. It is also extensive in the mountains and mapped further south in the Halfway Map Area by Thomson (1989), to the north in Tuchodi Lakes Map Area by Taylor and Stott (1973), and in the Toad River Map Area by Taylor and Stott (1999). The unit is composed of fine- to coarse-grained moderately sorted quartz arenites with a number of diagenetic sequences. The earliest diagenetic feature is the growth of syntaxial quartz overgrowth; the original grain fabric is not visible. Rare, mostly dolomitized carbonate cement has infilled the crystalline pore space. Some zones were subjected to extensive pyrite participation, and in one slide, poikilotopic anhydrite cement is also seen, all indicating a complex diagenetic history. The quartz arenites are extensively strained, having a dense fabric of microfractures (Figure 10). Nadjivon and Morrow (in press) described the unit as indicative of a shallow-marine foreshore to nearshore environment with moderate to high energy levels, such as a barrier bar complex (Figure 11).

The Lower Elk Point evaporates are unconformably overlain by anhydrites and dolomites of the Chinchaga Formation on the east and the sandy dolomites of the Stone Formation on the west by transgression (Figure 12). The

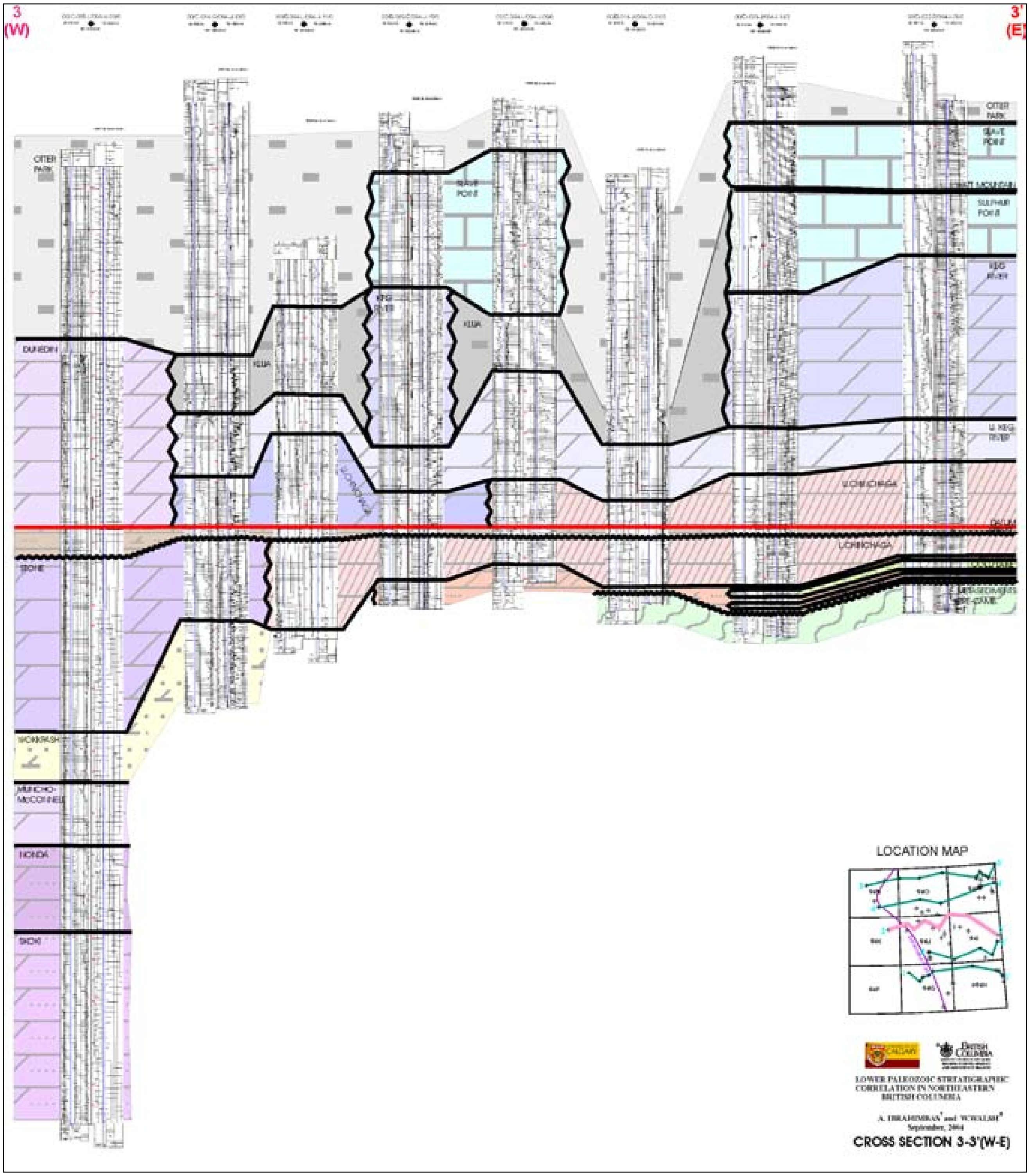

Figure 4. Stratigraphic subsurface correlation of the Lower Paleozoic strata. Cross section 3-3'.

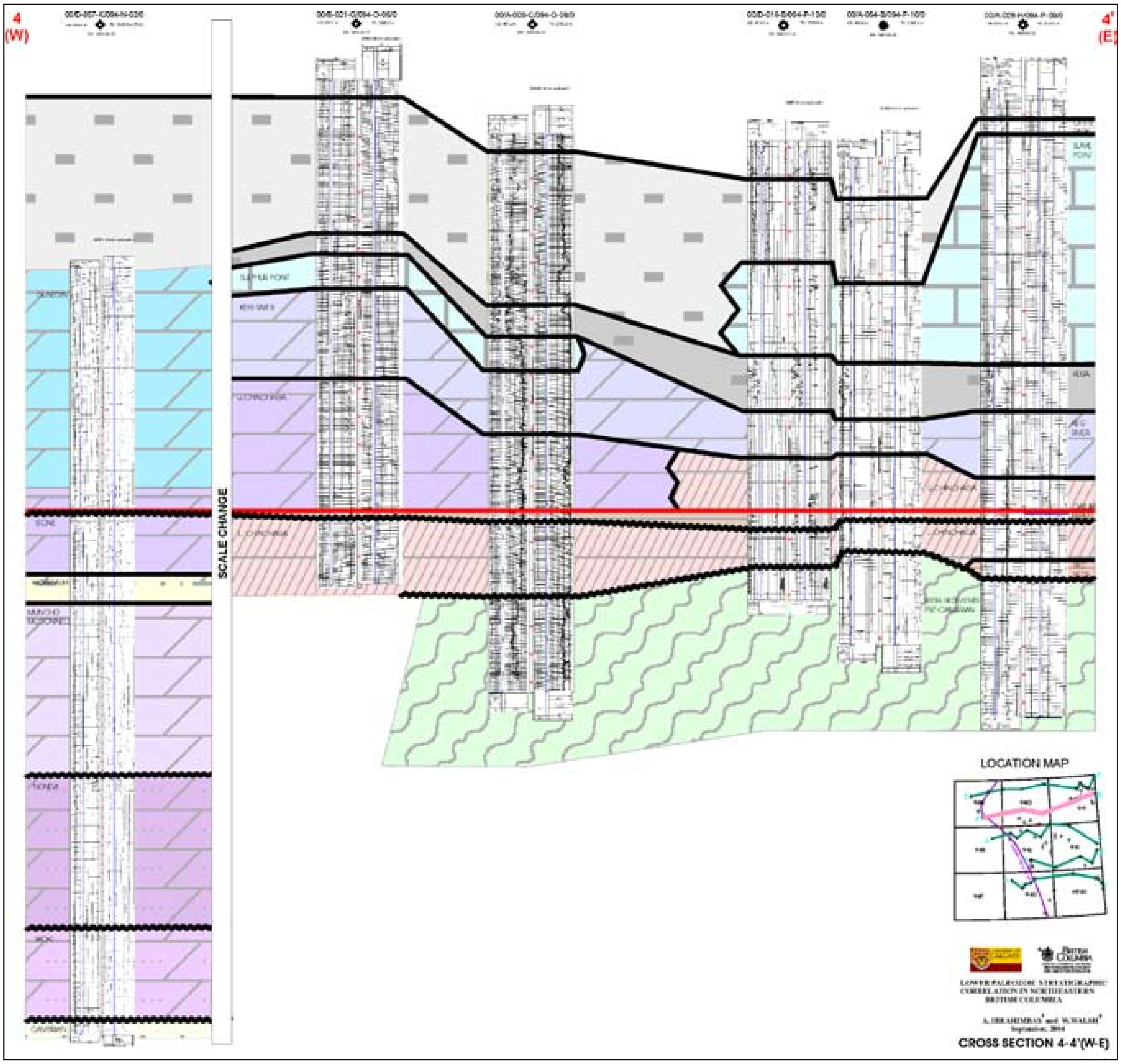

Figure 5. Stratigraphic subsurface correlation of the Lower Paleozoic strata. Cross section 4-4'.

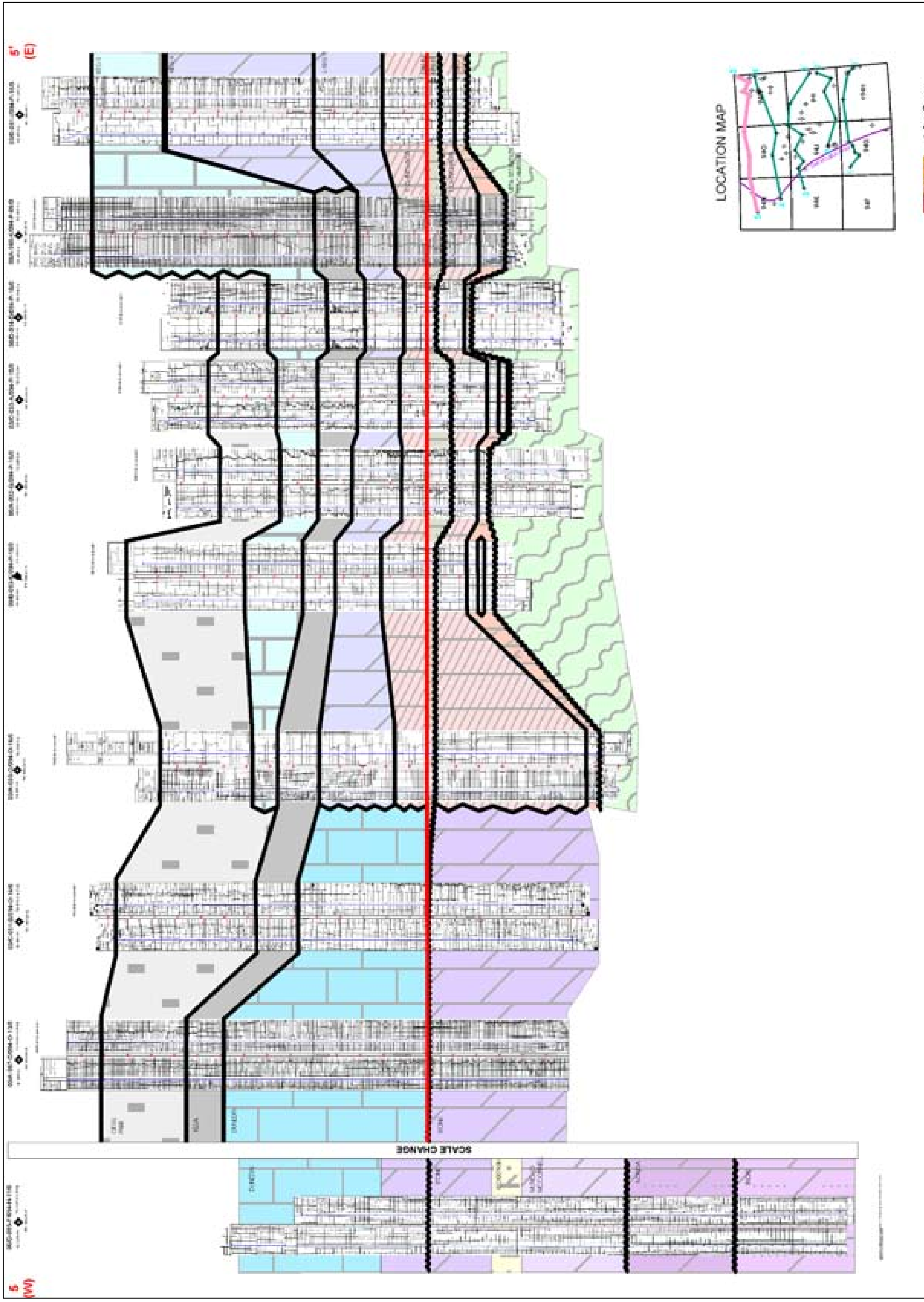

Figure 6. Stratigraphic subsurface correlation of the Lower Paleozoic strata. Cross section 5-5'.

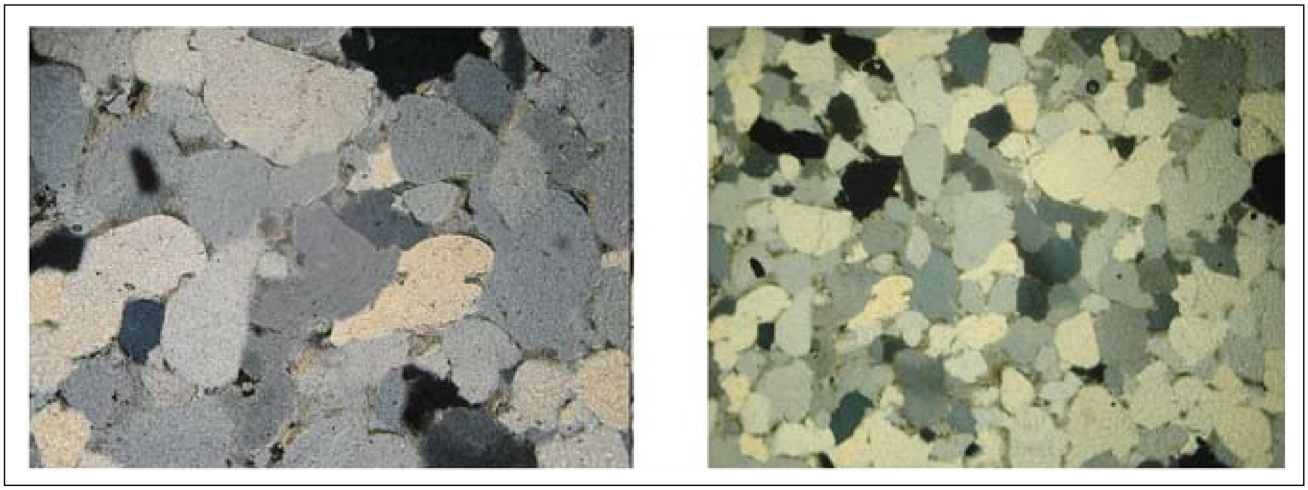

Figure 7. Photomicrographs of the Cambrian quartz arenite units from well A-49-B/94-H-16, 9760 m. (A) CPL, scale bar 0.25 mm (B) CPL, scale bar 0.5 mm .

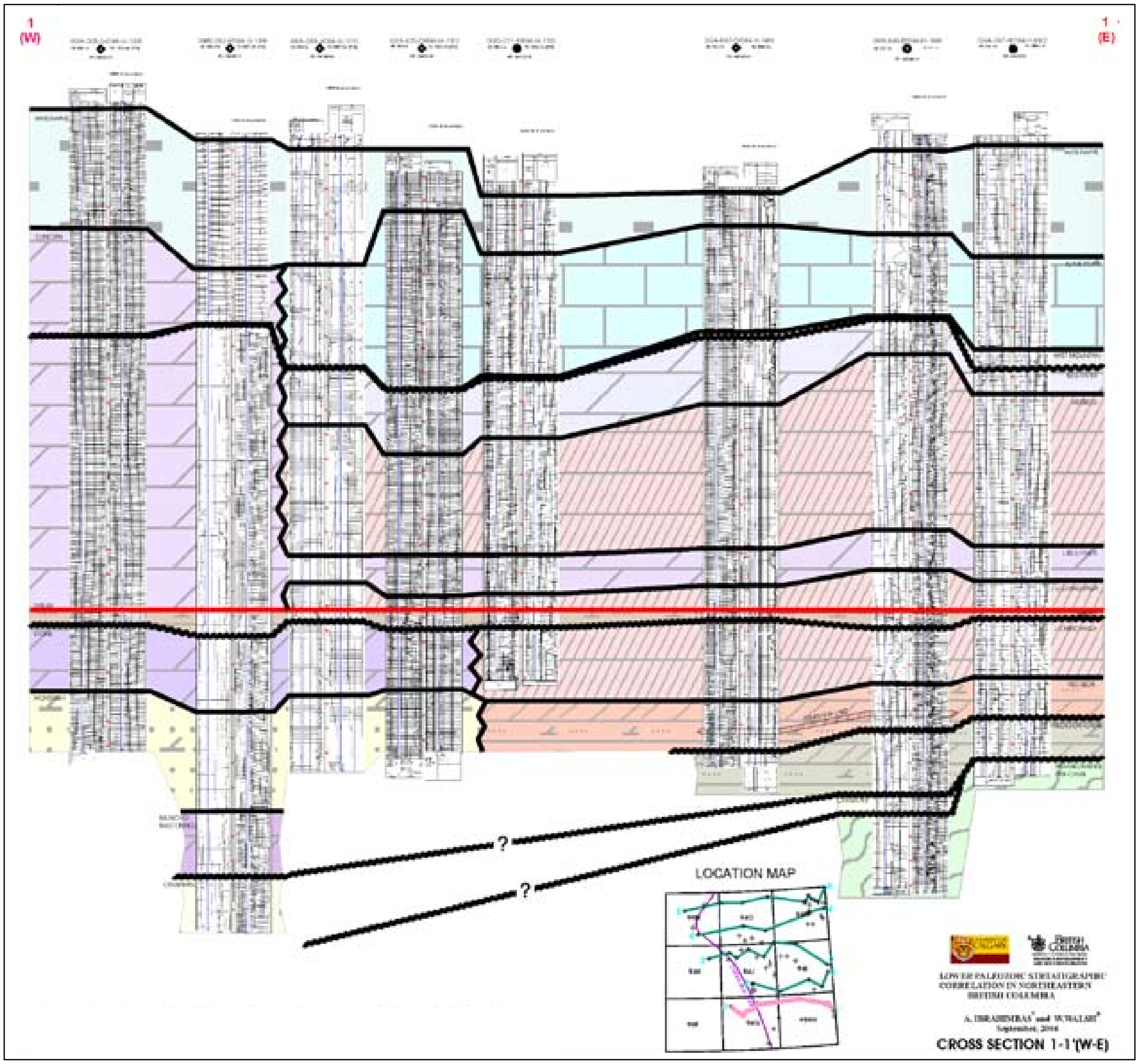

Figure 8. Stratigraphic subsurface correlation of the Lower Paleozoic strata. Cross section 1-1'.

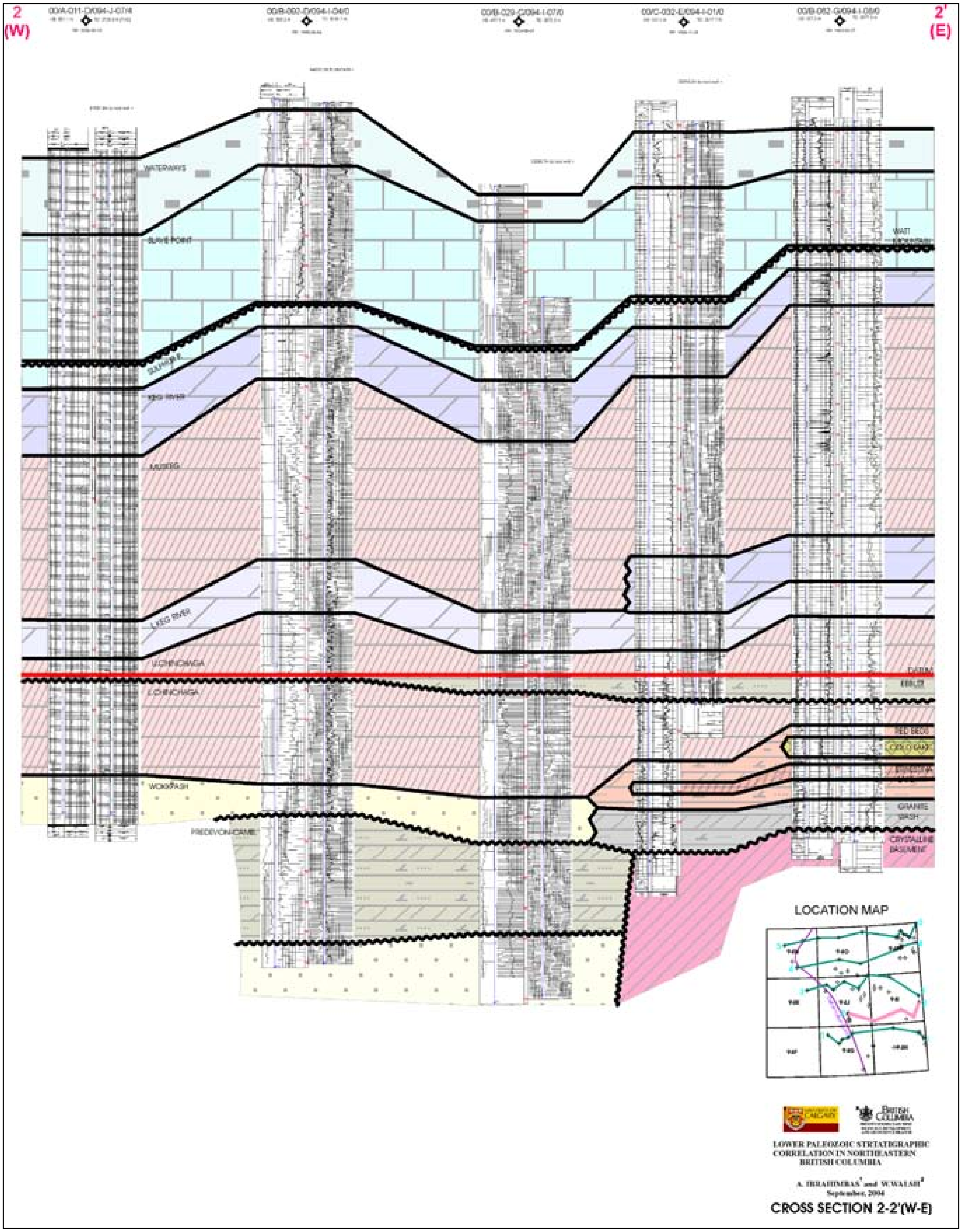

Figure 9. Stratigraphic subsurface correlation of the Lower Paleozoic strata. Cross section 2-2'.

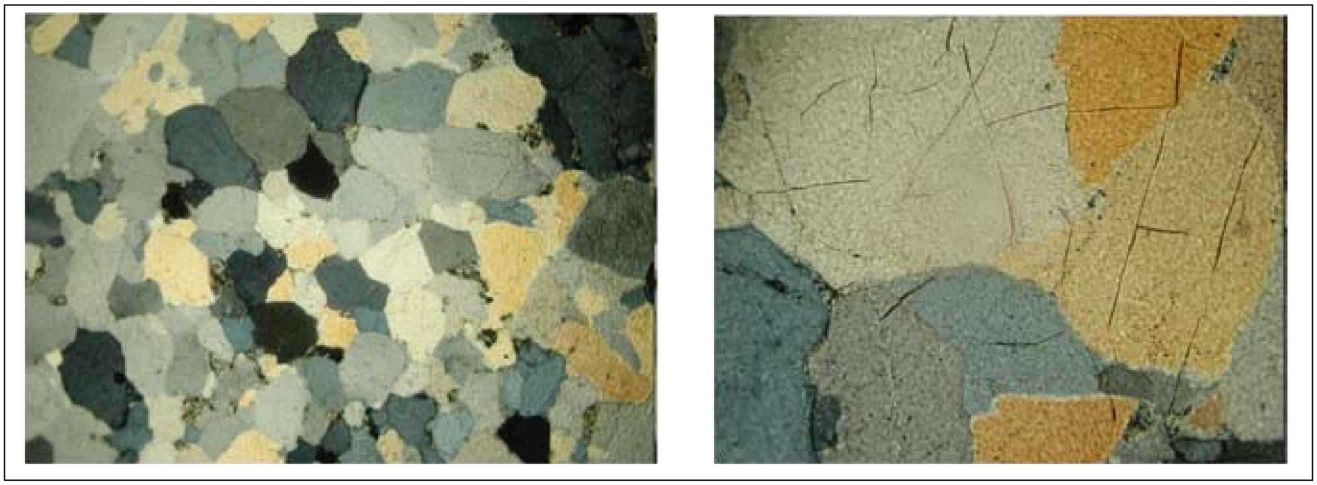

Figure 10. Photomicrographs of the Wokkpash sandstone units from well A-11-D/94-J-7, 2727.5 m. (A) CPL, scale bar 0.5 mm (B) CPL, scale bar 0.25 mm.

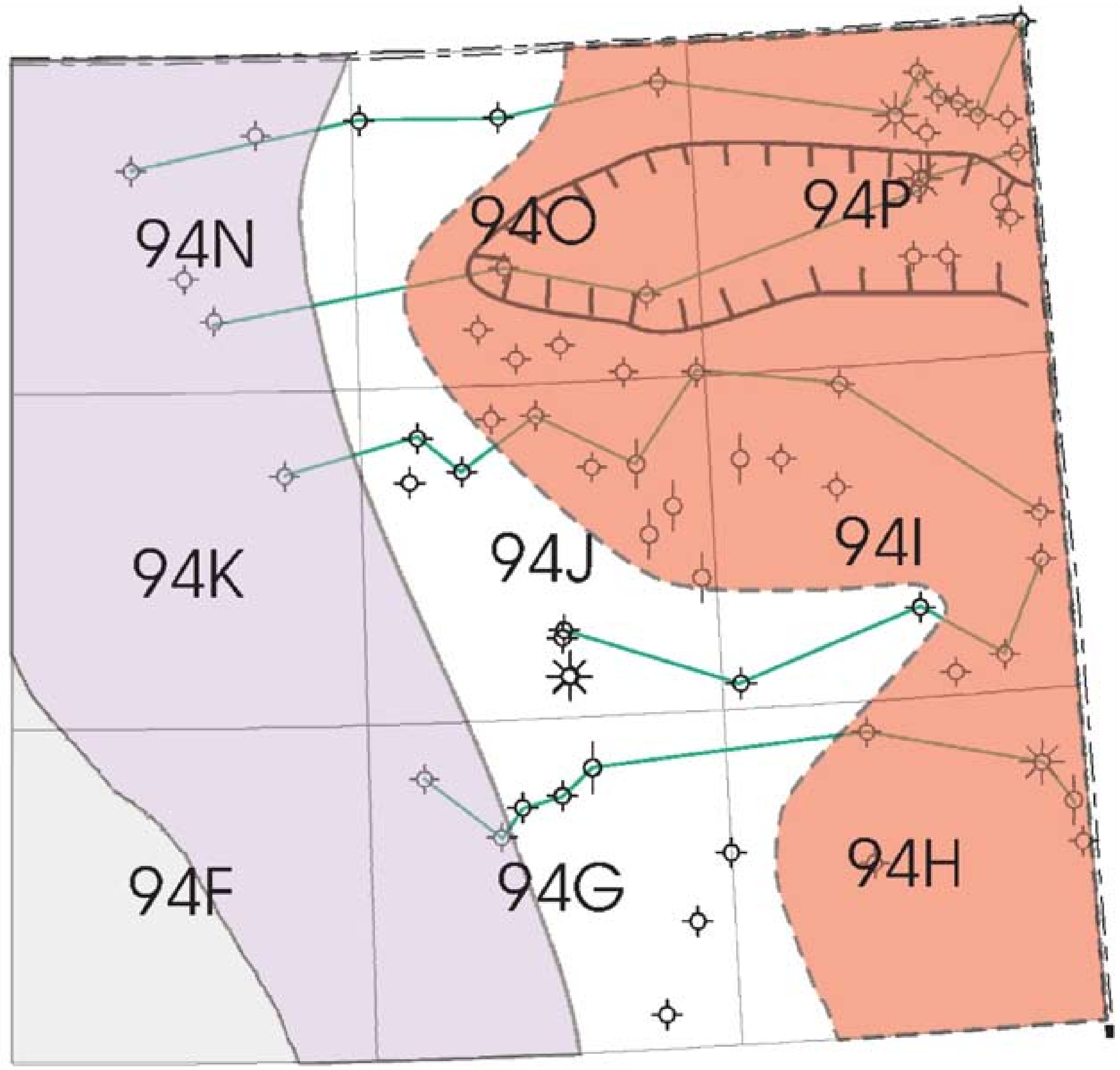

Figure 11. Paleogeography during the deposition of the Wokkpash Formation.

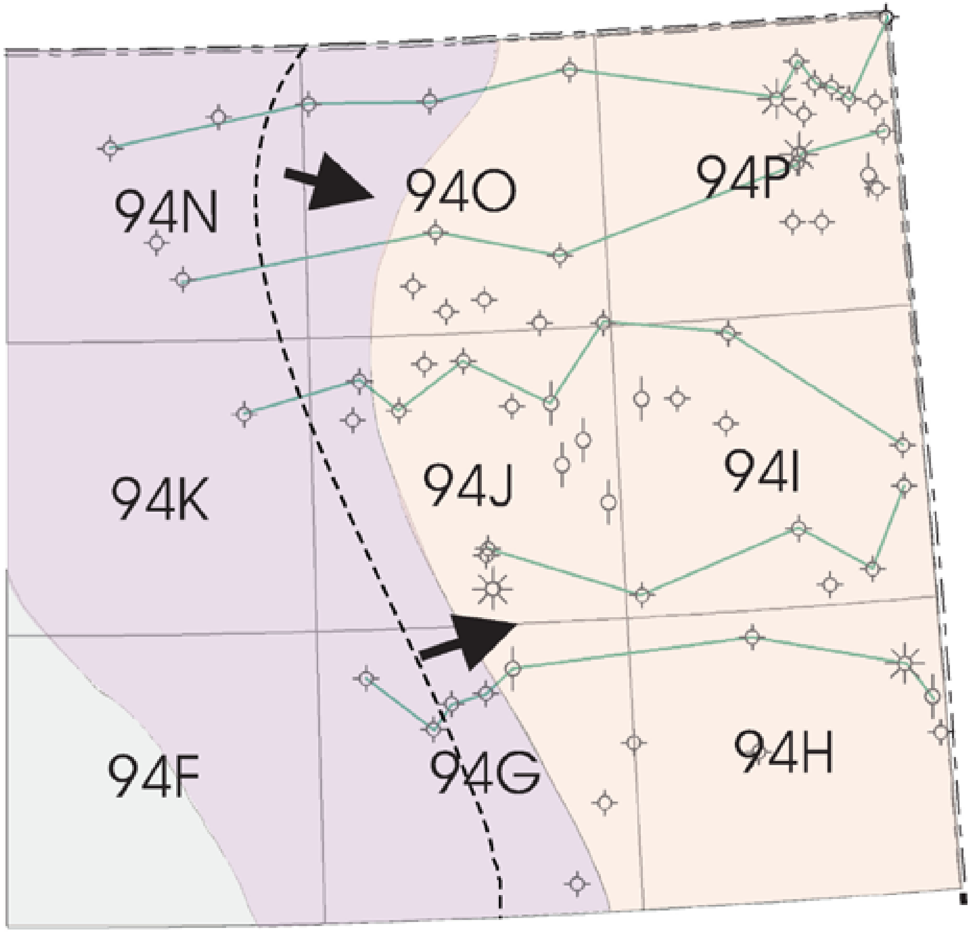

Figure 12. Paleogeography during the deposition of the Stone Formation.

Chinchaga Formation is composed of interbedded anhydrites and dolomites, with dolomite thicknesses increasing towards the west. The unit is divided into two zones of Upper and Lower Chinchaga by a regional unconformity, which can also be traced between the Stone and overlying Dunedin Formations. This unconformity can be traced extensively as a widespread detrital unit (Ebbutt Member), which can be seen in all of the cross sections. The abrupt influx of clastic material, especially quartzose sandstones, may be indicative of a sudden emergence of a source area containing clean quartzitic sediments. The transgression period after this clastic influx resulted in deposition of lagoonal to open-marine carbonates of the Dunedin Formation in the west, dolomites and anhydrites of the Upper Chinchaga Formation, and dolomitized, bioclastic mudstones and wackestones of the Lower Keg River Formation.

PETROLEUM SYSTEM POTENTIAL IN PRE-KEG RIVER–CHINCHAGA

Reservoir Potential

The only identified reservoir within the zone of interest is a high-porosity zone lying in the boundary between the Lower Keg River and Chinchaga Formations. The zone is generally within the Lower Keg River pools but may actually be a mappable unit in the northeastern part of the study area. The DST measurements from this zone show average to high permeability and recoveries as great as 4.18 million cubic feet per day (MMCF/day) (Figure 13).

The Chinchaga Formation, comprising mainly anhydrite and dolomite, displays occasional porosity development. The dolomites have a very compact grain arrangement with little if any intercyrstalline porosity. However, some wells display discrete zones with porosity. In well PCI EVIE LAKE B- 089-E/094-J- 15, DST#15 shows an average permeability, with gas recovery of 0.296 MMCF/day. The gross pay of this zone is 20 m with a net pay thickness of 9 m. The thin sections from this interval comprise

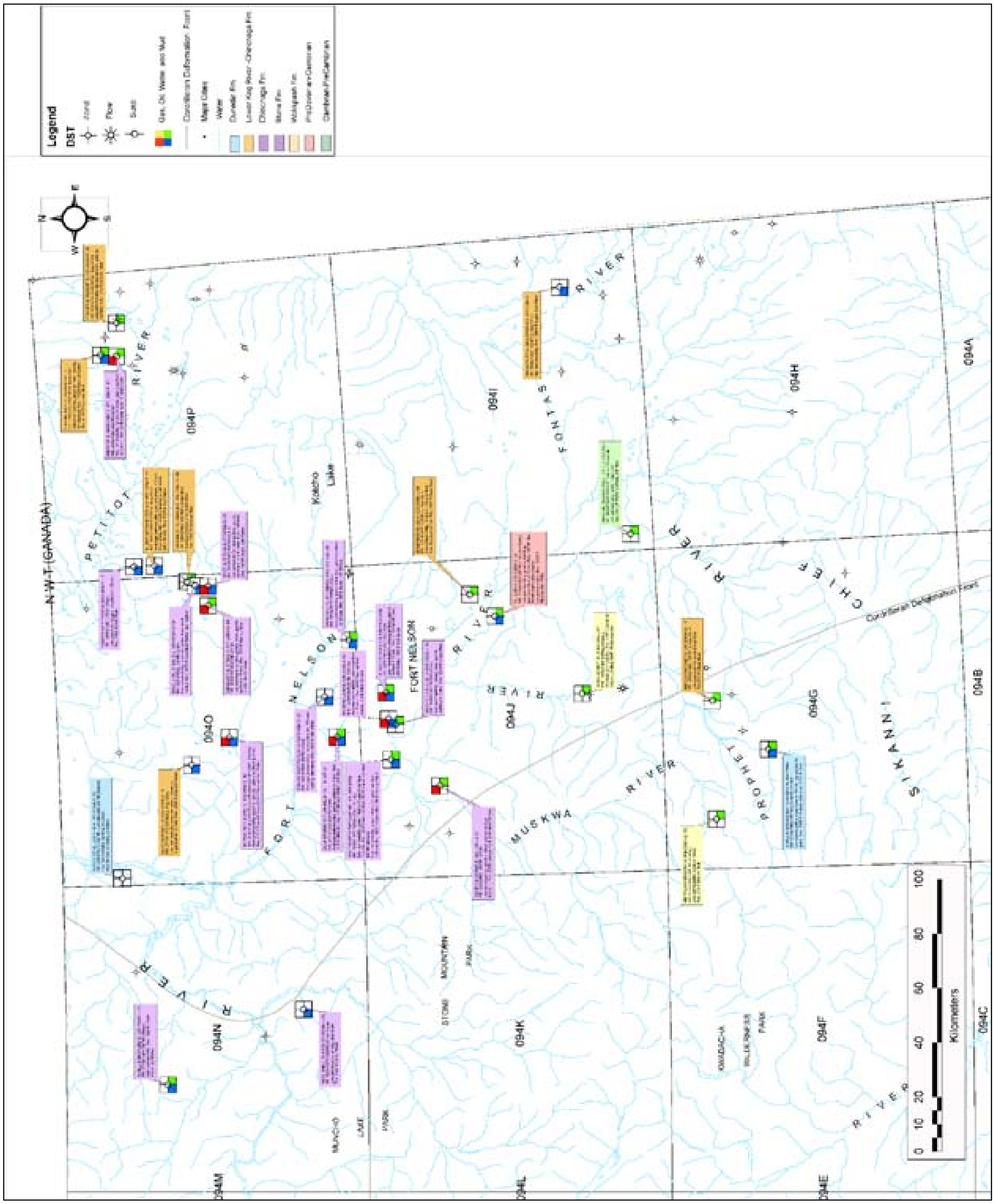

Figure 13. Hydrocarbon play map showing the DST results taken from the units of interest.

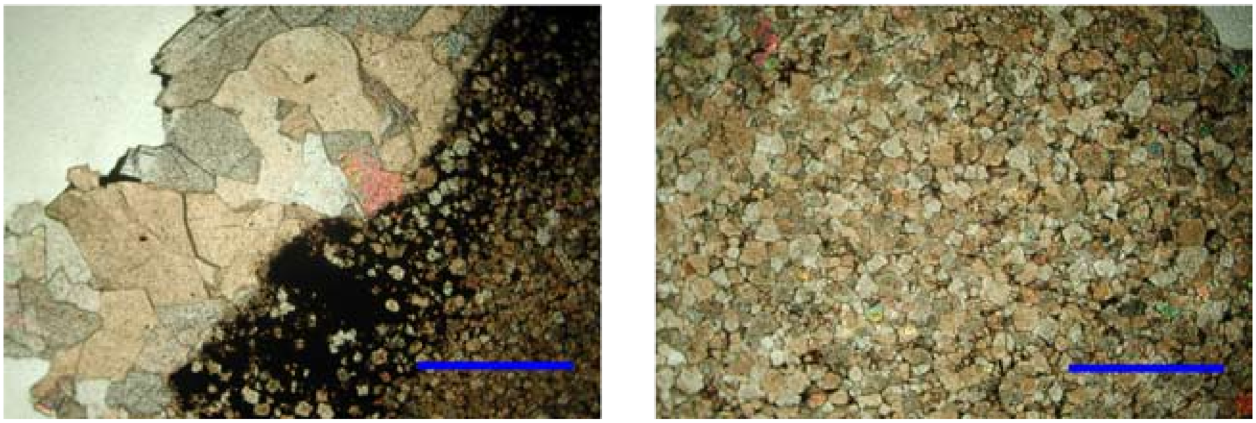

Figure 14. Photomicrographs of the Chinchaga Formation dolomites from well B-89-E/94-J-15, 8040 ft. CPL, scale bar 0.5 mm.

euhedral dolomite, with some rare intercrystalline porosity filled with pyrobitumen. There are also some large saddle dolomite crystals in these thin sections that might be filling either a vuggy porosity or fractured porosity (Figure 14). This unit may be of reservoir quality, depending on diagenetic features and fracture density and aperture. In addition, a number of wells show modest gas recoveries of up to 0.37 MMCF/day with low to average permeability within this unit, indicating hydrocarbon charge. Textures observed in dolomites of the Stone and Dunedin Formations are very similar to those in the Chinchaga Formation, with DSTs showing low to high permeability and some gas recovery.

Quartz arenites of the Wokkpash Formation are regionally extensive in Lower Devonian strata. This unit was likely deposited in a nearshore environment as the regressive phase of the Muncho-McConnell Formation carbonates, which is then transgressed and overlain by carbonates of the Stone Formation. Wokkpash sandstones are mature with well-sorted and rounded quartz grains, which are overprinted with anhedral-euhedral syntaxial quartz overgrowths. The quartz overgrowth appears to be an early phase of diagenesis that reduced porosity. The carbonate cementation pore fill also reduces porosity; therefore, no porosity is evident in the thin sections. However, the unit has probably gone through an extensive stress regime, which is seen as high-density strain fabric. These intense microfractures crosscut the grains and the cement, implying they had formed after the diagenesis (Figure 10). A few DST measurements taken from this unit show low to average permeability with some minor gas during tests. This unit may have reservoir potential depending on the density of the strain, open fractures, and the fracture patterns.

Source Rocks

Ordovician-aged immature to mature oil-prone source rocks with TOC values up to 35% are reported from the Williston Basin of the WCSB by Osadetz and Haidl (1989) and Osadetz et al. (1989). However, no potential source rock has been reported for pre-Devonian strata in the subsurface of WCSB. The Middle Devonian Elk Point Group contains several units with hydrocarbon potential, including the Evie Member and Keg River Formation in British Columbia (Fowler et al., 2001). The Evie Member of the Klua Shale is mostly overmature in the study area. A few source facies had been recognized from the well logs within the Keg River Formation that are source to some of the oils in the Rainbow-Zama area (Creaney et al., 1994).

There was no potential source rock observed in well logs or in the examination of drill cutting samples within the strata below pre-Keg River–Chinchaga from wells studied. However, outcrop samples taken from the 94G map area analyzed from the Ordovician–Silurian aged Road River Group, which is the basinal off-shelf sediments equivalent of Kechika Formation, yield high TOC values of up to 10% where they are thermally overmature (Stasiuk, personal communication). This suggests that the unit might have generated significant amounts of hydrocarbons. More detailed studies need to be done both to understand the timing of hydrocarbon generation from these units and to delineate possible migration pathways in relation to the structural evolution of the area in order to understand whether any of these hydrocarbons are trapped.

CONCLUSIONS

Geological history

The complex lower Paleozoic paleogeography and depositional setting are the result of variations (such as the asymmetrical rift) in the basement structures and steeply dipping extensional faults that affected the deposition of the later formations. The main structural features that controlled deposition are, from west to east (basin to platform), the Kechika Trough, the MacDonald Platform, MacDonald and Tathlina highs, and the positive Peace River Arch; there are also the basement lineaments of the Liard Line and Great Slave Lake shear zone. The units were deposited onto the miogeocline of the Canadian Cordillera with basinal shales of the Road River Group and offshore carbonates of the Kechika, Skoki, Nonda, Muncho-McConnell, Stone, and Dunedin Formations. The equivalent strata are barely preserved in eastern northeast British Columbia with a thin layer of Upper Cambrian(?) to Silurian(?) strata overlain by the Lower to Middle Devonian evaporites. The mixed carbonates and sandstones units and the sandstone sheets of the Cambrian sandstones and Wokkpash Formation are explained by periods of clastic influx (sourced from the Peace River Arch) during the carbonate sedimentation.

Reservoir Potential

The dolomite units of Lower Keg River-Chinchaga, Chinchaga, and Stone Formations and the quartz arenites of the Wokkpash Formation and Cambrian unit likely have the best reservoir potential. In thin section, each of the carbonate units displays similar characteristics, such as micro- to cryptocrystalline anhedral to euhedral crystals with little if any intercrystalline porosity and large saddle dolomite crystals possibly filling vuggy or fracture porosity. DSTs show low to high permeabilities with recorded gas recoveries of up to 4.18 MMCF/day from these zones. The Wokkpash Formation comprises mature quartz arenites with carbonate cement and there is no visible intercrystalline porosity in thin sections, though it may contain some microfacture porosity. The Cambrian quartz arenites also display no visible porosity in thin section due to quartz overgrowths and pore-filling carbonate cement. There is, however, the possibility of some microporosity development and the potential for fracture enhancement. The DSTs from this unit display low permeability with air blow and salt-water recovery.

Source Rock

No potential source rock has been identified from the subsurface of the study area. Rock Eval and TOC analyses from outcrop samples of the Ordovician to Silurian Road River Group taken from the 94G map area show that the unit is overmature, with TOCs as high as 10%. This unit was likely an excellent source for hydrocarbon generation. It may be a source for the reservoirs in the study area, depending on the timing of thermal and structural evolution. A detailed thermal maturity modeling should be done for a better understanding of the thermal history of this unit.

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POTENTIAL COALBED GAS RESOURCE IN THE HUDSON'S HOPE AREA OF NORTHEAST BRITISH COLUMBIA

Barry Ryan[1], Randy Karst[2], George Owsiacki[3] and Garry Payie[3]

ABSTRACT

The Gething Formation, which underlies an area around Hudson's Hope, east of the disturbed belt in northeast British Columbia, is prospective for coal bed gas (CBG or CBM). The formation has experienced little deformation and contains cumulative coal thicknesses up to 17 m. Coal rank is generally higher than high-volatile A bituminous. North and south of Hudson's Hope, the formation dips moderately to the east and is generally too deep for CBM exploration. However, in the vicinity of Hudson's Hope, dips are shallower, and a substantial area is prospective for CBM. This study estimates a potential resource of up to 25 trillion cubic feet (tcf) in the area and concentrations in places of more than 10 billion cubic feet (bcf) per section.

KEYWORDS: Gething Formation, coalbed gas resource, isotherms, rank, coal resource database.

INTRODUCTION

The Gething Formation, which underlies an area around Hudson's Hope in northeast British Columbia, is prospective for coal bed gas (CBG, or coalbed methane, CBM) for a number of reasons. The formation in the area contains a number of thin seams, whose cumulated thickness averages about 8 m, with values ranging up to 17 m in some areas. The area is east of the edge of the disturbed belt and has experienced little deformation. Coal rank varies, but in much of the area is higher than high-volatile A bituminous (mean maximum reflectance [Rmax] values greater than 0.8%). The combination of depth, cumulative coal thickness, and rank indicate that a substantial coalbed gas resource may exist in the area.

Many regional maps contain a line marking the boundary between the Western Canadian Sedimentary Basin and the "disturbed belt" or "deformation front", which marks the eastward extent of the Rocky Mountain Foothills (Figure 1). In reality, the degree of deformation increases gradually towards the west, and a single line on a map can be very deceptive in terms of defining areas of increased CBM potential. This is very much the case in the Hudson's Hope–Chetwynd area. However, for convenience the area of the Gething Formation discussed here is defined by the edge of the disturbed belt (if somewhat arbitrarily defined) and in part by the Peace River Arch as outlined by Marchioni and Kalkreuth (1992). The Arch was an area of increased subsidence and deposition in Early Cretaceous times, which resulted in a weakly defined thickening of the Gething Formation trending northeast along the trace of the Arch. The Arch is also overlain by thicker deposits of the Upper Manville Group, which explains a trend towards higher rank in the Gething Formation in the area. The edge of the disturbed belt, which trends northwest from the Alberta border to Chetwynd, deflects more to a northerly trend at about the location where it abuts the Peace River Arch.

In the battle of units of measurement, it seems that a compromise may be developing in the world of CBM in Canada. Depths and coal thicknesses are usually given in metres; gas contents may be in cc/g or cubic metres/tonne or scf/t; however, gas resource numbers are more often given in imperial units of bcf or tcf per section. One tcf equals 28.32 billion cubic metres, and 1 cc/g equals 32.037 scf/ton. Converting any resource in the area discussed here into a reserve depends on the degree of gas saturation of the coals, the ability to extract gas over intermediate distances through thin seams, and the composition of the gas. A previous resource assessment of the area (Smith et al., 1991) estimated a resource in the Gething Formation of 34.9 tcf to a depth of 1800 m. The area they studied included part of the disturbed belt, which is not included in this study.

A number of companies have acquired oil and gas exploration rights in the area, and Figure 2 illustrates the land position as of August 2004. Companies have drilled at least 8 holes in the area, and there has been limited test production from 2 holes.

COAL RESOURCE DATABASE

The 121 holes utilized in this study are located east of the disturbed belt (Figure 3). Coal intercepts in the Gething Formation were picked using a combination of density,

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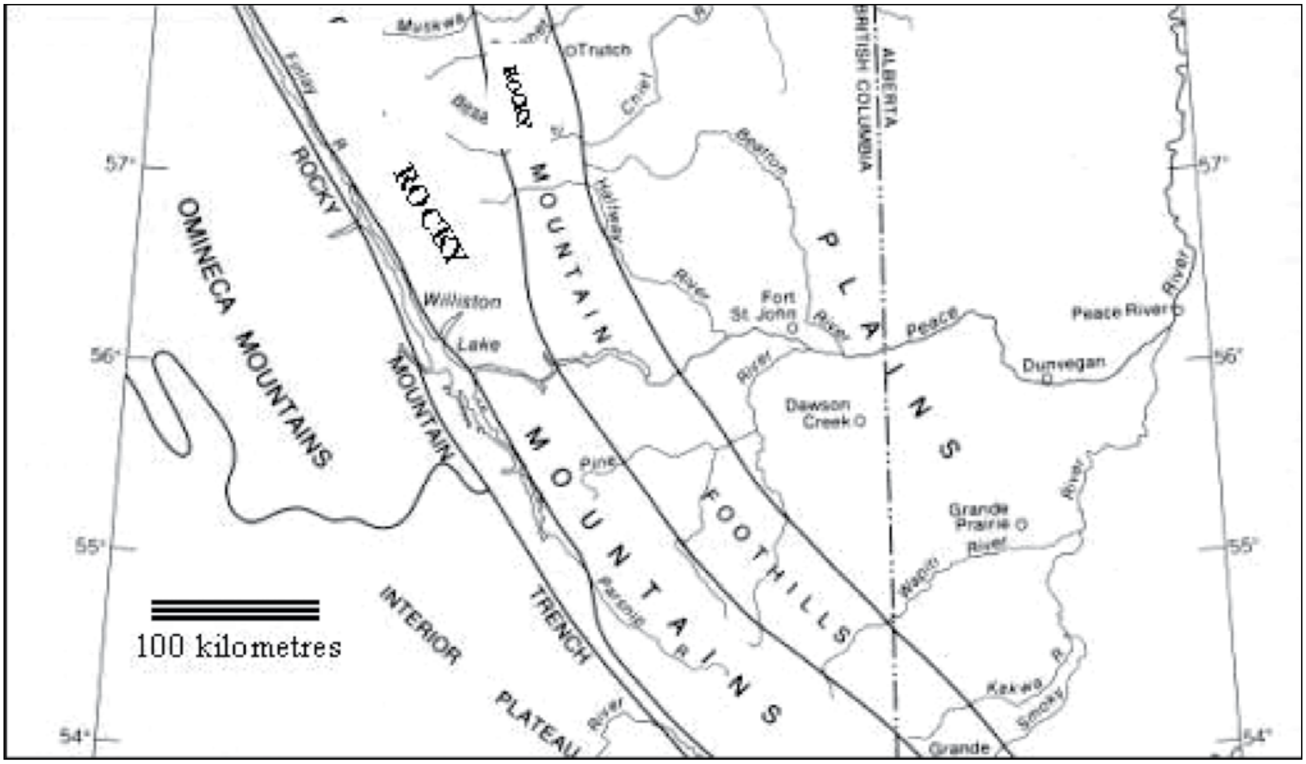


Figure 1. Physiographic divisions of northeast BC (from Stott [1982]).

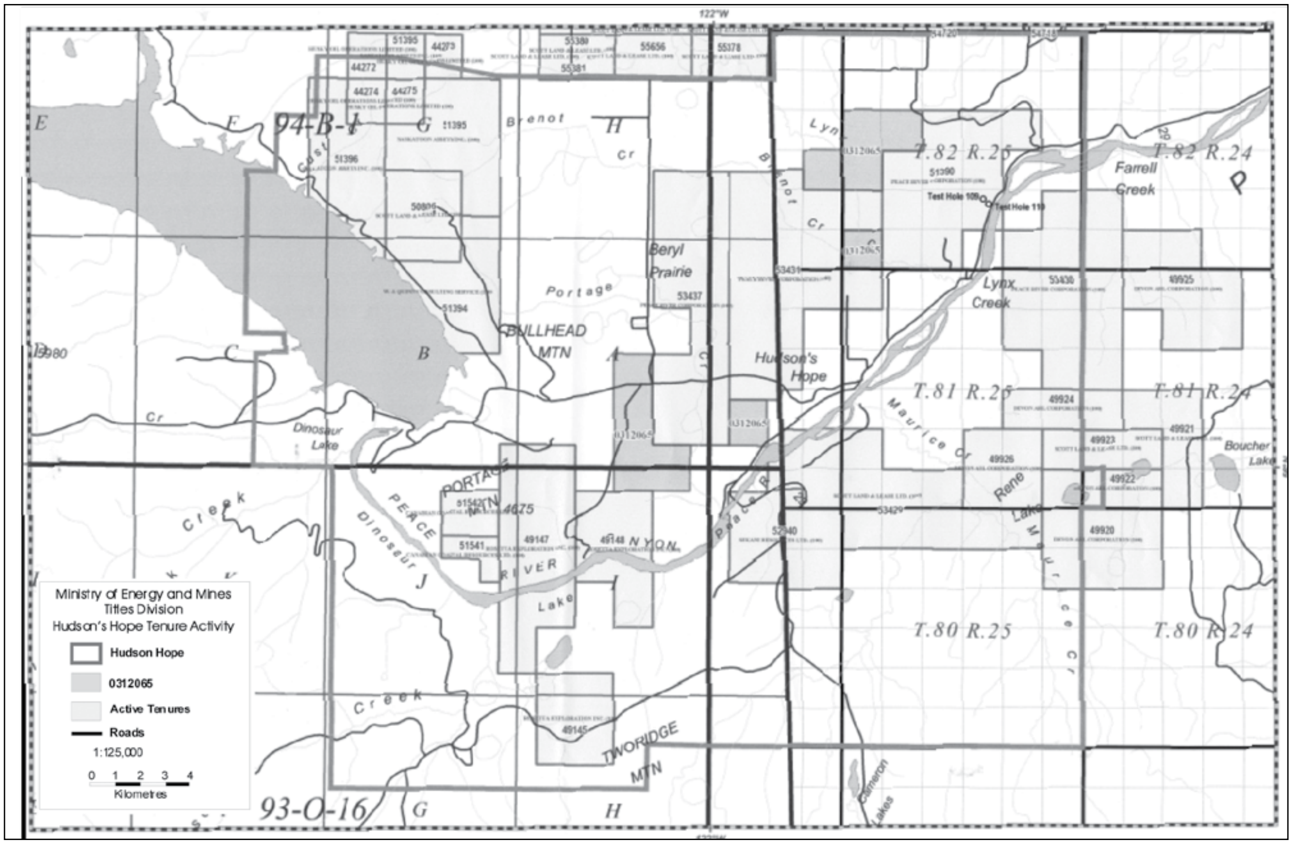


Figure 2. Coalbed gas tenures in northeast BC as of August 2004.

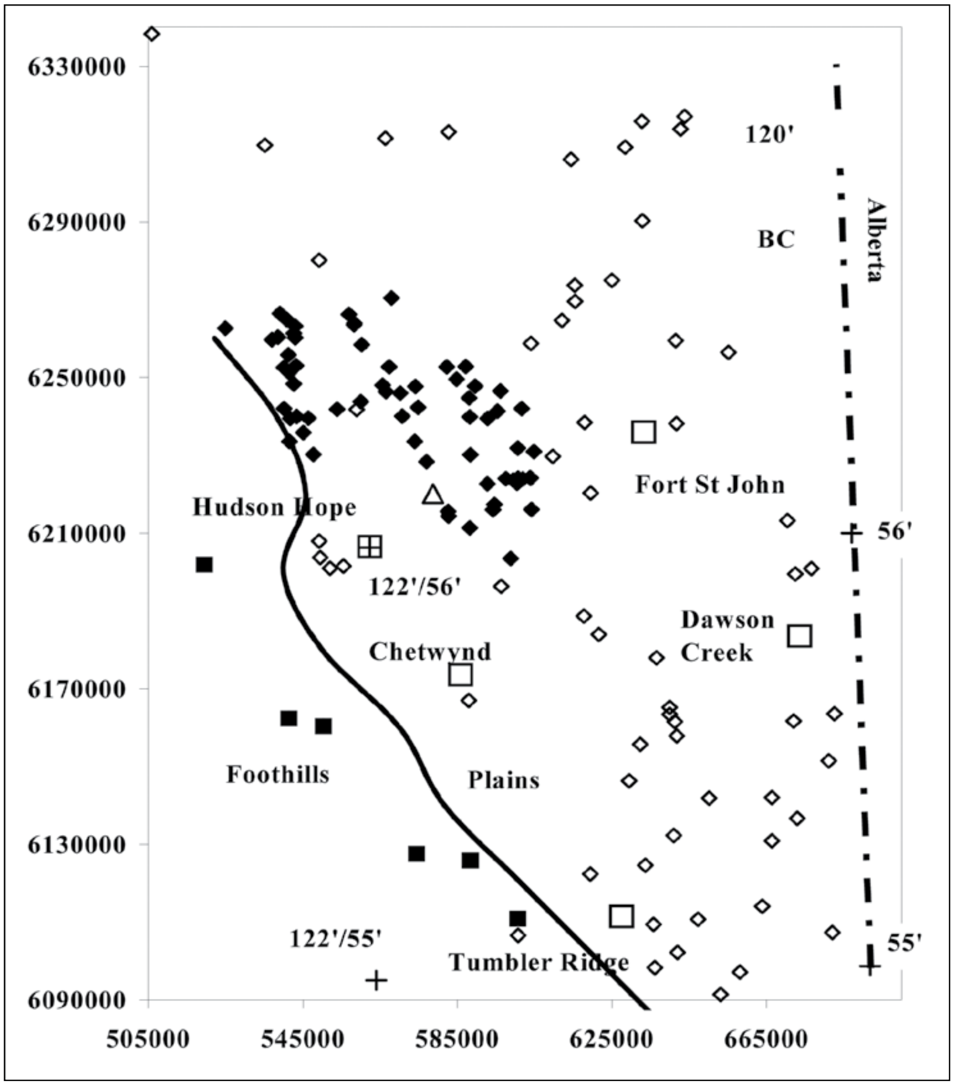


Figure 3. Map of holes used in the study. Black diamonds represent holes for which logs were picked in this study; open diamonds represent holes for which logs were picked in previous unpublished study. Solid squares are coal properties where coal thicknesses were estimated. The location of Dension hole 80-1 is indicated by a triangle.

caliper, and gamma logs that are available from the Ministry of Energy and Mines in Victoria. The resolution of oil and gas logs is marginal for picking thin coal seams because the detector–source spacing and travel rate for the tool do not allow good definition of the thickness or density of thin seams (Figure 4). Longer detector–source spacing tends to result in an over-estimation of seam thickness with an overestimation of ash content. There may also be an asymmetrical effect that smears the hanging-wall signal based on logging speed (Figure 4). If seam thickness is overestimated and this is accompanied by an overestimate of seam density, then the estimate of the amount of carbon in the section will not be affected as much as might be expected, and consequently errors in estimating the CBM resource will be minimized.

The database generated from the 121 holes includes hole location, collar elevation, and the depth to formation tops. Data for the Gething Formation includes depth, thickness, and ash code (3 low to 1 high) of all seams. All data were kriged and gridded using Surfer® software in such a way that grid nodes overlap and can be manipulated to produce computed node values. At each node, the average depth of the coal section and average mean maximum reflectance (Rmax%) values were used in conjunction with the cumulative coal thickness to calculate a potential gas content using the Ryan equation (Ryan, 1992). Rmax values were derived from Marchioni and Kalkrueth (1992), who provide values for the top and bottom of the Gething, and their data were re-digitized. Individual ash contents were not incorporated into the calculation, and average values were assumed for all seams.

An Excel spreadsheet capable of handling up to 5 grid matrixes, each with 5500 nodes, was used to manipulate the data. The spreadsheet applies conditions to resource

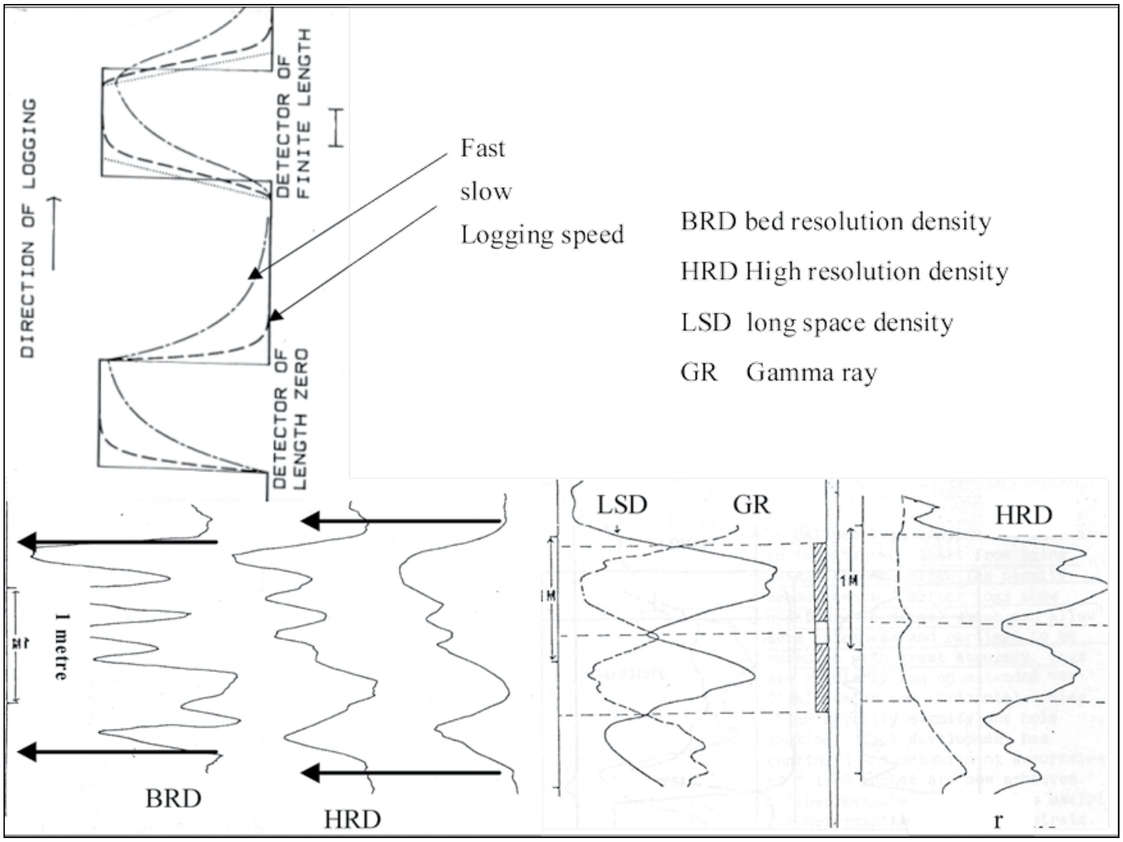


Figure 4. Schematic for log resolution.

calculations and generates derived grid matrixes for contouring in Surfer. Grid nodes west of the disturbed belt were blanked and do not add to the resource calculation.

Any calculation of resource is based on an assumption of what seams may be able to hold under depth and rank conditions and must therefore be considered an estimate of maximum potential resource. The Ryan equation provides estimates of maximum potential gas content based on rank, ash content, and depth. The equation works for ranks greater than Rmax 0.7% and tends to underestimate for ranks above 1.5%; ranks in the area range from Rmax = 0.80% to 1.63%. Figure 5 illustrates the range of gas contents predicted by the Ryan equation.

A sample of Gething coal from a hole drilled in the Hudson's Hope area was provided for isotherm analysis (Table 1, Figure 6). The sample has an Rmax value of 1.21% and is composed of 50% reactives, 45% inerts, and 5% mineral matter by volume (Figure 7). The data (Figure 6) are plotted on an as-received basis, and for comparison purposes the predicted curve using the Ryan equation is also plotted. It is apparent that for a rank of 1.21% and the Gething sample, the equation estimates adsorption capacity quite well but tends to over-estimate at shallow depths. This may bias the resource estimates discussed below. The sample depth is about 750 m, and the isotherm was run at a temperature of 25 ºC. Some geothermal gradient data for the area are available (Ryan and Richardson, 2004), and values for northeast BC average about 27 ºC/km with a surface temperature of 5 ºC; based on a depth of about 750 m, the average temperature should be about 26 ºC.

The CBM resource is calculated using the cumulative coal thickness, treated as a single unit and assigned a single depth that is the mid-depth of the coal-bearing section at that location. The average ash contents used (20% and 30%) are conservative, and depth cutoffs are set so that no resource is calculated above a depth of 100 m (plus depth to midpoint of the coal-bearing section at that location) and below depths ranging from 800 to 1400 m (Table 2). A more detailed calculation could apply the Ryan equation to each individual seam with individual estimates of ash content. The process may appear to provide a more precise number, but with uncertainties about degree of coal saturation it is unlikely that the result would be any more useful.

There are very limited public desorption data available for coals in the area. However, in 1980 Utah Mines explored the Bri-Dowling Property (which is centred on the Dowling and Gething Creeks below the Bennett Dam) and did some desorption tests on coal core samples (Duncan, 1980). The data indicate that Gething seams may be close to saturated, with gas contents that range up to 20 cc/g at 500 m (Figure 8). It is difficult to determine the calculation basis for the data from the report, but it may be air-dried.

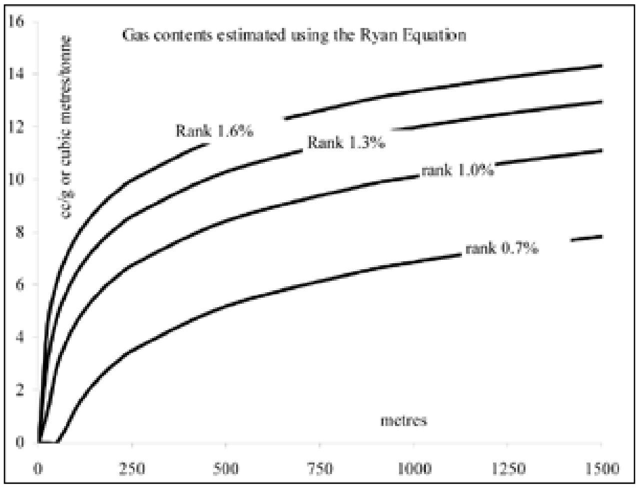
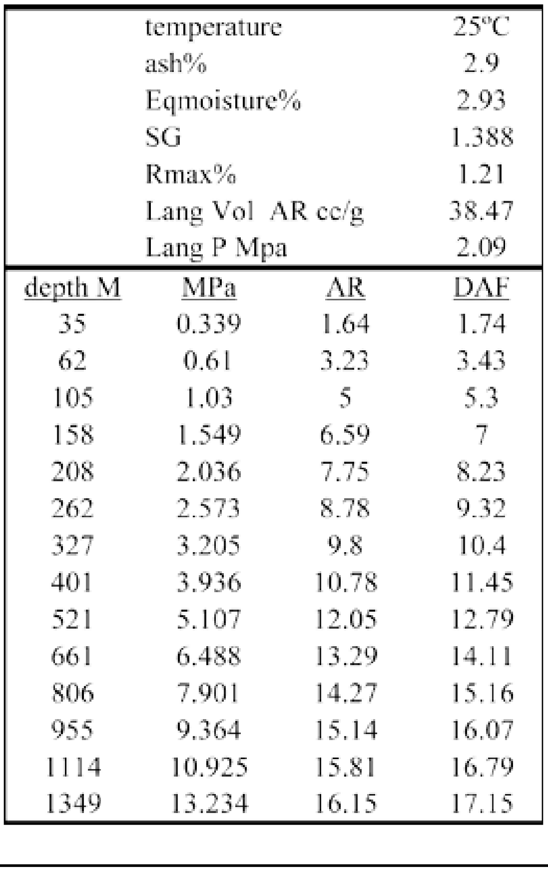


Figure 5. Ryan Equation curves for ranks Rmax=0.7 to 1.6% and 30% ash content.

The average ash content of seams is 14%, based on analyses in the coal assessment report (Duncan, 1980). This value, in conjunction with a rank of 1.2%, is used to construct the approximated isotherm in Figure 8, which also includes the desorbed gas contents. Samples were probably desorbed at room temperature, which is similar to formation temperature at about 500 m.

TABLE 1. ISOTHERM DATA FOR GETHING FORMATION COAL FROM DRILL HOLE, HUDSON'S HOPE AREA.



	temperature		25°C
	ash%		2.9
	Eqmoisture%		2.93
	SG		1.388
	Rmax%		1.21
	Lang Vol AR cc/g		38.47
	Lang P Mpa		2.09
depth M	MPa	AR	DAF
35	0.339	1.64	1.74
62	0.61	3.23	3.43
105	1.03	5	5.3
158	1.549	6.59	7
208	2.036	7.75	8.23
262	2.573	8.78	9.32
327	3.205	9.8	10.4
401	3.936	10.78	11.45
521	5.107	12.05	12.79
661	6.488	13.29	14.11
806	7.901	14.27	15.16
955	9.364	15.14	16.07
1114	10.925	15.81	16.79
1349	13.234	16.15	17.15

The total desorbed gas contents include estimates of the residual gas contents, which were obtained using the degree of fragmentation of samples (a plot is provided in the report). For "blocky" coals, the estimated residual gas content was up to 60% of the lost plus desorbed gas content. The desorption data tabulated in the report for the sample with the highest gas content (hole BC80-19, depth 459.03 m, Titan seam) is plotted in Figure 9 in conjunction with the total gas reported after addition of the residual gas. Based on the shape of the desorption curve, the estimate of residual gas used in the report is high, and this throws into question the validity of the data. When the desorption data is replotted minus the estimated residual gas components (solid diamonds in Figure 8), the gas contents are reduced but still seem to indicate that at about 400 m, coals were close to saturated. The sorption time constant for the desorption curve is about 25 hours, which indicates moderately fast diffusion from the sample.

REGIONAL STRATIGRAPHY

The Gething Formation underlies a large area of the Peace River Coalfields in BC and of the Western Canadian Sedimentary Basin east of the disturbed belt (Table 3). The formation is well exposed near Williston Dam, and a number of authors have described sections (Stott, 1973, 1982; Legun, 1990; Gibson, 1992). Stott (1973) provides a number of columnar sections, which provide an average thickness for the Gething in the Peace River Canyon of about 500 m. The formation maintains thicknesses in excess of 500 m in the area from Williston Dam south to Chetwynd. On the south shore of Williston Lake at Carbon Creek, the formation attains a thickness of 1067 m (Cowely, 1982). The formation gets progressively thinner to the southeast in the Peace River coalfield and is only 10 m thick under the Saxon Property near the Alberta border.

As a result of numerous coal exploration programs, the cumulative thickness of coal in the formation is well documented within the Peace River coalfield. Probably the maximum amount of coal occurs in the Pine River area, where cumulative coal thickness is about 20 m. North of the Pine River, the formation thickens, seams are numerous, and cumulative coal thicknesses are up to 14 m (Stott, 1973). In the Carbon Creek area, there are at least 12 seams more than 1.5 m thick and over 50 seams have been identified (Northeast Coal Study, 1977). Adjacent to the Bennett Dam on the Bri-Dowling property (Duncan, 1980), the formation is 475 m thick and contains 4 seams that have mineable thicknesses (greater than 1.5 m) and many seams thinner than 1.5 m (Northeast Coal Study, 1977).

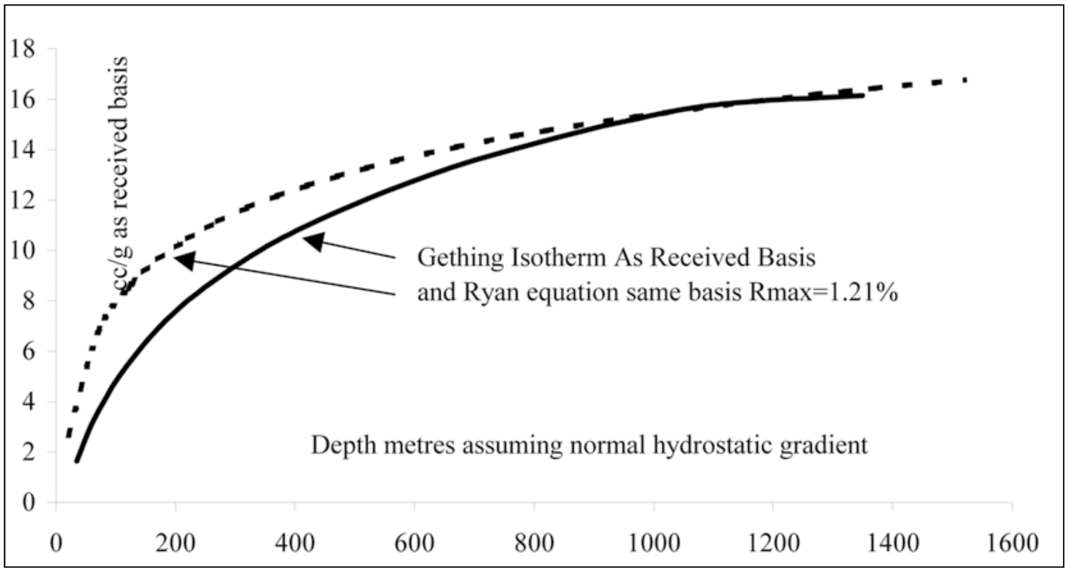
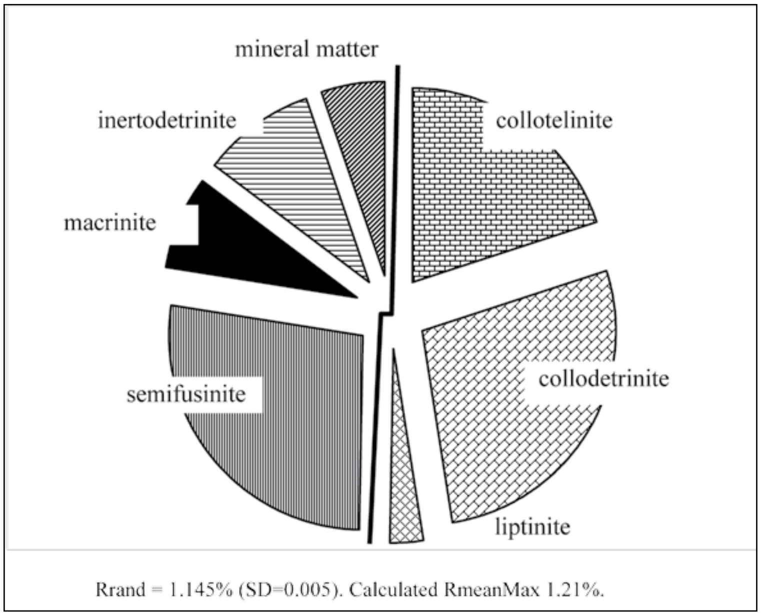


Figure 6. Isotherm Gething Formation coal, Hudson's Hope area.



Rrand = 1.145% (SD=0.005). Calculated RmeanMax 1.21%.

Figure 7. Petrography of Gething Formation isotherm sample

TABLE 2. TESTIMATED POTENTIAL RESOURCE IN THE GETHING FORMATION EAST OF THE DISTURBED BELT.

minimum depth 100 metres		depth to top Gething Formation metres			
	ash	800	1000	1200	1400
	%	tcf	tcf	tcf	tcf
total area	30	24	35.1	41.6	44
	20	25.9	37.9	44.9	47.4
Hudson Hope	30	16.8	25.3	28.7	28.8
	20	18.1	27.4	31	31.1

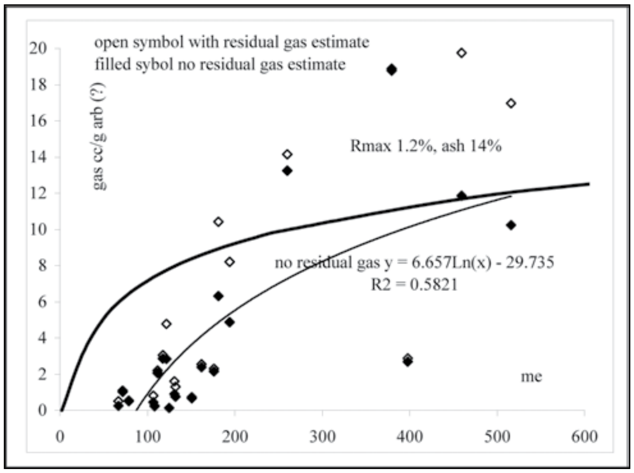


Figure 8. Desorbed gas contents for coals from the Bri-Dowling Property.

COAL QUALITY AND REFLECTANCE DATA

There are a number of exploration properties in the disturbed belt that extend from Carbon Creek west of the Bennett Dam in the north to Sukunka (near Sukunka. River) in the south. These properties provide coal quality information for the western edge of the area of interest. Data from these reports was discussed by Ryan (1997). Coal in the formation is often characterized by low raw-ash contents and variable inertinite maceral contents. Other than rank data, there is very little quality information on Gething coals at depth to the east.

Data from the Carbon Creek property (Cowley, 1982) indicate that the in situ ash content for thicker seams averages 12.6% and that the seams are high-volatile A bituminous in rank. Raw-ash contents from exploration holes on the Bri-Dowling property average 13.6%, and the rank (based on proximate analyses) is on the border between high-volatile A bituminous and medium-volatile bituminous. Raw-ash contents for 7 seams in the coal section at Willow Creek (Pine Valley Coal Mine) ranges from 7.9% to 14.5%, with no specific trend up-section. Rank on the Burnt River property is higher (low-volatile bituminous to semi-anthracite), but the average ash contents of the 3 major seams are still low (7.2% to 10.5%). The Sukunka property was explored extensively as a potential underground coking coal mine; the 2 major Gething seams in the area are medium-volatile bituminous in rank and average less than 10% raw ash.

Gething Formation seams can contain moderate proportions of inert coal macerals, and this can influence the adsorption ability of the coal. Ryan and Lane (2002) discuss the adsorption capacity of Gething coal from the Willow Creek Property, where the coal is low-volatile bituminous. Lamberson and Bustin (1993) studied adsorption characteristics of Gates Formation coals with ranks of 1.02% to 1.14% in northeast BC (Table 3). The formation overlies the Gething Formation, and the rank is similar to the rank of the Gething Formation in the Hudson's Hope area. Both papers indicate that adsorption capacity tends to decrease as the inertinite content in coal increases. The effect is greater for low-rank coals than it is for high-rank coals (Figure 10). In fact, based on data from Lamberson and Bustin (1993), the adsorption capacity of high-volatile coals may decrease by 4.3 cc/g as the vitrinite content decreases from 80% to 40% (mmfb) at a depth of about 500 m. The effect appears to be much less as rank increases, and for low-volatile Gething coals the decrease is only 1.4 cc/g for the same change in petrography.

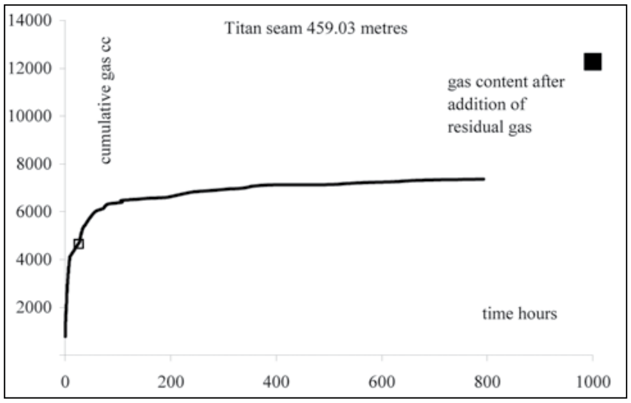


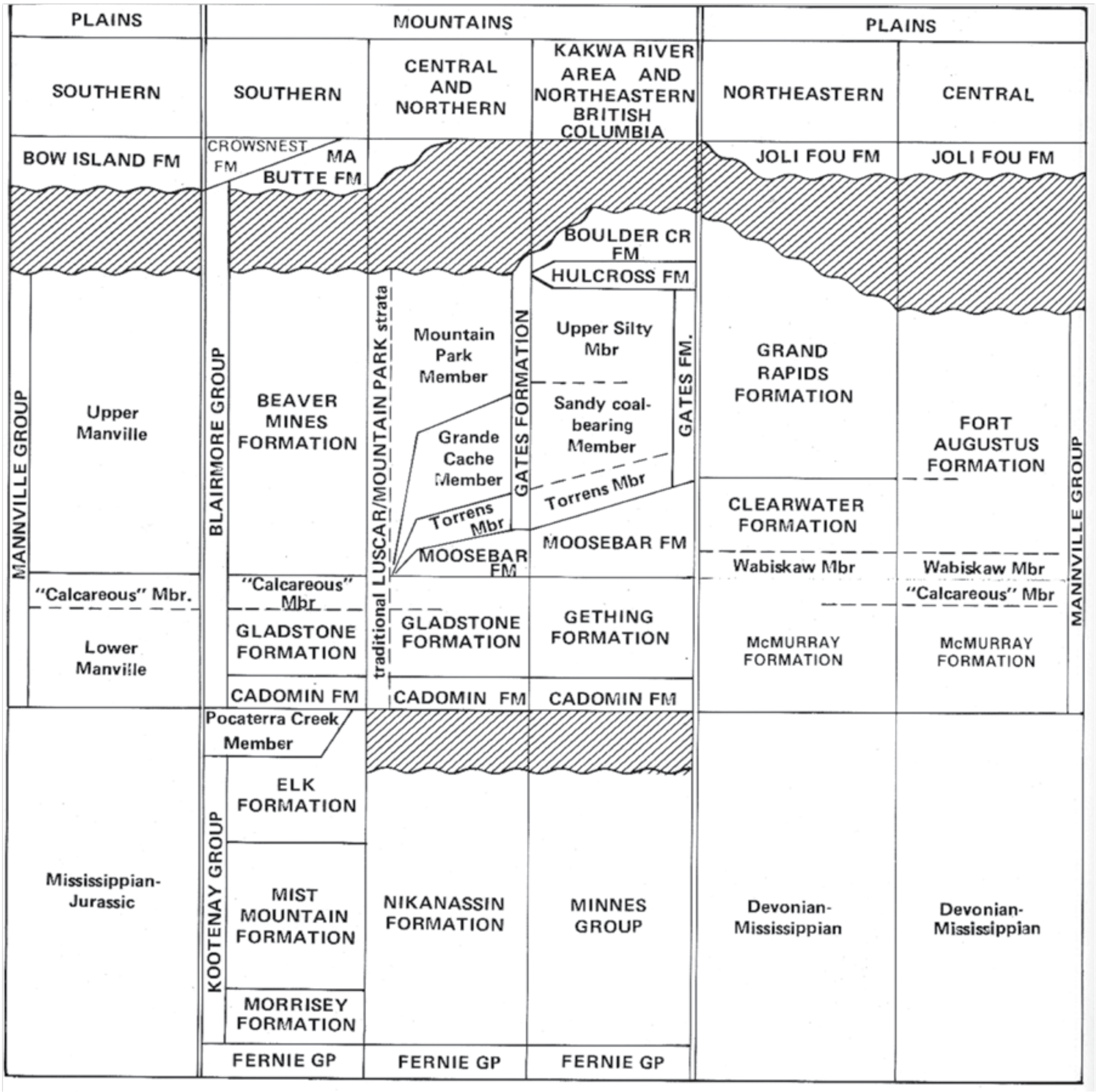
Figure 9. Plot of desorption data from Bri-Dowling hole BC80-19, depth 459.03;,Titan seam.

When coal core or chip samples are recovered, there is a tendency to lose the vitrinite component of the coal. Consequently, based on the lower adsorption ability of inertinite macerals, the gas content and adsorption capacity of the seam will be underestimated. This will make it difficult to determine the true level of saturation of coal seams at depth. The problem will be exasperated by the difficulty of getting good coal recovery from thin seams.

One of the earliest studies of the rank of seams in the Peace River area was by Karst and White (1979). More recent studies (Marchioni and Kalkrueth, 1992) provide mean maximum reflectance (Rmax%) values for the top and bottom of the Gething Formation (Figure 11). The rank of the Gething is variable, with a number of high rank areas within the disturbed belt. East of the disturbed belt, the rank decreases but in the Hudson's Hope area is generally above a reflectance of 1.0%.

Samples from a hole drilled in 1980 by Denison (Figure 3, triangle) are analyzed for petrography and rank. The top of the Gething in the hole occurs at a depth of 313 m, and samples were collected from depths ranging from 313 to 461 m. Rmax values range from 0.81% to 1.21% over a depth range of 313 to 461 m. The depth range is limited, and there is a lot of scatter in the data, but it appears that the coalification gradient was quite low. Marchioni and Kalkrueth, (1992) indicate that coalification gradients increase

TABLE 3. REGIONAL STRATIGRAPHY FOR CRETACEOUS ROCKS PEACE RIVER COALFIELD.



PLAINS	MOUNTAINS			PLAINS	
SOUTHERN	SOUTHERN	CENTRAL AND NORTHERN	KAKWA RIVER AREA AND NORTHEASTERN BRITISH COLUMBIA	NORTHEASTERN	CENTRAL
BOW ISLAND FM	CROWSNEST FM MA BUTTE FM			JOLI FOU FM	JOLI FOU FM
			BOULDER CR FM		
			HULCROSS FM		
MANNVILLE GROUP Upper Manville	BLAIRMORE GROUP BEAVER MINES FORMATION	traditional LUSCAR/MOUNTAIN PARK strata Mountain Park Member	GATES FORMATION Upper Silty Mbr	GRAND RAPIDS FORMATION	MANNVILLE GROUP FORT AUGUSTUS FORMATION
		Grande Cache Member	GATES FM. Sandy coal-bearing Member		
		Torrens Mbr	Torrens Mbr	CLEARWATER FORMATION	
		MOOSEBAR FM	MOOSEBAR FM		
"Calcareous" Mbr.	"Calcareous" Mbr			Wabiskaw Mbr	Wabiskaw Mbr
					"Calcareous" Mbr
Lower Manville	GLADSTONE FORMATION	GLADSTONE FORMATION	GETHING FORMATION	McMURRAY FORMATION	McMURRAY FORMATION
	CADOMIN FM	CADOMIN FM	CADOMIN FM		
Mississippian-Jurassic	Pocaterra Creek Member			Devonian-Mississippian	Devonian-Mississippian
	KOOTENAY GROUP ELK FORMATION	NIKANASSIN FORMATION	MINNES GROUP		
	MIST MOUNTAIN FORMATION				
	MORRISEY FORMATION				
	FERNIE GP	FERNIE GP	FERNIE GP		

From Horachek, (1985)

to the west where there are areas of increased rank in the Gething Formation.

OUTCROP OBSERVATIONS

There are good outcrops of the Gething Formation around the Bennett Dam and in the Peace River Canyon below the dam (Photo 1). The lithology and stratigraphy of these outcrops were studied in detail by a number of authors who generally did not record orientations of cleats in seams or of joints in surrounding lithologies. This type of information is critical for a CBM assessment because of its effect on permeability. In this study a number of outcrops were studied on the road to the Bennett Dam and in the Peace River Canyon below the dam (Figure 12). There are numerous thin (less than 1.5 m thick) seams in the section. Seams are not sheared, and there is an absence of conjugate shear joints forming acute angles to bedding.

Cleats are well-developed in seams, with 2 orthogonal sets present in most outcrops. They are perpendicular to seam contacts, and surfaces are generally clean and not coated by any cementing minerals. It is possible to differentiate through-going face cleats from butt cleats that are truncated by face cleats. Cleat spacing is dependent in large part on coal petrography. Dull bands, presumably rich in inert macerals, have wider spaced cleats than bright (vitrinite-rich?) bands. In bright bands, cleat spacing on face cleats is about 1 cm and for butt cleats is about 5 cm (Photo 2). Dull bands tend to occur toward the top of seams, indi-

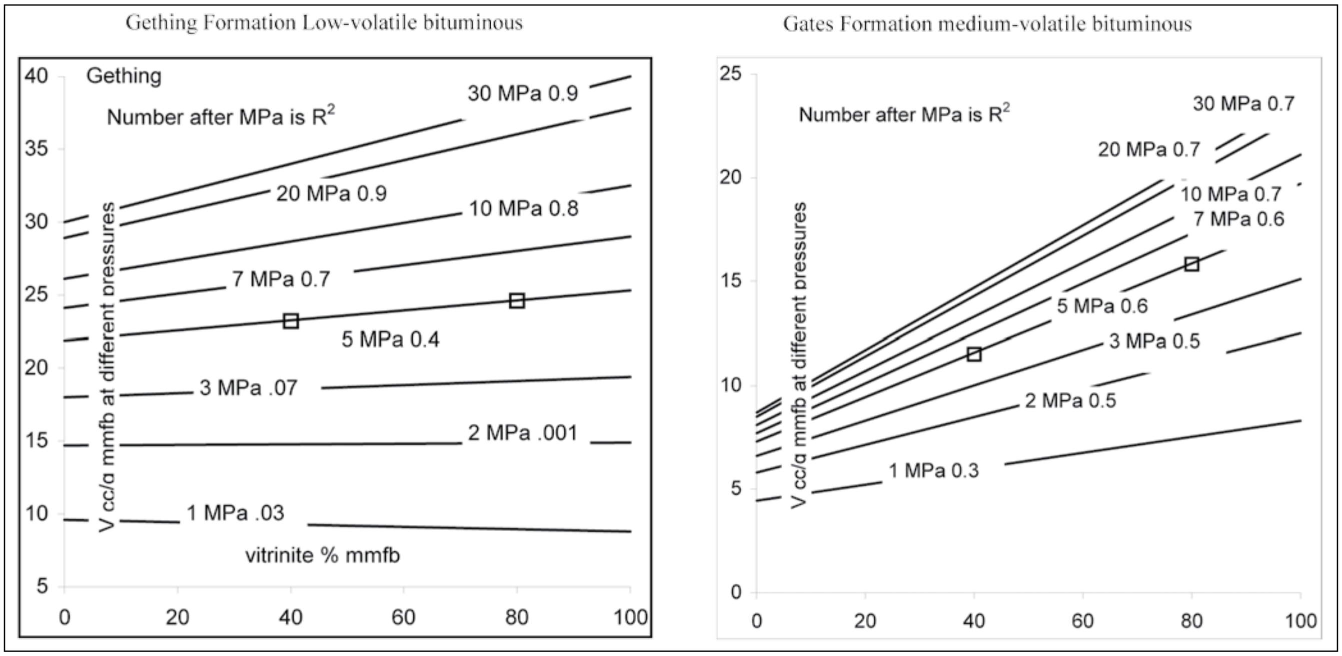


Figure 10. Adsorption capacity versus vitrinite content for low-volatile Gething Formation and high-volatile Gates Formation coals. Data from Ryan and Lane (2002) and Lamberson and Bustin (1993).

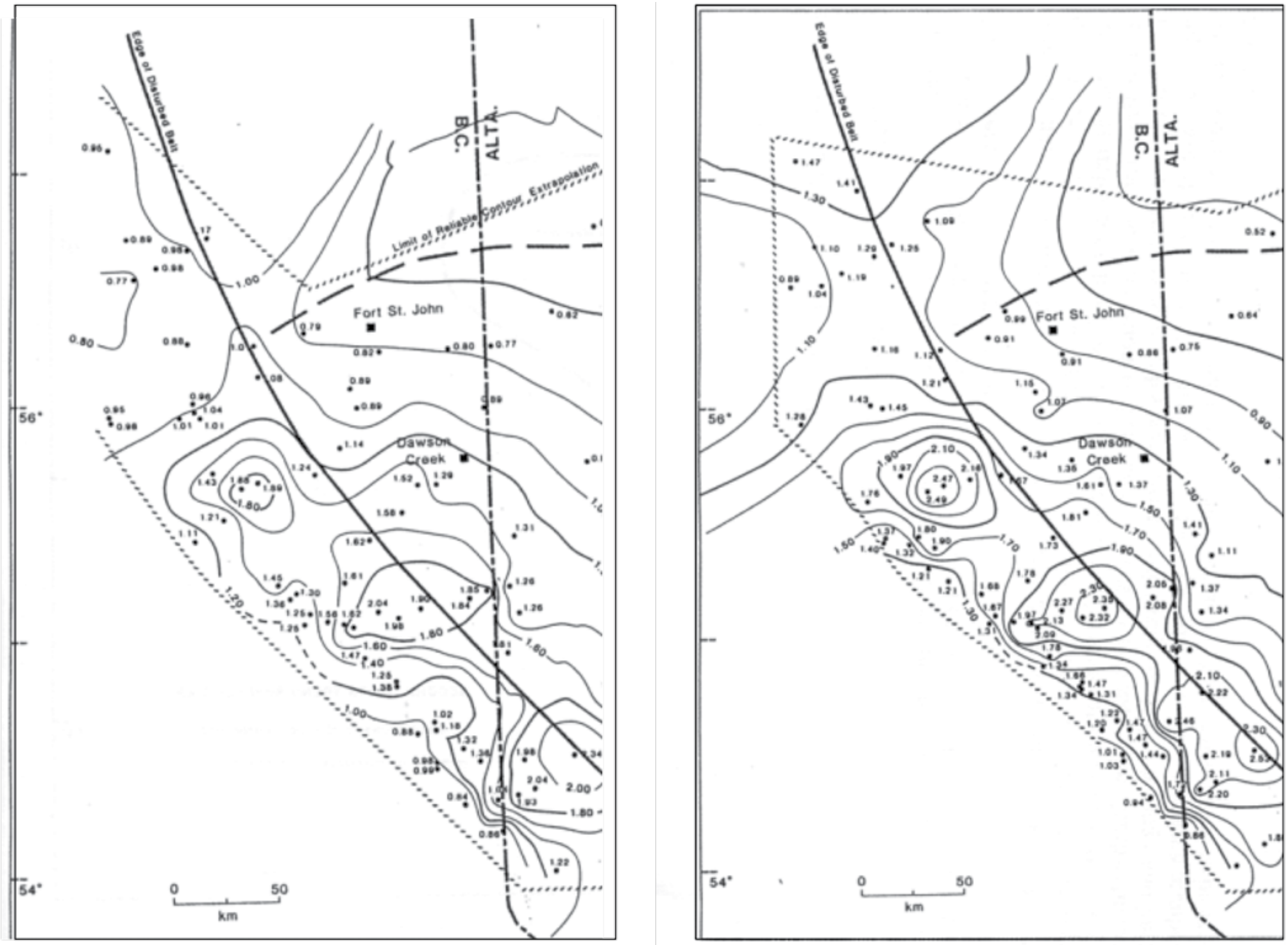


Figure 11. Mean maximum reflectance contours for the top and bottom of the Gething Formation (from Marchioni and Kalkrueth [1992])

Photo 1. Outcrop of the Gething Formation below the Bennett Dam.

cating a regressive depositional environment (Banerjee and Kalkrueth, 2002).

Joints in hanging-wall and footwall rocks are generally, but not always, parallel to cleats in seams. The joint frequency is always less than cleat frequency in seams and varies with lithology. Seams are frequently overlain by up to 2 m of brown mudstone with a few centimetres of material with bedding fissility adjacent to the seam. Joints in this material are widely spaced, and often through-going joints are more than 1 m apart. Sandier units include planar-bedded sandstone, which may have well-developed widely spaced joints. Sandstone channel lithologies are usually not well jointed, probably because cross-bed surfaces provide planes to accommodate any tensional stresses in the rock. Footwall lithologies are more often sandstone or siltstone than mudstone.

Kilby and Oppelt (1984) examined 16 cores from holes in the Peace River area, mainly below the Bennett Dam. They subjected the lithology descriptions to various numeric analytical techniques, including a matrix analysis, indicating the probability of which lithologies would overlie each other. They found that coal was frequently overlain by sandstone with mudstone flasers (0.89 correlation) or mudstone with sandstone lenses (0.81). Coal was underlain by sandstone with mudstone, and siltstone interbeds (0.71)

STRUCTURAL INTERPRETATION

On the regional scale, the fold trends in the Peace River coalfield trend at about 42º west of north up to a latitude of about 56°, at which point they deflect to a more northerly trend of 12º to 30º west of north (Legun, 2003). The change in direction occurs in the area where the Peace River Arch intersects the Rocky Mountain Foothills. Face cleats are perpendicular to the fold axis direction characteristic of the southern part of the fold belt. Butt cleats are normal to face cleats and bedding (Figure 13). Langenberg (1990) also found that face cleats in the Rocky Mountain front ranges are oriented northeast-southwest and are therefore perpendicular to the fold axis trends.

Cleats and fractures were observed in 2 properties (Willow Creek and Sukunka) in the northern part of the Peace River Coalfield within the disturbed belt (Figure 14). At both properties, there are low-angle conjugate shear fractures in seams, and cleats normal to bedding tend to parallel axial planes of the regional folds. Obvious extensional cleats normal to the fold axis trend were not observed.

Areas where fold trends change orientation are often areas where there is enhanced cleat development and improved permeability (Ayers, 2002). In the area around the Bennett Dam, there is no indication of multiple cleat sets. Changes in cleat orientation in the subsurface east of the Bennett Dam where outcrop is sparse could be important in terms of permeability. Formation Micro-Imager (FMI) logs are powerful tools in determining fracture geometry, but it is difficult to identify spacing and orientation of vertical cleats or fractures. If the technology can be adapted to inclined holes, the amount of structural information col-

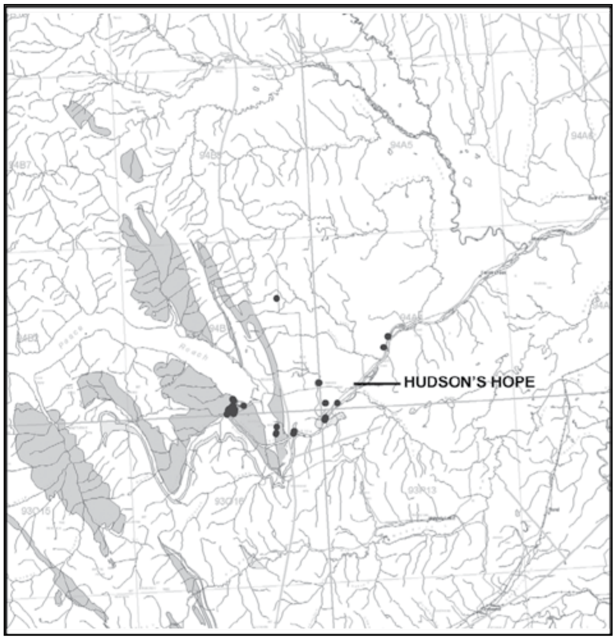


Figure 12. Location of outcrops where cleat measurements were obtained in 2004.

Photo 2. Cleat spacing in vitrain- and inertinite-rich bands.

lected would increase considerably. There are a number of graphic techniques for deciphering structural data from inclined drill holes.

During the Cretaceous, the Peace River Arch was an area of increased deposition, yet at present the Precambrian basement in the area is elevated and depth to the Gething Formation decreases over the Arch (Figure 15). If there was recent uplift of the Arch this could produce extension and open cleats. Bell (2002) studied the present in situ stress regime in the coal-bearing strata of the northeastern plains area of British Columbia. The minimum horizontal stress direction (Shmin) is oriented northwest-southeast in the study area (Figure 16, redrafted from Bell, 2002) and is therefore perpendicular to face cleats. Permeability will be enhanced in a direction northeast-southwest, and fractures with this orientation will have more chance of being open.

The tectonic history of the Cretaceous rocks over the Peace River Arch influences the present stresses in rocks. Increased burial and a thicker sedimentary sequence result in more compaction and a greater vertical stress gradient in Cretaceous rocks. More recent uplift should result in a decrease in magnitude of Shmin over the Arch (Figure 16), which appears to be the case, though this is in part related to present depth of burial. There is, therefore, some evidence that recent uplift along the Arch may have influenced the magnitude, though not the direction, of the minimum horizontal stress.

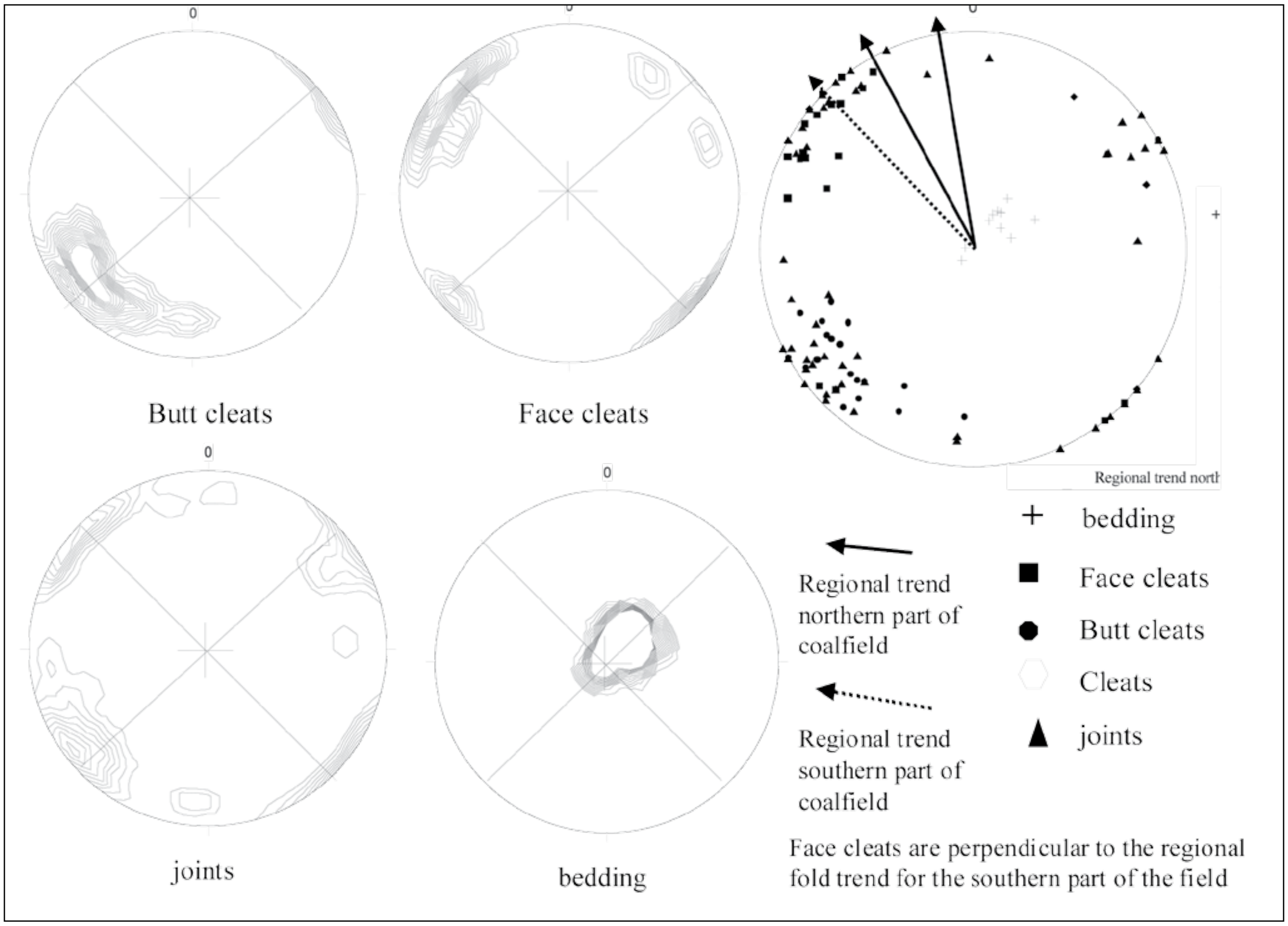
Methods of measuring Shmin require opening fractures and measuring closure pressure. Usually measurements will be on pre-existing fractures, and if cohesion on the fractures is low then at least the local Shmin will be at 90° to orientation of the fractures. As cohesion on the fracture increases, the ability of Shmin to rotate away from perpendicular to the fracture increases. In rock with a well developed system of vertical fractures with low cohesion surfaces present, Shmin will be perpendicular to this system. Any other orientation would result in shear movement.

There is a strong log-linear correlation between Shmin and permeability, but the relation varies for different coal basins. For example, in the Black Warrior Basin, a 6 MPa change in Shmin results in a one order of magnitude change in permeability; the same change in permeability in the Bowen Basin (Australia) requires only a 1.5 MPa change in Shmin. (Sparkes et al, 1995). Data indicate that Shmin is probably a more important influence on permeability than is fracture density (Enever et al., 1994). If vertical stress is constant, then closure pressure on a fracture is dependent on Young's Modulus and Poisson's Ratio for the coal. It is obvious that an understanding of the physical properties of the coal in conjunction with values of Shmin may provide some indication of the relative permeability from area to area.

CBM RESOURCE EAST OF THE DISTURBED BELT IN THE GETHING FORMATION

The potential CBM resource in the Gething Formation is calculated in the area east of the disturbed belt. To the southeast, the margin of the disturbed belt is easily defined by the Gwillum Lake Thrust, east of which the Gething Formation is substantially deeper than it is to the west above the thrust. To the north in the Hudson's Hope area, the transition from undeformed beds of the Western Canadian Sedimentary Basin to folded beds of the foothills is gradational and not as easily defined.

This paper estimates the CBM resource within the area confined by the disturbed belt to the west and depth of the Gething to the east. In addition, the area is subdivided and the area around Hudson's Hope analysed in greater detail. The extent of these two areas is indicated in Figure 17, based on a depth to the top of the Gething of greater than 100 m and less than 1000 m. The figure indicates the active grid nodes used in the resource evaluation. In the northern area, the cell sides are 2 km, and in the total area they are 3 km. The areas increase somewhat as the depth cutoff criteria is increased.



Face cleats are perpendicular to the regional fold trend for the southern part of the field

Figure 13. Stereonet plot of poles to bedding, joints, and cleats.

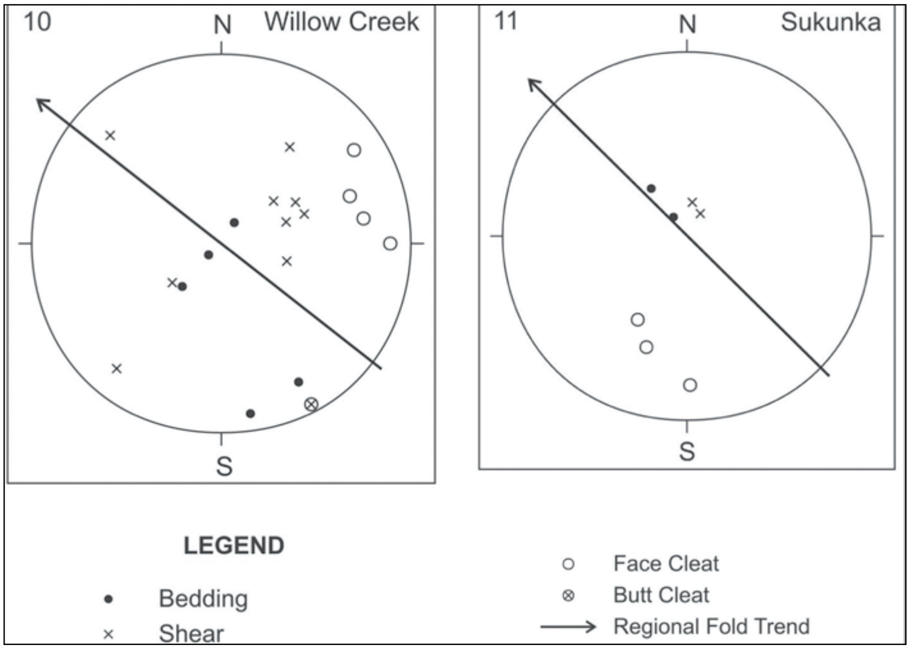


Figure 14. Cleats and fractures in seams at the Willow Creek and Sukunka properties, northern Peace River coalfield.

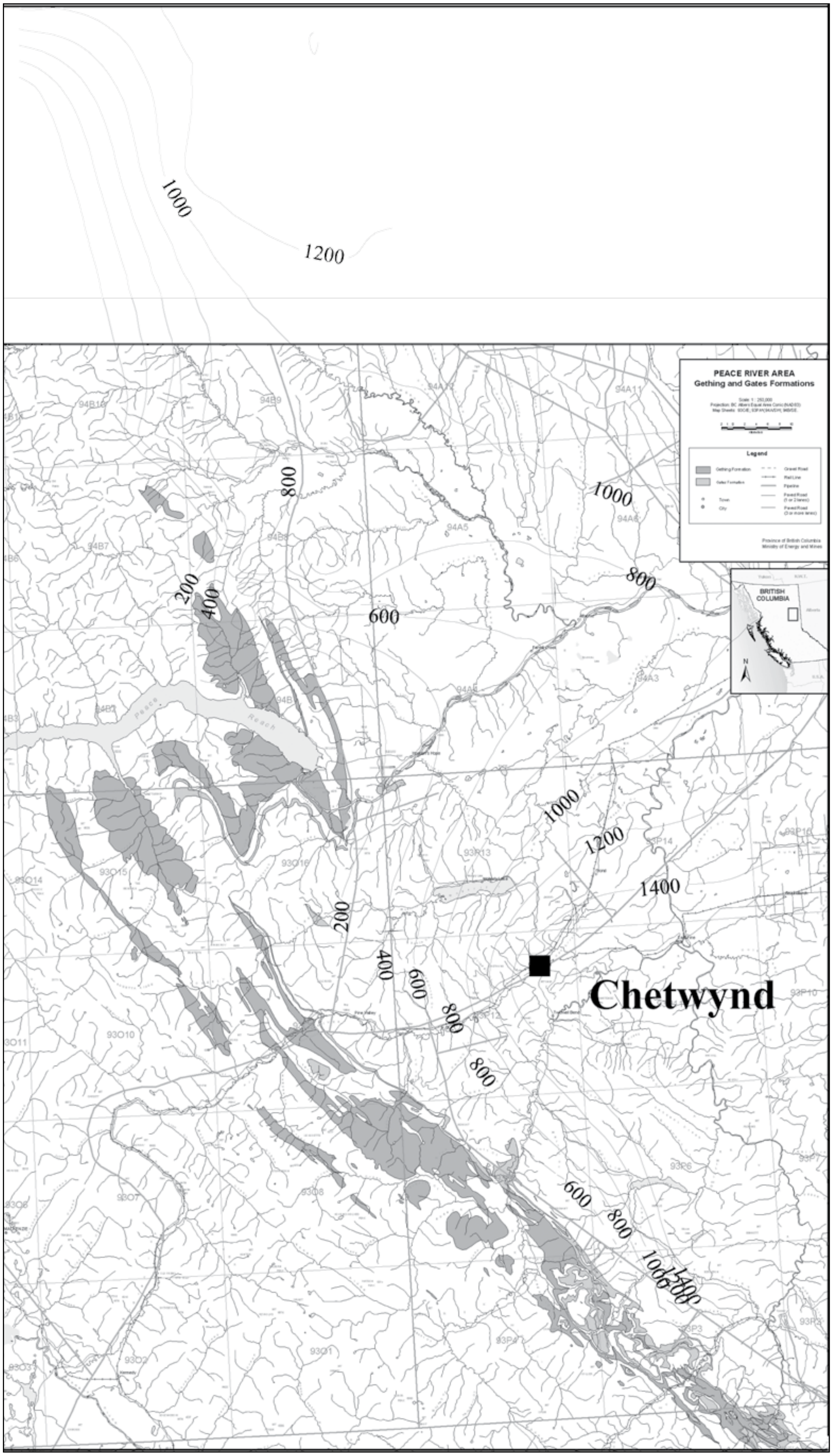


Figure 15. Depth (m) to the top of the coal in the Gething Formation.

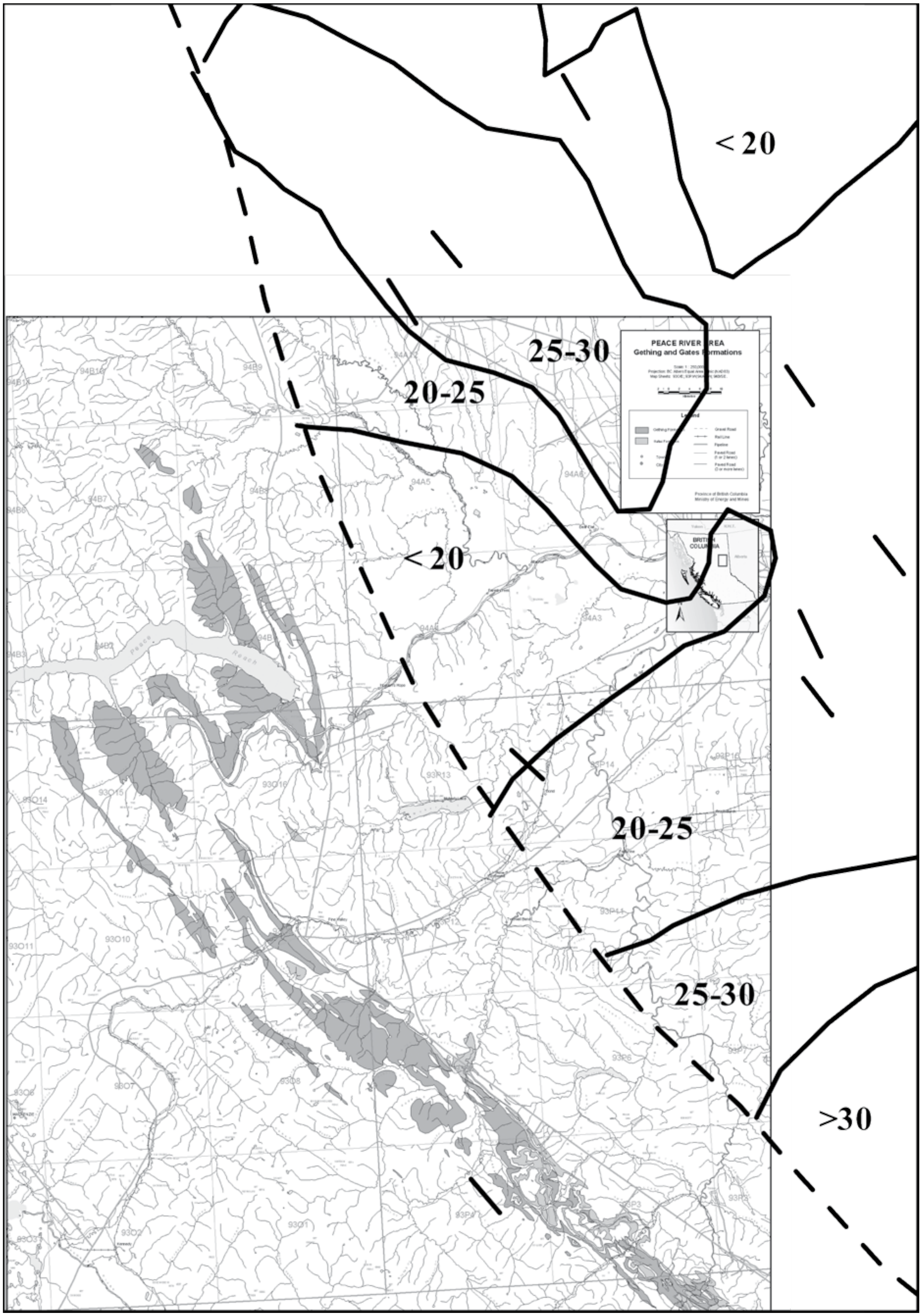


Figure 16. Minimum and maximum horizontal stress directions and magnitude of Sh_{min} (Mpa) at the top of the Bluesky Formation (from Bell [2002]).

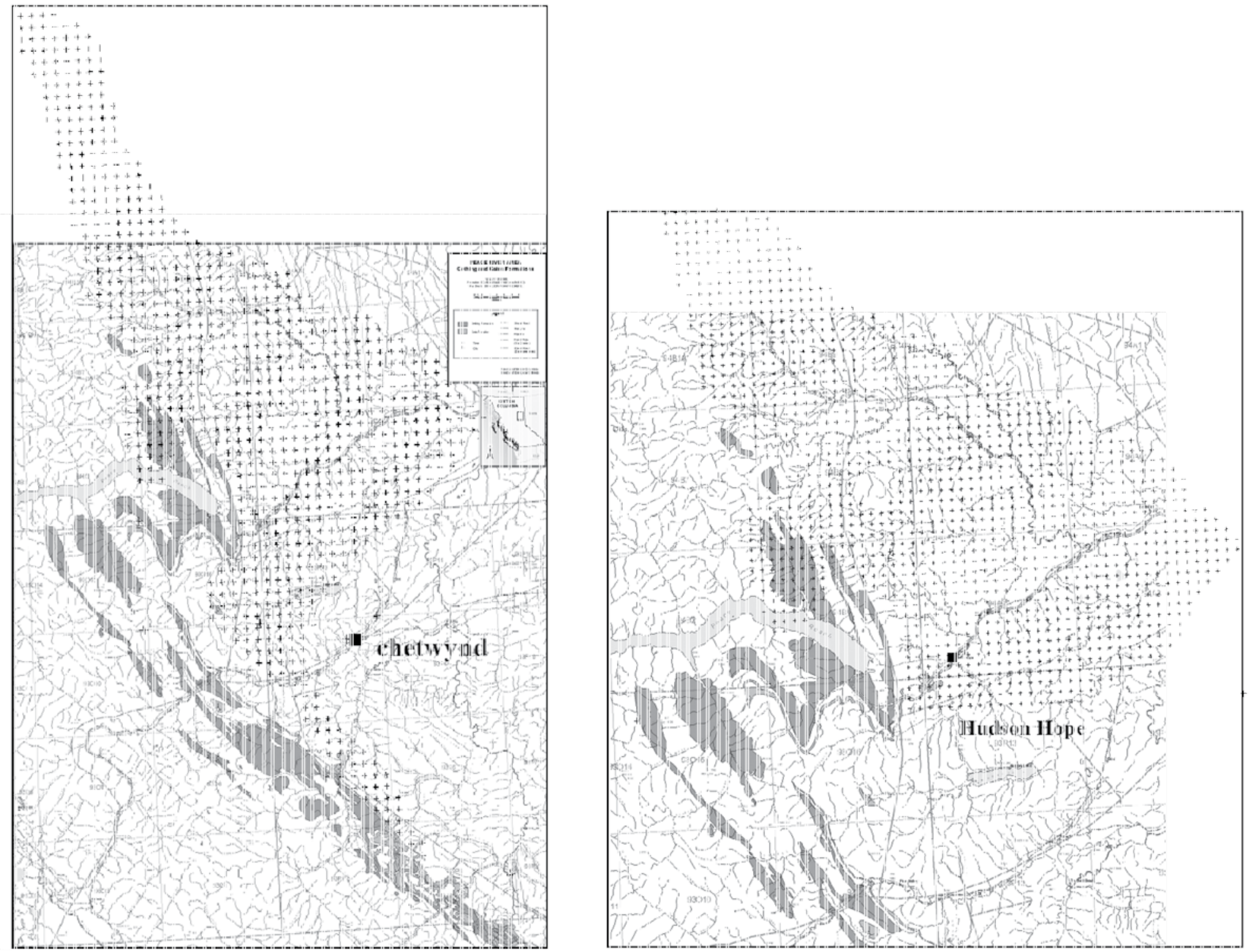


Figure 17. (a) Total resource area defined by deformation front to the west and depth of 1000 m to the top of the Gething Formation. Area is outlined by active grid nodes on a 3 km by 3 km grid; (b) Sub-area of (a) Hudson Hope area; active grid nodes on a 2 km by 2 km grid.

A number of parameters were kriged, gridded, and contoured for the whole area and for the area around Hudson's Hope. They include depth to the top of the first coal in the Gething; thickness of the coal section in the Gething; cumulative coal in the section; Rmax at the top of the Gething; and Rmax at the bottom of the Gething. Based on these gridded surfaces, a number of values are calculated at each node: average depth of the coal section; average rank; density of the coal based on an ash content of 20% or 30%; potential saturated-gas content based on rank and depth; potential resource as bcf per section. Coal density is calculated using an equation (Ryan, 1995) that utilizes estimates of zero-ash coal density, mineral matter density, water content, and void porosity volume to determine coal density at varying ash contents.

The formation is at relatively shallow depths in the Hudson's Hope area but is generally deeper to the northwest and southeast (Figure 18). The thickness of the coal section (Figure 19) varies but is generally quite thick when compared to the cumulative coal thickness present (Figure 20). The thickness of the coal section calculated from the 121 logs used in this study compares well with the thickness of the Gething Formation as documented by Gibson (1992), both tend to be at a maximum in the Hudson's Hope area and decrease to the northwest and southeast. In the Hudson's Hope area, cumulative coal thicknesses are generally over 6

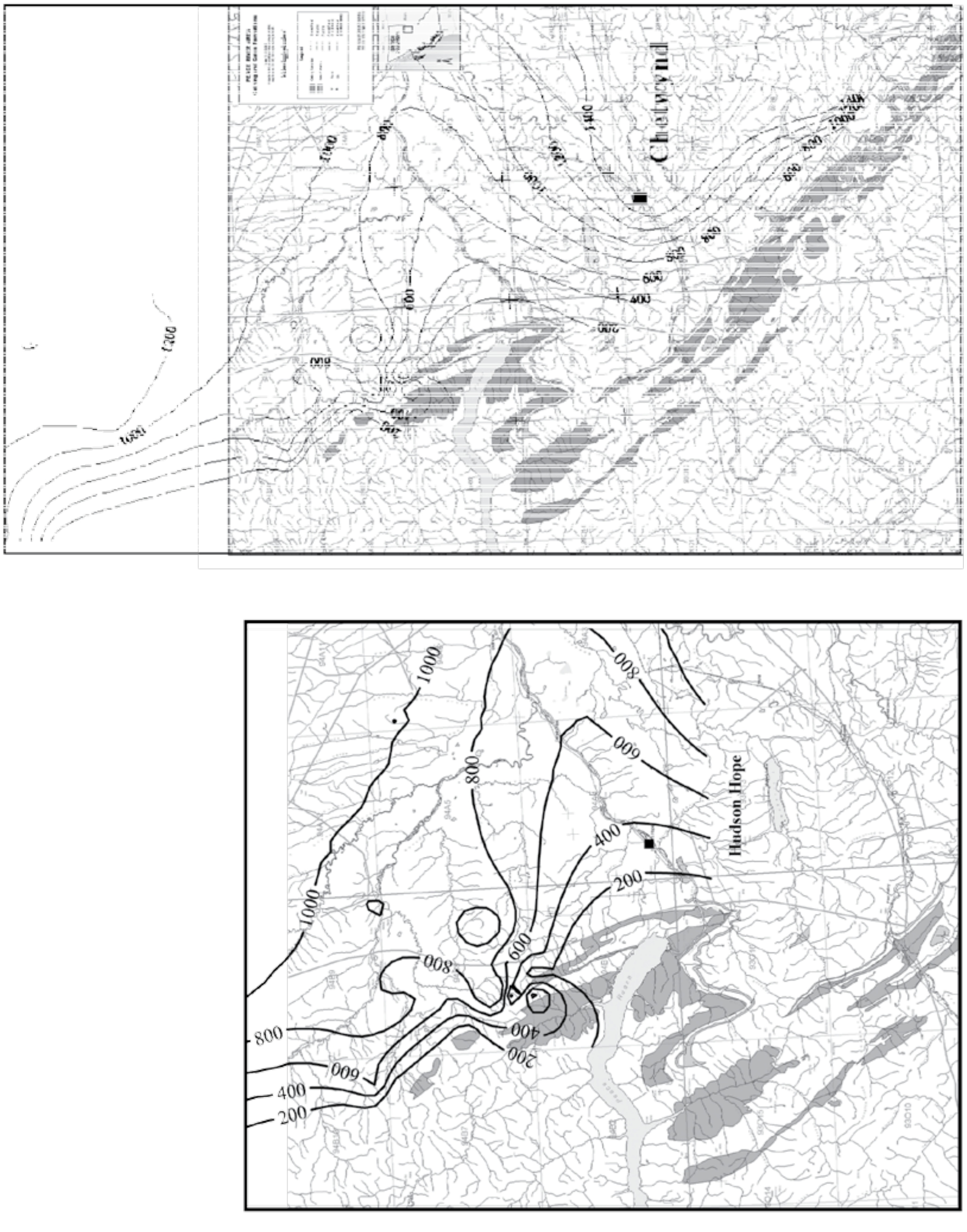


Figure 18. Depth to the first coal in the Gething Formation (a) Hudson Hope area (b) total area.

m and the section thickness over 200 m. Rank on the top of the Gething Formation is high south of Hudson's Hope but in the area there is little coal in a prospective depth window. Rank decreases to the northeast towards Hudson's Hope, but is still in the range of Rmax = 1% (Figure 22).

The resource calculated as bcf per section in each cell (cell areas 4 km^2 for Hudson's Hope area and 9 km^2 for total area; Figure 23) is high south of Hudson's Hope where the rank is high and reaches 22 bcf per section. However, the increasing depth of the Gething Formation to the east restricts the total resource available in this area. Most of the area around Hudson's Hope is better than 6 bcf per section and much of it is better than 14 bcf per section.

The potential CBM resource in the Gething Formation in the area east of the disturbed belt from the Alberta border to north of Hudson's Hope is in the range of 25 to 40 tcf (Table 1). Most of this resource (17 to 29 tcf) is in the Hudson's Hope area and to the north. West of the disturbed belt, the rank of the formation is variable and high and the potential resource is substantial; however, folding limits the area prospective for exploration.

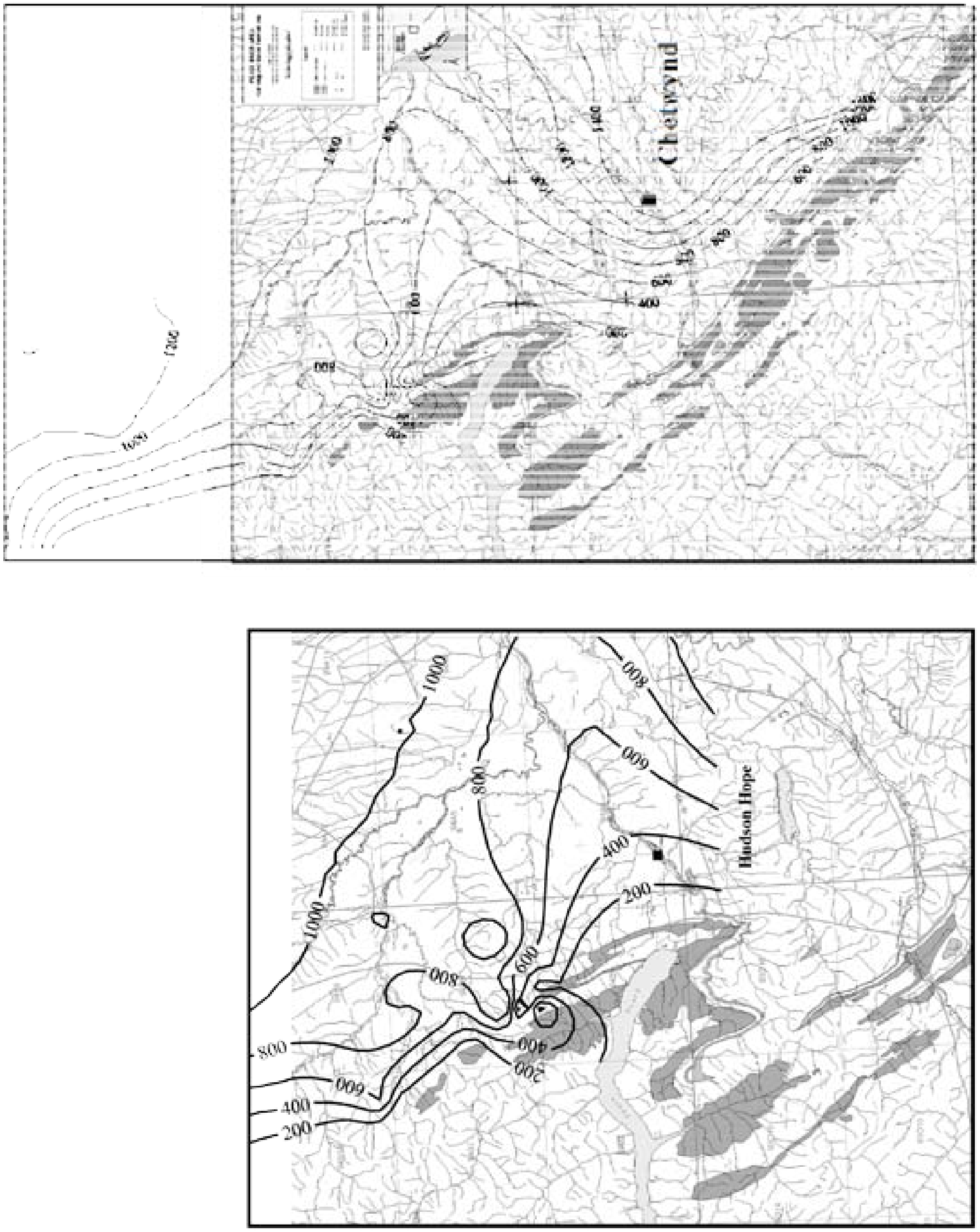


Figure 19. Thickness of coal section in the Gething Formation.

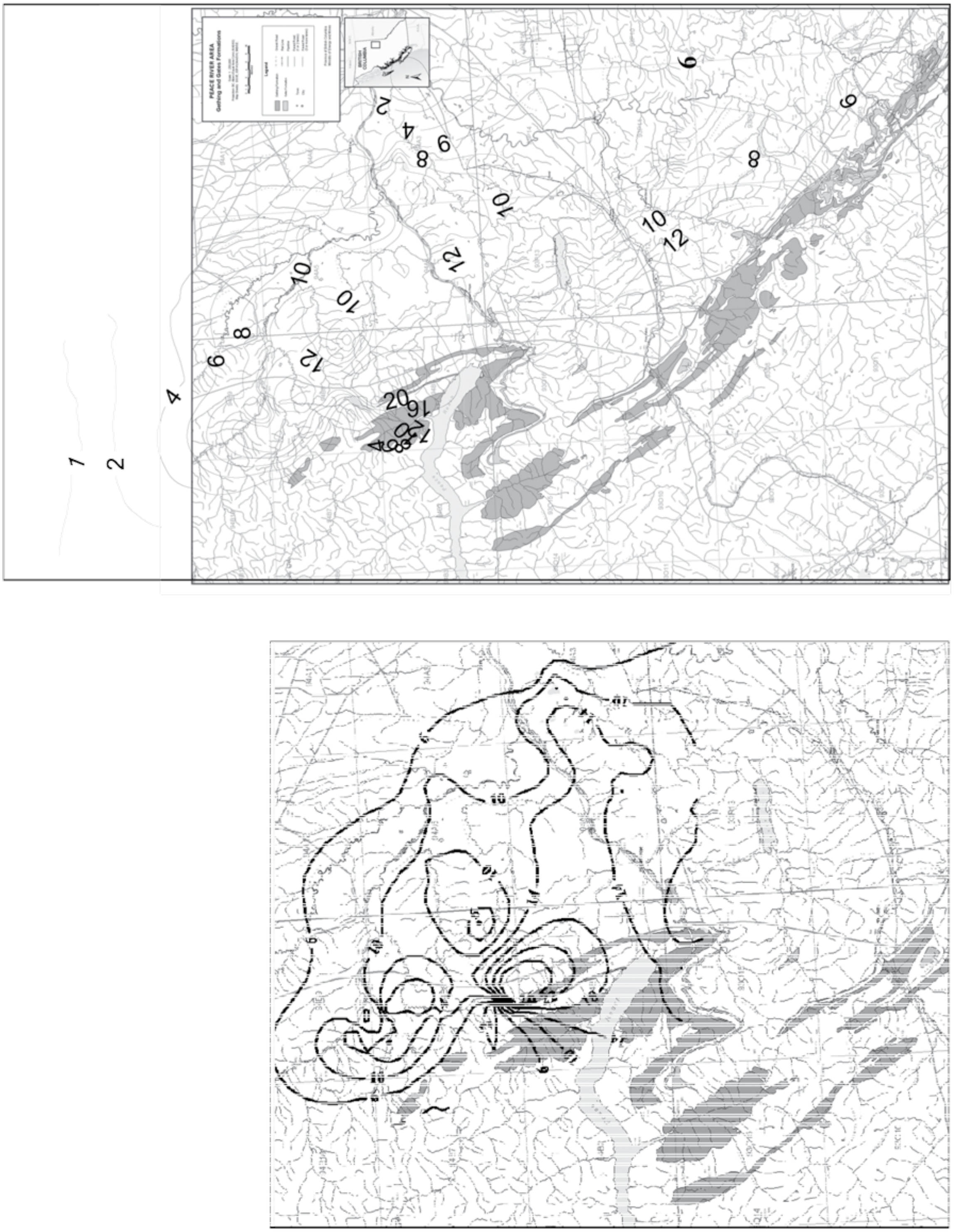


Figure 20. Cumulative coal in the coal section.

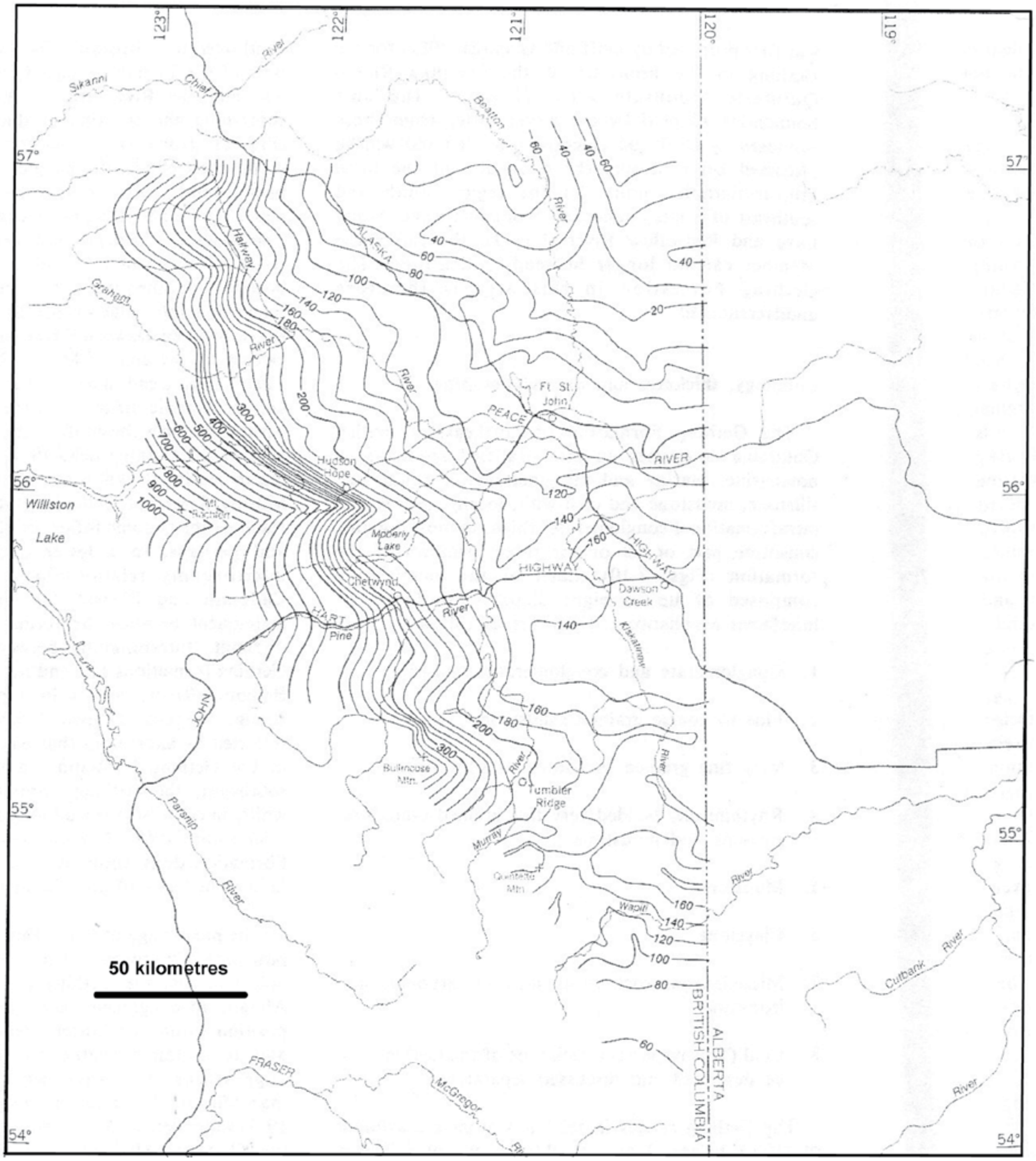


Figure 21. Thickness of the Gething Formation (from Gibson [1992]).

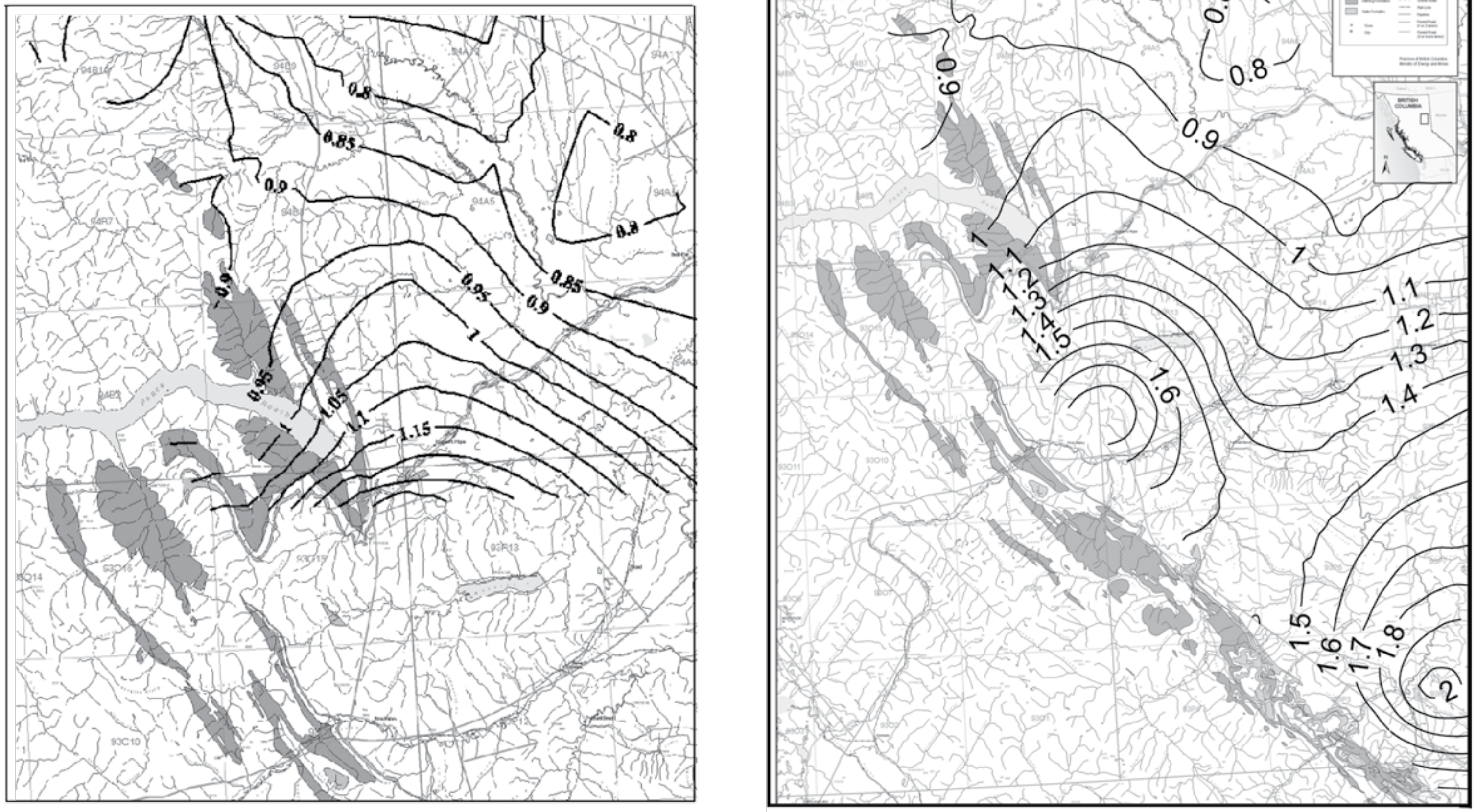


Figure 22. Rmax for the top of the Gething Formation; data derived from Marchioni and Kalkrueth (1992).

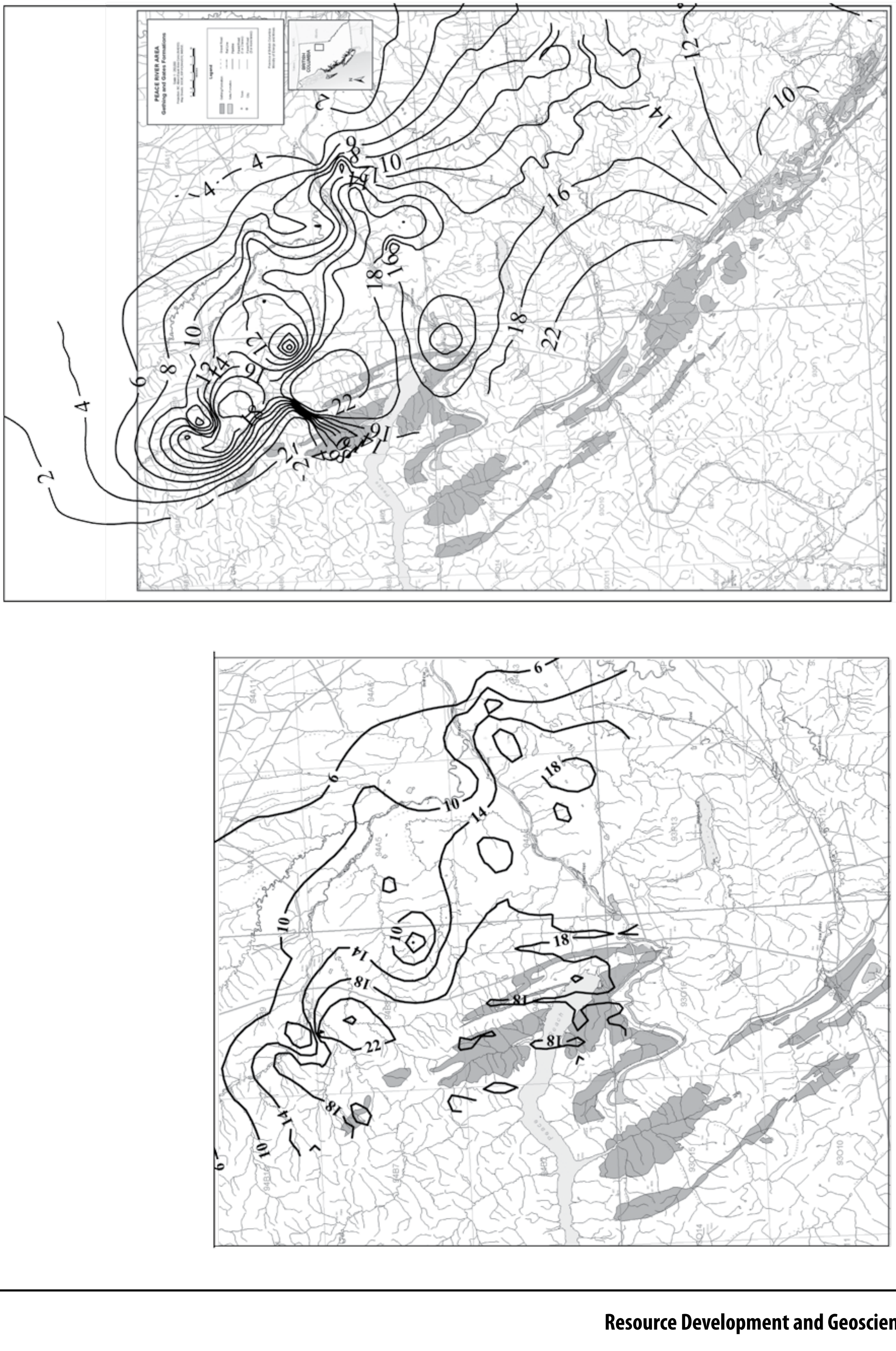


Figure 23. Resource estimate as bcf per section; (a) Hudson Hope area and (b) total area.

CONCLUSIONS

There is an enormous volume of coal within the Rocky Mountain Fold Belt contained within the Gething and Gates Formations and based on rank it probably contains a very large resource of CBM. However, initial exploration has indicated that low permeability and deformation may provide challenges to CBM development.

The Gething Formation extends east of the Rocky Mountain Fold Belt. South of the Sukunka River, the formation thins and contains less than 10 m of cumulative coal. In addition, the formation is overridden by thrusts and dips steeply into the Western Canadian Sedimentary Basin. However, to the north the formation is thicker and remains at a shallow depth east of the fold belt. In this area, which is centred on the town of Hudson's Hope, the formation contains from 5 to 20 m of cumulative coal occurring in a number of thin seams. Rank in the Hudson's Hope area is generally greater than 0.9%, decreasing to the north and increasing to the south.

The combination of favourable cumulative coal thickness, depth to coal, and rank ensure that there is the potential for good concentrations of gas in the area. In fact most of the Hudson's Hope area has the potential for a resource of greater than 14 bcf per section. Total resource calculations used depth cut-offs of 800, 1000, 1200, and 1400 m with average ash contents of 20% and 30%. The potential resource to 1000 m is estimated to be 27 tcf in the Hudson's Hope area and 38 tcf in the total area, which includes the Hudson's Hope area and extends to the south. It must be emphasized that this is an estimate of the potential resource assuming gas-saturated coals. How much, if any, of this total will eventually be recovered depends in part on information yet to be obtained by exploration in the area.

Outcrops of Gething coals do not extend east to Hudson's Hope, but in the Peace River Canyon below the Bennett Dam to the west there are good outcrops of coal seams. Seams are well cleated, and the face cleats are oriented across the fold trend and at 90° to the minimum horizontal stress direction. In addition, the magnitude of the minimum stress tends to be less over the Peace River Arch in the Hudson's Hope area than to the north or south. There are, therefore, indications that there may be improved permeability in the area, and this in conjunction with the high potential resource per section makes the area very prospective.

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LIARD BASIN MIDDLE DEVONIAN EXPLORATION

Warren Walsh[1], Osman Salad Hersi[2], Mark Hayes[1]

ABSTRACT

The Liard Basin is a sub-basin of the Western Canada Sedimentary Basin (WCSB) system, straddling the Northwest and Yukon Territories boundaries with the province of British Columbia. The basin contains over 5 km of sedimentary strata of Cambrian through Upper Cretaceous age.

Exploration for Manetoe dolomite reservoirs hosted within Middle Devonian carbonates of the Dunedin and Nahanni Formations began in the 1950s. Several pools have been found within the fold and thrust belt both in northeastern British Columbia and the Yukon and Northwest Territories (NWT). Recent gas discoveries within the Devonian Nahanni Formation north of Fort Liard, NWT have renewed interest in this play. Resource assessments for the Middle Devonian play in the Liard Basin estimate between 2.8 and 6.6 trillion cubic feet (Tcf) undiscovered gas, with approximately 2.5 Tcf estimated to be located within northeastern British Columbia.

The British Columbia Ministry of Energy and Mines (BC MEM) is currently working with the University of Regina and the Geological Survey of Canada (GSC) to expand our knowledge and understanding of the Liard Basin. Through a contribution agreement, the BC MEM, in conjunction with Dr. Osman Salad Hersi of the University of Regina, is supporting graduate-level studies on the sedimentology, stratigraphy, and diagenesis of Middle Devonian shallow-marine carbonates of the Dunedin Formation of subsurface Liard Basin, with application to petroleum exploration. The BC MEM also continues their relationship with the GSC, which has recently published a reinterpretation of the Bovie Structure which included the identification of new conceptual plays within the Liard Basin.

KEYWORDS: Northeastern British Columbia, Liard Basin, Dunedin Formation, Manetoe Dolomite Facies

INTRODUCTION

The Liard Basin is a sub-basin of the extensive Western Canada Sedimentary Basin (WCSB) system, straddling the Northwest and Yukon Territories' boundaries with the province of British Columbia. The basin covers a total area of approximately 2.5 million hectares (ha) with up to 5000 m of Paleozoic and Mesozoic sedimentary fill. The Liard Basin is a frontier basin whose hydrocarbon potential is only just beginning to be appreciated.

The eastern boundary of the Liard Basin is delineated by the Bovie Fault System, which also marks the approximate eastern limit of Mississippian through Upper Cretaceous strata (Monahan, 2000). Recent work by the Geological Survey of Canada (GSC), supported by the British Columbia Ministry of Energy and Mines (BC MEM), has reinterpreted the nature and history of the Bovie Structure (MacLean, 2002; MacLean and Morrow, 2004). MacLean and Morrow (2004) have reinterpreted the Bovie Fault as a two-stage compression: (i) a Late Carboniferous to Permian westward-convergent steeply dipping thrust fault that is cut by (ii) the Larimide-aged Bovie Lake Thrust. This reinterpretation of the Bovie Structure has also identified several potential play types in Devonian, Carboniferous, and Cretaceous strata associated with the Bovie Fault (MacLean and Morrow, 2004).

The western side of the Liard Basin is referred to as the Liard Plateau or the Liard Fold and Thrust Belt, a northward continuation of the fold and thrust belt of the Rocky Mountain foothills. Within this area, several hydrocarbon pools have been discovered within carbonates of the Middle Devonian, and several gas shows have been found at Mississippian through Permian intervals. The Middle Devonian carbonate play type has upwards of 2.35 Tcf of remaining undiscovered gas in place within northeastern British Columbia (NEB, 2000). The stratigraphy, sedimentology, and diagenetic history of the Middle Devonian Dunedin Formation of British Columbia is the focus of a multi-year collaboration between the University of Regina and the BC MEM.

A geological map of the Liard Basin has been created and is now available to aid exploration. The 1:250 000 scale map is a compilation of geology maps separately issued by the Geological Survey of Canada and has been updated with infrastructure, land tenure, and petroleum and natural gas wells for the entire Liard Basin. Production data and drill stem test results and interpretation for the Middle Devonian have also been summarized.

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GEOLOGIC SETTING, PALEOGEOGRAPHY, AND STRATIGRAPHY

Dunedin Formation

In the Devonian Period, northeastern BC and nearby regions of Alberta, Yukon, and Northwest Territories were cut by several rifting events that produced deep depressions and uplifted shoulders that later became shallow-marine shelf areas (Cecile et al. 1997, Pyle et al. 2003). The Macdonald-Mackenzie shelf was the most prominent in northeastern BC and nearby regions, allowing deposition of thick carbonate successions that include the largest carbonate reservoirs in the region (Moore, 1989, Pyle et al. 2003).

The Dunedin Formation consists of Middle Devonian (Eifelian) carbonate strata that were deposited on the MacDonald shelf. The shelf continued across BC's border with the Yukon and Northwest Territories, where equivalent strata, the Landry and Nahanni Formations, were deposited. Southward (i.e., southern northeast BC and NW Alberta), the Dunedin Formation merges with the prolific Keg River Formation (Nadjiwon, 2001). These Middle Devonian carbonates contain hydrothermally dolomitized facies (Manetoe dolomite facies and equivalents; see below) with potentially good reservoir quality.

The Dunedin Formation is a transgressive unit dominated by peritidal and subtidal shallow-marine carbonates and, due to southward facies retrogradation, the Besa River Formation oversteps the Dunedin Formation in the southeast (Morrow, 1978, Nadjiwon, 2001). Broad subdivision of the Dunedin Formation documents that the formation consists of a lower lithofacies characterized by a bioclastic dolomitic wackestone and an upper lithofacies of bioclastic grainstone to wackestone units (Morrow, 1978, Nadjiwon, 2001). Further south, where the formation passes to the reefal Keg River Formation, intercalations of coral and stromatoporoid reef facies are common. Due to the reefal "tongues", the thickness of the Dunedin Formation varies significantly (e.g., from 108 m to over 300 m within a distance of 11 km; Nadjiwon et al., 2000); however, the causes of this abrupt thickness change are not clear. Possibilities may include synsedimentary faulting and/or establishment of reefal margin defined by differential reef growth in response to sea-level fluctuations (cf. transgression-instigated catch-up situation of Jones and Desrochers, 1992). The Dunedin Formation continues across the northern provincial-territorial borders, where it is equivalent with the gas-producing Landry-Nahanni Formation in the Yukon and Northwest Territories.

The Manetoe Dolomite Facies

Dolomites associated with subsurface Middle Devonian carbonates of southeast Yukon Territory, southwest Northwest Territories, and northeastern BC host one of the world's largest Mississippi Valley-type (MVT) deposits (Rhodes et al. 1984, Qing, 1998). These dolomites are also important gas reservoirs (Collins and Lake, 1989; Morrow and Davies, 2001). The dolomitized strata are known as the Manetoe dolomite facies (Manetoe) in the Northwest and Yukon Territories (Morrow and Potter, 1998; Morrow et al. 1986, 1990); they form good reservoir intervals in many gas-producing fields in the region (e.g., Pointed Mountain, Kotaneelee, Fort Liard, Beaver River, and Crow River gas fields). The Manetoe is characterized by a fractured and brecciated white sparry dolomite (Morrow et al. 1990; Morrow and Potter, 1998). Although the Manetoe dolomite facies that occur within the Dunedin and Nahanni-Landry successions of Yukon and NWT, respectively, are fairly well documented (Morrow and Potter, 1998; Morrow and Davies, 2001, Morrow et al. 1986, 1990), knowledge is lacking in northeastern BC, as the equivalent dolomites of the Dunedin Formation are less well understood. Understanding the origin, fabric, porosity, reservoir potential, and vertical and lateral distributions of this dolomite facies is essential for gas exploration activities within this prospective frontier basin.

MIDDLE DEVONIAN HYDROCARBON POTENTIAL

Fold and Thrust Belt

Exploration to date for Middle Devonian Manetoe dolomite within the Dunedin and Nahanni Formations has been focused within the Liard Fold and Thrust Belt. The Liard Fold and Thrust Belt of BC covers an area of approximately 1.25 million ha. Exploration has resulted in the discovery of two fields, Beaver River and Crow River. Outside of these two fields, only six exploration wells have been drilled targeting the Middle Devonian, all drilled prior to 1974. Within the Yukon and NWT, a total of five Middle Devonian fields have been discovered with less than ten exploration wells outside of proven fields.

Exploration within the Liard basin began in the 1950s with the first well drilled in the Liard Fold Belt at the Toad River Anticline (Joint Venture No. 1 c-10-E/94-N-7; rig released in 1954). Amoco Canada Petroleum Co. Ltd. made the first discovery at the Beaver River Field in 1958. Further drilling delineating the Beaver River pool and subsequent discoveries were made in the 1960s at Pointed Mountain in the Northwest Territories and Kotaneelee, Yukon Territory.

Originally over 1.4 Tcf of reserves were associated with the Beaver River pool alone; however, high water-to-gas ratios resulting from the highly fractured reservoir and active water drive led to lower than expected recoveries from these fields, which were subsequently shut-in during the mid-1970s (see Davidson and Snowdon, 1978). Recent exploration has resulted in new pools being discovered in the Fort Liard region, NWT. Beyond this, however, there has been only limited exploration for Devonian-aged reservoirs within the Liard Basin.

In the past, resource assessments have been conducted with the aim to identify the resource potential of the Liard Basin. The National Energy Board (NEB) assessed the resource potential for the northeast BC portion of the play to be 2.5 Tcf of ultimate resource total, with 2.35 Tcf remaining undiscovered. A 2001 assessment of the Manetoe facies reservoirs in the Yukon assigned an initial gas in place (IGIP) estimate of 3.4 Tcf. This is a total ultimate resource potential of 5.9 Tcf, though it does not include the NWT. For the entire fold and thrust belt, the natural gas potential in Canada was assessed in 2001 by the Canadian Gas Potential Committee (CGPC) as a total IGIP of 5.6 Tcf (CGPC, 2001), with 2.8 Tcf remaining undiscovered, mainly in Middle Devonian reservoirs.

Basin Centre / Bovie Fault Zone

The centre of the basin between the western foothills and the Bovie Fault zone covers approximately 1.0 million ha. Within this immense area only two wells, Amoco et al. La Biche (a-67-D/94-O-13 RR: 1974-08-28) and Burlington Chevron Patry (c-86-B/94-O-5/02 RR: 2000-01-25), have penetrated Middle Devonian carbonates. Subsea depth to the Middle Devonian carbonate in these wells is −4635 m (15 207’) and −3696 m (12 126’) respectively. Burlington Chevron Patry found dolomite at a depth of −3846 m (subsea). However, of these wells, only Amoco et al. La Biche was tested. Two drill stem tests were run over the Middle Devonian carbonate, with an inhibited water cushion of 2590 m. No blow was recorded during the flow, and recoveries were not recorded because the tool became stuck in the hole following the second test; however, a sample bomb did recover gas (97% C1) from the second drill stem test. These wells indicate that both dolomite and gas are present within the Middle Devonian carbonates of the Liard Basin centre.

To date, no resource assessment has been made for the Middle Devonian within the Liard Basin centre. However, conceptual plays along the western margin of the Bovie Structure were identified by MacLean and Morrow, 2004.

FUTURE WORK

The sedimentologic, stratigraphic, and diagenetic attributes and basin-fill architecture of the Middle Devonian Dunedin Formation (of northeastern BC) are not well understood despite the great potential for hydrocarbon content. In order to attract industry interest to this frontier basin, a clear understanding of these attributes and reservoir qualities of the Dunedin Formation is crucial.

The Ministry of Energy and Mines is working with Dr. Osman Hersi of the University of Regina through a contribution agreement supporting graduate-level studies on the sedimentology, stratigraphy, and diagenesis of Middle Devonian Dunedin Formation shallow-water carbonates of subsurface Liard Basin, with application to petroleum exploration. The objective of the proposed study is essentially two-fold: 1) to study the microfacies, lithostratigraphic, and biostratigraphic attributes of the formation, its vertical and lateral lithofacies variations and correlations, and a model for its depositional setting; and 2) to decipher the diagensis, origin, areal and vertical distributions, and reservoir characteristics of the dolomite facies associated with the formation (i.e., Manetoe-equivalent dolomite facies).

These goals are achievable by performing and integrating detailed sedimentological, lithostratigraphic, and biostratigraphic analyses; 3-D lithofacies mapping (integrating subsurface data with interpretation of seismic profiles); and detailed diagenetic and porosity evolution studies and reservoir characterization of the formation. Integration of these data interpreted in the light of a sequence stratigraphic approach will also better constrain the 3-D evolution of the depositional systems through time. This will eventually enhance our understanding of the lateral and vertical distributions of the reservoirs. The overall scope of the proposed research is the enhancement of our knowledge with respect to the nature and internal architecture of this formation, diagenesis and subsurface distribution of the dolomite facies associated with the formation, and reservoir characterization of both dolomitized and undolomitized intervals of the formation.

The Ministry of Energy and Mines continues their relationship with the Geological Survey of Canada (GSC) through support for their ongoing work on the Liard Basin. The GSC is continuing interdisciplinary studies incorporating seismic, stratigraphic, and source rock studies (see Morrow *et al.* 2002; Morrow and Shinduke, 2003; Potter *et al.*, 2003; Maclean and Morrow, 2004).

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SURFICIAL GEOLOGY AND AGGREGATE STUDIES IN THE BOREAL PLAINS OF NORTHEAST BRITISH COLUMBIA

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ABSTRACT

This paper summarizes the results of several studies conducted as part of the northeast British Columbia surficial geology and aggregate mapping program. The detailed results of some of these studies are discussed in a number of articles within this volume following this introductory paper. Much of the work has focused on the identification of aggregate deposits in the region, which typically are rare and difficult to identify with traditional mapping methods. The rarity of aggregate deposits has resulted in excessively high road construction, improvement, and maintenance costs. To address these problems, the program has applied a number of innovative techniques, such as high-resolution airborne electromagnetic surveys, LiDAR data analysis and interpretation, and digital compilation of large volumes of subsurface borehole and geophysical data.

The results of this work to date have led to the discovery of eight new major aggregate deposits, twenty-five new prospects, and a large number of showings. Eleven of these new prospects have an estimated value of $120 million in direct royalty revenue to the province. Six of the new prospects were identified in a successful winter drilling program in 2005. More than half of the new deposits have been developed into aggregate operations. In addition to two new mines opened in 2004, three of the deposits were developed into gravel operations in the winter of 2005. These are the first significant aggregate mining operations that have been developed in the study region in over 15 years. Gravel from these mines has been used extensively on a number of provincially supported road initiatives.

KEYWORDS: Quaternary Geology, Aggregate Resources, Surficial Geology Mapping, Shallow Gas, Quaternary Gas, Diamonds, Northeast British Columbia

INTRODUCTION

In this paper we provide an overview of ongoing Quaternary geology studies being conducted by the Resource Development and Geoscience Branch of the Ministry of Energy and Mines (MEM) in northeast British Columbia (Figure 1), an area of active oil and gas exploration and development. A number of papers follow that provide details on some of the components of this project. The project has involved collaboration with the Terrain Science Division of the Geological Survey of Canada (GSC), the Alberta Geological Survey, the BC Ministry of Transportation, Land and Water BC Inc., and various oil and gas companies.

Applications of Quaternary geology data to the oil and gas industry include identification of aggregate resources for petroleum development road (PDR) construction, provision of a stratigraphic framework for the Quaternary–Tertiary gas exploration play, and the identification of areas of thick Quaternary deposits and permafrost for engineering purposes. Recent well blow-outs and serious drilling problems associated with shallow gas and artesian aquifers have further highlighted the importance of Quaternary geology studies in the region. Surficial geology map data, such as drift thickness information, also have applications in estimating drilling costs (e.g., casing depths), as well as in improving design of seismic surveys and interpretation of geophysical data. Another application of Quaternary geology studies in the region relates to the evaluation of diamond potential, which is becoming increasingly important in northern Canada.

Study Area

The study area occurs within the Boreal Plains region of northeast BC and includes the area between the Alberta border and the Alaska Highway, extending north from the Fort St. John region to the Northwest Territories. The main areas of focus for the 2003 and 2004 field seasons (Figure 1) were the Fontas River and Petitot River map areas (NTS 94 I and P, respectively) and the eastern half of the Fort Nelson map area (NTS 94 J). Work in the 2005 field season is also planned for the Dawson Creek area (NTS 93 P).

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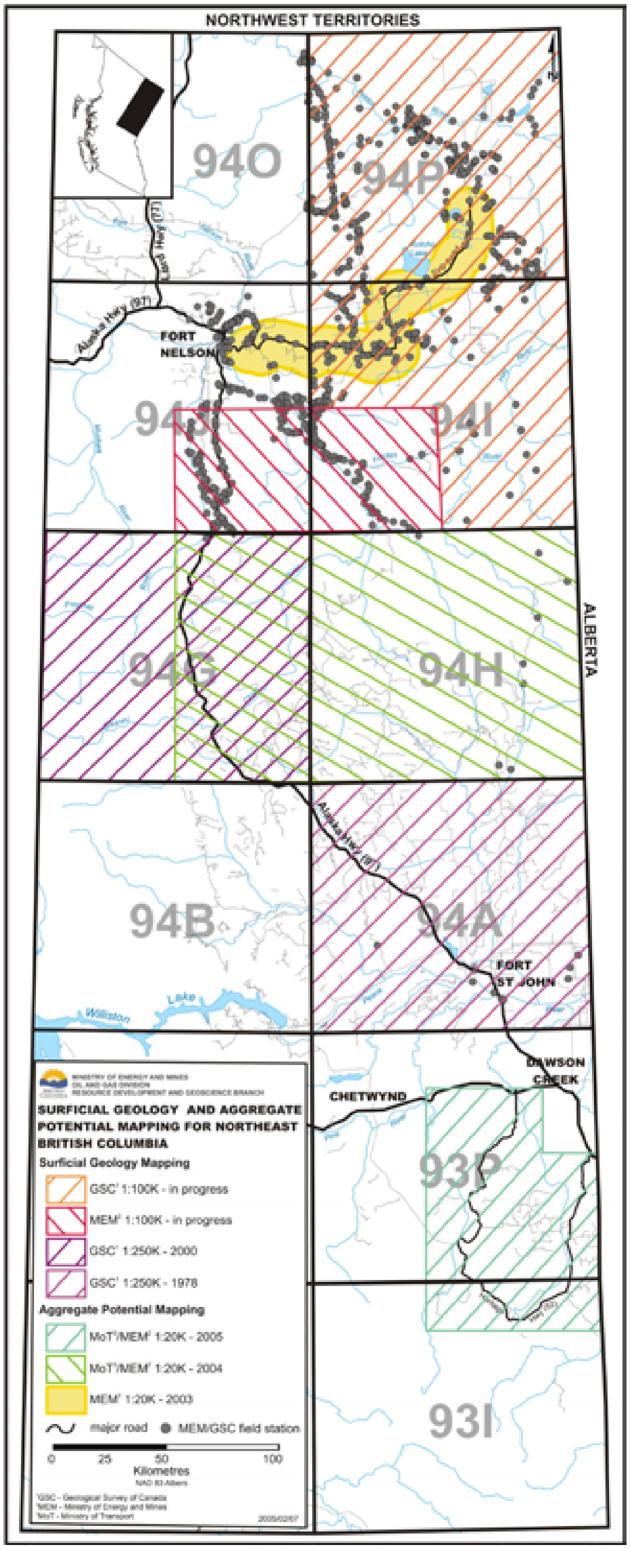

Figure 1. Location of study area and coverage of previous and current surficial geology and aggregate potential mapping programs. The SYD Road is highlighted by a yellow 10 km buffer along which MEM reconnaissance mapping was conducted in 2003.

Previous Work

Previous geologic studies in the region northeast of Fort Nelson have been mainly regional in nature and have included soils, surficial geology, and aggregate potential and bedrock geology mapping (e.g., Valentine, 1971; Thompson, 1977; Mathews, 1980; Stott, 1982; Mollard, 1984a, b). Surficial geology mapping farther south includes the work of Mathews (1978), Reimchen and Bouvier (1980), and Bednarski (2001). The Quaternary geology of the study area and a number of recent aggregate potential and surficial geology studies, conducted as part of this program, were summarized by Levson et al. (2004).

SURFICIAL GEOLOGY

The surficial geology of the study area is dominated by clay-rich tills and glaciolacustrine sediments. In places, these fine-grained Pleistocene deposits completely cover glaciofluvial sands and gravels with aggregate potential. For example, a number of recently discovered gravel deposits underlying clay-rich diamicton are interpreted to be subglacial channel deposits overlain by meltout till. Poorly drained areas with thick organic deposits are also common in the region. Glaciofluvial deposits are relatively rare at surface and occur mainly within or near large meltwater channel systems.

The timing of glacial events in the Late Pleistocene is poorly constrained, but a few radiocarbon dates from sediments underlying till indicate that the last glaciation in the region was Late Wisconsinan. Fossiliferous organic sediments (of inferred Sangamonian age) underlying till have been discovered in the study area and indicate a paleoclimate somewhat similar to the present. Glaciers did not move into the region until after about 24 ka (as radiocarbon years BP), and ice-free conditions probably existed from then until well before 40 ka (Levson et al., 2004).

AGGREGATE PROGRAM

In northeast BC, aggregate typically accounts for 30% to 75% of the total cost of road building and maintenance projects. For example, a $111 million upgrade option on the Sierra-Yoyo-Desan Road (SYD) included $83 million in gravel costs (McElhanney, 2003a). A particularly critical shortage of aggregate in the Fort Nelson region has resulted in high prices and, in a few projects, has necessitated shipping gravel by train from Fort St. John at the expense of the provincial government. Prior to the beginning of this program, a study to evaluate the quantity of aggregate at ten gravel reserves along the SYD indicated that only three of the areas had more than 100 000 cubic metres (m^3) of gravel remaining, and most was available at only one location at the north end of the road (Thurber, 2001, 2002). Four of the reserves were completely depleted, and two had less than 20 000 m^3 of gravel. Clearly the identification of additional local aggregate sources was required.

To meet this need, a program was initiated by MEM to systematically explore for new local aggregate sources in northeast BC. The program includes both regional and site-specific aggregate evaluations. The identification of regional sand and gravel resources will provide the necessary information for developing a long-term strategy to ensure that roads in the region are capable of supporting the future demands of industry. Improved access and transportation cost savings to resource companies will also enhance viability of projects and encourage exploration investment, leading to new oil and gas discoveries. This program was initiated as part of the British Columbia Oil and Gas Development Strategy (OGDS).

A key component of the OGDS is a comprehensive road infrastructure plan aimed at promoting better access to resources through improved infrastructure. The completion of road improvements (such as the upgrade of the SYD Road and construction of the new Clarke Lake Bypass at the start of the SYD in the Fort Nelson area) is expected to promote longer drilling seasons, accelerate exploration and production programs, and increase industry and provincial revenues.

HIGHLIGHTS

Aggregate discoveries

One of the main highlights of the northeast BC aggregate program has been the discovery of a number of new aggregate deposits, leading to significant savings in road development programs in the region (Ferbey *et al.*, 2005). The results of this work to date have led to the discovery of eight new major aggregate deposits, most of which have been developed into aggregate operations, including two new mines opened in 2004 and three in 2005. Gravel from these mines has been used extensively on the SYD Road, the new Clarke Lake Bypass, and on a number of PDRs sponsored under the MEM Royalty Credit Road Program. The latter provides 50% provincial funding on approved projects via royalty credits on future production. Aggregate from the Kotcho East deposit (see below) was hauled out via winter roads and stockpiled for use on the Spruce Road. The other two new mines in 2005, at the Courvoisier Ridge deposit and the South Gunnell-1 prospect (see Figure 1 in Ferbey *et al.,* 2005), were discovered the same winter. Gravel from these deposits was used on the Yoyo, Gunnell, and Courvoisier Royalty Credit Roads within weeks of the first field exploratory excavations of the deposits.

To date, twenty-five new aggregate prospects have been identified as well as a large number of additional showings (Ferbey *et al.*, 2005). Six of the new prospects were identified in a winter field program in February and March of 2005. This winter program was exceptionally successful, and a number of prospects were drilled with positive results (i.e., they contained coarse gravel deposits greater than 4 m in thickness). The largest prospect found to date is the Hay River glaciofluvial fan-delta located on the east side of the Fontas River map area (NTS 94 I) in the vicinity of the proposed Northern Link Road (Levson *et al.*, 2004). This landform covers an area of about 100 km^2, similar in size to the Fraser River delta, and is likely the largest sand and gravel deposit in northeast BC. It contains up to 25 m of sand and gravel overlying till. Gravels are exposed near the surface along low terraces of the Hay River, which incised through the deposit and concentrated coarser materials in the terraces. The eleven largest of the new prospects have an estimated aereal extent of approximately 125 million m^2. Conservatively assuming that these prospects have an average thickness of 3 m and that only 10% can be economically mined, they represent about 40 million m^3 of aggregate. The value of this aggregate in direct revenue to the province, in royalties alone, is \$120 million (at \$3/m^3).

Cost savings as a result of this program are further exemplified by an engineering cost study conducted prior to the SYD upgrade (McElhanney, 2003a, b). Estimates of the quantity of gravel required for the upgrade varied from 1.8 to 2.7 million m^3. The estimated cost of hauling gravel by rail from the Teco pit south of Fort St. John to Fort Nelson was \$34/m^3 (McElhanney, 2003b). An additional \$19/m^3 would be required for the average haul along the SYD, for a total of \$53/m^3. The cost of the option of hauling gravel 180 km via winter road from the Fort Nelson River pit at km 44 on Highway 77 was estimated at \$40/m^3 plus \$11/m^3 for average haul costs along SYD. In contrast, average costs for hauling from local sources along SYD, although limited in volume, varied from about \$15 to \$20/m^3, or 60–70% less. As McElhaney (2003b) reported, each dollar decrease in the unit price for gravel on the project would result in a cost savings of approximately \$2 million.

Preliminary mapping by MEM in the fall of 2002 (Blyth *et al.*, 2003) resulted in the identification of nine targets that were followed up with test-pit investigations in the winter of 2003 (Dewar and Polysou, 2003). The work was done under contract with oversight provided by MEM staff. Granular materials were encountered at eight of the sites in over 50% of the 458 test pits excavated. The results of the program were summarized by Levson *et al.* (2004). A total of more than 5 million m^3 of gravel potential was identified at five locations in the region. One of these sites, in the Elleh Creek area, had a potential volume of well over one million m^3. This site was selected as a primary source of aggregate for the SYD upgrade, and mining began there in the winter of 2004 (Figure 2). The Elleh deposit is in-

Figure 2. Active gravel mining operation during the winter of 2004 at the Elleh deposit. Aggregate from the operation was stockpiled at various locations for use on the SYD and Clarke Lake Bypass Roads. Gravels in the area are extensive and include mainly glaciofluvial gravels deposited during the last glaciation. (Photo provided by Quentin Huillery, Ledcor CMI Ltd.)

terpreted to consist mainly of advance-phase glaciofluvial deposits but also locally includes interstadial sands and gravels deeper in the deposit. Late-glacial (retreat-phase) gravels that stratigraphically overlie till also occur at the surface in the area (Levson *et al.*, 2004).

A second site referred to as the Kotcho East (Area 10a) deposit (NTS map area 93I/15), first identified from EnCana Corporation seismic shot-hole data, was found to potentially contain approximately 450 000 m^3 of aggregate. The deposit is entirely buried and has virtually no surface expression (Levson *et al.*, 2004). It is overlain by 1 to 5 m of clay-till and is interpreted as a subglacial stream deposit. It was further investigated with an airborne electromagnetic survey (see below), and in the winter of 2005 a new aggregate mine was opened at the site by EnCana Corporation (Figure 3). The deposit is located 27 km south of the SYD and is easily accessed via the Kotcho winter road or the Spruce PDR. The closest gravel pit to this deposit is more than 50 km away by air and more than 75 km by road. It is the only gravel pit in an area of more than 2500 km^2. The value of this deposit to the province is over $1.3 million in royalties alone. In addition, gravel removed by EnCana Corporation will be used on royalty credit roads resulting in a cost savings to the province of $0.50 for each dollar spent.

Surficial Geology and Aggregate Mapping

The northeast BC aggregate mapping project is part of a regional surficial geology cooperative mapping program involving researchers from the British Columbia, Alberta, and Canadian governments. Current and previously completed mapping project areas are identified on Figure 1. The results of surficial geology mapping conducted in northwestern Alberta by the Geological Survey of Canada and the Alberta Geological Survey are presented by Smith *et al.* (2005). Two 1:50 000 scale surficial geology maps have recently been released by Bednarski (2005a, b) for key road development areas in the Petitot map area (NTS 94 P). Two 1:20 000 scale airphoto aggregate potential mapping projects have been completed as part of this project in collaboration with the BC Ministry of Transportation and Land and Water BC Inc. (Savinkoff, 2004a, b).

Surficial geology mapping and Quaternary geology studies in the Fort Nelson (NTS 094J/SE) and Fontas River (NTS 094I/SW) 1:100 000 scale map areas (Figure 1) are provided by Trommelen *et al.* (2005). One highlight of this work was the discovery of a deep paleochannel of the Prophet River, locally containing highly compressed peats of probable interglacial age (Sangamonian?).

Figure 3. February 2005 exposure in the southwest corner of the Kotcho East gravel pit, operated by EnCana Corporation. Buried gravels in the area are up to several metres thick, and the overlying clay-rich sediments are typically 1 to 2 m but up to 5 m thick. The upper part of the overburden has been stripped here, and the base of the gravel is below the base of the exposure.

Subdued topography and a widespread forest cover in the study area make the use of air photo interpretation of relatively little value in identifying subtle landforms in much of the region. The use of new geomatics technologies (Kerr et al., 2005) and detailed application of LiDAR data (Demchuk et al., 2005) have proven to be highly effective methods for the identification and mapping of surficial geology and aggregate deposits in this challenging area. A highlight of the LiDAR work has been the identification of a number of low-relief landforms that are indiscernible on air photos. Many of these features are glaciofluvial in origin and have high aggregate potential. Detailed mapping of the landforms using LiDAR data is expected to greatly facilitate our understanding and use of these important deposits.

Bedrock Topography and Drift Thickness Mapping

Another component of this project has involved the mapping of the subsurface bedrock topography. There are a number of applications of this work, including shallow gas exploration, identification of subsurface gravel deposits, mapping shallow groundwater aquifers, identification of thick low-velocity surficial zones for seismic interpretation, and identification of artesian aquifers and potentially over-pressurized shallow gas zones. The importance of the latter has recently been highlighted by blow-outs in northeast BC and northwest Alberta in the winter of 2005. One blow-out resulted tragically in the loss of life. All of these applications have emphasized the need for an improved understanding of the bedrock topography and drift thickness of the study region.

Preliminary bedrock topography map data for NTS map areas 94 I and P were initially compiled from water well logs, wireline-geophysical logs, and other oil and gas well records (Levson *et al.*, 2004). The data revealed drift thicknesses in the area of up to 280 m and indicated that a number of possible paleochannels exist in the region. Just across the Alberta border from this area, a number of wells have been drilled into Quaternary sediments and completed at depths of less than 300 m. One field has yielded more than 4 billion cubic feet (bcf) of gas, with one well producing up to 4.4 million cubic feet per day (mmcf/d) (Canadian Discovery Digest, 2001). More detailed mapping of the bedrock topography is now being accomplished by the use and interpretation of other data sources, such as chip samples from oil and gas wells and various types of geophysical data (Hickin and Kerr, 2005).

Mapping buried gravels with high-resolution airborne electromagnetics: Kotcho East Deposit

Due to the difficulties associated with identifying buried aggregate deposits in the region, new subsurface investigation and geophysical techniques are being tested and used during this program. One of the most successful of these techniques is an airborne high-resolution electromagnetic (EM) survey. The results of a pilot EM survey of a buried gravel deposit in the Kotcho East area were summarized by Levson *et al.* (2004). Excavations in the vicinity of the deposit show gravels underlying 1 to 5 m of clay-rich till (Figure 3). The EM survey was flown with 100 m line spacing over the Kotcho East deposit and 200 m spacing over a larger area (25 km^2). The helicopter-borne RESOLVE multi-frequency EM system was used (Cain, 2004). The flat, till-covered deposit, which was originally detected only in seismic shot-hole logs, was mapped remarkably well with the high-frequency (115 kHz) data, which best reflects the shallow geology (Best *et al.*, 2004). Gravels in the region have high resistivity values (greater than 50 ohm-metres) and show a marked contrast with the adjacent fine-grained glacial sediments, which exhibit low resistivity values (less than 15 ohm-metres). This contrast in electromagnetic properties allows for relatively high-resolution mapping using airborne EM.

All of the goals of the pilot EM survey were achieved, including an attempt to evaluate the utility of the method for mapping shallow gravel deposits, to trace the extent of the Kotcho East gravel deposit beyond the field tested boundaries, and to identify any new gravel targets in the region. Recent results of this work have been described by Best *et al.* (in press) and show that three main areas of high resistivity were identified in the survey. The southern two areas are much larger than the Kotcho East deposit and were the focus of reconnaissance ground investigations that revealed the presence of sand and gravel deposits in these areas of high resistivity (Levson *et al.*, 2004; Best *et al.*, in press).

The Kotcho East deposit is characterized by crudely stratified, poorly sorted, large cobble- to boulder-sized gravels interbedded with well-stratified, moderately well sorted sands and pebble-sized gravels (Figure 4). Contrasts in grain size and sorting from bed to bed are large and remarkably sharp; they are interpreted to reflect sudden changes in flow energy; low-angle, large-scale, trough cross-bedding; cut-and-fill structures; and large clast clusters reflecting strongly channelized flows. The gravels are sharply overlain by a clay-rich diamicton (Figure 5) interpreted to be a meltout till. The diamicton is moderately dense, silty, matrix-supported, contains both local clasts and distally derived (Canadian Shield) erratics, and has thin laminae of sorted silts and very fine sands. The presence of angular, soft siltstone clasts that dip steeply and show little sign of shear precludes a lodgement till origin. The geometry of the Kotcho East deposit could not be determined from aerial photographic interpretation of geomorphic data due to the subdued relief created by the till blanket (Figure 6).

A new gravel pit was opened in this area in the winter of 2005, and the mine excavations to date have further confirmed the size and geometry of the deposit as predicted by the EM survey and as mapped out by the initial field investigations. The results of this work strongly indicate that high resolution EM surveys are an effective tool for mapping buried sand and gravel deposits in the study region.

Diamond Potential Studies

As part of this program, reconnaissance sampling of glaciofluvial deposits was conducted as a first step in the evaluation of the diamond potential of the region. Prior to this program, there were no published reports of diamond indicator minerals in the area and little work had been done. Consequently, bulk sand samples were collected from glaciofluvial deposits at representative sites, and concentrates were produced in the laboratory using heavy liquids. Kimberlite indicator minerals (KIMs) were detected at a number of sites, and microprobe analyses were used to evaluate their chemistry and potential significance. These results led to the conclusion that the study area has some diamond potential and that further exploration is warranted (Levson *et al.*, 2004). The detailed results of the microprobe analyses of the KIMs were released in January 2005 (Simandl, 2005a, b) and immediately led to mineral staking in six different areas. This is the first diamond staking in the Western Canada Sedimentary Basin in northeast BC.

Figure 4. Close-up photo of the gravels and sands at the Kotcho East gravel pit. Note the crude bedding, large clast clusters, sharp changes in grain-size distribution, and localized oxidation. The gravels are interpreted to be a subglacial stream deposit (see text).

Figure 5. Close-up photo of the contact between gravels and the overlying diamict at the Kotcho East gravel pit. Note the white friable siltstone clast (about 5 cm long) in the diamict at right side of the photo. The diamict is interpreted as a basal meltout till (see text).

Figure 6. Overview of the landscape beside the Kotcho East gravel pit. The edge of the deposit as indicated by test pits, and EM data approximately extends from left to right across the centre of the photo. Note the lack of topographic relief marking the edge of the buried deposit, even though the area has been cleared (seedlings are about a metre high). The dark area at right-centre is a soil stockpile.

CONCLUSIONS

A number of studies have been conducted as part of the northeast BC aggregate program. This research has been carried out by the MEM Resource Development and Geoscience Branch in conjunction with industry, consultants, universities, and other governments. The detailed results of some of these studies, discussed in a number of articles that follow this introductory paper, include research on the Quaternary geology of the region, surficial geology mapping programs and aggregate potential studies. Most of the work has focused on the identification of aggregate deposits, the general absence of which has resulted in excessively high road construction, improvement, and maintenance costs. The rarity of aggregate deposits in the region is partially due to the fact that many are buried by a thick clay-rich till blanket and many have subtle surface expressions. In addition, ground-based exploration techniques are costly in this vast area, and the widespread forest cover and subdued topography make traditional geomorphological methods relatively ineffective. To address these problems, the program has applied a number of innovative techniques, such as high-resolution airborne electromagnetic surveys, LiDAR data analysis and interpretation, and digital compilation of large volumes of subsurface borehole and geophysical data.

The results of this work to date have led to the discovery of eight new major aggregate deposits, twenty-five new prospects, and a large number of showings. Gravel from several of these deposits has been used extensively on a number of government-supported road programs, including construction of the new Clarke Lake Bypass Road, the SYD upgrade, and PDRs within the MEM Royalty Credit Road Program, including the Yoyo, Gunnell, and Courvoisier Roads.

Products from this program that were released in 2004–2005 include three papers in 2004 Summary of Activities and Geological Fieldwork and fourteen posters and presentations at numerous conferences and meetings, including the Canadian Society of Petroleum Geology, the Cordilleran Geology Roundup, the GeoTech Conference, and the Canadian Society for Unconventional Gas. In addition, the release of the details on the 2003–2004 KIM results led to diamond staking in six areas, the first such activity in northeast BC. A digital field station database, including data from over 1000 field sites, was also completed.

Other products for the year include three new unpublished aggregate reports (for the Fort Nelson Airport, Muskwa Heights, and Fontas Road discoveries), one new aggregate potential evaluation (1:20 000 mapping for parts of 93 P and I) by the Ministry of Transportation and Ministry of Energy and Mines, a completed digital reference library, and a new aggregate website (http://www.em.gov.bc.ca/subwebs/oilandgas/aggregates/aggregates.htm). Products expected in the 2005–2006 fiscal year include seven papers in the 2005 Summary of Activities (this volume), a paper in the Journal of Environmental and Engineering Geophysics, an interactive web-based aggregate map, chip-sample logging for five 1:250 000 NTS sheets, and a completed subsurface database containing over 8000 records.

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SURFICIAL GEOLOGY AND AGGREGATE POTENTIAL MAPPING IN NORTHEAST BRITISH COLUMBIA USING LIDAR IMAGERY

Tania E. Demchuk[1], Travis Ferbey[1], Ben J. Kerr[1] and Victor M. Levson[1]

ABSTRACT

Light detection and ranging (LiDAR) digital elevation models (DEMs) have proven to be an effective tool for mapping surficial features and aggregate potential in northeast British Columbia (BC). Northeast BC is characterized by low relief and by subtle glacial landforms commonly masked by forest cover. For these reasons aerial photograph interpretation alone is a somewhat ineffective aggregate exploration technique. The BC Ministry of Energy and Mines, in partnership with EnCana Corporation, is using LiDAR data with 10 m and 2 m horizontal resolution and vertical accuracies of up to 30 cm to map aggregate potential for portions of NTS map areas 94 I and P. To date, these data have helped in the identification and interpretation of glacial features and are responsible for numerous recent aggregate exploration successes in areas where there is a demand for construction aggregates. Some of these features are visible in lower resolution data sets, such as aerial photographs and RADARSAT DEMs, while others are visible only in LiDAR DEMs. The latter is particularly true for low-relief features (i.e., up to 3 m high), which can be masked by vegetation in aerial photographs and are often not resolved in RADARSAT DEMs. LiDAR DEMs have also proven to be a useful tool for detailed aggregate potential assessments of glaciofluvial features that are identifiable but poorly defined in other data sets.

KEYWORDS: Quaternary geology, LiDAR, aggregate potential, northeast British Columbia, surficial geology, RADARSAT, surficial landforms, glacial features

INTRODUCTION

There is a demand for more surficial geology and aggregate potential data in northeast BC; this demand is the result of the increased activity of the oil and gas industry in the region and the need for construction aggregate for infrastructure development, upgrade, and maintenance. In 2002, the Oil and Gas Division of the British Columbia Ministry of Energy and Mines (BCMEM) initiated a Quaternary mapping program in northeast BC (Levson *et al*., 2004; Ferbey *et al.*, 2005, this volume). The primary objective of this program is to identify new local sources of construction aggregate in areas where there is a demand.

Traditionally, surficial geology and aggregate potential mapping is carried out using aerial photograph interpretation. In northeast BC, however, this method on its own has proven to be somewhat ineffective due to the generally low topographic relief in the region and the masking effect of vegetation on subtle surficial landforms. Other methods for aggregate potential mapping have therefore been used, including the interpretation of seismic shot-hole data, oil and gas logs, water-well records, and geophysical surveys. This year, in partnership with EnCana Corporation, the Quaternary geology mapping group at BCMEM began to use LiDAR data to map surficial geology for portions of NTS map areas 94 I and P. The objectives of using LiDAR data are to (1) delineate surficial landforms and materials, particularly those associated with sands and gravels and (2) interpret the Quaternary history of the region. This paper will address the first of these objectives.

STUDY AREA

Figure 1 outlines the study area (NTS map areas 94 I and P). The reader is directed to Levson *et al.* (2004) and Ferbey *et al.* (2005, this volume), for a more extensive discussion of the study area included in the northeast BC surficial geology and aggregate potential mapping program.

Northeast BC is generally characterized by subdued topography and a blanket of clay-rich morainal and glaciolacustrine sediments. Glaciofluvial landforms, which typically are composed of sand and gravel, are rare in the region. The water table is near surface throughout much of the area, and black spruce (*Picea mariana*) bogs dominate. Locations even slightly elevated are typically vegetated by stands of trembling aspen (*Populus tremuloides*) and white spruce (*Picea glauca*).

LIGHT DETECTION AND RANGING TECHNOLOGY

Light detection and ranging (LiDAR) data are collected using an active sensor, mounted on the bottom of a fixed-wing aircraft or helicopter. LiDAR systems are

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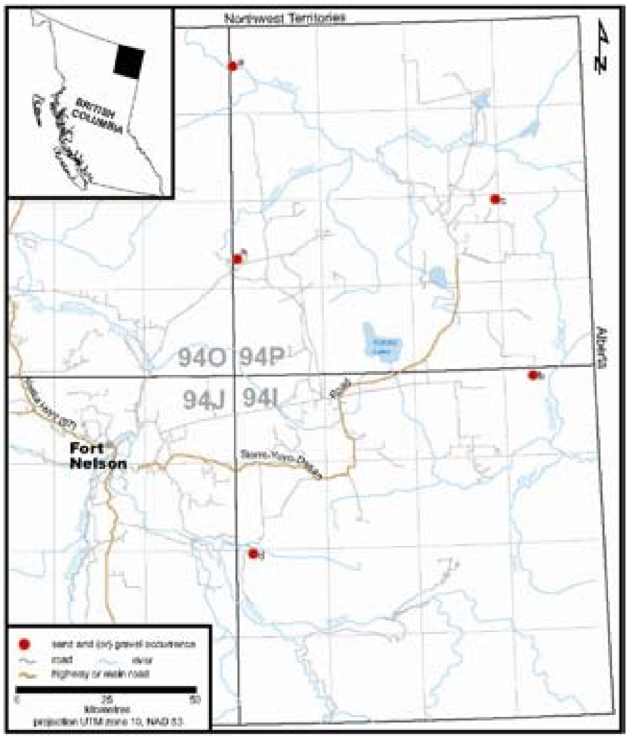

Figure 1. Study area and locations of selected aggregate occurrences.

based on principles similar to those of RADAR systems. Instead of using microwave frequency radiation (about 10^{10} Hz), a swath of laser pulses within the infrared frequency range (about 10^{13} Hz) is fired at the ground at a user-specified rate. The transmitted laser pulses reflect off various surfaces, and those reflections are recorded by a sensor onboard the aircraft. The point spacing of the laser pulses (i.e., closeness of reflected pulses) is usually small (e.g., 1 point per 1.15 m^2 to 1.35 m^2), resulting in a high point density. This also differentiates LiDAR and satellite RADAR systems, as the latter typically record a lower point density. The LiDAR system also includes a differential GPS and an inertial measuring unit; these allow for both exact position of the aircraft and x, y, z coordinates of point reflections to be determined.

Light detection and ranging systems can be used to determine the range or distance to a target, for example, the Earth's surface. Known as range finders, these LiDAR sensors are able to detect multiple returns for a single laser pulse. In topographic mapping applications, the first return can be associated with the top of vegetation cover or tree canopy and the last with the ground surface. Because multiple returns can be detected, the resulting data is a series of x, y, and z coordinates that form a point cloud. This point cloud includes every point for which a reflection off a surface was recorded. Using a variety of software algorithms, the top layer and bottom layer of points can be separated into 2 data files of x, y, and z coordinates. These 2 data files are typically associated with the first reflected and last reflected returns, respectively. From these 2 data files, digital elevation models (DEMs) are created at user-specified resolutions that can highlight relative differences in elevation as small as 30 cm. Depending on how the data are interpolated, 2 elevation models are typically produced: (1) *full-earth* for generating a vegetation inclusive image, using the first returns detected by the sensor, and (2) *bare-earth* for generating a vegetation exclusive image, using the last returns detected by the sensor. In areas with very dense vegetation cover, the laser pulse may not penetrate to ground surface, making it more difficult to create an accurate bare-earth DEM (Krabill *et al.*, 1984).

The accuracy of LiDAR data depends on various acquisition and post-processing parameters. Important acquisition parameters to consider are flight altitude, scanner frequency, inertial update rate (provide corrections for yaw, pitch, and roll of aircraft), point spacing, and base station range (Bufton *et al.*, 1991). Post-processing of acquired data can involve a variety of software algorithms that interpolate the data clouds generated from the recorded laser pulse returns. Experience in data handling is important as the data smoothing that takes place during post-processing can remove important features or leave noise or unwanted information in the final data set. A discussion of several algorithms used to remove early returns (i.e., vegetation) is provided by Haugerud and Harding (2001).

LIDAR IN OTHER QUATERNARY GEOLOGICAL APPLICATIONS

LiDAR data have been used in many Quaternary geological applications. For example, digital elevation models derived from LiDAR data are currently being used to investigate landslide history and help predict areas that may be susceptible to future slides (Carter *et al.*, 2001; Gold *et al.*, 2003; McKean and Roering, 2004; Schulz, 2004). Similar models are being used to map sinkhole development, which is often masked by vegetation and can pose serious hazards to existing and new infrastructure (Carter *et al.*, 2001). LiDAR data have also been used successfully to map Holocene faults around the Puget Lowland area of Washington State (Haugerud *et al.*, 2003; Sherrod *et al.*, 2003). In some cases these faults were previously unknown due to the masking effects of vegetation. LiDAR data are also being used in the Puget Lowland to update existing surficial geology and topographic mapping, as inaccuracies in previous mapping throughout this heavily forested area have been revealed by LiDAR imagery (Cox *et al.*, 2003; Easterbrook, 2003).

MAPPING SURFICIAL GEOLOGY USING LIDAR

The high point density of LiDAR data results in high vertical and horizontal accuracy and is, therefore, very useful for mapping surficial geology and glacial features. This high accuracy makes DEMs produced from these data effective for identifying small changes in elevation and, therefore, particularly useful in areas of low topographic relief, such as northeast BC. LiDAR DEMs have proven to be a useful tool for mapping Quaternary landforms including kame-like deposits, fans, terraces, eskers, meltwater channels, and shorelines.

LiDAR DEMs are also useful for mapping details within a feature that are not seen in other data sets (e.g., lower-resolution RADARSAT DEMS, DEMs produced by photogrammetry, and analog aerial photographs), because the bare-earth model can remove the masking effects of vegetation. Cross-sections through selected features or areas, used to aid in interpretation of genesis, can be produced in the digital environment because these data have x, y, and z values. These 2 attributes make LiDAR data particularly useful in areas of limited vertical relief.

Although a powerful data set on its own, a LiDAR DEM can be even more effective for mapping purposes when used in combination with other spatial data. For example, seismic shot-hole data, geophysical well data (e.g., gamma logs), and orthophotos have been used in conjunction with LiDAR DEMs to assess the aggregate potential of glacial features in the region.

The detail inherent to LiDAR DEMs can, however, show surface textures that do not represent surface topography. Areas with very dense ground vegetation, such as black spruce bogs, can make it difficult for the laser to penetrate through to bare ground surface. Mosses and other ground cover and periglacial features such as peat palsas can create

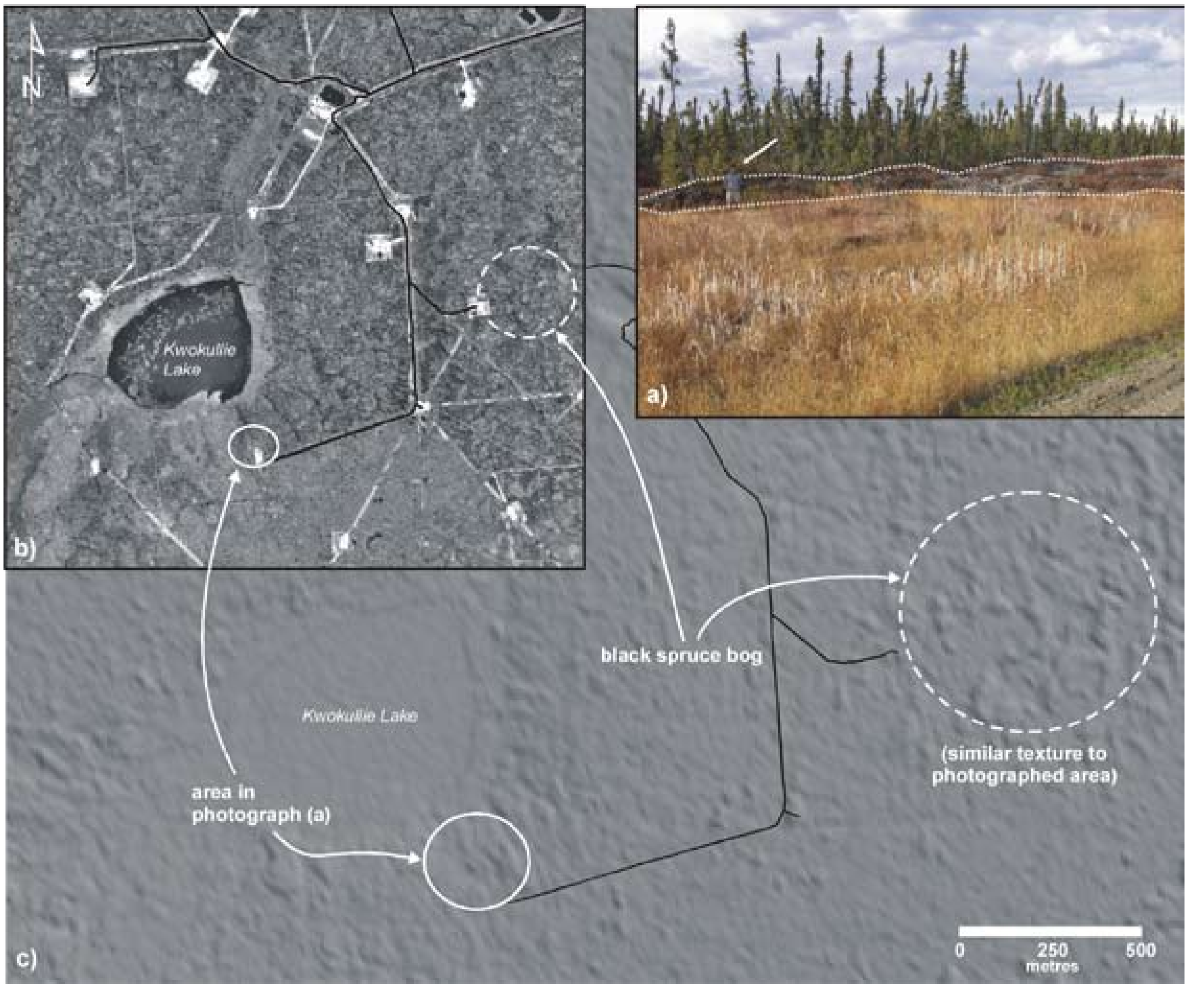

Figure 2. Dense vegetation mounds observed along Ish Road. (a) Thick vertical vegetation growth indicated by dashed line (person for scale, identified with arrow). (b) Black spruce bog is visible in aerial photographs and can coincide with the surface texture visible in LiDAR DEMs. (c) Vegetation-related ground texture can be observed in bare-earth DEMs (area circled coincides with bog area on aerial photograph). These textures are a result of the laser not being able to penetrate the dense, hummocky vegetation growth.

mounds and hummocks independent of the underlying topography; in some cases elevation changes created by these vegetation surfaces can be up to 1 m (Figure 2a). The result is that textures in bare-earth LiDAR imagery occasionally represent surfaces of dense vegetation. In places where the image displays this texture, digital orthophotos can be draped on top to investigate the genesis of these textures. In areas where this hummocky texture coincides with black spruce bog, it may represent changes in vegetation thickness rather than underlying topography (Figure 2b and c).

Acquisition of LiDAR data can be expensive (approximately \$250/km^2). However, the additional applications for LiDAR data in the oil and gas industry (such as locating dry well pad sites, siting pipeline routes, road alignments, and seismic survey layouts, in addition to the potential operational savings that can result from identifying new local sources of construction aggregate) could make investment in these data worthwhile.

AGGREGATE POTENTIAL MAPPING

LiDAR DEMs have been used successfully to map glacial features that are not seen in any other data sets. The following summary of features highlights some of the aggregate occurrences that have been found using LiDAR data. Figure 1 shows the locations of the features described below within the study area. References to field sites and data refer to shallow roadcuts, shovel excavations, and hand-auger holes, all 1 to 2 m below surface.

A series of sub-parallel southeast-trending ridges up to 8 m high, 75 m wide, and 400 m long occur near Komie Creek (Figure 1, location a) and are clearly visible in LiDAR DEMs (Figure 3a). A cross-section through the ridges shows typical heights and widths of about 5 m and 50 m, respectively. As determined by field investigations, the composition of these ridges is variable and they can contain fine to medium sands, pebble- to cobble-sized gravels, and

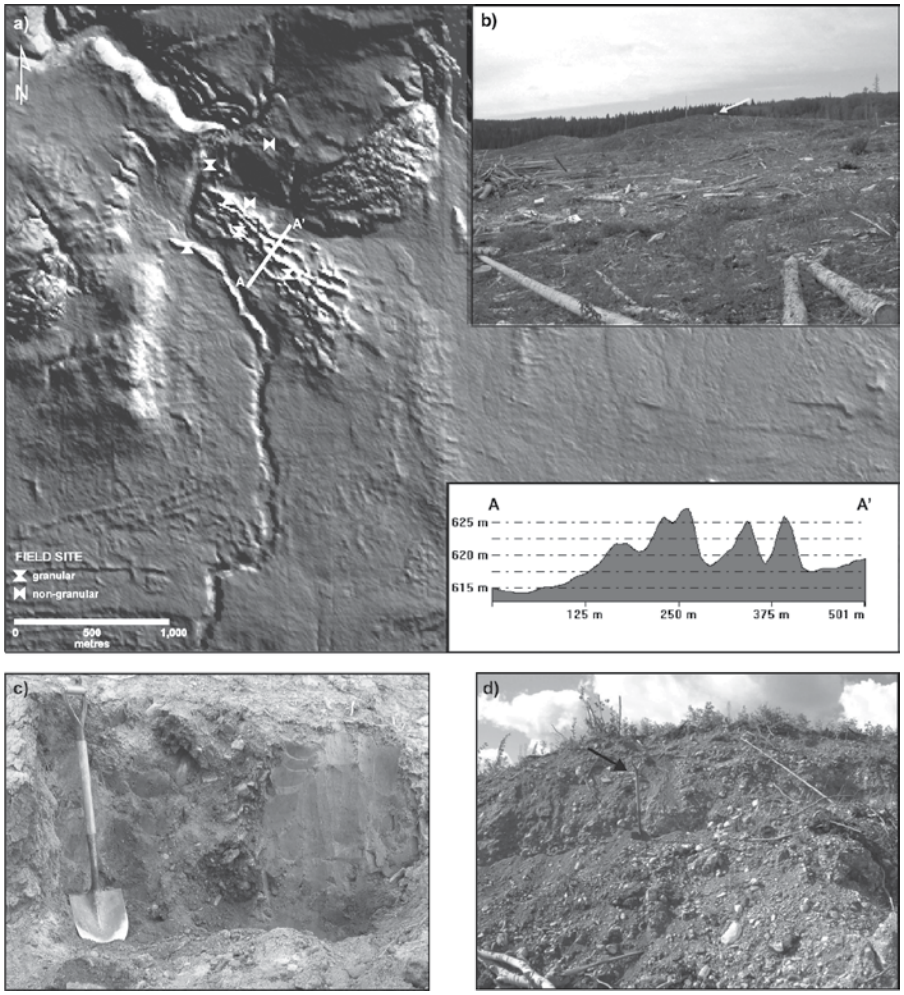

Figure 3. The Komie Creek gravel occurrence. (a) LiDAR DEM showing sub-parallel ridges composed of sands, gravels, and diamictons. Inset cross-section (A to A') shows typical morphology and heights of ridges, interpreted collectively as an esker complex. (b) An 8 to 10 m–high ridge in cutblock (person for scale, identified with arrow). (c) The composition of a single ridge can be variable, as seen here with a silty diamicton in vertical contact with pebble- to cobble-sized gravels and sands (1.2 m shovel for scale). (d) Exposure of sandy, cobble-sized gravels in roadcut through ridge (1.2 m shovel for scale, identified with arrow).

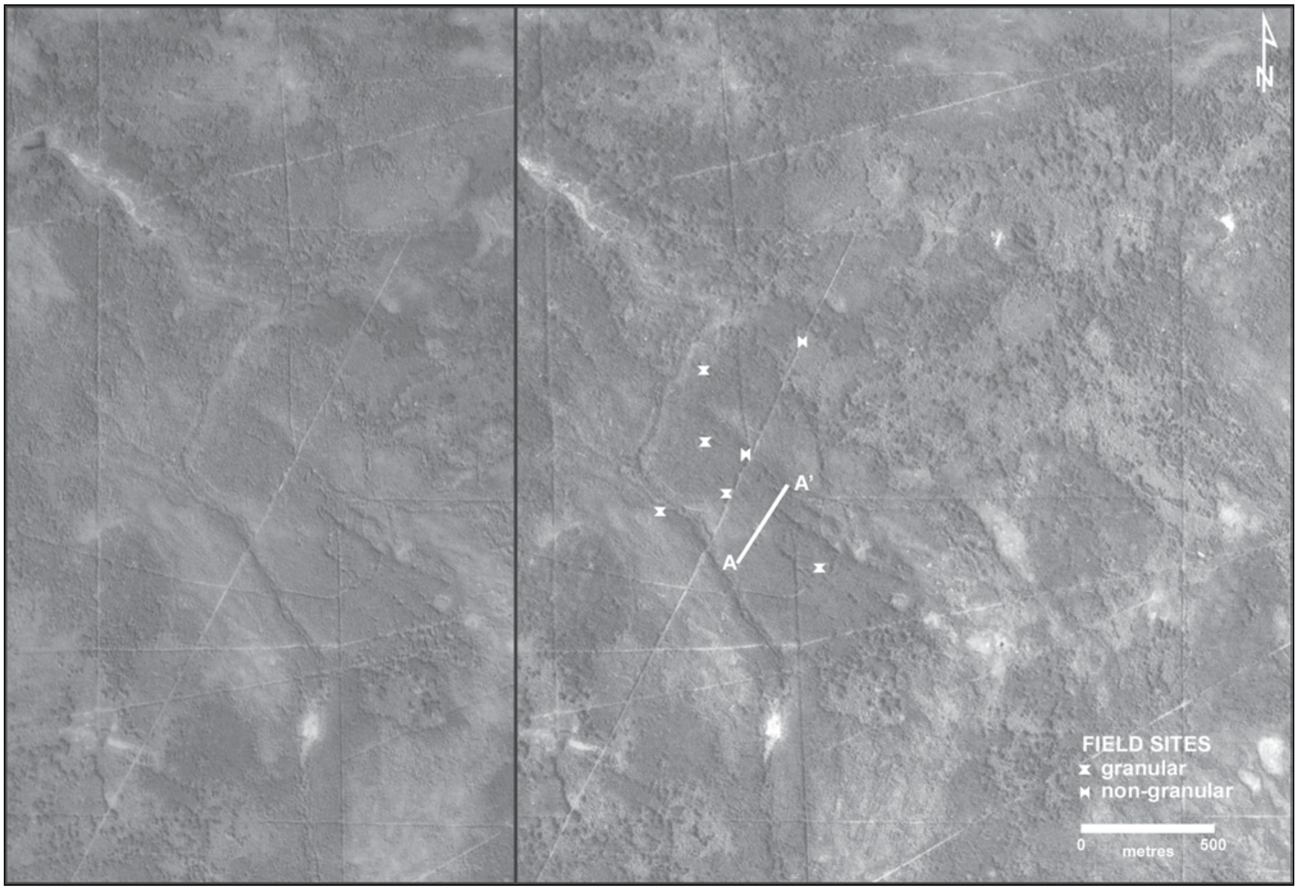

Figure 4. Aerial photograph stereogram of the Komie Creek gravel occurrence. Vegetation masks the detail of ridges within an esker complex that is clearly visible in a LiDAR DEM (*cf.* Figure 3a). Cross-section A to A' and field site locations are the same as those provided in Figure 3a.

silty diamictons (Figure 3c and d). While these features are very well defined by LiDAR DEMs, the RADARSAT DEMs show only a vague outline of them. Several ridges are discernible in aerial photographs (Figure 4). However, where closely spaced, different ridges or the breaks between them are difficult to distinguish. As seen in Figure 4, vegetation nearly completely masks the detailed relief that is seen in LiDAR DEMs, including the northwest limit of these features. For example, in LiDAR DEMs this limit is clearly seen to be at a creek that drains south, while in aerial photographs the northwest portion of these features appears to grade into a forested slope. Interpreted as an esker complex, some of these ridges host an aggregate occurrence.

Sands and gravels near Shekilie River (Figure 1, location b) occur in 2 separate areas. Within Area 1 is an asymmetrical ridge-like feature that is elevated 10 m above surrounding topography, while within Area 2 is a series of curvilinear features that are slope-parallel and southwest-trending (Figure 5). Sediments within Area 1 are composed mainly of well to very well rounded, pebble- to cobble-sized quartzite gravels that have a medium sand matrix with a minor silty component. Northwest of the ridge, off the elevated area, a hand-auger excavation encountered silty sands. This feature may be a kame-like deposit.

Features within Area 2 are mainly composed of pebble- to cobble-sized gravels that have a silt to silty-fine sand matrix. Exposed in a shallow shovel excavation, clasts are sub-angular to very well rounded and include abundant disc-shaped quartzites. Occurring at surface, these gravels likely overlie clays or silts as suggested by a hand-auger excavation directly to the south of and below the elevation of the gravels (Figure 5). These curvilinear features are interpreted as wave-washed shorelines of Glacial Lake Hay, which formed during the final retreat of the Laurentide ice-sheet from the region (Matthews, 1980). Alternatively, it is possible that these features are bedrock-controlled and represent differential erosion by ice of the flat-lying shales and sandstones that underlie the region.

Another topographic high has been identified northeast of and at the same elevation as Area 1 (Area 3, Figure 5). Within Area 3 is a feature that forms a flat-topped circular knob 10 m high and up to 425 m wide and appears to be slightly drawn out to the west-northwest. The perimeter of the flat-topped area appears to be slightly elevated as the-

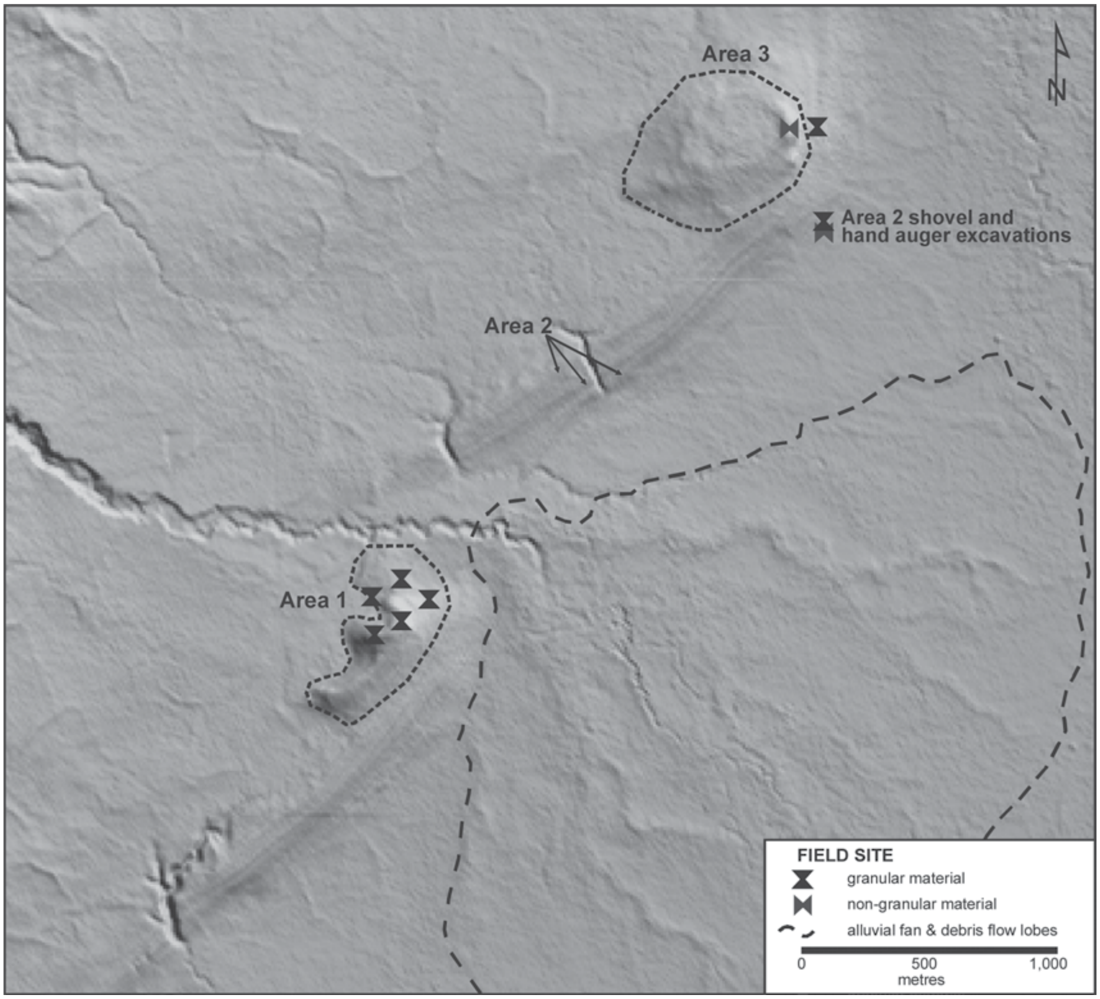

Figure 5. LiDAR DEM of Shekilie River area. Area 1 is a 10 m–high kame-like feature that hosts sands and gravels at surface. Area 2 is a series of curvilinear features (indicated with arrows) that host pebble- to cobble-sized gravels at surface and are interpreted to be wave-washed shorelines. Within Area 3 is a feature, similar to that identified in Area 1, that has potential to host an aggregate occurrence. Also delineated here are a low-gradient alluvial fan and debris flow lobes.

central portion of this feature is lower than the outer edge. Field assessment of this feature indicates that, at least at the top of the eastern perimeter, sandy silt diamicton occurs at surface. Area 3 has not been identified as an aggregate occurrence here. However, given that sands and gravels do occur in a morphologically similar feature 2 km to the southwest (i.e., Area 1), Area 3 does have potential to host granular material and warrants further field investigations.

LiDAR DEMs can also be used effectively to map glacial features that are visible in RADARSAT DEMs and aerial photographs, as LiDAR imagery can highlight details within features that may not otherwise be apparent; 2 such examples are discussed below. Locations of these features are provided in Figure 1.

The East Kimea Creek gravel occurrence (Figure 1, location c) is a pronounced topographic high approximately 30 m high, 1000 m long, and 600 m wide. Surface observations and shallow shovel excavations indicate that cobble-sized gravels occur at surface. The kame-like feature is clearly visible in the RADARSAT DEM and in aerial photographs (Figure 6a and b, respectively). However, the LiDAR DEM provides a much more detailed image of the feature that not only enables more accurate mapping of it but could also identify areas within it that may have better potential to host an aggregate occurrence (Figure 6c). Other kame-like deposits that are only visible in LiDAR DEMs have been identified in other parts of the region, in some cases within 1 km of an existing road; one such example is provided in Figure 7 (Figure 1, location d). This feature is up to 8 m high, 50 to 75 m wide, and 225 m long (cross-sections A-A’ and B-B’, Figure 7) and appears to be part of a larger south-trending ridge system that may extend for 500 m or more. Exposed in a roadcut, the upper 150 cm of this feature is composed of 10 to 20 cm of silty diamicton that overlies 30 cm of silty pebble-sized gravels, which in turn overlies more than 100 cm of silty-fine to coarse sand. The sandy unit appears to contain lenses of silty pebble-sized gravel similar to that of the overlying unit and, as the

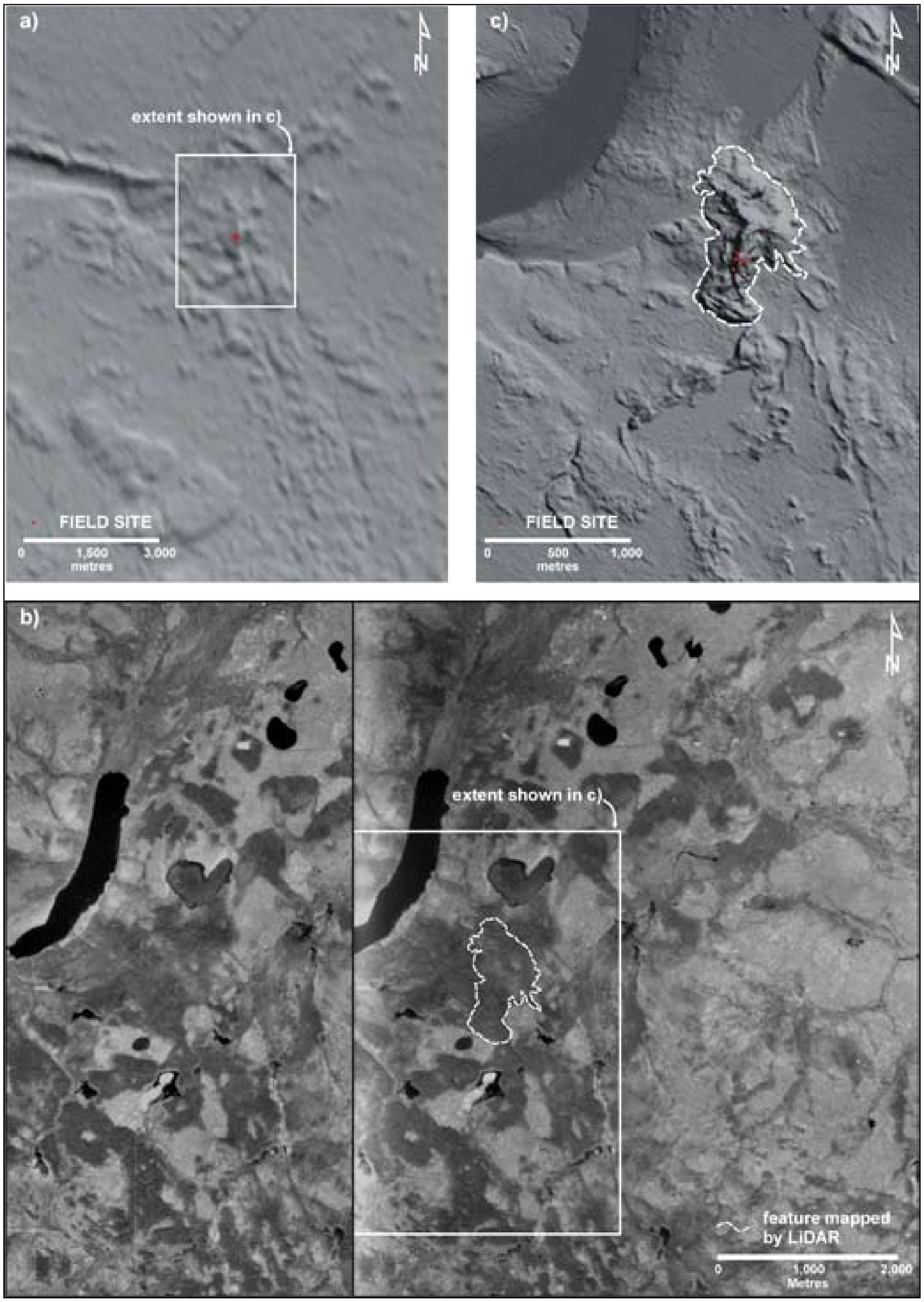

Figure 6. East Kimea Creek gravel occurrence. (a) This feature, which forms a prominent topographic high and is interpreted to be a kame deposit, is visible in the RADARSAT DEM (in vicinity of field sites) and (b) in aerial photographs. The polygon shown here was mapped using LiDAR data. As seen here, mapping using aerial photographs would produce a different polygon as the detail of the feature is masked by vegetation. (c) The LiDAR DEM provides more detailed information on the morphology of this feature and enables more accurate mapping of it and other related features that also have potential to host an aggregate occurrence.

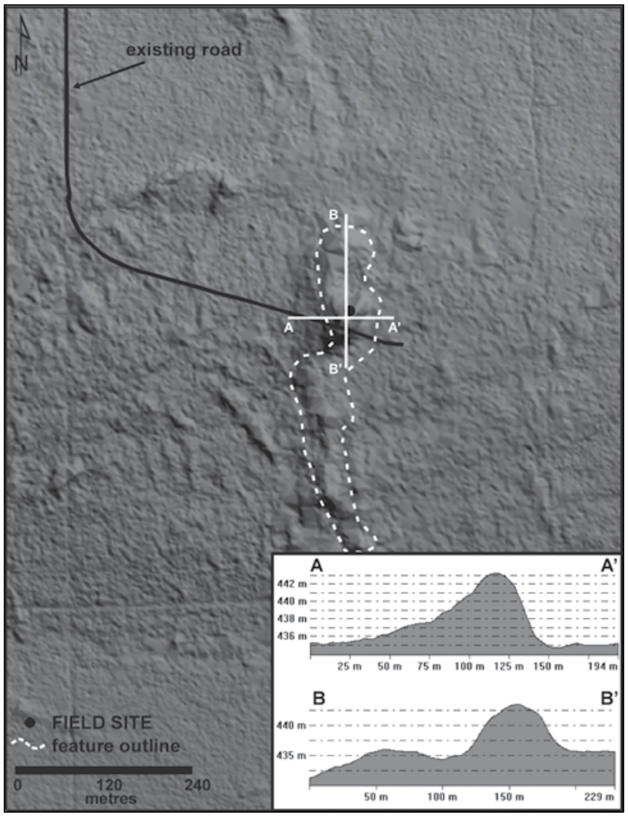

Figure 7. A small kame feature. Likely part of larger south-trending ridge system that extends for at least 500 m, this feature is mainly composed of sands and pebble-sized gravels. Small features like the one shown here can be found in the region, in some cases close to existing roads, making them useful as sources for construction aggregate.

lower contact was not found, is thought to extend below the 150 cm exposure. Other similarly sized features, composed of similar materials, occur in central and west-central 94P, also near existing roads. Features such as these, given their proximity to existing infrastructure, may provide useful local sources of sands and gravels for ongoing road maintenance.

Using LiDAR DEMs, the aggregate potential of a large bench (5.25 km long and up to 1.5 km wide) along the Petitot River has recently been assessed (Figure 1, location e). Field investigations on smaller terraces superimposed on the eastern end of the bench encountered sands and poorly sorted pebble- to cobble-sized gravels at surface in tree throws and in shallow shovel excavations. Although this bench can be observed in both lower resolution RADARSAT DEMs and in aerial photographs (Figure 8a and b, respectively), the LiDAR DEM clearly shows the details of the local geomorphology (Figure 8c). These higher-resolution DEMs, in combination with field data, enable areas with higher aggregate potential to be identified. Many other features that do not have aggregate potential can be seen Figure 8; for example, flutings trending southwest and

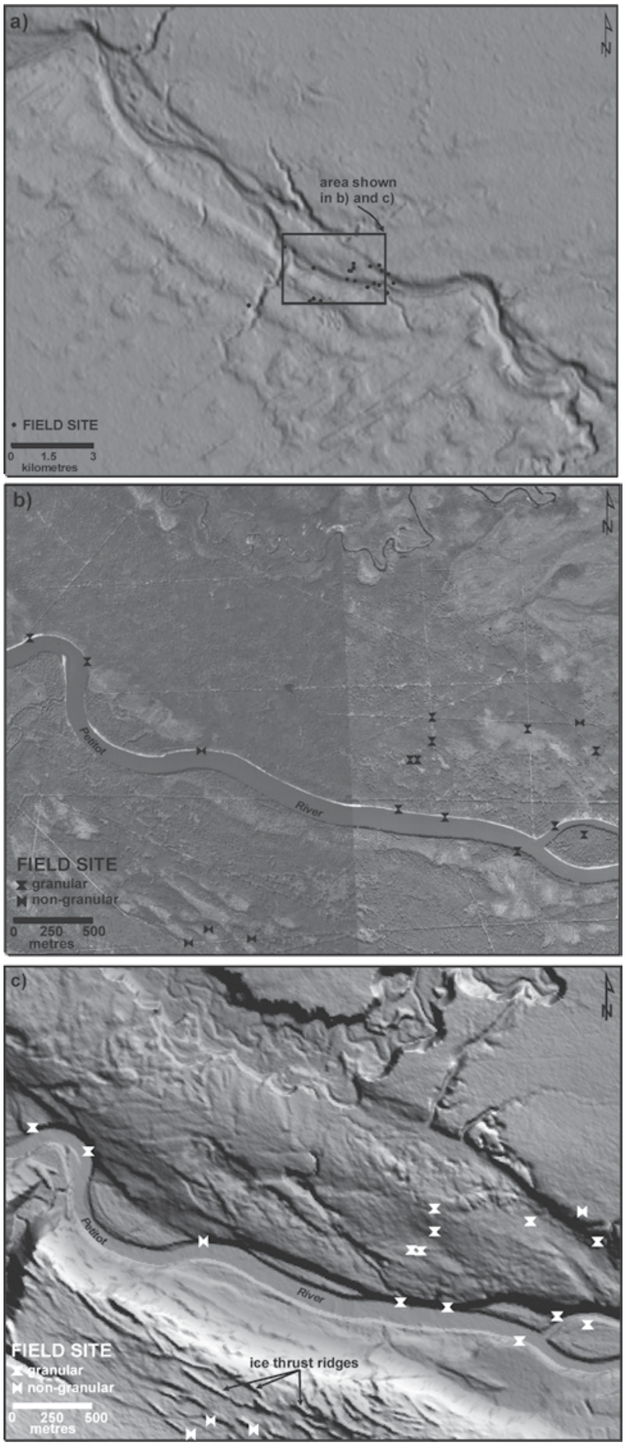

Figure 8. The Cabin Crossing gravel occurrence. This large bench along the Petitot River is visible in (a) RADARSAT DEMs, (b) aerial photographs, and (c) LiDAR DEMs. LiDAR imagery, however, is particularly effective at mapping the details of the feature (e.g., smaller terraces on the flanks of the large bench). Other geomorphic features visible in these figures are ice-thrust ridges superimposed on a morainal ridge (identified with arrows), large moraines and flutings, and Holocene point bars and terraces along Petitot River.

moraines that generally parallel the Petitot River channel are visible in the southeast portions of both the RADARSAT DEM and the aerial photograph (Figure 8a and b). In the LiDAR DEM, however, 1 to 2 m–high asymmetrical ridges, interpreted as ice-thrust features, can be seen on top of a morainal ridge south of Petitot River (Figure 8c, arrowed). Also more easily discernible in the LiDAR DEM are Holocene features such as point bars and terraces (visible along the length of Petitot River), meandering channels and oxbows (e.g., north of the bench), and gullies.

SUMMARY

LiDAR DEMs have proven to be an effective tool for identifying areas with good aggregate potential and are responsible for numerous recent aggregate exploration successes. Some of these occurrences are visible in other, lower-resolution data sets, such as aerial photographs and RADARSAT DEMs, while others are only visible in LiDAR DEMs; this is particularly true for small, low relief features. These features can often occur near existing infrastructure, making them a useful local source of road-maintenance aggregate. LiDAR DEMs have also proven to be a useful tool for more detailed aggregate potential mapping of features that are identifiable but poorly resolved in other data sets. The accuracy and high resolution inherent in LiDAR data allow for the assessment of aggregate potential and calculation of preliminary volume estimates for either a single feature or specific area of it. Operational savings that may result from identification of aggregate resources using these data could make them a worthwhile investment for areas where there is a demand for local sources of sand and gravel.

ACKNOWLEDGEMENTS

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NORTHEAST BRITISH COLUMBIA AGGREGATE MAPPING PROGRAM: A SUMMARY OF SELECTED AGGREGATE OCCURRENCES NORTHEAST OF FORT NELSON

Travis Ferbey[1], Adrian S. Hickin[1], Tania E. Demchuk[1] and Victor M. Levson[1]

ABSTRACT

The main objective of the Northeast British Columbia Aggregate Mapping Program is to complete an inventory of new and existing local sources of aggregate in areas where there is a high demand. Mapping aggregate potential in the region has been challenging due to the subdued topography and ubiquitous presence of thick organics and clay-rich morainal and glaciolacustrine sediments. Various innovative methods and data sets have been employed to meet program objectives. To date, the program has identified 8 aggregate deposits northeast of Fort Nelson, in the vicinity of the Sierra-Yoyo-Desan (SYD) Road, that contain a total resource of more than 6 000 000 m^3 of aggregate. Twenty-five sand and gravel prospects have also been discovered in the same region. All are contained within a mappable geomorphic or geophysical feature and have been field tested. Based on the genesis and size of the mappable feature, field observations, and a preliminary assessment of aggregate demand, the majority of these newly identified prospects have high potential to host an economic sand and gravel deposit.

KEYWORDS: Quaternary geology, aggregate resources, aggregate potential, northeast British Columbia, surficial geology

INTRODUCTION

The Northeast British Columbia Aggregate Mapping Program was initiated by the British Columbia Ministry of Energy and Mines (MEM) in order to meet the construction aggregate needs of the province's growing oil and gas industry (Levson *et al.*, 2004). The objectives of this program are to 1) carry out a regional-scale inventory of existing and new local sources of construction aggregates and 2) conduct detailed area-specific aggregate potential investigations to address aggregate needs of provincially supported road initiatives such as the Royalty Credit Road Program, the Sierra-Yoyo-Desan (SYD) Road upgrade, and the Heartlands Oil and Gas Road Rehabilitation Strategy (HOGRRS). Various innovative methods and data sets have been employed to meet these objectives including, but not limited to, airborne geophysics, light detection and ranging (LiDAR) and RADARSAT digital elevation models (DEMs), and waterwell, shot-hole, and conductor-pipe logs. The reader is directed to more detailed discussions on the use of these methods and data sets provided by Best *et al.* (2004), Levson *et al.* (2004), Demchuk *et al.* (2005), and Best *et al.* (in press). The purpose of this paper is to summarize selected new aggregate deposits and prospects discovered over the past 2 years.

LOCATION AND PHYSIOGRAPHY

This paper focuses on selected aggregate prospects that occur within NTS map areas 94I, J, and P (Figure 1). Occurring mainly within the Fort Nelson Lowlands physiographic region, a subdivision of Canada's Interior Plains (Holland, 1976), this area has flat to subdued topography that reflects the horizontally bedded sedimentary rocks that underlie the region. The combination of low-relief topography and clay-rich soils results in poor drainage with a shallow water table in most areas. As such, small (less than 5 ha) shallow lakes and narrow (less than 3 m), meandering, low-gradient streams are common.

The Etsho Plateau (Figure 1) is a prominent physiographic feature located in the central portion of the study area and is considered to be an outlier of the Alberta Plateau (Holland, 1976). Rising approximately 350 m above the surrounding Fort Nelson Lowlands to an elevation of approximately 700 m above mean sea level, the plateau area forms a broad topographic high about 140 km long and 80 km wide that trends roughly northwest. The surrounding lowlands are areally extensive and continue north into Northwest Territories and east into Alberta. Relief in these low areas is negligible.

In topographic lows and on level ground, black spruce (*Picea mariana*) dominate. These trees commonly occur in close association with thick peat deposits, forming areally extensive black spruce bogs. Areas that are elevated even slightly (less than 1 m) above the regional water table

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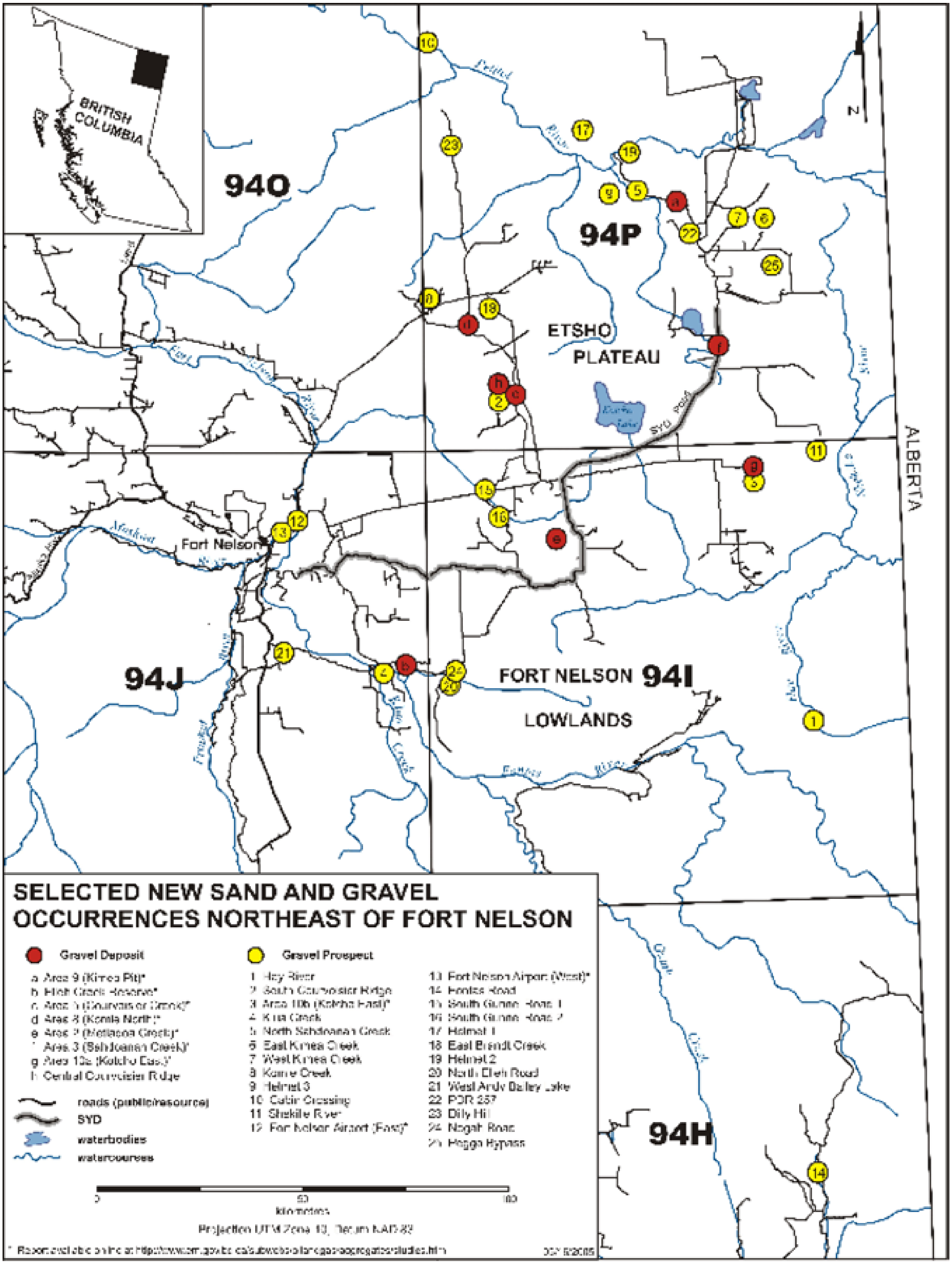


Figure 1. Location of selected new sand and gravel deposits and prospects northeast of Fort Nelson.

are largely forested with trembling aspen (*Populus tremuloides)* and white spruce (*Picea glauca*). Lodgepole pine (*Pinus contorta* var. *latifolia*) is most commonly observed on this higher ground but does grow locally in black spruce bogs.

The study area is mainly accessible by helicopter and all terrain vehicle (ATV). Truck access during summer months is limited to a small network of all-season petroleum development roads (PDR) that branch off of the SYD Road, the major resource trunk road for the region. Truck access to the area increases significantly during the winter months due to the construction of numerous winter roads and ice-bridges.

BEDROCK GEOLOGY

The Fort Nelson Lowlands are predominantly underlain by marine shales of the Lower Cretaceous Fort St. John Group and probably belong to the Shaftsbury Formation (Stott, 1982; Thompson, 1977). These shales are dark grey and can be flaky to fissile but, at surface, are commonly weathered to clay. The upper contact of this formation with the overlying Dunvegan Formation is gradational with sandy siltstones and fine-grained sandstones occurring as interbeds within silty shales (Stott, 1982). Shales of the Fort St. John Group are interpreted to have been deposited in a prodelta or shelf environment in the Early Cretaceous (Thompson, 1977).

The Duvegan Formation of the Upper Cretaceous Smoky Group forms the resistive cap of the Etsho Plateau. Here, these sandstones are fine-grained, whereas equivalent assemblages range from clay-rich shale and mudstone to boulder conglomerate. This variability reflects facies changes in the terrestrial, deltaic, and pro-deltaic environments in which the sediments were deposited (Stott, 1982; Thompson, 1977). Shales have also been observed in direct contact with overlying Late Pleistocene till in borrow pits at higher elevations on the Etsho Plateau. It is not known whether these shales belong to the Dunvegan Formation or are marine shales of the overlying Kaskapau or Kotaneelee Formations. Other outcrop in the region is rare and is limited to stream cuts and some borrow pits resulting from PDR development activity.

SURFICIAL GEOLOGY

The surficial geology of the region has been summarized by Levson *et al.* (2004). During the Late Pleistocene, the Laurentide ice sheet advanced westward up the regional slope into northeast British Columbia. The dominant surficial materials in the study area are organic-, silt-, and clay-rich morainal and glaciolacustrine deposits. Elevated areas that support tree cover are invariably underlain by morainal deposits, whereas organic materials and glaciolacustrine sediments dominate lower, more poorly drained areas. Morainal landforms include low-relief plains, crevasse-squeeze ridges, flutes, and rolling, recessional, and interlobate moraines. Glaciofluvial landforms are relatively uncommon to the region but eskers, kames, fans, deltas, and terraces do occasionally occur. The latter occur mainly within larger meltwater channel systems such as the Kimea Creek–Petitot River system (Figure 2).

The configuration of advancing and retreating ice fronts during the Pleistocene appears to have been complex. Cross-cutting relationships observed in large-scale landforms (e.g., flutes, recessional and interlobate moraines) suggest that regionally there was more than one ice-flow event (Figure 2). Although the entire region was covered by the Laurentide ice sheet during the glacial maximum, the preserved large-scale landform record indicates that, at least during the later stages of glaciation, ice lobes rather than a single ice sheet were active in the region.

During deglaciation, numerous meltwater channels were incised by streams generally flowing west from the retreating Laurentide ice sheet (Figure 2). Although sands and gravels were locally deposited in association with meltwater channels, many of these channels appear to be entirely erosional and may have formed subglacially. During retreat of the Laurentide ice sheet, some rivers were dammed in front of the ice margin as it retreated back down the regional slope. This resulted in the widespread deposition of glacial lake sediments over pre-existing Quaternary deposits (Mathews, 1980). These glaciolacustrine deposits, in addition to morainal sediments, are common at the surface and are one reason why shallow or surface sand and gravel deposits are relatively rare in the region. The majority of aggregate occurrences identified to date are hosted in late-glacial or retreat-phase glaciofluvial features.

Dating of Pleistocene sediments in the area has been facilitated by the discovery of an interglacial peat underlying a thin till approximately 30 km east of Kotcho Lake. Radiocarbon analyses on 2 wood pieces yielded ages of less than 38 690 radiocarbon years BP (Beta 183832) and more than 40 590 radiocarbon years BP (Beta 183831). Another fragment of wood recovered from gravels stratigraphically underlying till in the Elleh Creek area, 100 km southwest of the interglacial site, was dated at 24 400 +/- 150 radiocarbon years BP (Beta 183598). Collectively, these ages and the associated stratigraphy provide new constraints on the Pleistocene history of the region and indicate that ice-free conditions probably existed from before 40 000 until after about 24 000 years BP.

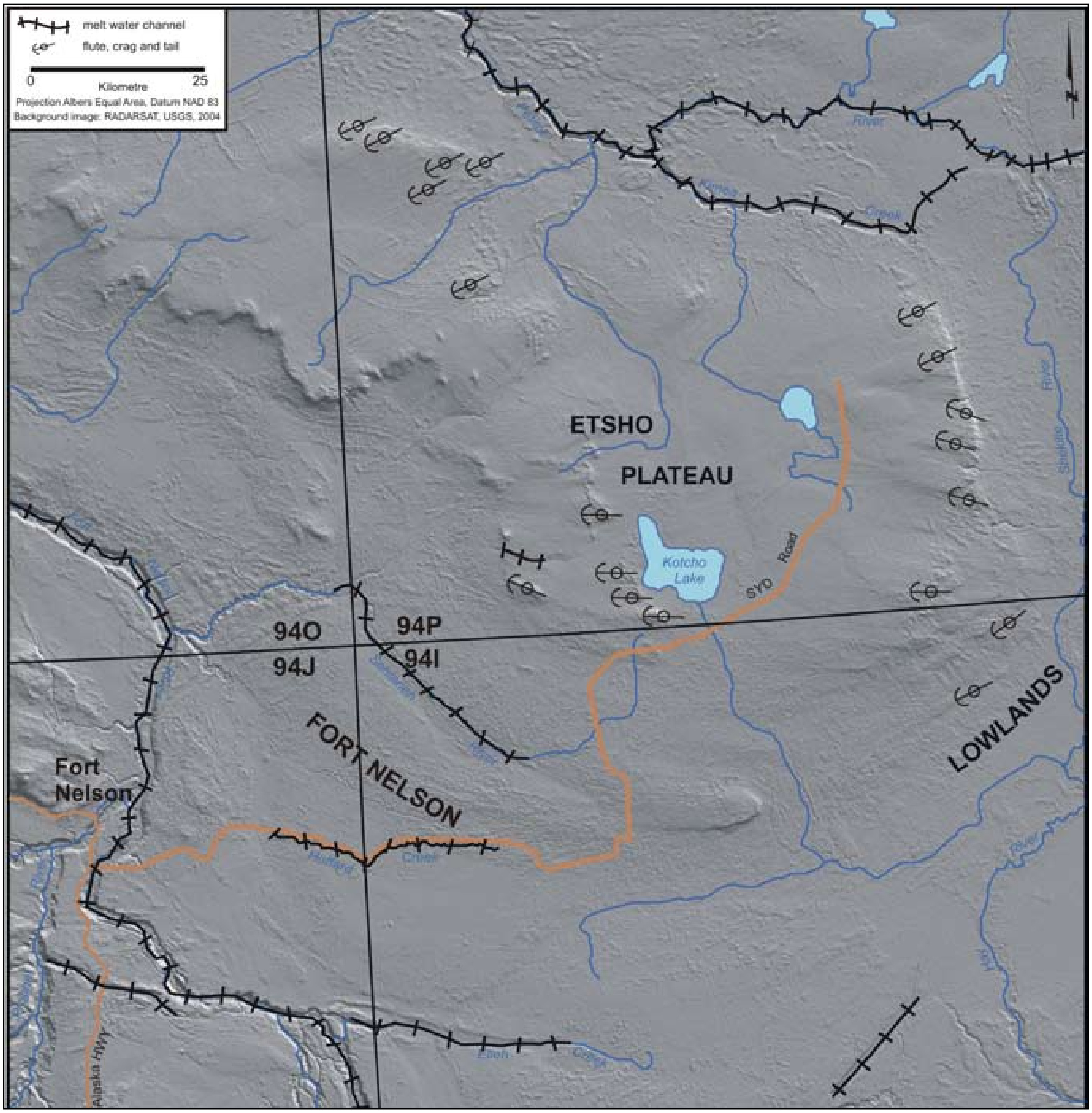


Figure 2. Selected glacial features of the study area.

SAND AND GRAVEL OCCURRENCES

Sand and gravel occurrences can be divided into 3 categories: 1) deposits, 2) prospects, and 3) showings. As used here, a deposit is defined as an occurrence that can be mined economically (typically assessed by a detailed test-pit program) and (or) that is a current or past producer of construction aggregate. A prospect is an occurrence within a mappable geomorphic or geophysical feature that is known to contain sand and (or) gravel. Although detailed field investigations have not been conducted, a reasonable preliminary assessment of the occurrence's potential to host an economic aggregate deposit can be made based on the genesis and size of the mappable feature and field observations of surficial materials present. A showing is simply an occurrence that contains sand and (or) gravel but that is not part of a mappable geomorphic or geophysical feature and (or) that has had insufficient work done to establish economic potential (i.e., potential volume and quality). Aggregate volume and quality constitute a portion of the economic potential of a prospect. Location of demand for construction aggregate and resultant transportation costs must also be considered in an economic assessment because hauling costs almost always exceed the cost of extraction and processing. For example, shorter-haul distances from a lower-quality deposit may be chosen over longer-haul distances from a higher-quality deposit.

The following is a discussion and summary of newly identified sand and gravel deposits and prospects in the region that have resulted from field and office work conducted as part of this program.

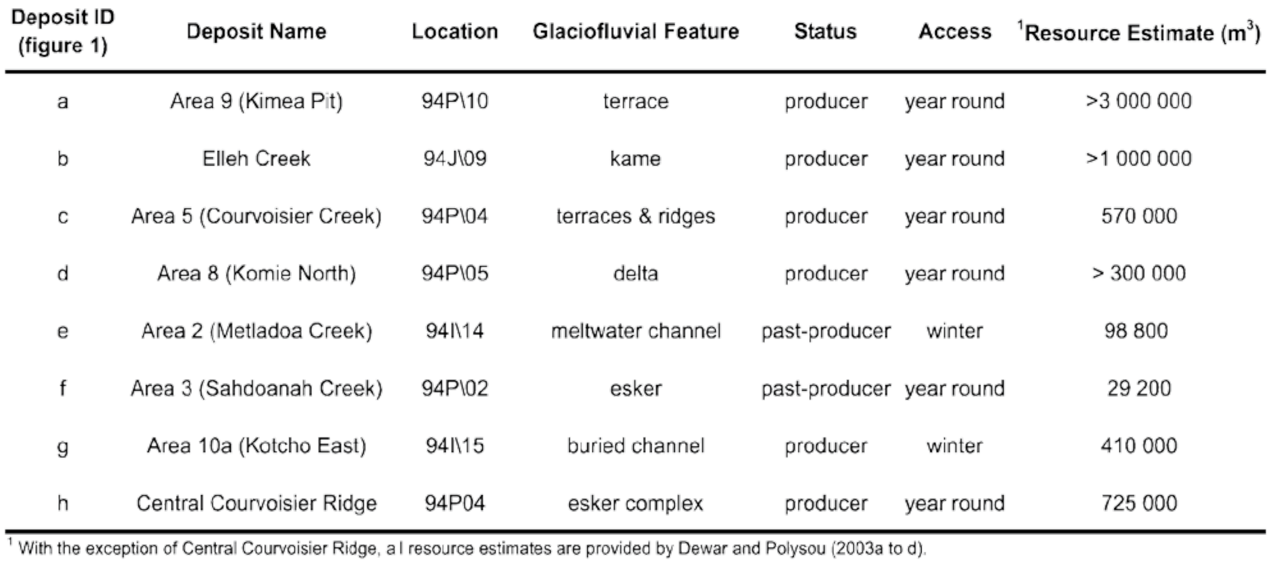
Deposits

To date, 8 sand and gravel deposits have been identified within the study area (Figure 1). Four of these deposits—Kimea (Area 9), Courvoisier Creek (Area 5), Metladoa Creek (Area 2), and Sahdoanah Creek (Area 3) (sites a, c, e, and f, respectively, Figure 1)—are former producing gravel pits that were initially thought to contain a depleted or exhausted resource (Thurber Engineering, 2001, 2002). In spring 2003, a test-pit program was designed by MEM and implemented by AMEC Earth and Environmental to determine what volume, if any, of sand and gravel existed within or adjacent to these areas and in a number of new areas identified by MEM (Dewar and Polysou, 2003a to d; Levson *et al.*, 2004). The primary objective of this program was to identify the required volume of construction aggregate for the proposed upgrades to and future maintenance of the SYD Road (Levson *et al.*, 2004). Not only did this program expand the known resource of these 4 deposits, but it also identified 3 new occurrences that have since been classified as deposits—Elleh Creek, Komie North (Area 8), and Kotcho East (Area 10a) (sites b, d, and g, respectively, Figure 1). In addition, an 8th deposit—Central Courvoisier Ridge (site h, Figure 1)—was discovered and investigated in the winter of 2005 (see below). The details, including preliminary volume estimates, of these 8 deposits are summarized in Table 1.

In total, the test-pit program identified a preliminary resource estimate of more than 5 000 000 m^3 of sand and gravel in 5 key areas in the vicinity of SYD Road. A subsequent study of aerial photographs, airborne geophysical data, and RADARSAT and LiDAR DEMs shows that only portions of the mappable features (i.e., geomorphic or geophysical) in Elleh Creek, Komie North (Area 8), Kimea (Area 9), Courvoisier Creek (Area 5), Sahdoanah Creek (Area 3), and Kotcho East (Area 10a) deposit areas were tested. This suggests that these 6 deposits have potential to host an even larger resource. Detailed discussions of all deposits mentioned above, including test-pit results, are provided in individual reports by Dewar and Polysou (2003a to d). These reports are available for download at www.em.gov.bc.ca/subwebs/oilandgas/aggregates/studies.htm.

The Central Courvoisier Ridge deposit (site h, Figure 1) was first identified by aerial photograph interpretation in 2003, and became an exploration target in 2004 after reviewing LiDAR DEMs for the area. Located in the south-central portion of NTS map area 94P/04 on the western flank of Etsho Plateau (Figure 1), this deposit is approximately 34 km north-northwest of the SYD Road and, since the construction of the new Courvoisier Road in early 2005, it is accessible year-round on all-season roads. Detailed field investigations were conducted on the deposit during the winter field program (March 2005), and it has since been put into production. This deposit is hosted in the central and widest portion of a north-trending, 10 km

TABLE 1. SUMMARY OF AGGREGATE DEPOSITS IN STUDY AREA.



Deposit ID (figure 1)	Deposit Name	Location	Glaciofluvial Feature	Status	Access	[1]Resource Estimate (m^3)
a	Area 9 (Kimea Pit)	94P\10	terrace	producer	year round	>3 000 000
b	Elleh Creek	94J\09	kame	producer	year round	>1 000 000
c	Area 5 (Courvoisier Creek)	94P\04	terraces & ridges	producer	year round	570 000
d	Area 8 (Komie North)	94P\05	delta	producer	year round	> 300 000
e	Area 2 (Metladoa Creek)	94I\14	meltwater channel	past-producer	winter	98 800
f	Area 3 (Sahdoanah Creek)	94P\02	esker	past-producer	year round	29 200
g	Area 10a (Kotcho East)	94I\15	buried channel	producer	winter	410 000
h	Central Courvoisier Ridge	94P04	esker complex	producer	year round	725 000

[1] With the exception of Central Courvoisier Ridge, all resource estimates are provided by Dewar and Polysou (2003a to d).

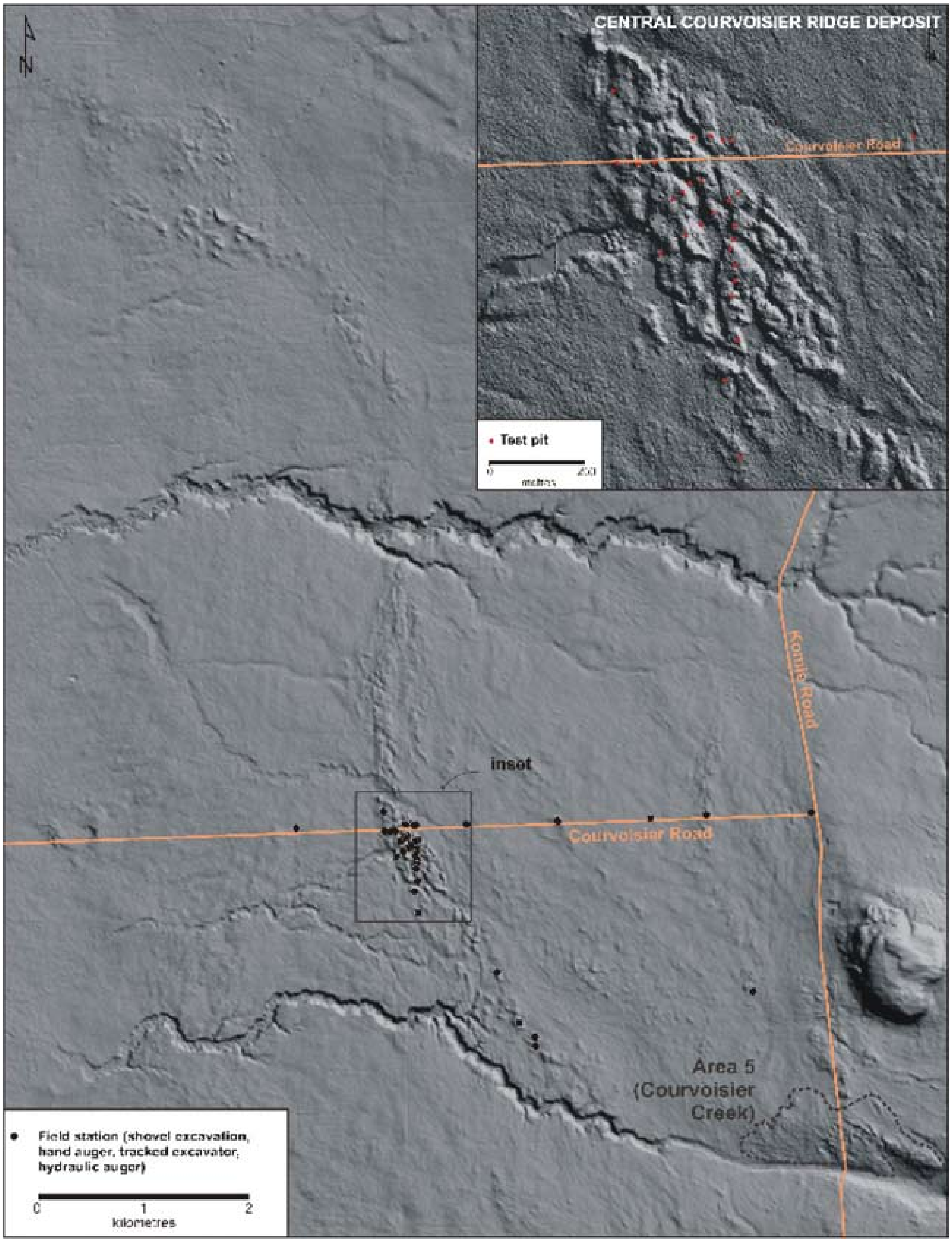


Figure 3. The Central Courvoisier Ridge deposit. Shown here in a LiDAR DEM, this deposit is hosted in the central portion (inset) of a large ridge system interpreted to be an esker complex (inset). Detailed test-pitting (25 test pits) was conducted in this central portion, and results were used to delineate the deposit. Preliminary field investigations in the southern portion of this complex suggest that this area could also host an aggregate deposit. Note the extension of the ridge complex well to the north of the area investigated to date.

long ridge system that is composed of a series of discrete, sub-parallel, sinuous ridges (Figure 3). Typical dimensions of these ridges are 2 to 4 m high, 50 to 200 m wide, and 100 to 450 m long. North of the deposit, the ridge system appears to curve northwest and possibly terminate in a fan-like feature. The southern extent of the system is situated at the western end of the west-trending Courvoisier Creek meltwater channel (Area 5, Figure 3). Access to northern and southern portions of the ridge is limited to winter only.

Exposed in new roadcuts and in 2 borrow pits, individual ridges in the central portion of this system are composed of stratified (slope-parallel), pebble to cobble-sized gravels and trough cross-bedded medium to coarse sands. Locally, within the gravels, sandy channel-fill sequences occur. Although all exposed ridges are composed of granular material, compositionally this material varies from one ridge to another. This ridge system is interpreted as an esker complex that may be contemporaneous with the formation of the Courvoisier Creek meltwater channel. The source of sediment for this ridge system could have been from the incision of this meltwater channel and (or) the transport of sediment from Etsho Plateau towards the west. The details of this deposit are summarized in Table 1.

In March 2005, detailed field investigations were conducted in the central portion of the ridge system. In total, 24 test pits were dug (up to 5 m deep) along existing seismic cutlines. Observations were also made in 2 borrow pits that exposed 3 m–high sections in ridges. In general, there are massive to crudely stratified pebble- to cobble-sized gravels at surface on the ridge-tops, varying in thickness from 2 to more than 4 m. These gravels are typically underlain by silty sands (containing 5% to 10% silt) with occasional pebble- and cobble-sized clasts. On some ridges, a thin silty sand unit (less than 1.5 m thick) overlies the gravels. Ridge flanks and low areas between ridges also contain pebble- to cobble-sized gravels but are typically overlain by up to 1.5 m of silty diamicton or silty medium to coarse sand. Smaller ridges, investigated along the margins of the system, are composed of more than 2 m of silty diamicton. The water table typically was encountered at approximately 2 m below surface in test pits between these ridges. For exposures within ridges, water was encountered only once at 6 m below surface in a borrow pit located in the centre of a large ridge near the eastern edge of the deposit. Based on test-pit results and field observations in 2 borrow pits the Central Courvoisier Ridge deposit was delineated and a preliminary volume estimate of 725 000 m^3 determined (Figure 3, inset). To date, approximately 12 000 m^3 of pit-run gravel has been mined from this deposit and used to surface local PDRs being built and maintained by EnCana Corporation.

Reconnaissance-scale field investigations were also conducted at the southern end of the feature northwest of the Courvoisier Creek meltwater channel (Area 5, Figure 3). Ridges occurring in the southern 2 km of the ridge system are less densely spaced and narrower than those occurring to the north (Figure 3). Five hydraulic auger holes were drilled (ranging in depth from less than 1.0 up to 9.5 m below surface), 4 of which encountered granular material. Sands and gravels in this portion of the ridge system typically are buried under 3 to 4 m of silt that grades into a pebbly silt, or perhaps diamicton, with depth. Pebble- to cobble-sized gravels can, however, occur at surface or can be overlain by up to 3.5 m of poorly sorted sands. The only auger hole that did not encounter granular material was located between 2 ridges. In this hole, more than 3 m of clayey-silt diamicton was overlain by 2.5 m of silt. Preliminary results indicate that this southern area has potential to host a deposit similar to that of the central portion of the ridge system. Further field investigations in this area and the area north of Central Courvoisier Ridge deposit will likely result in an increase in the estimated volume of aggregate in the Courvoisier ridge system.

Prospects

To date, 25 new sand and gravel prospects have been discovered in the region (Figure 1). All are contained within a mappable geomorphic feature and, at a minimum, have been tested by shallow hand excavations (shovel or auger to about 1 m below surface) in some portion of the mappable feature. South Courvoisier Ridge, Kotcho East (Area 10b), Fort Nelson Airport (east and west), Dilly Hill, and Peggo Bypass (sites 2, 3, 12, 13, 23, and 25, respectively, Figure 1) are exceptions in that an excavator and (or) hydraulic auger have been used to test for granular material. Of the 25 new prospects, Dilly Hill and Kotcho East (Area 10b) are unique as they are both buried under 2 to more than 5 m of silt and clay-rich morainal and glaciolacustrine sediments and cannot be mapped from surface landforms. In the case of Kotcho East (Area 10b), however, the deposit has been mapped using airborne electromagnetic data (Best *et al.*, 2004; Best *et al.*, in press).

Based on the genesis and size of the mappable feature, field observations of surficial materials, and a preliminary assessment of aggregate demand, the majority of the 25 newly identified prospects have high potential to host an economic sand and gravel deposit. To further evaluate the potential of these prospects and to determine preliminary volume and quality estimates, systematic test-pit programs will be required. The details of these prospects, including location, feature morphology, access, and investigation method, are summarized in Table 2. A detailed discussion on the Fort Nelson Airport East and West prospects are provided by Ferbey *et al.* (2004) and Johnsen *et al.* (2004). A preliminary discussion about the correlation between high resistivity values and the occurrence of granular material in Kotcho East (Area 10b) is provided by Best *et al.* (2004)

TABLE 2. SUMMARY OF AGGREGATE PROSPECTS IN THE STUDY AREA.

Prospect ID (Figure 1)	Prospect name	Location	Glaciofluvial Feature	Access	Exposure and Investigation Method[2]
1	Hay River	94I\08	delta	winter	streamcut, shovel excavation
2	South Courvoisier Ridge	94P\04	esker	winter	hydraulic auger
3	Area 10b (Kotcho East)	94I\15	buried	winter	test pit
4	Klua Creek	94J\09	fan-delta	year round	roadcut, shovel excavation
5	North Sahdoanah Creek	94P\11	terrace	year round	streamcut, shovel excavation
6	East Kimea Creek	94P\07	kame	winter	shovel excavation
7	West Kimea Creek	94P\07	terrace	winter	shovel excavation
8	Komie Creek	94P\05	esker complex	winter	shovel excavation, hand auger
9	Helmet 3	94P\11	?	winter	shovel excavation, hand auger
10	Cabin Crossing	94P\13	terrace	winter	shovel excavation, hand auger
11	Shekilie River	94I\16	kame, shorelines	winter	shovel excavation
12	Fort Nelson Airport (east)	94J\15	?	winter[1]	test pit
13	Fort Nelson Airport (west)	94J\15	?	winter[1]	test pit
14	Fontas Road	94H\08	esker	winter[1]	shovel excavation, hand auger
15	South Gunnel Road 1	94I\13	esker	winter[1]	roadcut, shovel excavation
16	South Gunnel Road 2	94I\13	?	year round	shovel excavation
17	Helmet 1	94P\11	esker	winter	shovel excavation, hand auger
18	East Brandt Creek	94P\05	kame	winter	shovel excavation, hand auger
19	Helmet 2	94P\11	esker	winter	shovel excavation, hand auger
20	North Elleh Road	94I\05	kame	year round	roadcut, hand auger
21	West Andy Bailey Lake	94J\10	?	winter	shovel excavation, hand auger
22	PDR 257	94P\07	kame	year round	roadcut, shovel excavation
23	Dilly Hill	94P\12	?	year round	test pit
24	Nogah Road	94I\12	burried	year round	shovel excavation
25	Peggo Bypass	94P\07	terrace	winter	hydraulic auger

[1] Winter access only, but less than 1 km from existing all season road.
[2] Unless specified, exposure is from surface.

and Best *et al.* (in press). All of these reports are available for download on the website provided above.

SUMMARY

To date, the Northeast British Columbia Aggregate Mapping Program has identified more than 6 000 000 m^3 of construction aggregate northeast of Fort Nelson in the vicinity of the SYD Road. This resource is hosted in 8 sand and gravel deposits: Kimea (Area 9), Courvoisier Creek (Area 5), Metladoa Creek (Area 2), Area 3 (Sahdoanah Creek), Elleh Creek, Kotcho East (Area 10a), Central Courvoisier Ridge, and Komie North (Area 8). The latter 3 deposits have been put into production since their identification during this program. Seven of the 8 deposits—Kimea (Area 9), Courvoisier Creek (Area 5), Area 3 (Sahdoanah Creek), Elleh Creek, Kotcho East (Area 10a), Central Courvoisier Ridge, and Komie North (Area 8)—have the potential to host an even larger aggregate resource.

Additionally, 25 new sand and gravel prospects have been discovered. All are contained within a mappable geomorphic or geophysical feature and have been tested to approximately 1 m below surface (in some cases up to 9.5 m) by shovel excavation and hand-auger, excavator, and (or) hydraulic auger. Based on the genesis and size of the mappable feature, field observations, and a preliminary assessment of aggregate demand, the majority of these newly identified prospects have high potential to host an economic sand and gravel deposit.

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BEDROCK TOPOGRAPHY MAPPING AND SHALLOW GAS IN NORTHEASTERN BC

Adrian Hickin[1] and Ben Kerr[1]

ABSTRACT

The British Columbia Resource Development and Geoscience Branch is conducting a bedrock topography and drift thickness mapping program in northeastern British Columbia. The program aims to provide a basic understanding of the Quaternary geology of and shallow-gas potential in the northeastern region of the province. This paper outlines the methodology proposed for the program. The process involves 1) compiling all available data sources; 2) standardizing the data in a database; 3) analyzing data spatially and modeling subsurface horizons; and 4) adding geological interpretation. The program will result in the production of 1:250 000 scale bedrock topography and drift thickness maps for the plains region of northeastern BC. The maps provide a framework for interpreting the glacial history of the area, assisting in seismic interpretation and drilling logistics, and identifying buried paleovalleys that have the potential to host Quaternary gas deposits.

KEYWORDS: Bedrock topography, drift thickness, Quaternary gas, shallow gas, northeast British Columbia

INTRODUCTION

The British Columbia Resource Development and Geoscience Branch (RDGB) has established a bedrock topography and drift thickness mapping program to provide a basic understanding of the Quaternary geology and shallow-gas potential of northeastern British Columbia .

The bedrock topography mapping program is focused on 1) providing the stratigraphic framework for “shallow gas” plays in northeastern BC; 2) identifying areas with thick unconsolidated deposits in order to assist with seismic interpretation (slow velocity zones); 3) identifying areas where artesian aquifers may cause significant drilling problems; and 4) providing estimates of casing depths to minimize environmental impact and militate against well cave-ins. Gas from Quaternary-hosted reservoirs has been known in northwestern Alberta since the 1993 discovery at Sousa (Canadian Discovery Digest, 2001). Unfortunately, at that time the host strata of this shallow discovery were not recognized as Quaternary in age and consequently further exploration for this type of play received little attention. Quaternary plays only gained momentum as an exploration target in the late 1990s (e.g., the Sousa and Rainbow fields have produced since 1998). In BC there are no reported perforations in Quaternary age deposits, but it is likely that any Quaternary reservoir may have been misidentified as a near-surface bedrock formation, such as is the case in the Desan shallow gas field. In this field the Ish Desan d-81-K (WA# 14894) well reports gas in the Dunvegan Formation. However, lithologic logs show the top of the Dunvegan Formation approximately 300 m lower in elevation than would be expected for the area (Stott, 1982). It is possible that shallow gas in this area is hosted in the Quaternary fill of a buried paleovalley.

In this paper we propose a methodology for bedrock topography mapping in northeastern BC. The objectives of the mapping program are to

- Provide 1:250 000 scale bedrock topography and drift thickness maps,
- Identify areas where buried paleovalleys may potentially host Quaternary gas deposits,
- Provide a framework for interpreting the glacial history and exploring for buried sand and gravel in northeastern BC.

Previous Work

The BC Oil and Gas Division began drift thickness and bedrock topography initiatives in 2003 as part of an intergovernmental project that includes the Alberta Geological Survey (AGS) and the Geological Survey of Canada (GSC) as part of Northern Resource Development Project 4450. Initial work was directed at identifying bedrock top picks in gamma logs for map sheets 94I and 94P. The initial data compilation identified several depressions believed to represent paleovalleys that presently have no surface expression (Levson *et al*., 2004). Continuing work in these map sheets has been expanded to include additional datasets and incorporates bedrock topography and drift thickness mapping methods established by Hickin *et al.* (2004a, 2004b) and Pawlowicz *et al.* (2004).

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Study Area

The study area is located in the Boreal Plains of northeastern British Columbia and includes the Fontas River (NTS 94I) and Petitot River (NTS 94P) map sheets (Figure 1). Low relief and clay-rich surficial deposits typify the area, resulting in poor drainage. Lakes, marshes, fens, and peat bogs are common, and the vegetation can be characterized largely as a mix of young aspen forest and black spruce bog. Areas slightly elevated above the surrounding terrain are commonly vegetated with trembling aspen (*Populus tremuloides*), lodgepole pine (*Pinus contorta*), and white spruce (*Picea glauca*). Black spruce (*Picea mariana*) is dominant in the lower, wetter areas. Permafrost is present, particularly in the muskeg and peat-rich areas, and both active and relict thermokarst is responsible for many of the lakes.

BEDROCK GEOLOGY

The uppermost bedrock units in the study area include Lower to Upper Cretaceous shale and sandstone of the Fort St. John Group and Dunvegan Formation (Thompson, 1977; Stott, 1982). The subsurface units relevant to this study (to a depth of approximately 800m) include the Banff Formation (Mississippian), Rundle Group (Mississippian), Diaber Group (Triassic), Bullhead Group (Lower Cretaceous), Fort St. John Group (Lower to Middle Cretaceous), and the Dunvegan Formation (Upper Cretaceous). The following unit descriptions are from Glass (1997) (Figure 2).

The Banff Formation consists of shale and marlstone that grade upward and eastward into spiculite, bedded chert, and carbonates. The upper portion of the unit, which is truncated by a regionally extensive sub-Cretaceous unconformity in northwestern Alberta, occurs as a succession of interbedded sandstones, siltstones, and shales.

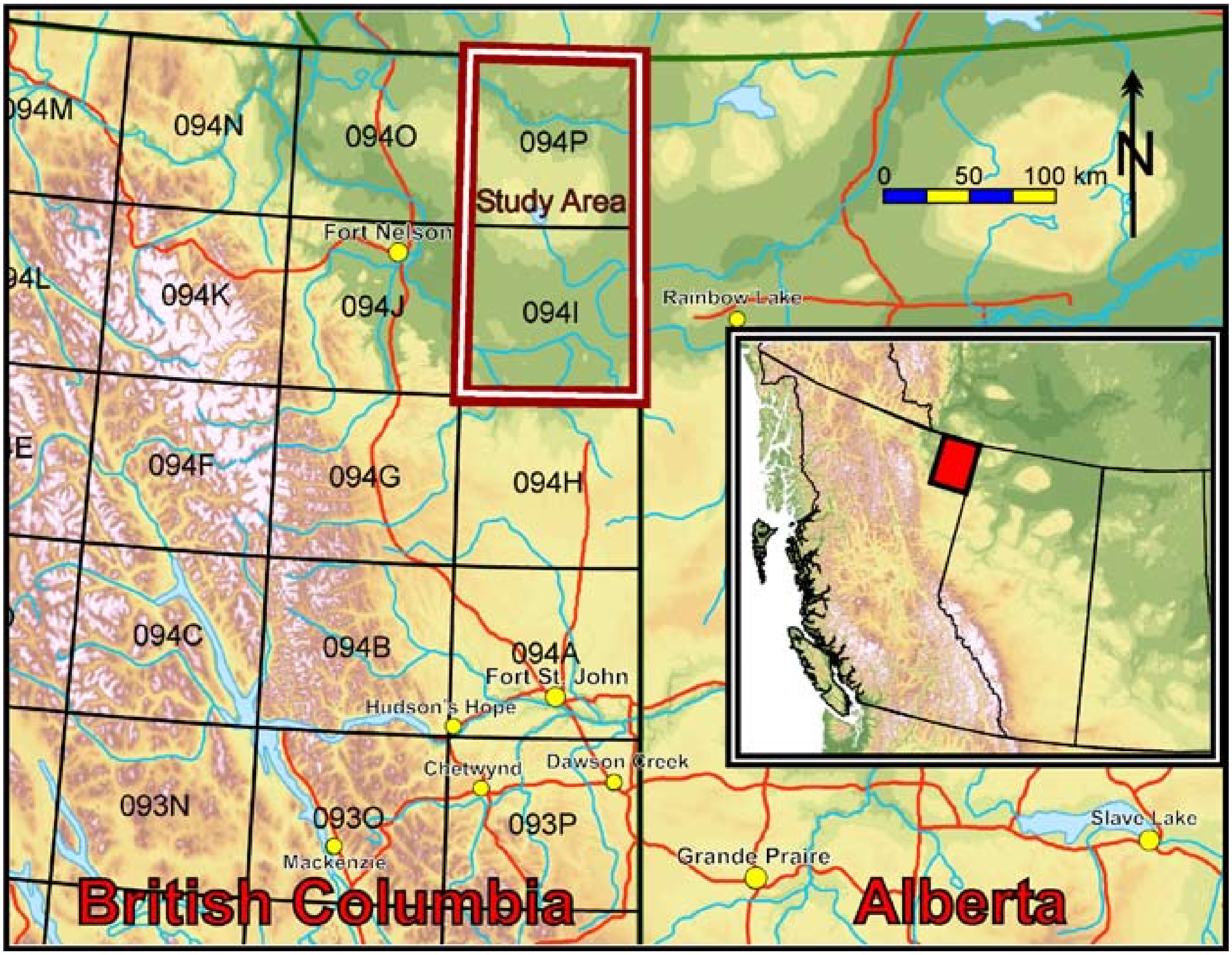

Figure 1. The study area is located in the northeastern corner of the province in the Western Canadian Sedimentary Basin. Preliminary bedrock topography mapping has focused on NTS map sheets 94P and 94I.

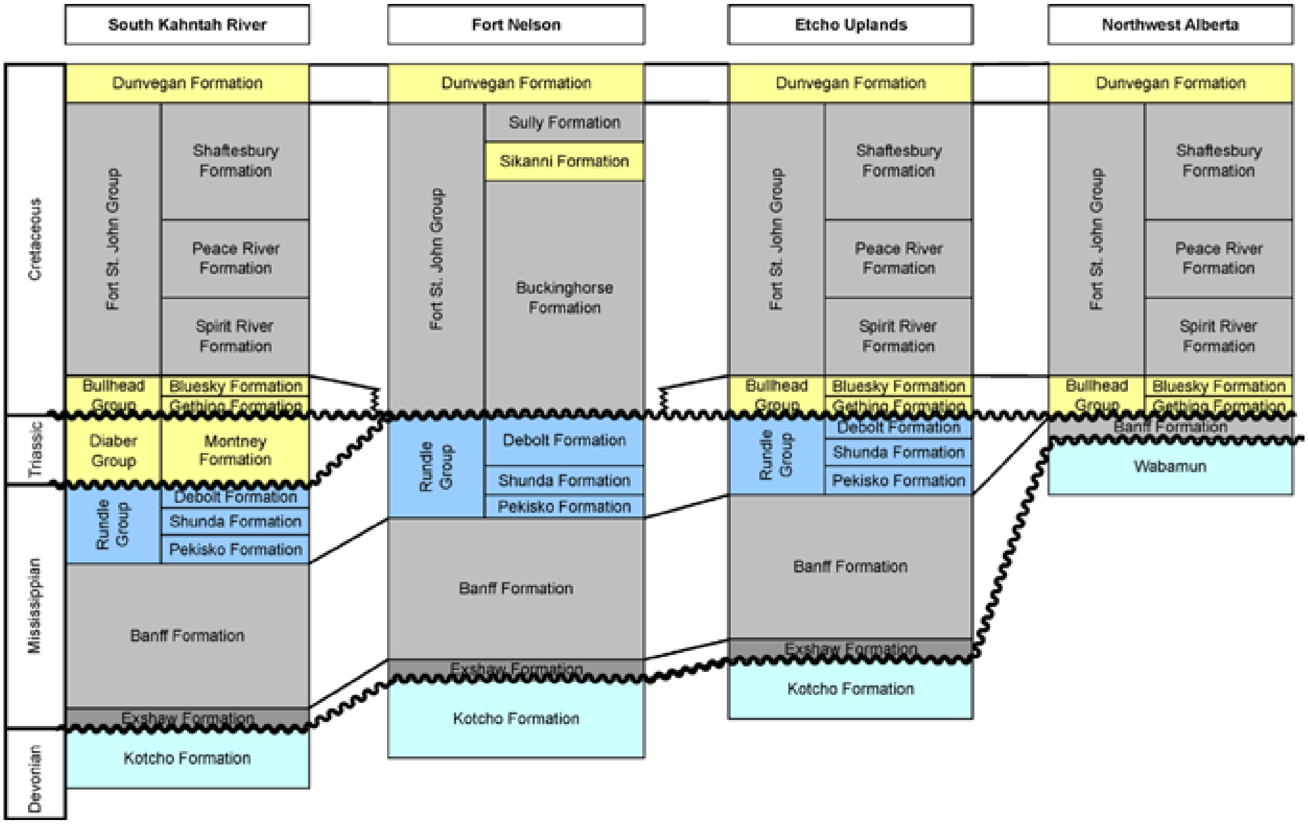

Figure 2. The bedrock stratigraphy of the area is transitional between the nomenclature from the northwestern plains of Alberta and that of the Fort Nelson area (after Stott, 1982 and Thompson, 1977).

The Rundle Group includes the Pekisko, Shunda, and Debolt Formations. The Pekisko is a crinoidal to fine-grained dense limestone. The Shunda consists of interbedded limestone, dolostone, siltstone, sandstone, shale, and breccia. The type section for the Debolt consists of cherty, massive bioclastic limestone and dolomite. In northeastern BC, it is mainly limestone with less dolomite and shale.

The Montney is the only formation of the Diaber Group identified in the map area. The Montney is an important unit because it occurs in the southern portion of the map area (Kahntah River area) as a gas-bearing sandstone. The Montney typically consists of siltstone and shale with the arenaceous content increasing in the eastern portion of the study area. The Montney is also truncated by the sub-Cretaceous unconformity and is not present to the north of the Hay and Fontas Rivers.

The Bullhead Group is represented by the Gething-Bluesky Formations (undifferentiated in this study). The Bluesky Formation is a fine to medium sandstone, usually glauconitic, and may contain chert pebbles. The unit is typically thin, ranging from absent to 46 m thick, though typically not more then 10 m thick where present in the map area. The Bluesky is a well known gas-bearing unit in Alberta. The Gething Formation is a heterogeneous stratigraphic unit consisting of conglomerate, coarse- to fine-grained sandstone and marine siltstone and mudstone. The formation has been extensively studied south of the study area as it is a well known coal-bearing unit. The Bullhead Group has only been identified in the southern and south-eastern portions of the study area.

The Cretaceous rocks of the Fort St. John Group and Bullhead Group (where present) are separated from the Mississipian rocks by the sub-Cretaceous unconformity. The lower Fort St. John Group includes the Spirit River and Peace River Formations, which are equivalent to the Buckinghorse Formation around the Fort Nelson area. The upper Fort St. John Group includes the Shaftesbury Formation. All of these units occur as shale or siltstone in the map area.

The uppermost unit in the area is the Dunvegan Formation, which outcrops on the Etsho Plateau. The Dunvegan consists of marine, deltaic, and channel sandstone, conglomerate, and shale.

PRE-GLACIAL AND PLEISTOCENE HISTORY

Tertiary and Pleistocene processes have played an important role in shaping the Boreal Plains. Tertiary erosion and deposition began influencing the landscape following regression of the Cretaceous seas. During the Pleistocene, climate cooled and glaciers advanced into the area. Pleistocene glaciers are responsible for most of the surficial sedimentary cover and current landscape of northeastern BC (Ferbey *et al*., this volume).

The late Tertiary and early Pleistocene was a period of significant erosion in northeastern BC. During this time, drainage systems from the Rockies carved valleys that extended east from the mountains, transporting and depositing sediment as far as central Alberta (Edwards, 1994).

As the climate deteriorated, Laurentide ice advanced up the regional slope from the northeast. Large proglacial lakes formed as the advancing ice impounded drainage. The ice eventually overrode the lake sediments, depositing a thick blanket of till and masking the older valleys with as much as 300 m of sediment. At glacial maximum, Cordilleran and montane ice also played a role in depositing sediment, though their influence was generally restricted west of the study area along the Rocky Mountain foothills (Trommelen *et al*., this volume). As the climate warmed the ice retreated, again impounding drainage and forming large recessional proglacial lakes (e.g., glacial Lake Peace and glacial Lake Hay) (Mathews, 1980). The area was ice-free by the Holocene (approximately 10 000 years ago).

METHODS

The process used to map the bedrock topography is summarized in four steps (Hickin *et al*, 2004a, 2004b; Pawlowicz *et al*., 2004): 1) compile all available data sources; 2) standardize the data in a database; 3) analyze data spatially and model subsurface horizons; and 4) add geological interpretation.

Data Sources

A variety of data sources are available for mapping key subsurface horizons. These include oil and gas well petrophysical logs, drill cuttings, surficial and bedrock geology maps, and water-well lithology logs.

The bulk of the subsurface data come from the downhole petrophysical logs collected by the oil and gas industry (Figure 3). From these data, depth to bedrock and other key horizons can be extracted. The most commonly used logs in this study are gamma and neutron density logs, as they can provide lithologic information for both the cased and

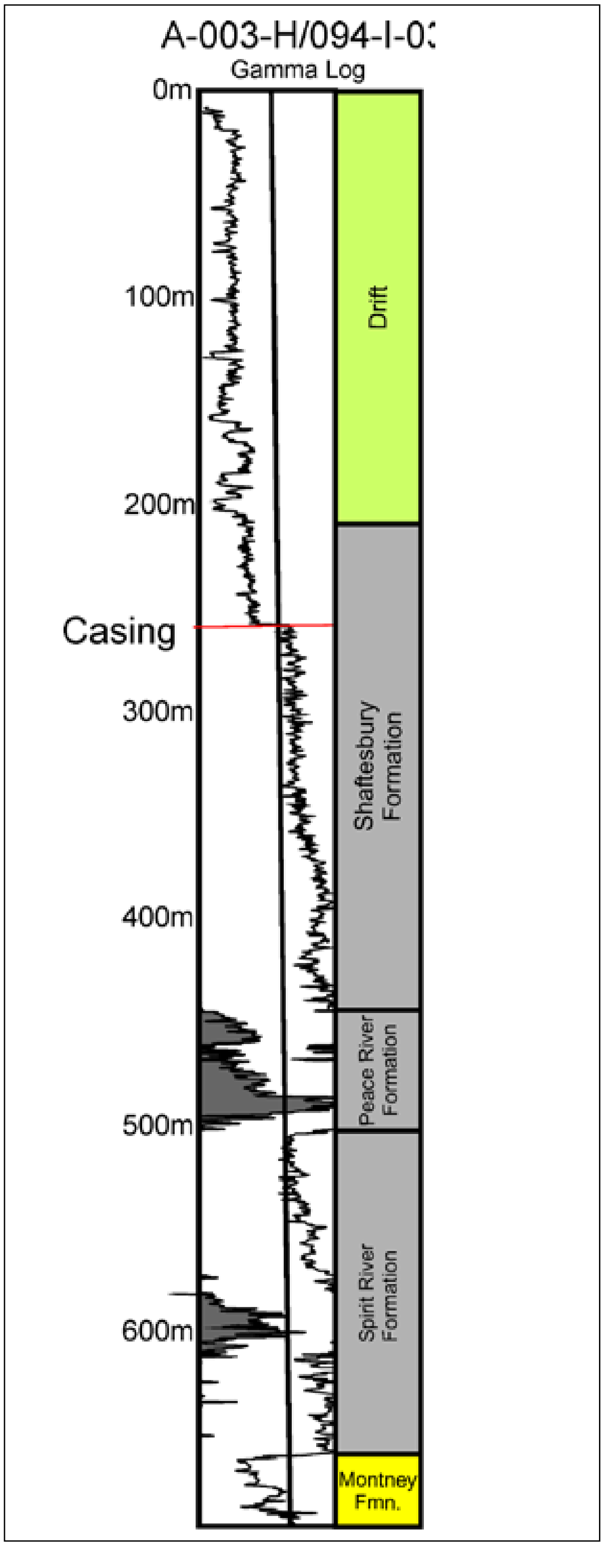

Figure 3. Gamma logs are the most common petrophysical log used in this study. Despite the contact occurring behind the casing, the bedrock–drift interface can easily be identified. In this example (A-003-H/094-I-03; WA# 8977), the base of drift occurs where there is a shift from a relatively high, uniform gamma response in the Shaftesbury marine shale to a prominent decrease in radioactivity associated with coarser terrestrial sediments in the drift.

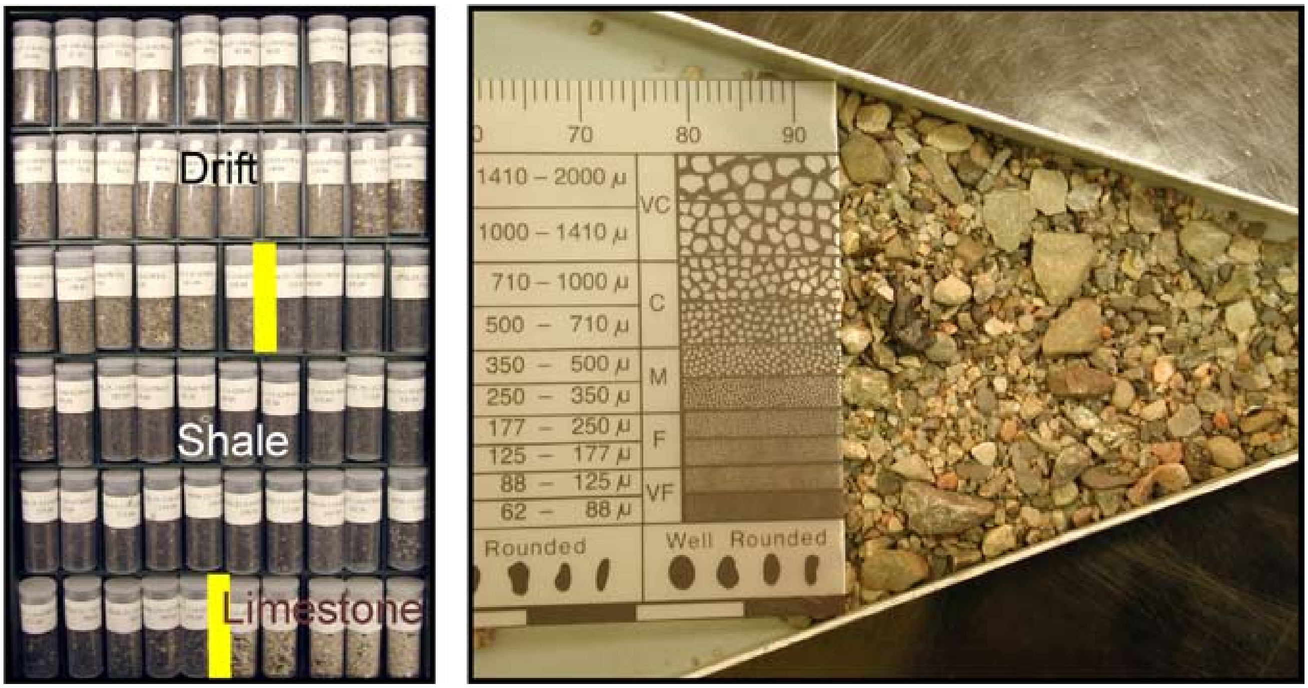

Figure 4. Drill cuttings can also provide an estimate of the depth to bedrock. Drift drill cuttings contain an abundance of granitic and metamorphic fragments often dominated by feldspar. These lithologies are derived from the Canadian Shield, deposited as till after being transported by glaciers. Bedrock chips contain shale, siltstone, and sandstone fragments as all local bedrock has a sedimentary origin (photo on left courtesy of John Pawlowicz).

uncased portions of the wells. Prior to 2003, surface casing was required to be set at a depth of 15% of the planned total depth of the well or 150 m, whichever was greater. Current BC regulations require casing to be set below all strata expected for drinking water and at least 25 m into a competent horizon for blowout prevention (*Petroleum and Natural Gas Act*, 1998). As a result, wells are often cased into bedrock with the drift contact occurring at some depth behind the casing. This contact will manifest as a suppressed gamma or neutron shift. Unfortunately there are circumstances when the contact may be undetectable—for example, where the contact is coincident with the bottom of the casing or where clay rich drift sediment is in contact with clayey, weathered bedrock shale (both with similar radioactive properties). It is, therefore, important to determine the bedrock stratigraphy so that the absence of key radioactive or density markers can be used to infer an erosional contact between the bedrock and the drift.

Drill cuttings can also provide an estimate of the depth to bedrock. The contact between the drift and the bedrock surface is marked by a shift from granitic and metamorphic fragments associated with Laurentide till to shale and sandstone associated with the Cretaceous Fort St. John Group and Dunvegan Sandstone (Figure 4). The contacts determined from drill cuttings should be considered an estimate as several factors can contribute to changes in fragment lithology. Contamination, loss of circulation, gradational contacts, and lag time can all contribute to ambiguity in the precise depth of a contact. Whenever possible, a drill cutting lithologic contact should be confirmed by a geophysical log.

Currently, the Oil and Gas Division of the BC Ministry of Energy and Mines is working cooperatively with the GSC to map the surficial geology of northeastern BC. These maps will be incorporated into the subsurface program as an additional source of information. The surficial geology maps help to anchor the bedrock topography model to the surface digital elevation models (DEMs). This is achieved by including in the generated bedrock topography model those mapped areas noted as having thin drift or bedrock outcrops. The result is that elevations in the bedrock topography model and the DEM will be similar in areas of thin drift or identical where bedrock outcrops.

The final source of data collected for this program is lithology logs provided by the water-well drilling industry. Typically, companies drilling water wells record general comments regarding the lithologic observations (often in lay terms). This data, though not definitive, can provide information such as depth to bedrock or the absence of bedrock over a stated interval (Figure 5). The Ministry of Water, Land and Air Protection's aquifer and water-well database has, in the past, been the major source for water-well data for the province. However, as there is a limited population in map sheets 94I and 94P, there are few data available for this area. To augment provincially held data, lithologic information has been provided by drilling com-

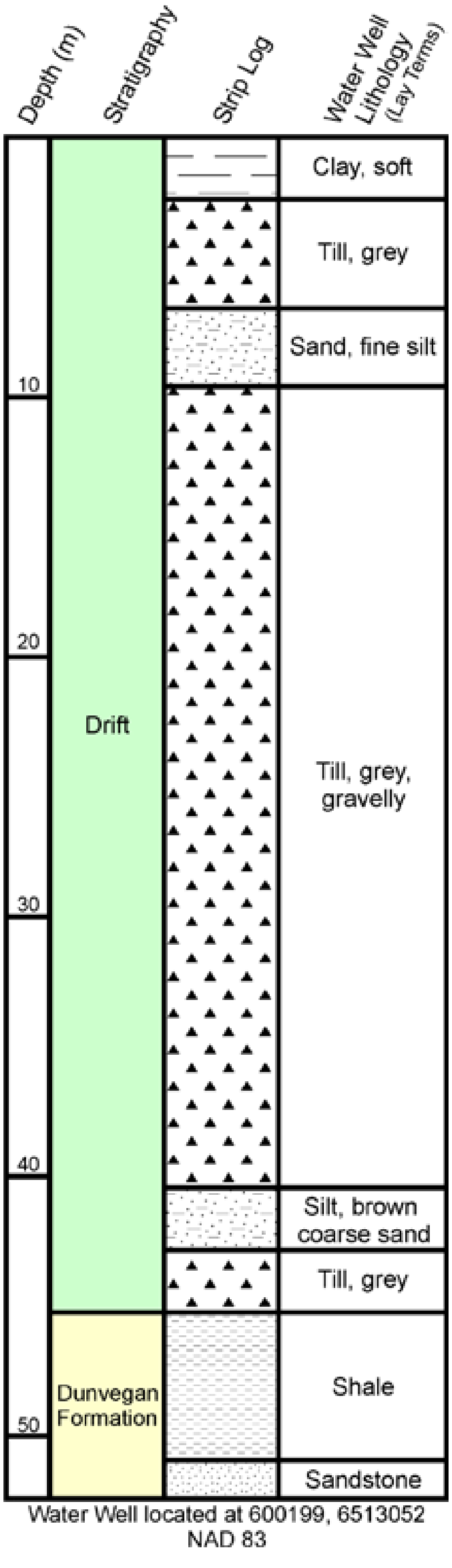

Figure 5. A typical water-well log will describe the materials encountered during drilling. The descriptions are generally in lay terms, therefore caution should be exercised when assigning the material to a genetic sediment type (e.g., till vs. diamict). Strip logs

panies contracted to drill water wells (to support remote oil and gas camps and to access water for drilling fluid) and shotholes for setting seismic charges.

Data Entry

To properly manage and use the various datasets, it is important to compile and standardize the data. This is achieved by entering the data into a pre-structured database that the RDGB has developed in *MS Access*. All data is entered using menu entry forms that make certain the data is entered consistently. This ensures that the information required for querying and geostatistical analysis is available for the modeling software.

The data can be separated into two types—lithologic and stratigraphic. Lithologic data from a water well may describe the material drilled over a 30 m interval as 0 to 10 m of sand; 10 to 20 m gravel; 20 to 30 m shale. Units are described only and are not related from one well to another, nor is an age relationship inferred. Stratigraphic data assigns to a unit both an age and a name, placing it within the stratigraphic framework of the area. The stratigraphy of the same interval described above would be: 0 to 20 m Quaternary drift; 20 to 30 m lower to upper Albian Shaftesbury Formation.

Spatial Data Analysis and Modeling Subsurface Horizons

Once the data have been sorted and extracted from the database, they can be spatially analyzed. Histograms and semivariogram/covariance clouds are used to investigate the distribution of the data. These characteristics provide insight into the most suitable interpolation method for the data. Interpolation is a statistical method of predicting values between known points. (*c.f.* Bailey and Gatrell, 1995). Parameters used in the interpolation are then fine-tuned in an iterative process in an attempt to minimize the root-mean-square error (the difference between the predicted values for the surface and the known data points).

Adding Geological Interpretation

Because interpolated surfaces are generated from point data by the interpolation algorithms built into the gridding software, they do not always represent the real geological situation. Therefore it is important not to accept the generated surface without appropriate quality control. Furthermore, the modeled geological surfaces should include the valuable non-point data and incorporate the geologist's geologic and geomorphologic observations in order to ensure the interpretation reflects the true nature of the subsurface.

Interpolated surfaces are generated from point data that contains *x*, *y* locations (UTM eastings and northings) and a *z* value (elevation above sea level); however, some *x, y* locations will not contain a meaningful *z* value but still contain information that affects the model. This information is valuable and needs to be incorporated into the surface modeled for a geological horizon. An example of such a case is when the well or borehole ends before the horizon of interest is intersected. In this case the horizon of interest is known to be deeper than the bottom of the well. If the interpolated surface passes above or at the bottom of the well then it violates known information (although there is no real *z* value that the algorithm can invoke) and must be corrected to pass at a depth below the bottom of the well. Similarly, a well log may start at some depth below ground surface and contain data that clearly shows bedrock to the top of the log. From this data, it is known that the bedrock-drift interface must occur above the top of the logged portion of the well and the projected surface must be consistent with this condition.

The interpolated surfaces can be manipulated for quality control in a variety of ways. In this project, the gridded surfaces are brought into or generated in ViewLog™. Cross-sections are constructed at regular intervals displaying the stratigraphic horizons, and well logs with both stratigraphic and lithologic strip logs are displayed. Polygons of thin drift and outcrop (from surficial geological mapping) are incorporated into the model and horizons visually inspected so that they do not violate any of the available data. Errors are corrected and new surfaces generated for contour maps of the bedrock topography. The drift thickness is a calculated surface generated by subtracting the bedrock topography from the surface DEM.

CONCLUSION

Rapid expansion of the oil and gas industry in northeastern BC has increased the demand for baseline geological information. Bedrock topography mapping is one of the initiatives the British Columbia Resource Development and Geoscience Branch has undertaken to support and develop the oil and gas industry. The primary objective of the bedrock topography mapping program is to provide the stratigraphic framework, geological setting, and potential target areas for shallow-gas exploration in the BC portion of the Western Canadian Sedimentary Basin.

Preliminary studies have identified several areas in NTS map sheets 94I and 94P that may have buried paleovalleys. In an effort to verify and map these valleys, methodology adapted from collaborative work in Alberta is being utilized. The methodology incorporates several data sources, including traditional point data from petrophysical logs, as well as non-point data such as surficial geology maps (outcrop maps), water-well lithology logs, and drill cuttings. These data are managed in a database, standardizing information for later extraction into geological modeling software. The modeling software uses both statistically predicted surfaces and geologic and geomorphologic interpretations to produce the best representation of the available data.

The final contour maps will depict the bedrock surface with the Tertiary and Quaternary cover removed as well as isopach maps of the drift thickness. This information can then be used to identify areas of deep incision that may have shallow-gas potential, areas requiring deep casing, and potentially, stratigraphic information valuable for sand and gravel exploration and other Quaternary studies.

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IMPLEMENTING GEOMATICS TECHNOLOGY FOR AGGREGATE EXPLORATION, NORTHEAST BRITISH COLUMBIA

Ben Kerr[1], Travis Ferbey[1] and Victor M. Levson[1]

ABSTRACT

Leveraging the spatial data resources of the Province of British Columbia and industry partners, geomatics technologies and techniques have been successfully implemented in the exploration for construction aggregates in northeast British Columbia. The pairing of GIS and GPS technology on laptop computers allows for real-time navigation and for morphometric and vegetative analysis methods to be tested and refined in the field. High-resolution orthophotos and LiDAR DEMs enable precise navigation to features of interest and the discovery of geomorphic features and systems not apparent using traditional photogrammetric methods. Handheld PC data collection and nightly compilation and distribution has ensured that the entire project team is familiar with all exploration activity and that an up-to-date record of locations visited is maintained. Information on the locations of digital photographs taken and samples collected is also available from the relational database into which the data from the handheld PCs is downloaded.

The integration of these technologies has provided improvements in efficiency as well as in the ability of geologists to identify potential aggregate sources in the field.

KEYWORDS: geographic information systems, GIS, Global Positioning System, GPS, personal digital assistant, PDA, fieldwork, surficial geology, construction aggregates, exploration.

INTRODUCTION

In June 2003, the Province of British Columbia initiated the Oil & Gas Development Strategy, which outlined four key pillars to the oil and gas industry in British Columbia: Roads, Royalties, Service Sector and Regulation. In response to an increase in demand for gravel and a chronic shortage of supply, a group was formed within the Ministry of Energy and Mines (MEM) to explore for suitable construction aggregate deposits in northeast BC (Figure 1) to support the upgrade and construction of oil and gas roads. This paper reviews the geomatics technologies and data that have been used in this program.

Aggregate shortages elsewhere in the province have been addressed by utilizing sources such as bedrock quarries and dredged river gravels. In northeast BC, however, large fluvial systems capable of transporting sands and gravels appropriate for construction aggregate are geographically limited, and incompetent local sandstone and shale bedrock are unsuitable for crushing. As a result, expensive solutions have been used, such as transporting aggregates 400 km into the region by train and then 50 km by truck.

From the outset, MEM has researched and implemented new technologies and used innovative datasets to assist in office- and field-based data collection, analysis, visualization, and presentation. This has resulted in significant success both in improving operational efficiencies and

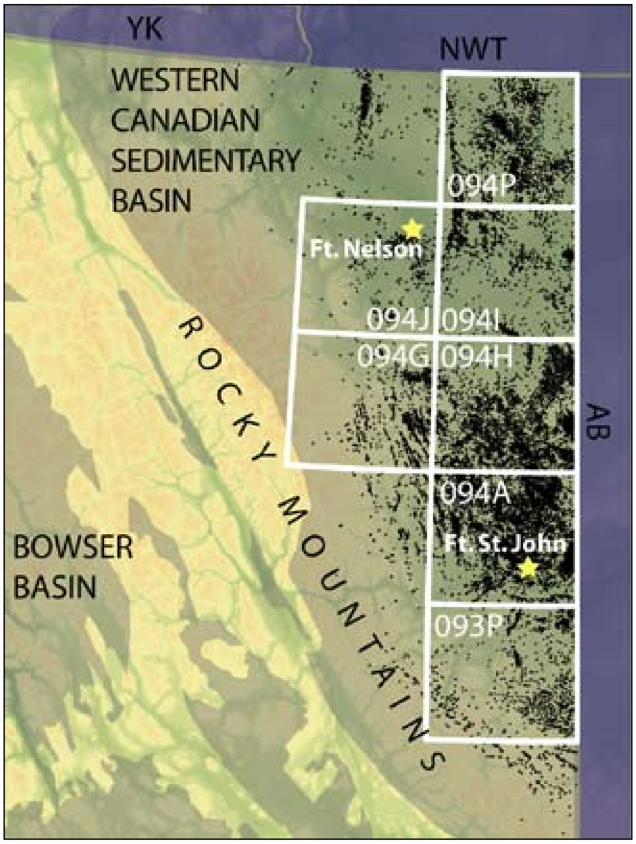

Figure 1. Location of study area. Aggregate inventory and exploration activities are currently taking place in seven 1:250 000 scale NTS map areas. Oil and gas wells drilled to date are shown in black.

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in discovering resources that otherwise may not have been found. This success has also been due to the collaboration between federal and provincial government agencies and industry partners and the contributions of high-quality data from all parties involved.

AGGREGATE EXPLORATION

Construction aggregate exploration is a field that combines the disciplines of Quaternary geology, geomorphology, geotechnical engineering, and geophysics and focuses on a process-based examination of surficial geology. Conceptually, aggregate exploration can be thought of as having three discrete but interrelated stages or components:

1. Office-based interpretation:
    a. Examination of existing literature (e.g., geological reports),
    b. Air photo interpretation,
    c. Compilation of spatial data sets,
    d. Identification and compilation of areas with aggregate potential, and
    e. Preparing maps for fieldwork.
2. Fieldwork:
    a. Field-checking or ground-truthing of areas thought to have aggregate potential,
    b. Sampling of prospects to confirm presence or absence of granular material, and
    c. Detailed geotechnical evaluation of aggregate quality and quantity.
3. Office-based data compilation, analysis, visualization, and presentation:
    a. Compiling and reviewing field observations,
    b. Analysis and mapping of data,
    c. Refinement of interpretations, and
    e. Publishing results.

Various geomatics technologies are implemented in all three stages. These allow for enhanced interpretations and refined analysis both in the office and in the field. Several innovative techniques and data sets have been used, some of which are summarized by Best *et al.* (2004) and Demchuk *et al.* (2005, this volume).

GEOMATICS TECHNOLOGY

The utility of hardware and software technology, regardless of application, is dependent on how it is implemented. Making technology work requires an understanding of research questions that need to be answered and, in the case of aggregate exploration, an understanding of geologic and geomorphic processes as well. It is also important to understand, from a geomatics perspective, what data are suitable for a given application.

In the discussion that follows, hardware and software, data, and data processing and analysis (as they apply to aggregate exploration) will be addressed separately. In cases where commercial hardware or software are described, alternative solutions to those used by MEM in northeast BC will be mentioned.

Hardware and Software

The backbone to the systems implemented is a geographic information system (GIS), which allows for the combination and analysis of spatial data and geo-rectified imagery. ArcGIS (by ESRI) is the corporate GIS standard for the Province of BC and thus the vast majority of data available from the provincial data warehouse is available in ESRI format (shapefile, coverage, SDE). ArcGIS was therefore the obvious choice for use in project activities. Some alternative software options are AutoCad Map, MapInfo, Manifold GIS, or GlobalMapper, which are other commercially available GIS packages that allow for the visualization and analysis of a wide range of spatial data. PC laptop computers have been configured with ESRI ArcGIS 8.2 and ArcView 3.2 and equipped with mobile AC/DC power inverters to allow for use away from standard AC power in the field.

Navigating in the plains region of northeast BC is challenging as the area is largely forested and has subdued topography and few natural landmarks suitable for establishing accurate locations. To overcome this difficulty, real-time tracking software on the laptop computers is used in combination with a GPS to provide consistent, accurate positional information (Figure 2).

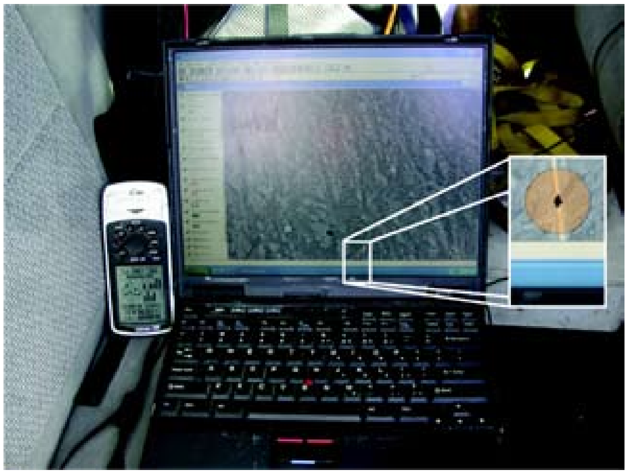

Figure 2. Laptop and GPS with tracking system enabled; arrow shows present location on orthophoto in the GIS.

The DNR Garmin extension (Minnesota DNR) was used in conjunction with ESRI ArcView 3.2 GIS software and Garmin Handheld GPS units (Figure 2). Although used almost exclusively for this project, this is not the only option for real-time tracking capabilities. For example, GlobalMapper and ESRI ArcGIS 8.3+ GIS, in conjunction with any NMEA compliant GPS unit, provide similar functionality.

The benefits of real-time tracking are two-fold. Firstly, it enables field crews to identify their location quickly and accurately at any time; at the same time, field crews are able to examine digital orthophotographs and other spatial data sets while making and recording observations from the ground. Secondly, centrelines for newly constructed roads, which do not exist in the spatial data sets collected prior to the field season, can be mapped using the tracking system. This has resulted in an up-to-date and accurate digital record of the road network in northeast BC.

For field data collection, handheld personal digital assistant (PDA) computers are used. A Palm OS–based solution, similar to that developed by Gilbert *et al.* (2001a, 2001b), running Pendragon Forms data-collection software was chosen. A relational database developed by the Alberta Geological Survey (Fenton *et al.*, 2002) has been modified and is used to record information on geomorphic and geologic characteristics of field stations, paleoflow direction, sample locations, and photo numbers and locations. Data is downloaded into a Microsoft Access database at field camps and distributed to all laptop computers frequently, giving field crews the most up-to-date information for use both in analysis and interpretation of other spatial data sets in the GIS and for the planning of future traverses.

Other field data collection solutions are available; for example, ESRI ArcPad software and PocketPC hardware provide similar functionality as well as additional features such as a 'light' GIS on the PocketPC itself. This implementation is described by Irwin (2003).

Data

Prior to the field season, spatial data and imagery are collected from the large (larger than 2 terabyte) data holdings of the Province of British Columbia. These include:

- 1:20 000–scale base mapping (hydrography, hypsography, transportation)
- Public and resource roads
- Digital orthophotography
- Landsat 7TM satellite imagery
- 1:20 000 vegetation mapping
- 1:20 000 digital elevation models
- Bedrock geology
- Crown tenure (including aggregate reserves)
- Water-well location and lithology
- Aggregate potential mapping

Data held by private companies are also compiled and include:

- Petroleum industry "rathole" drilling information
- Petroleum industry water well drilling information
- 2 m spacing Light Detection and Ranging (LiDAR) elevation models
- Petroleum-industry seismic shothole drilling information

Data Processing and Analysis

Data is standardized and compiled into a comprehensive GIS database used to identify potential aggregate targets prior to field investigations. This information is then transferred to the laptop computers to be taken to the field. The same systems used in the office to generate potential aggregate targets are used in the field for ground-truthing.

Techniques used to identify potential aggregate deposits from the datasets compiled include

- analysing the relationship between vegetation and ground conditions;
- reprocessing elevation model data (LiDAR and traditional DEM) to automate delineation and classification of raised landforms; and
- classifying multiple, independent, sub-surface data sets to identify areas where gravel was concurrently identified.

There are anecdotal reports of a link between stands of lodgepole pine (*Pinus contorta* var. *latifolia*) and sand and gravel deposits; this phenomenon was observed in the field on several occasions. Attempts to identify sand or gravel by navigating to stands of pine as identified by digital vegetation data has met with mixed results, however. The distribution of lodgepole pine stands appears to be a result of the adaptability of the species and its colonizing ability after fire (Ministry of Forests, 2005). Vegetation characteristics of known sand and gravel deposits continue to be examined and recorded.

By far the two most beneficial data sets used thus far have been the digital orthophotography and LiDAR. The ability to have a 'birds-eye view' of a location while observing it from the ground has proved to be invaluable. The ability of the LiDAR to penetrate vegetative cover is also crucial in providing the ability to identify subtle features not always apparent using traditional photogrammetric methods. More information on the use of LiDAR in aggregate exploration can be found in Demchuk *et al*. (2005, this volume).

CONCLUSIONS

Real-time navigation allows for field geologists to gain a more thorough understanding of the characteristics of the region and the relationship between the appearance of features on aerial photographs and on the ground. It also allows for quicker and easier navigation to features of interest observed in aerial photographs or LiDAR data. Digital field data collection allows for frequent updating of progress in the field and rapid compilation of data in the office. Over 1000 field stations and sample locations and several thousand digital photographs have been collected to date and are managed in a relational database.

There exists an exciting potential to further improve on the hardware used in aggregate exploration by implementing new technologies, particularly for field data collection. Five discrete pieces of technology are used in this program: GPS, PDA, digital camera, GIS, and laptop computer. While it would be possible to use only a PDA with ArcPad (ESRI) GIS software and an attached GPS receiver and digital camera, this is not a suitably robust system at the present time. Bluetooth-enabled hardware may improve the connectivity between discrete hardware pieces in the short term. We believe, with the current popularity of location-based service provision in the business geomatics industry, a hardware solution integrating communications (cell phone), GPS, digital photography, GIS, and a PDA will be available in the near future.

The technologies described have helped in the discovery of 6 deposits with an estimated resource of more than 5 million m^3 of sand and gravel and 24 additional prospects with the potential to host significant quantities of granular material (Ferbey *et al.*, 2005, this volume). Prior to the initiation of the aggregate exploration program, there was thought to be little or no remaining aggregate reserve.

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SURFICIAL MAPPING AND GRANULAR AGGREGATE RESOURCE ASSESSMENT IN NORTHWEST ALBERTA

I. Rod Smith[1], Roger Paulen[2], Alain Plouffe[3], Chris Kowalchuk[4] and Ryan Peterson[5]

ABSTRACT

This paper highlights results of the past two years' fieldwork and surficial geology mapping by the Geological Survey of Canada and Alberta Geological Survey in NTS map sheets 84L and 84M, northwest Alberta. Identification of granular aggregate resources has been a key objective of this work, and several new discoveries (including kames and eskers) have been made. Sedimentological investigations and aerial photograph interpretation have helped determine the nature and genesis of various glacial deposits that are exposed in existing or inactive gravel pits. Based on this work, it is now recognized that there is considerable granular aggregate potential in the Rainbow delta, the Chinchaga River valley glaciofluvial deposits, and the Elsa Hill ice-advance phase kame terrace and overlying deglacial and glaciofluvial gravel deposits. Moreover, evidence suggests that the Zama Beach gravel pit and another pit 2 km to the southwest may be stratigraphically linked as part of a larger subglacial channel system. This study has thus substantially increased the potential regional granular aggregate inventory, which is of particular benefit to ongoing and future regional petroleum resource and infrastructure development.

KEYWORDS*: surficial mapping, glacial geology, northwest Alberta, aggregate, gravel, sand, glaciofluvial, glaciolacustrine*

INTRODUCTION

Northwest Alberta has a long-established history of oil and gas development, dating back to the initial 1965 Rainbow oilfield discovery in the Keg River Formation near Rainbow Lake. Subsequent discoveries of the Zama, Virgo, and Shekilie oilfields (also within the Keg River Formation) were made between 1966 and 1969. Natural gas exploration and development began in earnest in the mid-1970s. Northwest Alberta remains an active site for exploration and development of conventional oil and gas deposits. New exploration and development activity is also focusing around unconventional shallow gas targets in the Sousa field, approximately 50 km east of the town of Rainbow Lake, where natural gas is trapped within unconsolidated sediments, infilling buried channel systems (Canadian Discovery Digest 2001; Pawlowicz *et al.* 2004a). Northwest Alberta also serves as a major pipeline hub and includes the southern terminus of the Norman Wells pipeline, which transports oil from Norman Wells, Northwest Territories, to Zama City, Alberta. The proposed Mackenzie Valley gas pipeline will also terminate in northwest Alberta, connecting with existing transmission systems west of Zama City.

With ongoing and proposed development, there is a clear need by industry for a better understanding of the regional surficial geology, which serves to identify granular aggregate resources, areas underlain by permafrost, and mass wasting. In particular, the expeditious and economic development of road infrastructure networks is heavily dependent on acquiring substantial volumes of granular aggregate for projects such as the proposed Northern Link Road between the Sierra-Yoyo-Desan Road, British Columbia, and Rainbow Lake, Alberta.

As part of a four-year collaborative, multidisciplinary project initiated in 2003 under the Geological Survey of Canada's Northern Resource Development Program (NRD Project 4450), the Geological Survey of Canada (Natural Resources Canada), Alberta Geological Survey (Alberta Energy and Utilities Board), and Resource Development and Geoscience Branch (British Columbia Ministry of Energy and Mines) have undertaken extensive Quaternary geology studies in northwest Alberta and northeast British Columbia. Within Alberta, NTS map sheets 84L, M, N, and K are systematically being studied (Figure 1); results from map areas 84L and M are reported here. Objectives of the project include production of surficial geology maps at 1:100 000 scale, assessment of the nature and genesis of known aggregate deposits, and the identification and characterization of new and/or potential aggregate deposits.

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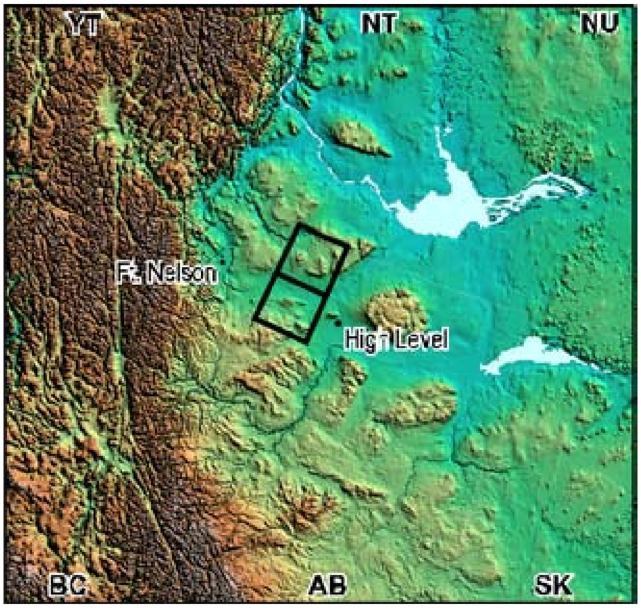

Figure 1. DEM image showing location of study area in northwest Alberta. The two NTS map sheet areas, 84L (lower) and 84M (upper) that are the focus of this paper are highlighted.

Previous Studies

Few Quaternary geology studies have examined the northwest Alberta region in detail. Reports containing information pertinent to the Late Wisconsinan glacial history include Bayrock in Lindsay *et al.* (1960), Taylor (1960), Green and Mellon (1962), Prest *et al.* (1968), Mathews (1980), EBA Engineering Consultants Ltd. (1984a), Fox *et al.* (1987a), Lemmen *et al.* (1994), Mandryk (1996), and Dyke (2004). Examination of granular aggregate resources in this area have also largely been conducted at the reconnaissance scale; various aspects of these investigations are reported by Lindsay *et al.* (1960), EBA Engineering Consultants Ltd. (1984b), Richardson (1985a, b), Fox (1986), Fox *et al.* (1987b), and Edwards *et al.* (2004a, b). Borneuf and Pretula (1980), in a study of hydrogeology of the region, provided data on transmissivity within subsurface sand and gravel aquifers north of Hay-Zama Lakes. Geotechnical research on surface sediments and permafrost has been conducted along the Norman Wells oil pipeline, which terminates at Zama City (Pilon *et al.* 1989; Geo-Engineering Ltd. 1992; Nixon and Burgess 1999). Zoltai (1993) examined the dynamics of peat and permafrost development in the region.

Study Area

Four 1:250 000 map sheets define the Alberta study area. The 2003 field season focused on the Zama Lake map area (NTS 84L), while the 2004 field season focused on the Bistcho Lake map area (NTS 84M; Figure 1). Subsequent fieldwork is planned for the Steen River (NTS 84N) and Mount Watt (NTS 84K) map sheets. The study area lies within the Fort Nelson lowlands and Cameron Hills physiographic regions (Pettapiece 1986), and is blanketed by boreal forest (white and black spruce, aspen, lodgepole pine) and extensive bogs and fens. Soils are generally poorly drained, commonly with shallow water tables, reflecting the high clay content (10% to 40%) of the tills in which they have formed. In raised areas, where soil development is more advanced, gray luvisols predominate. Static and turbic cryosols are found in regions of sporadic discontinuous permafrost, and solonetzic soils are found in areas of thin drift overlying marine shale bedrock.

The southern quarter of the Zama Lake (84L) map area is characterized by upland regions (more than 600 m above sea level [asl]; Figure 2) where rare outcrops of Cretaceous Dunvegan Formation sandstone are found. Dunvegan Formation is also found mantling the prominent, isolated hilltop (informally named Rainbow Ridge) south of Hay-Zama Lakes. Throughout the map area, outcrops of Cretaceous Shaftesbury Formation shale are found along modern stream channels and former glacial meltwater channels and canyons. The Hay River flows from the southeast westward through a conspicuous canyon (incorporating Rainbow Lake), passing into British Columbia where it bends 180° and then flows eastward through Hay-Zama Lakes, eventually merging with the northward-flowing Chinchaga and Meander Rivers (Figure 2). The Chinchaga River flows northward along the eastern margin of the map area and includes shallowly incised sections and areas of intense meandering (Figure 2). The latter occur within the Hay-Zama lowlands, where a blanket of easily eroded glaciolacustrine silt and sand is found (Paulen *et al.* 2005a). Four 1:100 000 surficial geology maps are now available for the 84L map area, and readers are referred to these for additional information and greater detail than that which is given in this summary paper (Plouffe *et al.* 2004; Paulen *et al.* 2005a, b; Smith *et al.* 2005).

The Bistcho Lake (84M) map area is characterized by Cameron Hills in the northeast (maximum elevation 775 m asl) and two other broad uplands (Bootis Hill and Elsa Hill) in the central map area, which have similar elevations of approximately 775 m asl (Figure 2). The large Bistcho Lake (more than 45 km long) is found in the north-central part of the map, and the Hay-Zama lowlands (more than 450 m asl) stretch across the southern quarter of the map area. There is little fluvial dissection of the landscape, which is instead characterized by expansive fen and bog deposits. Highlands in the Bistcho Lake and Cameron Hills region are characterized by strongly fluted terrain, the surface expression of which is accentuated by bog development and surface drainage in the low-lying inter-flute regions (Figures 2 and 3A). An area of intensive ribbed-moraine mantles Bootis Hill and the lower-lying region to the west,

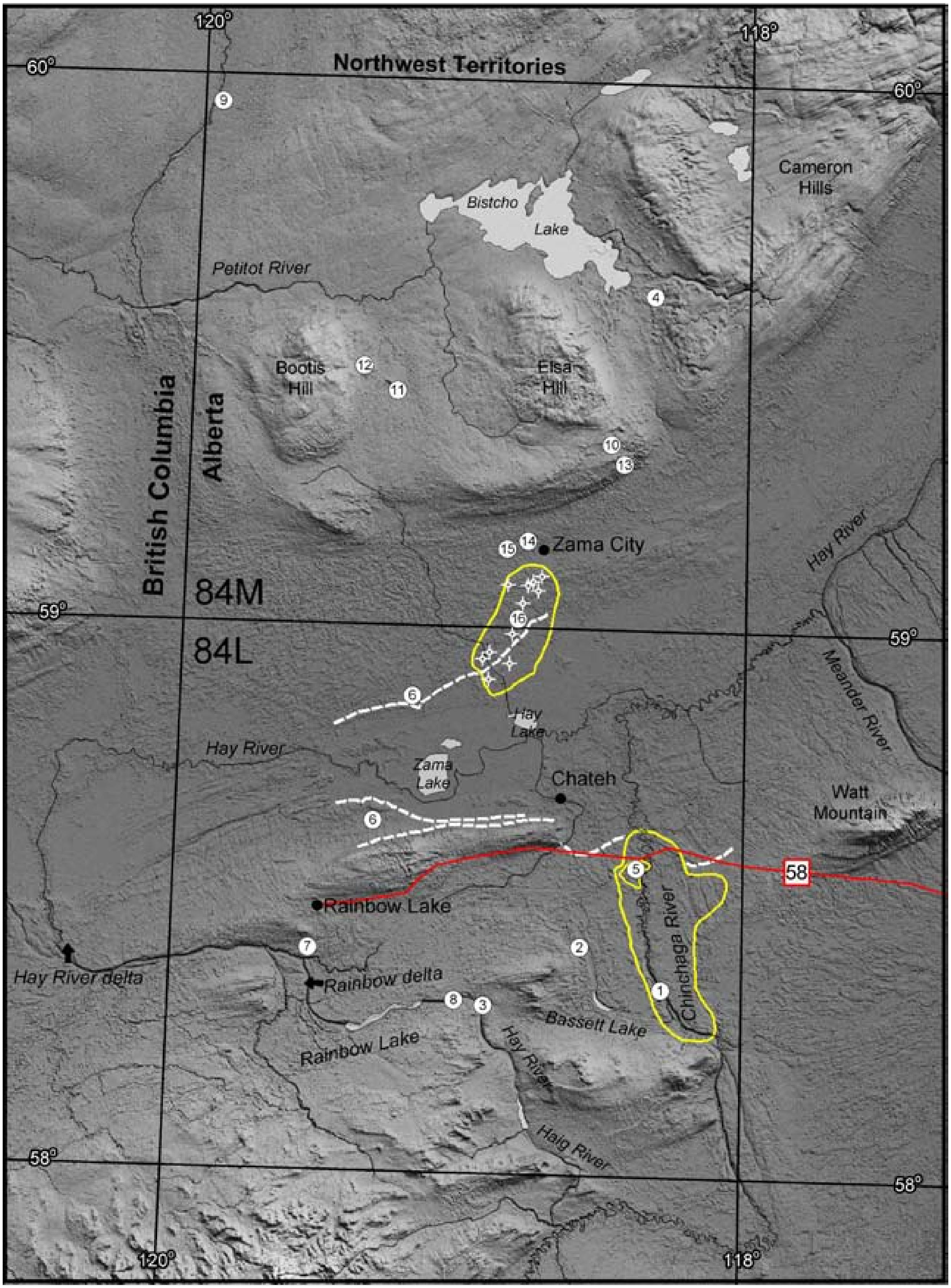

Figure 2. Digital elevation model (DEM) of map sheets 84 L and M and surrounding region (generated from NASA's Shuttle Radar Topography Mission [SRTM] data). Numbers and polygons refer to sites discussed within the text. Dashed lines correspond to raised shorelines of glacial Lake Hay.

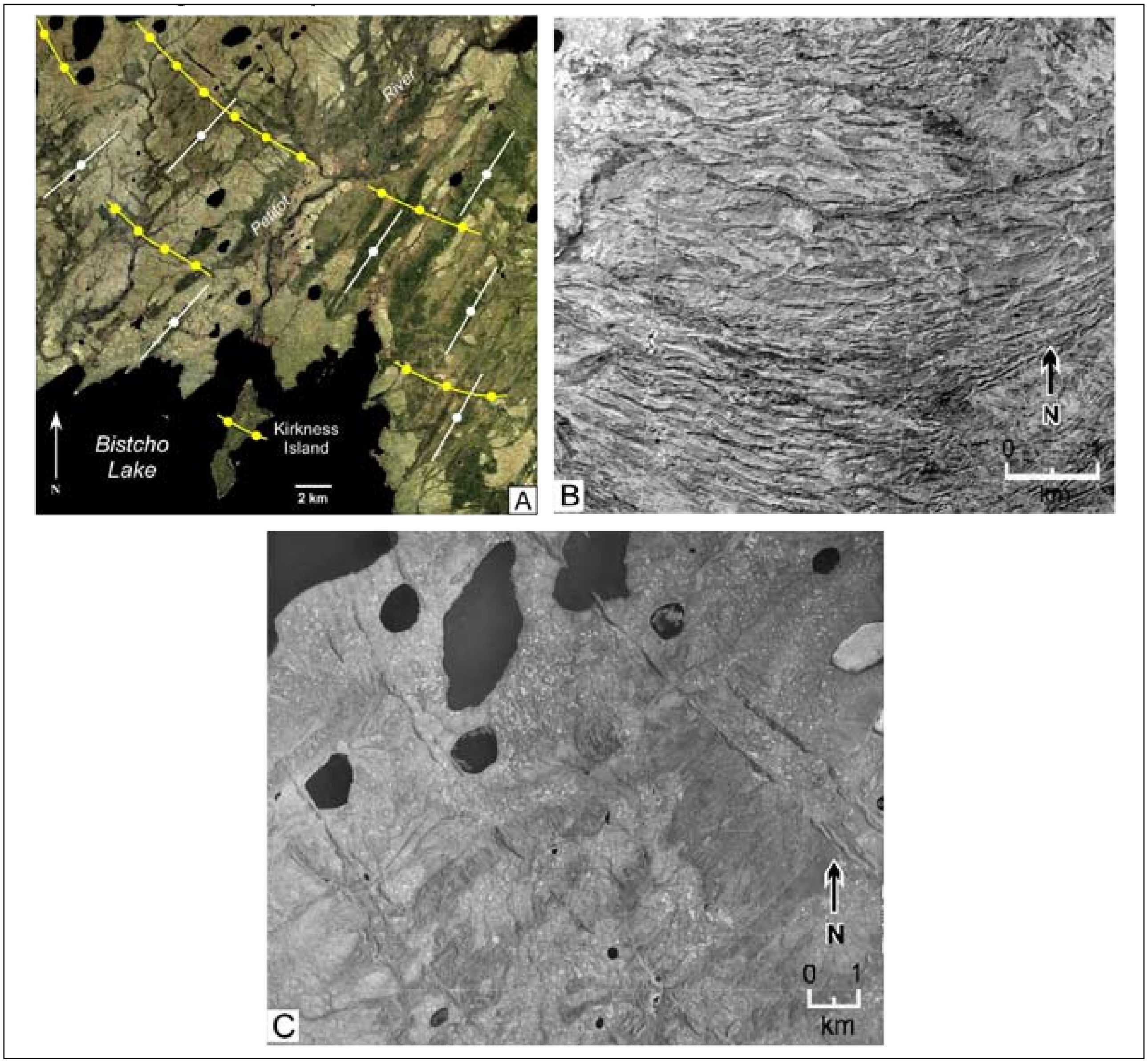

Figure 3. A) Landsat 7 image (courtesy of PhotoSat Information Ltd.) of large southwest-trending glacial flutings (white lines), draped by recessional moraines (yellow dotted lines), north of Bistcho Lake. B) Area of intensive ribbed moraines on Bootis Hill (59°26'N, 119°38'W). Moraines are tens of metres wide, 10–15 m high and hundreds of metres to kilometres in length; Airphoto 94–100 Line 23 AS4517-136, 1:60 000, ©Alberta Sustainable Resource Development. C) Prominent recessional moraines (aligned northwest-southeast) north of Bistcho Lake; Airphoto 94–100 Line 29 AS4519-207, 1:60 000, ©Alberta Sustainable Resource Development.

marking the northward retreat of an ice lobe (Figure 3B). Prominent, discontinuous recessional moraines north of Bistcho Lake mark the northeastward retreat of ice across Cameron Hills (Figures 2 and 3C).

GLACIAL GEOLOGY

The southwest-advancing Laurentide Ice Sheet inundated northwest Alberta during the Late Wisconsinan glaciation. Ice-flow direction is recorded by large southwest-trending flutings across upland regions (Figure 2), as well as by a subsequent set of smaller superimposed and cross-cutting flutings that trend south-southwest (Plouffe *et al.* 2004; Paulen *et al.* 2005a, b; Smith *et al.* 2005). Chronological constraint on the advance of ice is provided by a radiocarbon date of 24 400±150 yr BP (Beta 183598) on wood recovered from gravel underlying Late Wisconsinan till in the adjacent region of northeast British Columbia (Levson and Ferbey 2004; Levson *et al.* 2004). Retreat of ice from the area occurred between 11.5 and 11 ka BP (Lemmen *et al.* 1994; Dyke 2004).

During the ice-advance phase, the eastward drainage of regional rivers would have been impounded, leading to development of large proglacial lakes. Progressively, these were displaced by ice, which then deposited a blanket of distinctly clay-rich till across much of the region. The high clay content (10% to 40%) of this till reflects glacial erosion and entrainment of regional shale-rich bedrock and reworking of advance-phase glaciolacustrine sediment. This till is interpreted to have been deposited largely through basal lodgement processes. Thicknesses in excess of 15 m have been observed in some areas. Clast content tends to be very low, generally between 1% and 10%, although in areas north of Bistcho Lake clast content tends to be higher (15% to 25%), reflecting the proximity of outcrops of Paleozoic carbonates and Canadian Shield igneous and metamorphic rocks. A second thinner and distinctly sandier till (30% to 45% sand in the less than 2 mm size fraction of the matrix) overlies this basal clay-rich till. Fabrics in the two tills tend to be very similar, and contacts between them are often diffuse, suggesting that it is a second facies relating to deposition of a greater component of more far-travelled (Canadian Shield-derived) coarser englacial sediment rather than to a different trajectory of ice.

During deglaciation, large proglacial lakes formed in lowland basins along the retreating margin (Mathews 1980; Lemmen *et al.* 1994; Dyke 2004). Extensive blankets of fine-grained glaciolacustrine sediment up to 3 m thick are found along the southern Hay River (Smith *et al.* 2005), while in the Hay-Zama Lakes and Chinchaga River lowlands where glacial Lake Hay formed, glaciolacustrine blankets up to 10 m thick are found (Plouffe *et al.* 2004; Paulen *et al.* 2005a, b). Although glacial Lake Peace did not inundate the 84 L and M map areas, several of its outlets are inscribed upon the landscape. The uppermost Haig and Hay River channels in southeast 84L (hereafter referred to as the Hay River spillway) served as a major outlet of glacial Lake Peace (late Indian Creek stage—Mathews 1980), draining westward into a nascent phase of glacial Lake Hay and the Fontas–Nelson river system. As ice continued to retreat, outlets of glacial Lake Peace drained northwards along the ice margin, incising three prominent meltwater channels, including the present channel of the Chinchaga River (Figure 2; Keg River stage—Mathews 1980; Paulen *et al.* 2004b; Plouffe *et al.* 2004).

Two distinct strandlines of glacial Lake Hay are recognized at approximately 410 and 345 m asl (Paulen *et al.* 2005a, b). Fluted terrain along the northern edge of glacial Lake Hay indicates that sometime during its high-water phase, ice surged southwestward into the basin. Abundant iceberg scours (prow marks) preserved on the paleolakebed surface in the central and southern portions of the glacial lake basin may reflect widespread calving during this period. Subsequent retreat of ice is associated with the lower glacial Lake Hay stage, the northward drainage of glacial Lake Peace through the Chinchaga River channels (Keg River stage) and the eventual drainage of glacial Lake Hay northward along the present Hay River channel. Dense, deep-water (distal) silty clay is sharply and conformably overlain by shallow-water sandy beds in the Chinchaga River valley, which are interpreted to reflect a sudden drop in glacial Lake Hay water level. The Meander River spillway (confluent to the Hay River; Figure 2) marks the final northward drainage of glacial Lake Peace in the region (Mathews 1980).

GRANULAR AGGREGATE STUDIES

The methodologies used to assess granular aggregate resources in this study area included surficial geology mapping from 1:60 000 scale black and white aerial photographs, satellite imagery interpretation, ground truthing of sites accessible by truck, helicopter, all-terrain vehicles and boat, and the logging of sections within existing pits and naturally occurring exposures. The locations of various granular aggregate resources discussed in the text are shown on Figure 2.

Till and Bedrock

Till dug from borrow pits is the most abundantly used form of aggregate in the study area and is employed to build well pads and most petroleum development and access roads (Figure 4). The high clay content of local tills presents both problems and advantages. When wet, roads constructed from till are treacherously slippery. Areas of high traffic and other roads of importance are top-dressed with gravel, providing an all-weather surface. The high clay content of tills is an asset where roads traverse bogs and fens because it inhibits water infiltration upwards into the roadbed. This results in the reduction of both frost heaving and formation of segregated ice, particularly in areas overlying permafrost. Roads constructed with less clay-rich material quickly become deformed and ridged, requiring

Figure 4. Excavation of till from a borrow pit for construction of a well site access road. Photo R. Smith.

constant upgrading. Pit excavators do not appear to distinguish between the clay-rich and sandier till facies, and the size and density of borrow pits appears to be largely a function of groundwater seepage (rate of flooding) and logistics (relative travel time for hauling material versus establishing a new pit further down the road). Borrow pits are generally situated in direct proximity to roads being constructed and range in size from 50 to 150 m by 30 to 100 m and 3 to 10 m deep.

Bogs and fens blanket much of the study area, so immediate access to suitable borrow material is not always available. In these areas, till-cored ridges (easily distinguished because of their aspen forest cover) are opportunistically mined. Surficial geology mapping from this project has shown that many ridges in the area are morainal, formed by crevasse squeezing, or are glacial flutes, whereas elsewhere they constitute the general hummocky character of the till blanket (Plouffe *et al.*, 2004; Paulen *et al.*, 2005a, b; Smith *et al.*, 2005). North of Bistcho Lake there are numerous recessional moraines that extend discontinuously for several kilometres; their dimensions vary, but they average 20 m in width and can be over 5 m high. These moraines are much coarser than most material seen in the study area, containing abundant clasts and boulders (up to 25% by volume), which, if necessitated, could be screened and crushed as a potential gravel resource.

Outcrops and shallowly buried Fort St. John Group (Shaftesbury Formation) shale along the north face of the upland Rainbow Ridge has also been used as an aggregate source for building roads and well pads. The shale is poorly indurated, making excavation easy, and has generally low slaking tendency and acceptable Atterberg limits (EBA Engineering Consultants Ltd. 1984b). Outcrops of shale are found elsewhere in the study area along former glacial meltwater channel margins and may similarly be extracted as an aggregate base, although certainly in non-winter conditions, anything built with shale would require top-dressing with gravel to make it serviceable. Dunvegan Formation sandstone, which outcrops in the southern uplands of the 84L map area, could also be used, although it is also poorly indurated and in its lower reaches contains shale interbeds. Although regions of bedrock outcrop are not widespread in the study area, it should also be recognized that bedrock material may be easily accessed in regions identified as having only a thin cover of unconsolidated sediment, such as a till veneer (less than 2 m thick).

Glaciofluvial Channel Deposits

The winnowing of till by glacial meltwater streams is frequently associated with deposition of significant granular aggregate resources. In the present study area, such deposits are rare, likely reflecting the low clast content of the regional tills and the low-energy drainage systems that developed in the generally flat terrain. Exceptions exist with those channels relating to the drainage of glacial Lake Peace and a deglacial meltwater system east of Bistcho Lake.

Glaciofluvial terraces and meltwater channels along and adjacent to the Chinchaga River valley (Figure 2, site 1) represent key targets for granular resources. Gravel pits within these terraces are found a few kilometres south of Highway 58, and there is great potential for more economic gravel deposits in terraces stretching at least 20 km further south on both sides of the Chinchaga River valley (Fox *et al.* 1987; Edwards *et al.* 2004a; Plouffe *et al.* 2004). Gravel deposits along the Chinchaga River valley are 2 to 3 m thick and composed predominantly of pebbles and cobbles (70%) in a coarse to medium sand matrix (Figure 5). These deposits formed within meltwater channels draining northward from glacial Lake Peace into glacial Lake Hay (Keg River stage) and include a range of glaciofluvial deposits including overbank sand and gravel and aggradational terraces. The deposits are poorly to moderately sorted, with massive to crudely stratified planar beds. Clasts range up to 50 cm diameter, but most commonly are less than 5 cm diameter. Average clast size and content decreases from south to north (Edwards *et al.* 2004a), terminating in sandy deltaic and littoral deposits around Highway 58 that are interpreted to have been deposited in glacial Lake Hay. The contact between the Chinchaga River valley gravel deposits and the underlying till is sharp and undulating. Soft-sediment till clasts occur frequently in the gravel but rarely exceed 25 cm diameter. Using the extent of mapped glaciofluvial deposits along the Chinchaga River valley (Plouffe *et al.* 2004; Paulen *et al.* 2005a) and an estimated mean gravel thickness of 2 m, there are likely tens of millions of cubic metres of granular aggregate present in this region.

An earlier phase of northward drainage of glacial Lake Peace (Keg River stage) cut a meltwater channel west of the Chinchaga River valley (Figure 2). Aerial photograph interpretation has indicated an extensive cover of overbank

Figure 5. Recent extraction of thin outwash sediments adjacent (east) of Chinchaga River, 8 km south of Highway 58. The dark material at the base of the pit is the underlying till unit. Photo R. Paulen.

Figure 6. Inclined beds (20° dip to the north, 270–300° strike) of pebbly to bouldery gravel in the upper Hay River valley (Figure 2, site 3) exposed in an inactive gravel pit (July 2003). Photo A. Plouffe.

Figure 7. A) At the edge of a meltwater channel (approximately 150 m wide) east of Bistcho Lake and south of the Paramount Resources Ltd. gas plant. A bog has formed in the channel depression; a sand and gravel terrace occurs across the channel. Photo R. Paulen. B) A large gravel pit where the upper 2 m of coarse glaciofluvial material was removed, screened, crushed and stockpiled adjacent to the winter road for ongoing and future local use. Photo R. Paulen

gravel deposits adjacent to this meltwater channel (Figure 2, site 2). The presence of kettles and the general hummocky character of this deposit suggest that the gravel was deposited in an ice-contact position. The nature and extent of these deposits remain to be evaluated in the field.

Another significant glaciofluvial deposit is situated along the upper Hay River spillway (Figure 2, site 3). At this locality, there are several presently inactive gravel pits containing clean (less than 3% silt and clay) gravelly sand (Edwards et al, 2004a). Field inspections reveal that the gravel is moderately to poorly sorted, consists of pebbles and cobbles with minor boulders, averages 3 to 4 m thick, and lithologically is dominated by Canadian Shield rocks with a lesser amount of quartzite and limestone (Figure 6). One exposure in an inactive pit indicates that the gravel was deposited by a northward paleocurrent, probably at a time when a glacial lake occupied the upper Hay River valley. It also appears that considerably more granular aggregate resources remain in this deposit than have already been extracted.

An extensive glaciofluvial meltwater channel complex extends from the edge of Cameron Hills to the eastern edge of Bistcho Lake (Figure 2, site 4). Several meltwater channels are incised into the till blanket and large deposits of sand and gravel occur on terraces within the former meandering deglacial meltwater system (Figure 7A). These deposits are less extensive than those of the Chinchaga River valley; the largest deposits are approximatelly 2.5 km^2 and rarely exceed 3 m thickness. Gravelly sand deposits in this system are moderately sorted with a modal clast size less than 10 cm diameter with occasional cobbles and rare boulders (Figure 7B). Overbank material adjacent to these channels forms discontinuous ridges and hummocks of well-sorted medium sand. This favourable geology was one of the main reasons for locating the Paramount Resources Ltd. gas plant east of Bistcho Lake, allowing for the stable construction of a plant, camp, and all-season runway in a region of sporadic discontinuous permafrost. Several pits were excavated to supply granular aggregate material during the initial construction phase of the plant and related infrastructure. Stockpiles from these pits continue to be used for ongoing gas well and pipeline development. Although noted as a potential aggregate resource by Edwards *et al.* (2004b), these sites are only accessible via the Bistcho Lake Paramount Resources Ltd. gas plant winter road.

Glaciolacustrine Deltaic and Shoreline Deposits

It is perhaps surprising that no significant deltas were formed along the retreating ice-dammed margin of glacial Lake Hay, suggesting that subglacial drainage was diverted elsewhere. In contrast, a prominent delta formed at the mouth of meltwater channels draining northward from glacial Lake Peace into glacial Lake Hay (Figure 2, site 5), and two very large delta systems formed along the southern Hay River spillway—the informally named Hay River delta (Levson *et al.* 2004) and Rainbow delta (Figure 2).

At the north end of the Chinchaga River valley gravel deposits, aggregate pits have been established in the larger deltaic deposits where there are 2 to 10 m thick, northward-dipping, stratified, and moderately sorted sand and gravel beds (Figure 8A) with a coarse cobbly gravel topset lag. Trough cross-bedded gravels and gently dipping foresets of laminated pebbly sand occur at depth. At the north end of the deltaic deposits, the pits are comprised entirely of well-sorted, planar-bedded sand (Figure 8B), which likely represents subaqueous deposition at the delta margin. Sand beds deformed due to loading and dewatering are common in these northern sand pits. These pits are currently being mined, and despite the long distance for hauling, the paved highway leading to Rainbow Lake allows these pits to economically supply granular aggregate material for the town of Rainbow Lake.

Figure 8. A) Ongoing extraction of deltaic sediments west of Chinchaga River, 6 km south of Highway 58. Photo looks southward. Foreset beds dip gently towards the viewer, and are overlain by a coarser topset lag. Photo R. Paulen. B) Sand pit 3 km south of Highway 58, west of Chinchaga River. Here the sands were deposited subaqueously at the toe of the delta extending into glacial Lake Hay. Photo R. Paulen.

RAINBOW DELTA

The Rainbow delta represents the largest known granular aggregate resource in the area and is the primary aggregate source for the town of Rainbow Lake. It is a complex landform assemblage that includes an expansive ice-contact glaciolacustrine delta (Gdt) capped by a blanket of glaciolacustrine silt (Lb). The delta was dissected by meltwater channels leaving behind a series of glaciofluvial terraces (Gt) and two relatively deeply incised canyons along its western and eastern lateral margins in which the modern, under-fit Hay River (and its tributaries) now flow (Figure 9). Realizing that glaciolacustrine sediment may have levelled out some of the terrain, there is a trend in surface elevation from ~476 m at the proximal delta (south) to ~473 m in the central delta region to ~468 m in the distal delta margins (north; Figure 9). Five terrace levels mark glaciofluvial incision consistent with eastward retreat of the Laurentide Ice Sheet and drainage of the proglacial lake in which the delta formed: i) 473 m, ii) 465 m, iii) 463 m, iv) 458, and v) 454 m (Figure 9; elevations are interpreted from NASA SRTM imagery).

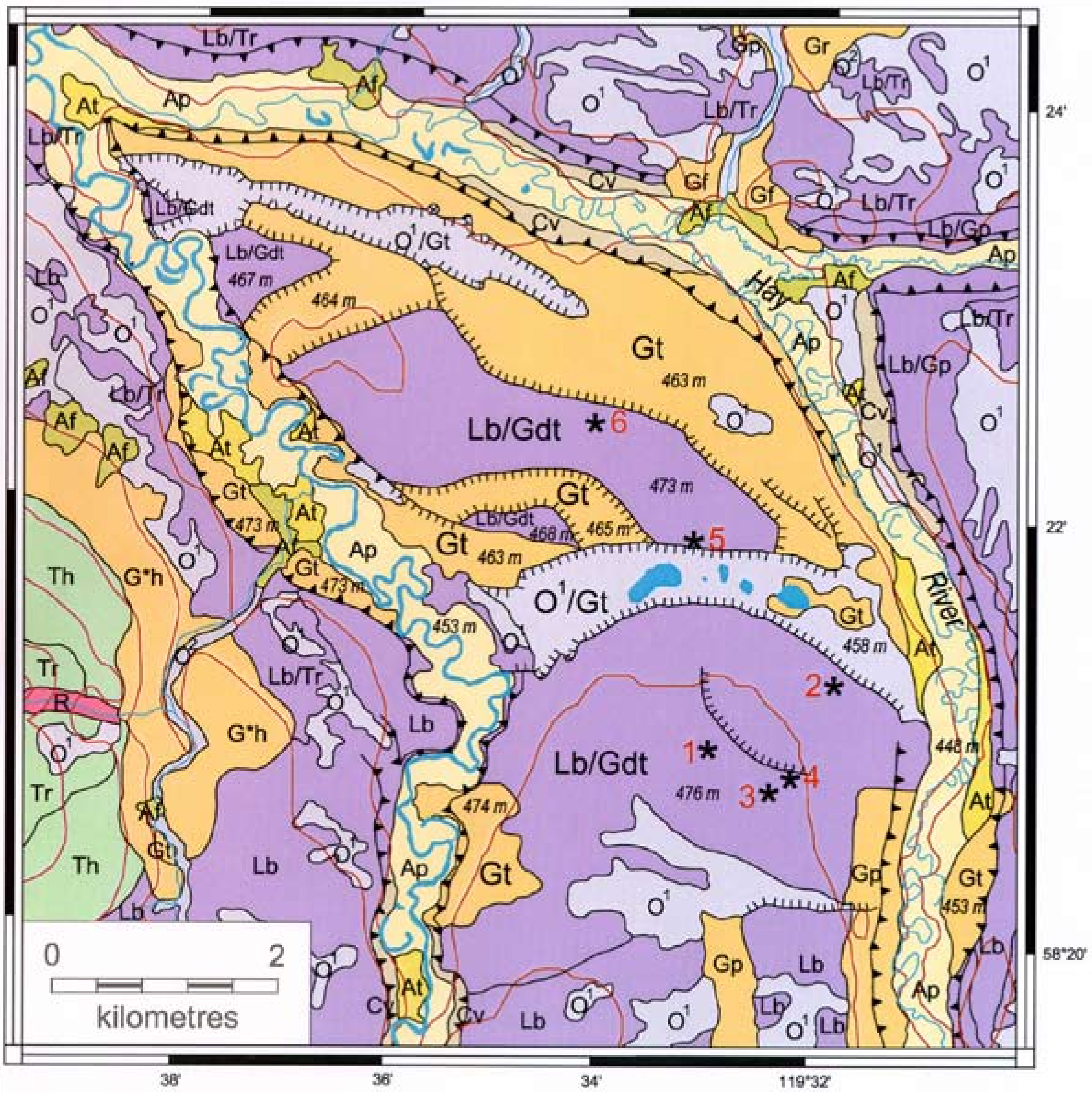

Figure 9. A portion of Smith et al.'s (2005) 84L/sw surficial geology map showing the Rainbow delta complex. Surficial geology units identified include: Gdt – glaciolacustrine delta, Gt – glaciofluvial terrace, Gp – glaciofluvial plain, G*h – kame terrace, Lb – lacustrine blanket, Tr – ridged till blanket; O1- bog, Ap – alluvial plain, At – alluvial terrace. Glaciofluvial terraces are bounded by hachured lines, while incised meltwater canyons are indicated by triangle-adorned lines. Where surficial materials overlie potentially important granular aggregate resources, polygons are labelled in the following manner: Lb/Gdt. Numbered stars identify gravel pits discussed in the text. Elevations interpreted from NASA SRTM imagery are provided for key sites.

Six active and former gravel pits are situated in the Rainbow delta complex, two of which exceed 1 km^2 in operational area (Figure 9, sites 1 and 2). The area containing pits 1 to 4 is considered the proximal delta front and has the coarsest deposits. Total depth of material excavated ranges from 4 to 14 m. In pit 1 (Figure 9), the largest active pit, deposits are characterized as stratified, closed-work bouldery gravel beds and trough cross- and planar laminated sandy gravel (Figure 10A). Three metre thick foreset beds of coarse sand and finer gravel directly underlie 2 m of glaciolacustrine silt at the distal (west) end of pit 2. Isolated, climbing ripple and trough cross-laminated sand bodies also are present in this pit. Gravel (larger than 2 mm) content is estimated to exceed 60%, while fines (silt and clay; less than 0.063 mm) are estimated to constitute less than 5%. Clasts (up to 60 cm diameter) are predominantly Canadian Shield-derived granites and gneisses (70% by volume), while the remaining 30% comprises limestones, dolomites, quartzites, sandstones, and minor shale (Figure 10B). Paleocurrents at depth are generally westward, shifting to progressively more northwestward in the upper sections, a trend visible in channel scour patterns on aerial photographs. As expected, deposits fine in a down-flow direction, and in pit 6 (Figure 9) there is 14 m of very well-sorted, trough cross- and planar-laminated, fining-upward, coarse to medium sand, with occasional gravel turbidite beds and dropstones (Figure 10C). Pit 5 (Figure 9) is predominantly sand with less than 30% gravel, although isolated gravel-rich beds are present. This pit is currently inactive, as is pit 2.

The proximal delta deposit represents the greatest aggregate potential and, as seen on Figure 9, occupies the entire southern Lb/Gdt polygon where pits 1 to 4 are located. Excluding the northwestern and southwestern extents of this area, where the stratigraphic relationship is uncertain, this is an area of approximately 7 km^2. If a conservative deposit depth of 5 m is applied, this would equal a total potential gravel-rich resource of approximately 35 million m^3. Estimates of largely well- sorted sand and minor gravel deposits in the central delta deposit (approximately 4 km^2), using an arbitrary deposit depth of 10 m, are approximately 40 million m^3. Field investigations and reports by EBA Engineering Consultants Ltd. (1984b) and Edwards *et al.* (2004a) have also shown that the upper glaciofluvial terraces in the central and western regions of the Rainbow delta complex contain gravelly sand at surface. Inspection of shallow pipeline trenching activity across the glaciofluvial terrace immediately north of pit 6 (Figure 9) revealed a coarse boulder lag at surface and gravelly sand below. The absence of other surface exposures or exploratory drilling makes resource assessment in these areas uncertain, but clearly further study is warranted as this could expand the aggregate resource inventory immensely.

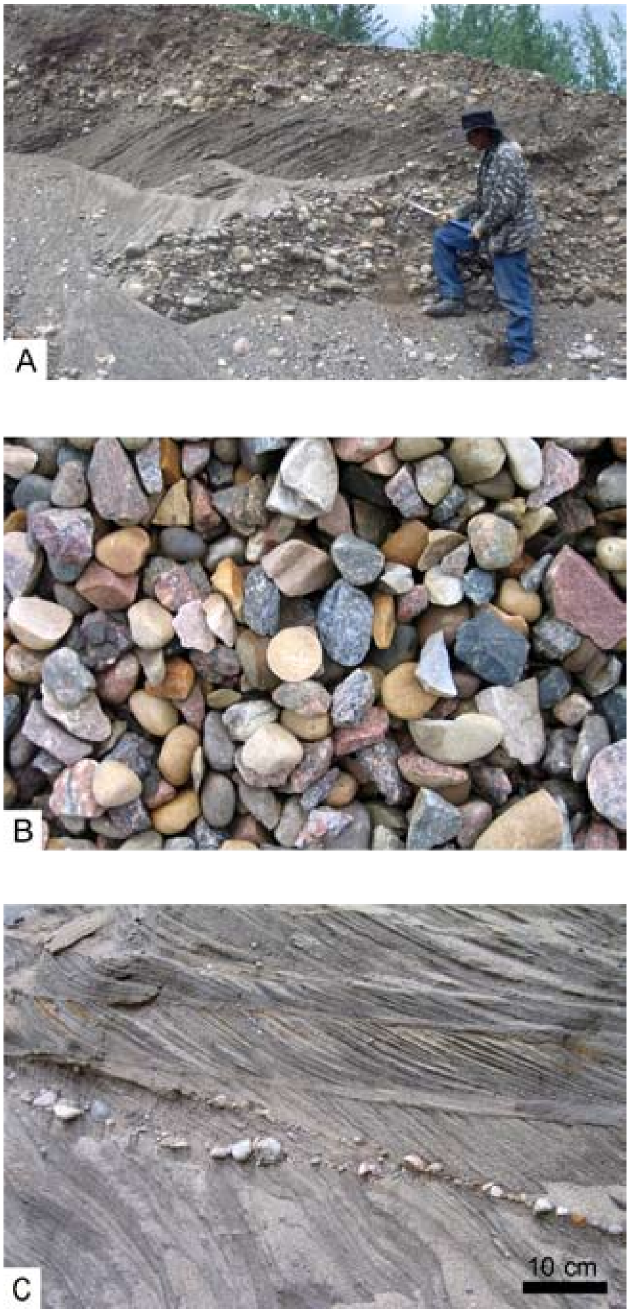

Figure 10. A) Open- and closed-work cobble-gravel beds and sandy fine-gravel inclined planar beds, proximal Rainbow delta pit 1 (Figure 9). Photo R. Smith. B) Crushed gravel (loonie for scale) from Rainbow pit 1 showing Canadian Shield-dominated lithologies. Photo R. Smith. C) Planar laminated and trough cross-bedded sand with gravel turbidite beds and dropstones in the distal Rainbow delta facies. Photo R. Smith.

Figure 11. The fall colours of poplar trees highlight a former shoreline of glacial Lake Hay that occupied the Hay-Zama lowland (at left). Photo R. Paulen.

GLACIAL LAKE HAY SHORELINES

Prominent raised shorelines left behind from glacial Lake Hay could potentially be exploited as a local source of sand and pebbly sand granular aggregate (Figure 2, site 6 [dashed lines]). These beach deposits are narrow, often less than 5 m wide, and occur as small ridges less than 2 m above the surrounding glaciolacustrine and till plains. The matrix texture of the beach ridges varies from coarse to fine well-sorted sand. Clast content ranges from less than 5% to 25%, but commonly a thin gravel lag (less than 0.5 m thick) mantles the beach ridge. As some of the beaches extend several kilometres in length (Figure 11), they should be taken into consideration by future road alignment planning.

Other Ice-contact Deposits

Eskers represent another potential granular aggregate resource. Only a few small eskers have been found within the study area (Plouffe *et al.* 2004; Smith *et al.* 2005); however, each occurrence could be targeted for localized granular aggregate needs. Site 7 (Figure 2) is a small esker complex with a series of subparallel ridges, 4 to 5 m high and 3.6 km long. The esker is made up of gravelly sand (gravel content estimated at less than 30%) with a modal clast size of 6 cm and maximum clast size of 25 cm. It is capped by 0.5 m of coarse till. Site 8 (Figure 2), in the Hay River channel, corresponds to an esker complex consisting of three parallel ridges that converge westward into a single esker ridge (total length approximately 3 km). Poor road access and a dense forest cover that prevented any helicopter landing nearby resulted in an inability to evaluate the granular aggregate potential of this esker. In the northwest sector of the study area, another esker complex extends for 4 km north of Lake May (Figure 2, site 9). A small natural exposure in the northern reaches of the esker revealed a 1.5 m cap of till overlying 2 m of well-sorted medium to coarse sand. Larger exposures or drilling would be required to assess the absolute granular aggregate resource potential of this esker.

A large kame, more than 30 m high, with the steeper slope oriented in the direction of up-ice glacial retreat (Figure 12), occurs on the eastern flank of Elsa Hill (Figure 2, site 10). The deposit consists of a moderately sorted pebbly gravel and sand with a coarser cobble-gravel lag on the surface. Hummocked and kettled sandy outwash adjacent to the kame corroborates its ice-contact nature. This single landform represents a large potential local source of sand and minor gravel. At site 11 (Figure 2) a complex of raised mounds (average height of approximately 2.5 m) and interconnecting ridges interpreted to represent kames or subaerial ice-contact fan deposits were found. They are comprised of fine gravel and coarse sand and, given their location proximal to an existing well access road, make an obvious choice for future exploration and development.

Kame terraces, formed by glaciofluvial processes and the impoundment of drainage between glaciers and topographic highs, sometimes yield suitable granular aggregate material. Three kame terraces, in close proximity, were found along the eastern flanks of Bootis Hill (Figure 2, site

Figure 12. A large kame on Elsa Hill, adjacent to an oil pipeline. A small kettle lake lies at left. Cameron Hills can be seen in the distance. Photo R. Paulen.

12). Field inspection revealed a fine gravelly sand composition in the upper metre of these deposits. Total thicknesses of these deposits are uncertain, but they nonetheless represent significant potential granular aggregate sources, particularly in areas of otherwise extensive bog and fen.

Subtill Aggregate Deposits

Sorted sand and gravel deposits found below till have a number of possible geneses, including Tertiary fluvial deposition (Edwards and Scafe 1996), interglacial/preglacial fluvial deposition, ice-advance phase glaciofluvial and glaciolacustrine deposition, intraglacial fluvial and lacustrine deposition (i.e., associated with an oscillating ice margin), and full-glacial subglacial channel or tunnel valley deposition. Several large subtill gravel deposits interpreted as preglacial and subglacial channel deposits have been found in northeast British Columbia as part of activities of this project (Levson *et al.* 2004). Sand and gravel deposits have also been logged within buried channel systems in the northwest Alberta study area (Canadian Discovery Digest 2001; Hickin *et al.* 2004; Pawlowicz *et al.* 2004b), although these generally occur at such depths below surface that they are uneconomic to recover. Of all the known subtill aggregate deposits in the Alberta and British Columbia study areas, none can be said to have a surface expression of relief, drainage, or vegetation that could be used to predict their occurrence. As such, their "discovery" is often dependent on indirect or unintended means, such as seismic shot hole operations (encountering gravel or "flowing" holes where there is an upward movement of groundwater) and geophysical logs from petroleum wells.

ELSA HILL

An active gravel pit on the southeastern flank of Elsa Hill currently supplies granular aggregate to the hamlet of Zama City as well as for local energy infrastructure demands (Figure 2, site 13). The gravel deposit accessed by this pit was recently discovered when well casing for a lease site was drilled through a 3 m thick till blanket and into several metres of cobble-gravel. Currently, the pit is small (less than 1 km^2) but will likely expand as the high-quality granular material is extracted. The pit actually consists of two separate deposits of differing character and age. The northeast portion of this pit consists of steeply dipping and sheared sand and gravel beds several metres thick that underlie varying thicknesses of till and waterlain diamicton (Figure 13A). This material is interpreted to be proglacial outwash that was deposited proximal to the advancing Laurentide Ice Sheet. This ice-advance outwash exhibits massive to planar and trough cross-bedded, moderately to well-sorted sandy gravel (Figure 13B) that coarsens upwards until truncated by the sharp erosional contact of the overlying till. At depth, these sand and gravel beds dip steeply to the north, upslope to the current topography (Figure 13C). The fact that the bedding is not subparallel to topography suggests

Figure 13. A) Sheared and rotated beds of a coarsening upwards ice-advance glaciofluvial deposit that was subsequently overridden by the Laurentide Ice Sheet. The clayey till at surface masks the underlying aggregate deposit. Photo R. Paulen. B) Typical coarse proximal glaciofluvial sediments that underlie the regional surface till. Photo R. Paulen. C) Lowermost gravel and sand beds dipping to the northeast. Photo R. Paulen. D) Coarse, poorly sorted proglacial outwash sediments deposited during glacial retreat. A coarse topset lag is seen with bouldery channel fills. Photo R. Paulen.

that glaciers already occupied the Hay-Zama lowland, and that these proglacial sediments were deposited as a kame terrace against the southeastern flank of Elsa Hill.

The southwest half of this gravel pit is stratigraphically younger, with coarse boulder and cobble-gravel interpreted as being deposited during glacial retreat. Approximately 7 to 8 m of coarse, poorly sorted, crudely stratified proglacial outwash sediment overlies the regional surface till unit. At this pit, however, the deglacial gravel deposit has eroded the till and thus directly overlies the advance-phase kame terrace deposits described above. Beds dip gently to the south-southwest, parallel to present day topography, with strong northeast imbrication of clasts (Figure 13D). Matrix-supported coarse sandy gravel and clast-supported boulder-cobble gravels define individual beds. Armoured till balls occur in the deglacial sediments but rarely exceed 30 cm diameter. A topset unit contains the coarsest material, and small channels eroded into the topset beds contain only cobbles and boulders. Most boulders in this upper deposit do not exceed 1 m diameter, and many of the harder lithologies (Canadian Shield-derived) still show faceted surfaces. Average clast content of this uppermost unit exceeds 50%. Current granular aggregate stockpiles in this pit comprise screened and crushed rock material.

ZAMA BEACH

The Zama Beach pit measures 1600 m by 500 m by 4 m and was inactive in the summer of 2004 (Figure 2, site 14). Bluff exposures at this site reveal a surficial cover of approximately 1 m of stratified glaciolacustrine sediment, atop 1 to 2 m of clay-rich till, which unconformably overlies 2 to 3 m of moderately to well-sorted interstratified sand and gravel (Figure 14A). Gravel constitutes up to 70% of the material with few fines (silt and clay less than 5%). Clasts are dominantly Shield-derived granites

Figure 14. A) Contact between upper till and lower gravels at Zama Beach. Note shear structures at base of boulder. Visible portion of ruler is 130 cm. Photo C. Kowalchuk. B) Sand body within gravels at active pit. Sand is planar bedded with an erosional upper contact with overlying gravels. Photo C. Kowalchuk. C) Climbing ripples in coarse sand. Photo is toward southeast. Pick is 65 cm. Photo C. Kowalchuk.

and gneisses with a modal size of 5 cm and a maximum size of 45 cm. Other clast lithologies include limestone, dolomite, quartzite, and shale. Stratified beds 0.2 to 1.0 m thick generally comprise open-work cobbles, 1 to 3 clasts thick, overlain by normally graded pebbles and granules. Sand beds generally exhibit planar lower contacts and horizontal bedding and have eroded upper contacts with overlying gravel beds.

A second presently active pit (200 m by 200 m by 5 m) is situated 2 km southwest of the Zama Beach pit (Figure 2, site 15). Up to 3 m of stratified sand and gravel underlies approximately 2 m of till; no glaciolacustrine cap was seen here. Just as in the Zama Beach pit, the contact between the gravel and overlying till is erosional. Here, however, there are also pronounced shears, folds, and injections of sand penetrating up to 5 cm into the till at high angles. The sedimentology in this pit is broadly similar to that seen in the Zama Beach pit, including erosional upper contacts in sand beds (Figure 14B). There is, however, a greater number of stratified sand beds, exhibiting large-scale trough cross-stratification and climbing ripples (Figure 14C). A bed of fine-grained sand and dark-coloured silt (0.4 m thick, 1.5 m long) was also observed at this site.

The amount of coarse-grained material and its sedimentological character at these two pits indicates a high-energy depositional environment. A subaerial glaciofluvial environment seems unlikely due to the lateral continuity of many of the beds and the regional context of glaciers advancing southwestward, up-drainage. It is instead interpreted to represent a subglacial channel fill, laid down under the advancing Laurentide Ice Sheet. The gravels were likely deposited rapidly and continuously because laterally extensive fine-grained beds of silt and clay, representing periods of low energy, are not found. Subsequent loading of the gravel deposit by ice during deposition of the overlying till is indicated by the abundance of both fractured clasts in the underlying gravels and injection structures into the till.

While the two pits and various sedimentary structures within appear to be aligned, the absence of any surface expression of the underlying gravels and the inability to easily probe through the regional overburden make delineation of potential aggregate resource in this area extremely difficult. Of relevance to the regional interpretation of these deposits is the report by Borneuf and Pretula (1980) on a number of sites north of Hay Lake where subsurface sand and gravel deposits, 5 to 23 m thick, were found (Figure 2, site 16 [polygon boundary]). These deposits represent an important aquifer from which water is extracted and then injected down oil wells in secondary recovery operations (location of wells indicated by symbols on Figure 2). The extent and sedimentological characteristics of these deposits is intriguing, particularly when they are placed in context of being down ice flow of the two Zama Beach gravel pits. Although a stratigraphic linkage between these two areas is unknown, it could be conjectured that if the Zama Beach gravel pits represent subglacial channel deposits emanating from the westward-advancing Laurentide Ice Sheet, then the thick subsurface sand and gravel deposits north of Hay Lake are deltaic deposits formed in an ice-dammed lake. Given the scarcity of aggregate resources in the Zama City area, it seems worthwhile to propose that a detailed study be conducted here in order to better delineate potential aggregate deposits. A study could take three levels of inspection. The first could consist of a survey of regional seismic shot hole logs (generally drilled to a depth of 10 to 20 m) and petroleum well geophysical logs in order to see if any report encountering sand or gravel. A second study could employ a power auger to drill a network of test pits across a representative area. A final approach to be considered is that of high-resolution electromagnetic (EM) surveying. This technique was used with a high degree of success in northeast British Columbia to locate and delineate a large gravel resource that was initially identified from seismic shot hole logs (Best *et al.* 2004).

CONCLUSIONS

This study was initiated in response to a need by industry for a better understanding of the regional surficial geology, including the assessment and expansion of the regional granular aggregate inventory. Field investigations over the past two summers have focused on two 1:250 000 map areas (NTS 84L and M), with subsequent fieldwork planned for NTS 84N and K. Four 1:100 000 maps covering the Zama Lake (84L) map area have been produced (Plouffe *et al.* 2004; Paulen *et al.* 2005a, b; Smith *et al.* 2005), and four 1:100 000 maps covering the Bistcho Lake (84M) area are in production. The new maps produced by this project will be of particular benefit to industries as they expand operations in the area by allowing them to orient roads or site potential borrow pits along identified raised terrain. In addition, many smaller potential granular aggregate sources such as eskers, discontinuous glaciofluvial terraces, and glacial lake shorelines are identified on the maps, and with further exploration and study, these may prove to be potential economic resources for local operations.

Another contribution of this work is its assessment of gravel resources exposed in active and inactive pits within the study area. This work has led to the considerable expansion of the potential granular aggregate inventory. Several gravel deposits presently or formerly mined are now recognized to contain vastly more granular aggregate resources. The Chinchaga River valley gravels, presently being mined just south of Highway 58, have been shown to occur in glaciofluvial terraces on both sides of the Chinchaga River stretching south for over 20 km. With gravel deposit thicknesses of 2 to 3 m, this would equate to tens of millions of cubic metres of potential granular aggregate. The Rainbow delta complex is estimated to contain approximately 35 million cubic metres of coarse sandy gravel deposits in the proximal delta facies and considerably more well-sorted sand and minor gravel material in the middle delta reaches and along incised glaciofluvial terraces. The Elsa Hill gravel deposits contain both ice-advance phase kame terrace deposits and 7 to 8 m of overlying deglacial, ice-contact outwash deposits. Opened only recently, this pit is likely to be increasingly important in the coming years as a primary aggregate source for Zama City and local infrastructure development. Also within the Zama City area, the Zama Beach and adjoining pit are interpreted to represent subglacial channel fills, possibly linked to extensive subsurface sand and minor gravel deposits previously identified to the south. If this interpretation is born out by further testing, then these same subglacial channel fills may extend laterally between these two pits as well as up- and down-flow of them.

The success of this study speaks volumes to the collaborative nature of its participants and reinforces the importance of conducting systematic and detailed field-based surficial geology operations to enhance the responsible and economical development of natural resources. It provides additional proof that even in largely flat-lying and boggy terrain with seemingly low aggregate potential, suitable granular aggregate resources can often be identified.

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QUATERNARY GEOLOGY OF FORT NELSON (NTS 094J/SE) AND FONTAS RIVER (NTS 094I/SW), NORTHEASTERN BRITISH COLUMBIA

Michelle S. Trommelen[1], Victor M. Levson[1], Adrian Hickin[1] and Travis Ferbey[1]

ABSTRACT

During the summer of 2004, Quaternary geology studies were conducted within the Fort Nelson and Fontas River map areas (NTS 094J/SE and 094I/SW, respectively) in northeastern British Columbia. The study area is situated within the Interior Plain physiographic region, encompassing parts of the Alberta Plateau and the Fort Nelson Lowland. The plateau is dominated by Cretaceous Dunvegan sandstone, while the more recessive Fort St. John Group shales underlie the lowland. Objectives of this study include delineation of the surficial geology and compilation of stratigraphy and aggregate potential studies within the map area. As the study area is located near the western extent of the Laurentide Ice Sheet and the eastern extent of the Cordilleran Ice Sheet, possible ice sheet interactions will be addressed. Preliminary investigations of river sections suggest the Prophet River valley is a re-incised paleovalley that provides new pre-glacial to Holocene stratigraphy, including a pre-Late Wisconsinan site. One site provided radiocarbon dates of more than 44 730 and more than 45 100 years BP from peat and wood within a massive to laminated clay unit with gradational pods of diamict.

KEYWORDS: *Surficial geology, Laurentide Ice Sheet, deglaciation, aggregate potential, paleovalley, Fort Nelson, Prophet River*

1.0 INTRODUCTION

Northeastern British Columbia is an important region for natural resource development, including forestry and petroleum. Given the increase in oil and gas development, the British Columbia Ministry of Energy and Mines recognizes the need for regional-scale Quaternary geologic studies to address such issues as the recent increase in demand for construction aggregates (Ferbey *et al.*, this volume). This study focuses on the southeast quadrant of the Fort Nelson map area and the southwest quadrant of the Fontas River map area (NTS 094J/SE and 094I/SW; Figure 1) for detailed surficial geology and stratigraphy investigations. Accessibility to the regions is good, and potential for large Quaternary exposures exists along major rivers. The region has received minimal Quaternary study, and the objective of this investigation is to fill this data gap as it relates to several areas of research. Specific goals include the following:

- map the surficial geology of the region on two 1:100 000 maps,
- compile the stratigraphy and document the character of glacial and preglacial sediments in paleovalleys and at plateau level, and
- investigate the interactions of the Laurentide Ice Sheet, Rocky Mountain glaciers, and Cordilleran Ice Sheet, addressing the eastern extent of Early or Late Wisconsinan Cordilleran ice.

These objectives will be addressed through aerial photograph interpretation, fieldwork (regional mapping, stratigraphy, sampling), and laboratory work (pebble lithology, grain size, geochemistry) in 2004 and 2005 as a contribution to a Master's thesis through the University of Victoria.

2.0 LOCATION

The study area is within the Fort Nelson and Fontas River map areas and is situated in northeastern British Columbia between 58˚ to 58˚30' N and 121˚ to 123˚ E (Figure 1). Specifically, the map area includes the 1:50 000 map regions of Niteal Creek (94I/03), Dehacho Creek (94I/04), Fontas (94I/05), Elleh Lake (94I/06), Klua Lakes (94J/01), Prophet River (94J/02), Big Beaver Creek (94J/07), Klua Creek (94J/08), and Clarke Lake (94J/09). The region is about 60 km south of Fort Nelson and includes Prophet River, a community of the Dene Tsaa Tse K'Nai First Nation. The Alaska Highway (Highway 97) transects NTS 094J/02 and 094J/07 with additional road access via active and inactive resource and petroleum development roads. The Canadian National rail line transects NTS 094J/08 and NTS 094I/05, 094I/04, and 094I/03 and provides access into road-inaccessible areas.

3.0 PHYSIOGRAPHY

The map region is part of the Interior Plain physiographic region, encompassing parts of the Alberta Plateau and the Fort Nelson Lowland (Holland, 1976; Figure

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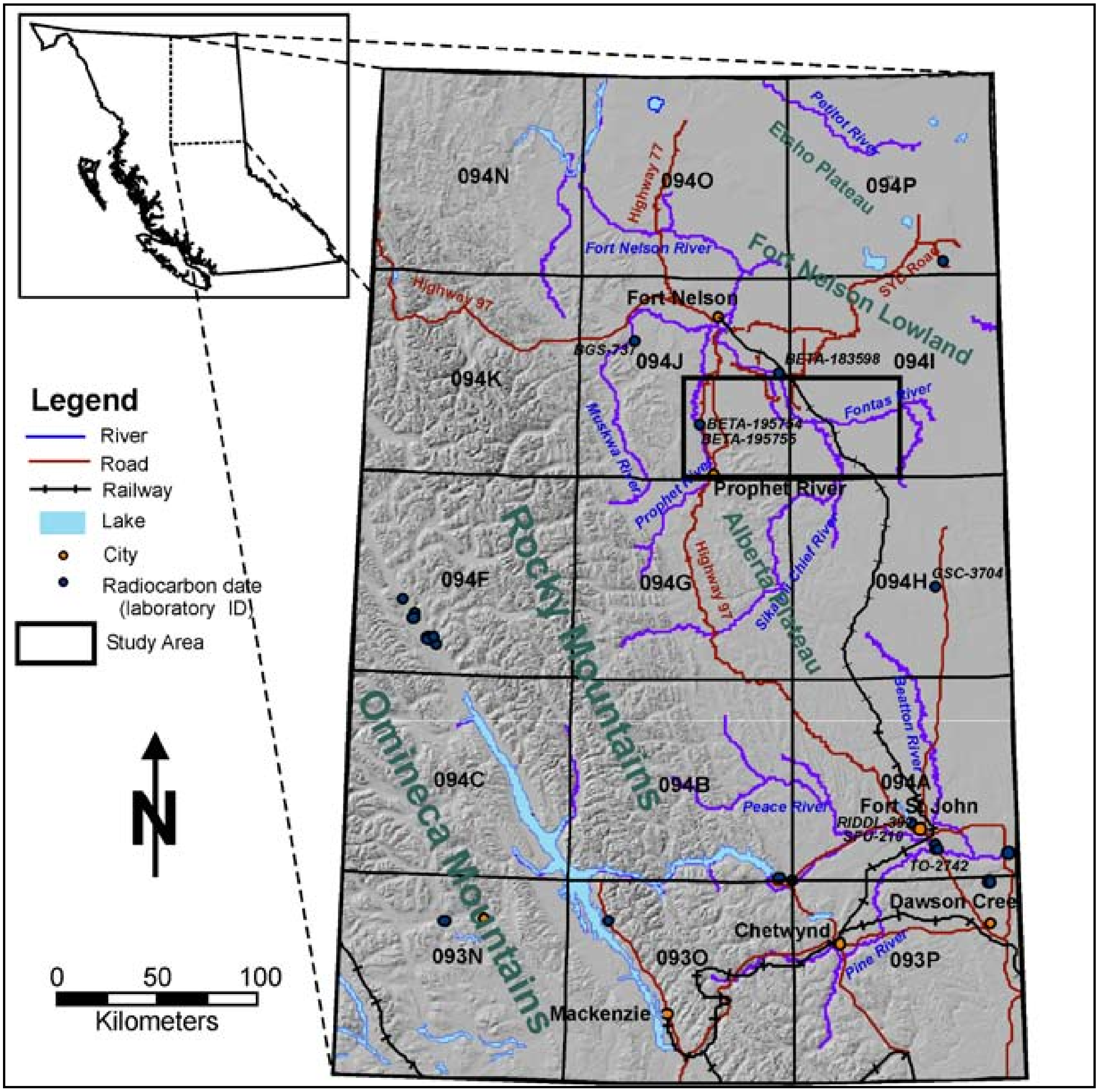

Figure 1. Location of the study area within the Fort Nelson and Fontas River map sheets (NTS 094J/SE and 094I/SW), northeastern British Columbia.

1). The Alberta Plateau is a predominately flat upland that lies east of the Rocky Mountain Foothills with elevations between 915 and 1220 m (Holland, 1976). In northeastern BC, rivers have incised the Alberta Plateau, resulting in remnant flat-topped cuestas caused by resistive sandstone and conglomerate beds overlying recessive shales. These cuestas can be found in the southwestern part of the map area exhibiting elevations up to 1070 m above sea level (asl). Arbitrarily designated below the 668 m (2000 ft) contour, the Fort Nelson Lowland exhibits elevations as low as 450 m asl. Dominating the map area, the Fort Nelson Lowland is an area of low relief, with poor drainage resulting in abundant bogs and fens (Holland, 1976). Further incision into the lowland by the Sikanni Chief, Fort Nelson, and Prophet Rivers results in valley bottom elevations from 330 to 520 m asl, with the Fort Nelson incised the deepest. The general relief in the area can be attributed to bedrock topography. Locally, however, the bedrock can be masked by up to 200 m of Quaternary (and possibly Late Tertiary) deposits. Quaternary landforms typically exhibit positive relief of less than 10 m relative to the surrounding area. The Elleh Creek gravel deposit, situated just north of the map area in NTS 094J/09, is anomalous in that its local relief due to Quaternary sediments varies from 20 to 65 m.

4.0 BEDROCK GEOLOGY

The study area is situated near the western edge of the Western Canadian Sedimentary Basin and is underlain by Cretaceous shale, sandstone, and conglomerate. Bedrock topography is variable as seen in river cuts. Bedrock outcrops are rare in the map area, except along river valleys and cuesta scarps where there is little or no Quaternary cover. Outcrops are predominately Lower Cretaceous Fort St. John Group, with the uplands capped by Upper Cretaceous Dunvegan Formation (Figure 2) (Taylor and Stott, 1968; Thompson, 1977). The Fort St. John Group is mainly a marine shale succession with minor siltstone and sandstone and commonly contains ironstone concretions, sulphur staining, and selenite crystals (Thompson, 1977). Within the Fort St. John Group are the Buckinghorse Formation, Sikanni Formation, and Sully Formations. The Buckinghorse Formation consists of silty shales with minor sandstone; the Sikanni Formation overlies the Buckinghorse and consists of four to eleven units of sandstone separated by silty shales; overlying the Sikanni is the Sully Formation, which consists of recessive shales. Stratigraphically overlying the Sully is the Upper Cretaceous Dunvegan Formation—a deltaic and pro-deltaic sandstone, conglomerate, and mudstone succession (Thompson, 1977); sandstone is dominant and chert-quartz conglomerate outcrop only at the highest elevations in the map area. This study has identified a new outcrop of Dunvegan conglomerate, previously not reported within the map area (Figure 2); this rock type may be suitable for crushed rock aggregate.

5.0 PREVIOUS WORK

Previous Quaternary geologic work in the region is limited. During original construction of the Alaska Highway, several road surveys were published, providing information on the general geology (Hage, 1944; Denny, 1952). Specific Quaternary research in the map area is limited to a large-scale geomorphology and ice-flow study of northeastern British Columbia and northwestern Alberta compiled by Mathews (1980). In regions near to the study area, surficial geology maps and reports have been completed for Charlie Lake (NTS 094A) and Trutch (094G) map areas (Mathews, 1978 and Bednarski, 1999 respectively). Aggregate potential has been mapped for Trutch (east half, NTS 094G) and Beatton River (NTS 094H) (Savinkoff, 2004). As part of the previously mentioned initiative of the British Columbia Ministry of Energy and Mines and the Geological Survey of Canada, surficial geology and bedrock topography studies are in progress for Petitot River (NTS 094P) and Fontas River (NTS 094I) respectively (Ferbey *et al.,* this volume; Hickin *et al.,* this volume).

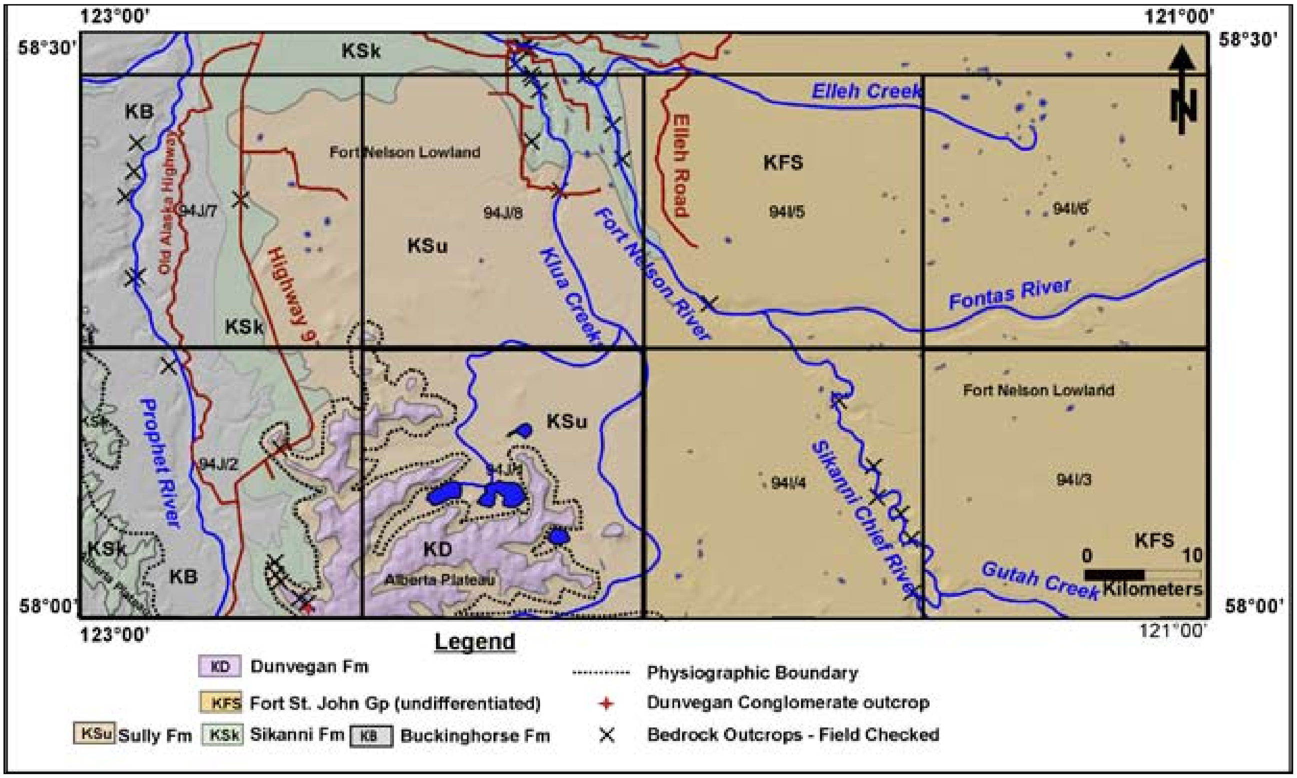

Figure 2. Cretaceous bedrock geology of the study area and observed bedrock outcrops in river sections, stream cuts, and road cuts. The Fort St. John Group is equivalent to the Buckinghorse Formation, Sikanni Formation, and Sully Formation; thus the straight-line boundary between 94I/SW and 94J/SE represents mapping divisions and not an actual geologic division.

6.0 BACKGROUND: REGIONAL GLACIAL GEOLOGY

Previous work within and adjacent to the map area indicates the study area is near the western extent of the Laurentide Ice Sheet and eastern extent of the Cordilleran Ice Sheet. As such, most authors assume both ice sheets covered the area at some time in the Quaternary. More specifically, Mathews (1980) recognizes that there were likely three glacier systems present in northeastern British Columbia during the last glacial maximum—the Laurentide Ice Sheet, the Cordilleran Ice Sheet, and coalescent valley glaciers (local montane) from the northern Rocky Mountains. The words montane and Cordilleran are often used interchangeably in the literature but should not be confused as they are spatially and lithologically distinct. Cordilleran refers to an ice mass that covered much of British Columbia and at one time extended locally west over the Coast Mountains and east to or over the Rocky Mountains. In contrast, montane refers to the development of local cirque and valley glaciers. The confusion arises because the Cordilleran Ice Sheet grew primarily by assimilating local montane glaciers and did not become a true Late Wisconsinan 'Cordilleran Ice Sheet' until about 19 to 13 ka (Ryder *et al.* 1991). During retreat, the Cordilleran Ice Sheet melted and once again took the form of local Rocky Mountain (montane) glaciers.

In order to interpret the presence and behavior of the three glacier systems, criteria are required to separately distinguish the sediments. The easiest method to use, especially in the field, is identification of distinct clast lithologies sourced from one specific area. This allows tracing of dispersal trains and determination of ice-flow and thus ice-sheet provenance. However, it may not be possible to determine one or two distinct lithologies diagnostic of one source area. Common practice is to identify an assemblage of lithologies from the source region of each glacier system. For example, red to pink felsic igneous and metamorphic clasts are commonly derived from outcrops of the Canadian Shield (which occur in northern Alberta, northern Saskatchewan, and the Northwest Territories); as such, these clasts were most likely brought to the study area by the Laurentide Ice Sheet. Similarly, Mathews (1980) notes that grey granitic fragments and low-grade schist and slate are derived from plutons and the metasedimentary Hadrynian beds within or west of the Rocky Mountain Trench; thus, these clasts are most likely brought to the study area by the Cordilleran Ice Sheet. The schist and slate weather fairly easily and it is thought that they would be mostly eradicated if the deposit had been reworked. Lithologies local to the area include ironstone, shale, siltstone, and sandstone clasts derived from the underlying Cretaceous bedrock. Outcrops of Dunvegan conglomerate provide a local source for black chert, tan chert, red chert, and quartz pebbles. The presence of these clasts may not be useful in determining specific provenance. In addition, sediments from all three source areas contain quartzite that may have been reworked from Tertiary River systems draining onto the plains of Alberta and British Columbia from the Rocky Mountains. Likewise, while certain fossils or types of fossiliferous limestone may indicate provenance, the presence of limestone itself does not. Platformal Devonian limestone rocks outcrop in northeastern Alberta and the Northwest Territories and could have been brought to the study area by the Laurentide Ice Sheet; however, Devonian limestone also occurs in the Rocky Mountains of southern Alberta and northern British Columbia. Thus, limestone could also have been transported to the study area by the Cordilleran Ice Sheet or Rocky Mountain glaciers.

Work within or adjacent to the study area has resulted in a general and somewhat debated glacial history. It is known that Laurentide ice advanced into the study area after 24 400±150 C^{14} BP (BETA-183598), indicated by a radiocarbon date on wood found in gravel underlying till at Elleh Creek (Levson *et al.,* 2004; Figure 1). Whether another ice sheet was present in the region before this period is unknown. In the Trutch sheet (NTS 094G, Figure 1), just south of the map area, the presence of eastward-pointing striae at elevations of 1860 m asl (Bednarski, 1999) suggests Cordilleran ice overtopped the Rocky Mountains and entered the foothills. It is not known whether the ice front extended onto the plains and into the field area. Shield-derived clasts are found extending west into the mountain valleys in the Trutch map area, and thus the Laurentide Ice Sheet reached the Rocky Mountain front, in this region, during a past glaciation (Bednarski, 1999). However, it is unknown whether the Cordilleran Ice Sheet had retreated west of the Rocky Mountain front when the Laurentide Ice Sheet was there or whether a period of coalescence occurred (Bednarski, 1999). The western limit of the Laurentide Ice Sheet has been mapped west of the study area, "where counts of red granite or gneiss drop off abruptly" (Mathews, 1980, page 4). His study suggests that coalescence of ice sheets occurred not in the map area but rather on the plains east of the Rocky Mountain front.

Coalescence between the Laurentide and Cordilleran Ice Sheets is believed to have occurred in southwestern Alberta in the Late Wisconsinan (Bobrowsky and Rutter, 1992). Mathews (1978) suggested a region of coalescence south of the map area (NTS 094A, Figure 1) in the plains east of the mountains, indicated by a continuous surficial till sheet with Cordilleran lithologies in the west and Laurentide lithologies in the east. Catto *et al.* (1996) contest that coalescence occurred in the Grand Prairie-Peace River region, suggesting instead that a pre-Late Wisconsinan Cordilleran advance (more than 51 ka BP) was the most extensive glaciation, followed by a smaller Late Wisconsinan Laurentide advance (approximately 22 ka BP).

Ice recession began around 14 ka for the northwest, southwest, and south margins of the Laurentide ice sheet

(Dyke *et al.*, 2002). Although very few radiocarbon dates exist in northeastern BC, dates ranging from 10 100±210 C^{14} ka BP (RIDDL-392) to 13 970±170 C^{14} BP (TO-2742) near Fort St. John indicate retreat of the Laurentide Ice Sheet southeast of the map area by this time (Bobrowsky *et al.*, 1991; Driver, 1988;Catto *et al.* 1996; Figure 1). Further north, though still southeast of the area, a 10 400±140 C^{14} BP (GSC-3704) date from Snowshoe Lake (MacDonald, 1987; Figure 1) suggests retreat by about 10.5 ka. Closer to the study area, Rampton (1986) identified three stages of a glacial lake occupying the Muskwa River valley and dated a terrace 27 m above modern river level at 8 930±230 C^{14} BP (BGS-737), representing a minimum deglacial date (Figure 1). Rampton suggests that the ice margins he mapped are comparable to ice margins mapped for the Clayhurst stage of glacial Lake Peace (Mathews, 1978; 1980). Using this analogy, he suggests that deglaciation of the Fort Nelson area occurred between 11 500 and 12 200 C^{14} years BP.

7.0 FIELD METHODS

Black and white aerial photograph (1:60 000 scale) interpretation was completed to obtain a detailed preliminary map of the surficial geology. Accessible areas were ground-checked during the 2004 field season along roads, rail, seismic lines, pipeline routes, and well sites using a truck, foot traverses, rail truck, and all-terrain vehicles (Figure 3). Surficial materials were studied in various exposures, including borrow pits (created during road and well site construction), newly cut ditches, road cuts, and river or stream cuts. In areas where exposures were not available, surficial materials were determined using an Oakfield soil probe or a Dutch auger to a depth of at least 1 m. Care was taken to ensure stations near well sites and roads were placed away from areas of human disturbance. Major river sections along the Fort Nelson and Prophet River systems were reached by jet boat. Sections were measured and sampled, noting stratigraphy, color, density, lithology, and sedimentary structure. Additional sections on the Prophet River and other remote areas are scheduled for investigation in 2005.

8.0 LABORATORY METHODS

A total of 32 samples were collected during the 2004 field season to be used for characterization of surficial sediments in the map area (Figure 3). Samples of sand and gravel were taken from representative glaciofluvial sites (n=10). One half to one kilogram of each sample was wet-sieved into >4 mm, 2 to 4 mm, and 1 to 2 mm size fractions. Lithologic pebble counts were completed for the >10 mm and 4 to 10 mm size fractions and will be used to identify different meltwater source regions. Wood was collected from two units in a section along the Prophet River. This wood was sent to the BETA Laboratory for conventional radiocarbon dating.

Samples of diamict were also collected throughout the map area (n=14). Select samples will be wet sieved, and pebble counts will be completed on the larger size fractions. This data will be used to investigate till provenance. Lastly, diamict and gravel samples collected from units within four sections on the Prophet River (n=8) will be used for correlation between sections.

9.0 SURFICIAL GEOLOGY

Ground-checking in the field area has resulted in the identification of the surficial sediment type at 203 field sites. This has led to the recognition of two diamict units, several sand and gravel units, and two silt and clay units. These deposits are found at surface throughout the map area and overlie other stratigraphic units (see section 10.0). As such, these units likely record the last glacial events in the region. Examples of each surficial geology unit are described below.

9.1 Glacial

Dense, clast-poor silty clay diamict is the dominant surficial material in the study area, encountered at approximately 90 field sites. Thickness of this unit is usually 1 to 10 m but can be up to 170 m (Hickin and Kerr, this volume). The clast content ranges from 1% to 5% and includes subangular to subrounded granule- to cobble-sized clasts with occasional boulders. Clast lithologies include potassium feldspar-rich granite and gneiss, limestone (some fossiliferous), oil-impregnated dolostone, minor mafic and volcanic clasts, siltstone, quartz, quartz sandstone, quartzite, black chert, tan chert, sandstone, shale, and ironstone. This diamict is primarily interpreted to be a basal till, identified by the presence of numerous local and striated clasts, high density, and a fine-grained matrix derived from local Cretaceous shales or advance glaciolacustrine sediment. Englacial and supraglacial tills likely exist in the study area but have not been specifically identified. One exception is a diamict exposed in a stream-cut at plateau level near the Fort Nelson River; the diamict is poorly stratified, has 5% to 15% clast content with a cobble-sized average clast diametre, and contains occasional metre-wide coarse gravel lenses. Due to these characteristics, the diamict at this site is interpreted as a meltout till.

The presence of abundant felsic granitic clasts at all till sites studied suggests that the till is of Laurentide provenance (see section 6.0). This till occurs at the surface throughout the map area and is overlain only by thin and geographically restricted glaciofluvial and glaciolacustrine

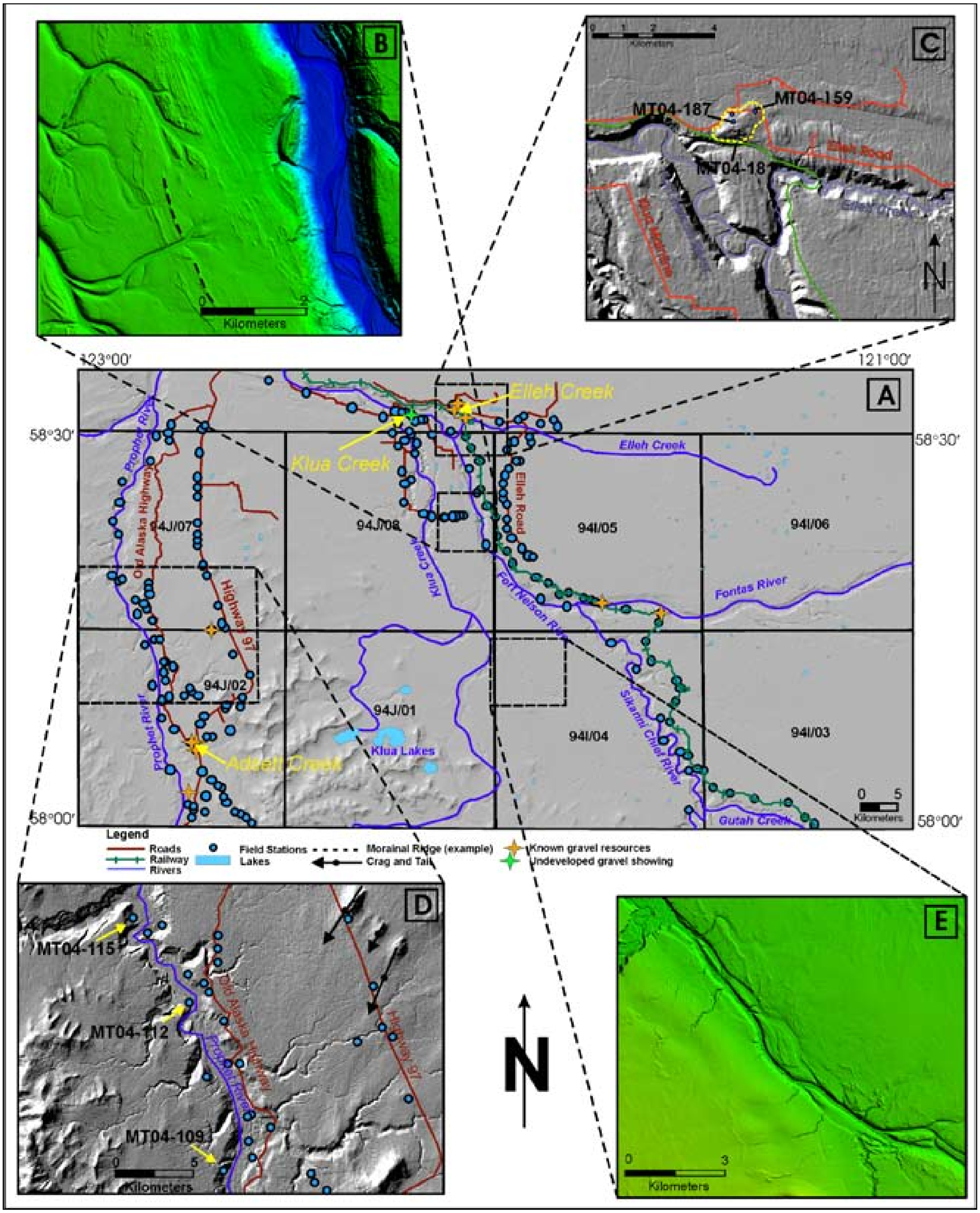

Figure 3. A. Location of field stations, aggregate occurrences and areas of geomorphic interest within and just outside of the map area. B. LiDAR hillshade (2 m resolution) showing morainal ridges and meltwater channels situated between Klua Creek and the Fort Nelson River. One ridge has been outlined with a dashed line C. Hillshade (30 m resolution) of the Elleh Creek gravel deposit (dashed polygon) and surrounding regions. D. Close-up hillshade (30 m resolution) image along a section of the Prophet River. The locations of sections discussed in the text are demarcated, as are several crag and tail features on the plateau. E. LiDAR hillshade (10 m resolution) showing an abandoned river system with meandering to braided channels. This channel system is thought to be an ice-marginal meltwater channel (see text).

sediments. As such, the till likely records the last glacial event and is Late Wisconsinan in age. Although the study area is near the margins of the Laurentide Ice Sheet, the ice was thick enough to overtop the Alberta Plateau uplands, as indicated by felsic igneous and metamorphic clasts at the highest elevation in the map region (1050 m asl).

Preliminary field studies have found few grey granitiod, schist, or slate clasts within the till (see section 6.0). This, combined with the abundance of Shield-derived clasts, suggests deposits of Cordilleran provenance have not yet been found in the map area. However, it is recognized that ice interaction can cause dilution of clast provenance, and the presence of Cordilleran till in the map region cannot be ruled out.

Till deposits in the region generally occur in low-relief till plains. However, there are numerous small-scale ridges concentrated in a corridor between Klua Creek and the Fort Nelson River but also occurring locally throughout the map area. These ridges are identifiable on aerial photographs and LiDAR DEM imaging and trend southeastward (Figure 3B). The ridges are continuous for thousands of metres with occasional gaps. Ground-checking at three sites indicates the ridges are 1 to 2 m tall (e.g., Figure 4). Relief is highlighted by the vegetative transition of stunted black spruce in the lows to poplar trees on the ridges with higher relief and better drainage. Lithologically, the ridges consist of silty clay diamict with approximately 5% subangular to subrounded clasts (granule- to cobble-sized) including granitic lithologies. The ridges are interpreted to be recessional moraines related to retreat of the Laurentide Ice Sheet. Combined with the initiation points of meltwater channels, these ridges delimit ice-margins in the corridor between Klua Creek and the Fort Nelson River.

9.2 Glaciofluvial

Glacial meltwater activity is indicated throughout the map area by the presence of meltwater channels at various elevations. These channels incise into till and bedrock, contain under-fit rivers, and commonly are occupied by lakes and Holocene organic deposits. A northwest-trending braided channel system up to 30 m deep, 8 km wide, and over 50 km long transects the study area through NTS 094I/04, just west of the Fort Nelson-Sikanni Chief River system (Figure 3E). The braided behavior and orientation of the parallel to the recessional moraines suggest these channels are the result of ice-marginal drainage. Also significant is a 1.5 km wide and 90 m deep steep-walled channel system with occasional terrace deposits that transects the map area, cross-cuts other systems (see below), and extends over 150 km. With its headwaters at Ekwan Lake, this channel is occupied by the Fontas and Fort Nelson Rivers and has been related to late-stage meltwater drainage from glacial Lake Peace (Mathews 1980); however, this feature may have first formed as an incised subglacial channel. According to regional deglaciation estimates, this meltwater channel was active from 11.5 to 11 C^{14} ka BP (see Dyke *et al.* 2003 and Mathews, 1980). Many of the smaller channel systems were largely erosional and generally lack glaciofluvial sediments.

Figure 4. A morainal ridge found in the region between Klua Creek and the Fort Nelson River.Ridge is approximately 2 m high. Relief of the ridge is highlighted by the growth of poplar trees on the high, better-drained ridge and spruce bog and/or fen in the regions of lower relief with poorer drainage.

There are also depositional systems, notably the Klua Creek deposit. This sand and gravel outwash extends approximately 1 km by 0.5 km and is situated just below plateau level near the confluence of Klua Creek and the Fort Nelson River (Figure 5). Southward extent of the deposit is unknown. At site MT04-139, cobble gravel is exposed at the edges of a meltwater channel (Figure 5A). This gravel contains 50% to 70% clasts in silt to coarse sand matrix and is matrix- to clast-supported, poorly sorted, and poorly to moderately stratified. To the north, the outwash plain is exposed in a 6 m section at site MT04-141 (Figure 5B). This section occurs on the edge of the Fort Nelson River valley, and from this crosscutting relationship it is interpreted that the Klua Creek gravels were deposited at an earlier stage than the formation of the steep-walled channel system occupied by the modern Fort Nelson and Fontas Rivers. The cobble pebble gravel here contains 40% to 60% clasts in clay to coarse sand matrix and is poorly sorted and matrix- to clast-supported. Pebble lithology data (n=256) indicate 27% limestone, 20% quartzite, 18% red granite, 14% ironstone, 12% chert, 7% sandstone (Dunvegan), and minor red gneiss, amphibolite, phyllite, and metaconglomerate (Figure 6). The geomorphic expression as a plain, the surficial nature of this deposit, and the granitic pebble lithology all suggest that Klua Creek is an outwash plain (fan?) deposited marginal to the Laurentide Ice Sheet.

Another region of interest is a 25 m high gravel hill dissected by the modern Adsett Creek near the community

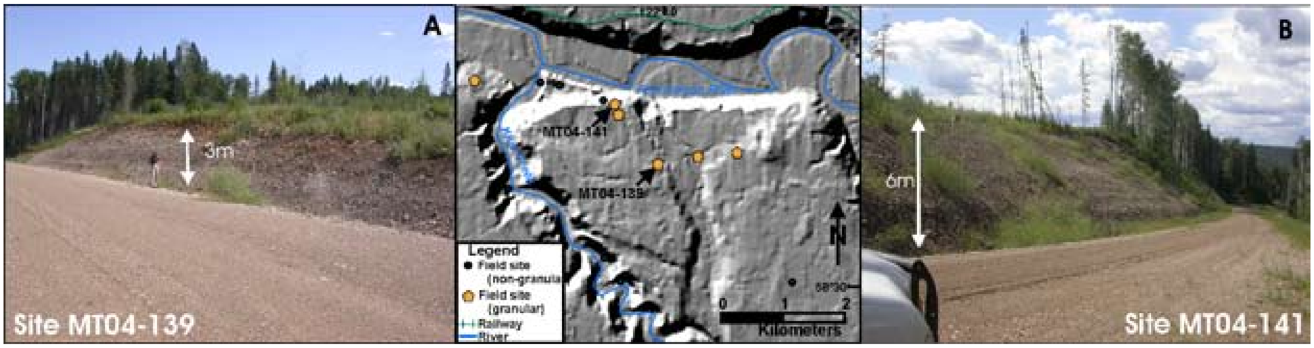

Figure 5. Location of the Klua Creek outwash plain situated in a region of coalescing meltwater channels. A. Gravel exposed in a road cut at the edge of a meltwater channel at site MT04-139. B. Gravel exposed in section at the edge of the Fort Nelson River valley at site MT04-141.

Figure 6. Clasts exposed at surface along section MT04-141 (see Figure 4 for site location). A. Larger clast is a phyllite. B. Pink gneiss. C. Largest clast is a metaconglomerate. Also present are ironstone, limestone, quartzite, and red granite.

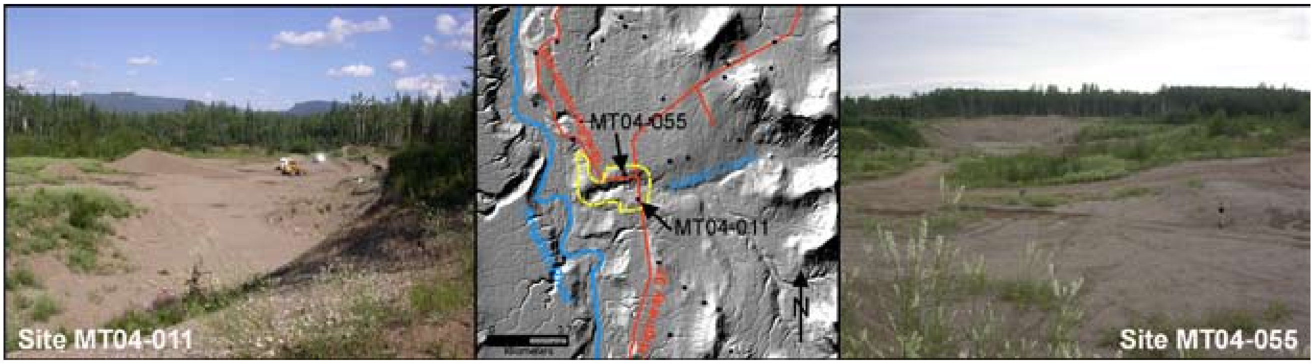

Figure 7. A 20 m high (dashed polygon) gravel hill dissected by the modern Adsett Creek near the community of Prophet River. This gravel deposit is interpreted to be part of a subglacial or englacial glaciofluvial system draining east from the uplands (see text).

of Prophet River (Figure 7). This gravel deposit covers an area of 2 km^2 and has been excavated for aggregate at several sites. At site MT04-011, the hill is 5 to 6 m high and consists of cobble-pebble gravel in a matrix- to clast-supported medium to fine sand. The gravel structure varies from massive to bedded, and matrix content varies from 30% to 80%. Pebble lithology data (n=580) indicate 28% sandstone (Dunvegan), 19% limestone, 16% red granite, 5.5% quartz, 5% quartz sandstone, 4% white granite, 2% red sandstone, and minor amphibolite, chert, shale, quartzite, and ironstone. A larger, active gravel excavation occurs at site MT04-055. This pit is roughly 150 by 200 m, excavated into the gravel hill, which varies from 10 to 25 m high. In some regions, a weak imbrication is apparent in the gravel, indicating a paleoflow direction to the west. Clast and matrix description are similar to site MT04-011. The lithology data are very diverse and the mixture of local and Shield-derived clasts suggests Laurentide deposition. This deposit is interpreted as a kame (rapid deposition at the end of a meltwater channel); this interpretation is supported by the variable structure, matrix percentage, and geomorphic expression as a hill.

Of geomorphic interest, a 2 m high, 6 m long ridge (Figure 8) was found at one site and consists of coarse sand to silt with 10% to 5% pebble to boulder content. The silt, sand, and gravel are poorly sorted and matrix-supported. Though this may be called a diamict, the high sand and gravel percentages differentiate this deposit from the regional diamict (interpreted as a till). The clasts within the ridge are subangular to subrounded, and lithologies include shale, chert, and granitoids (pink and white). This deposit was interpreted to be a crevasse-fill ridge, of which several are found throughout the map area.

Lastly, several crag and tail features exist within theBig Beaver Creek map area (NTS 094J/07) (Figure 3D). These features are hills with a tapering end, approximately 100 m high and 1.5 to 5 km long with azimuths ranging from 195° to 200°. The northernmost tail on Figure 3D is exposed in a road cut. The outcrop is 10 m high on the northeast side of the road, 6 m high on the southwest side of the road, and 200 m wide. The section exposes poorly sorted fine to coarse sand with beds that are dominantly clay and silt. Contacts within the beds are sharp, and most beds contain clay pellets or rip-up clasts. 1% clasts are weathered out on the slumped surface, and several subangular clasts were located within the section.

9.3 Glaciolacustrine

Well-sorted massive clay to fine sand was encountered at 19 field sites along the plateau adjacent to the Prophet River valley in the south half of the map area and at 6 field sites at plateau level near the confluence of the Fontas and Fort Nelson Rivers. These sediments are exposed in tributary stream cuts and borrow pits and exhibit thicknesses greater than 3 m. Near the confluence of the Fontas and Fort Nelson Rivers, active borrow-pit excavation reveals greater than 7 m of grey clay (Figure 9). The clay contains rare pebbles, including one granitic clast that indicates Laurentide provenance or reworking of Laurentide-derived deposits. As the deposits are well-sorted and contain only rare (much less than 1%) clasts, these sediments can be interpreted as glaciolacustrine in origin. This is substantiated by the flat topographic expression in areas where these sediments are found. These deposits occur at the surface and contain felsic granitic clasts, suggesting the sediments were deposited in the latest event and are related to Laurentide-derived deposits. The modern Prophet and Fort Nelson Rivers flow to the north. As such, it is likely that these deposits represent an episode of ponding due to the presence of northward-retreating Laurentide ice that temporarily blocked river drainage.

Figure 8. An example of a crevasse-fill ridge, of which several are found throughout the map area.

Though generally flat, at a local scale some regions along the plateau level of the modern Prophet and Fort Nelson Rivers exhibit extensive regions of 'hummocks.' These features are identified on aerial photograph and LiDAR hillshade images (Figure 10). Ground checking at 5 sites indicates that they exhibit 1 to 2 m of relief with diameters of 100 to 600 m. The relief is barely perceptible on the ground, but is somewhat highlighted by vegetative species change related to differences in drainage caused by the higher relief. Site investigation has determined that the lithology, both within the hummocks and in surrounding areas, is clay. Further study is required to determine the origin and geomorphic significance of these features.

10.0 QUATERNARY STRATIGRAPHY

Reconnaissance stratigraphic investigations were conducted at 34 sites along the Fort Nelson and Prophet Rivers in addition to several sites at plateau level. Most river sections expose a thin diamict over bedrock, but some sections expose 5 to 50 m of Quaternary sediment. Four key sites, three on the Prophet River and one at plateau level adjacent to Elleh Creek, are described below.

Figure 9. Massive grey clay seen in active borrow pits along Elleh Road near the confluence of the Fontas and Fort Nelson Rivers. The clay contains rare pebbles—in particular, granites of Canadian Shield provenance are present. Trowel blade is 20 cm long.

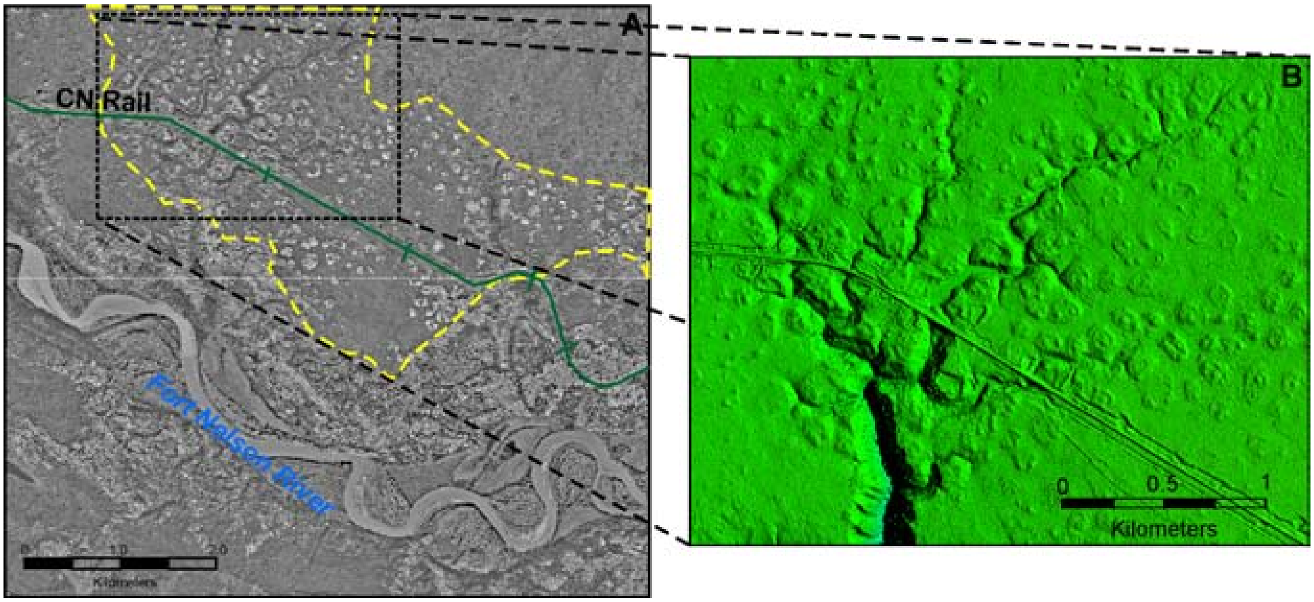

Figure 10. Orthophotograph (A) and Light Detection And Ranging (LiDAR, two-metre resolution) hillshade (B) image examples of 'hummocks' in glaciolacustrine clay at plateau level near the confluence of the Fort Nelson and Fontas Rivers. The 'hummocks' exhibit one to two metres of relief over 100-600 m.

10.1 Elleh Creek

The deposit of interest at Elleh Creek is a large hill, 2.25 km long, 1 km wide, and 20 to 50 m high, situated at plateau level near the confluence of Elleh Creek and the Fort Nelson River (Figure 3C). Four field sites were located at this deposit, three of which will be discussed here.

A BC Rail gravel pit excavation into the south hillside, site MT04-181 (Figure 3C), exposes more than 18 m of sand and gravel overlain by 1 m of diamict. The gravel matrix is silt to very coarse sand. The gravel is dominantly matrix-supported but locally clast-supported. Clast sizes range from granule to medium cobble, with an average 2 cm diameter. Clasts are mainlysubangular to rounded. A piece of wood from within this gravel was dated at 24 400±150 C^{14} years BP (BETA-183598) (Levson *et al.,* 2004; Figure 1). Pebble lithology data (n=805) indicate that the gravels consist of red granite (29%), quartzite (25%), angular ironstone (17%), limestone (6%), sandstone (6%), black chert (5%), and minor white granite, amphibolite, siltstone, quartz, and rounded ironstone. Pebble counts were completed to aid in correlation with other gravel deposits. The angular ironstone likely was locally derived and disaggregated during transport and is thus not indicative of any particular fluvial source. The gravels grade upwards into a thin sandy silt diamict containing abundant gravel lenses and centimetre-thick oxidized sand lenses. Further study is required to determine the origin of the diamict (colluvium, subglacial debris flow, till, etc.)

A second exposure into the Elleh Creek hill occurs near the top of the hill at a wellsite (site MT04-187, Figure 3C). The section consists of an upper 0.9 m thick unit of sandy silt diamict with 15% to 30% clasts. This unit is cemented with carbonate, and many clasts are highly weathered. This diamict is interpreted to be a till, based on lithology, structure, and stratigraphic position. Underlying the till is a 3.1 m thick sand and pebble-cobble gravel unit. Well log data (gamma) at this site suggests that there is approximately 50 m of gravel here. This unit is variably bedded to massive, with bed thickness ranging from 1 to 15 cm. Sorting is generally poor, and support varies from matrix- to clast-supported. Clasts are pebble- to small cobble-sized and most are subrounded to rounded. Pebble lithology data (n=345) indicate that the gravels consist of red granite (30%), quartzite (26%), chert (10%), white granite (10%), limestone (9%), sandstone (9%), red gneiss (2%), siltstone (2%), quartz (1%), and minor amphibolite and oil-bearing dolomite.

Lastly, an active gravel excavation at the LEDCOR pit was observed at the northwest side of the Elleh Creek hill; site MT04-159 (Figure 3C). Exposures here show a 50 to 80 cm thick upper unit of sandy silt diamict overlying a 5 to 15 m unit of sand and gravel. The gravels vary from pebble to boulder gravel and are matrix- to clast-supported. Sorting is generally poor, but some sections are well sorted. Vertical sections show several shears (metres long) and minor deformed bedding.

The 24.4 ka BP wood date suggests that the gravels at site MT04-181 are likely glacial advance-phase gravels. The high proportion of Shield-derived felsic clasts and stratigraphic position below a diamict, inferred to be a till, substantiates this interpretation. Both sites MT04-159 and MT05-187 are lithologically (Figure 11) and texturally

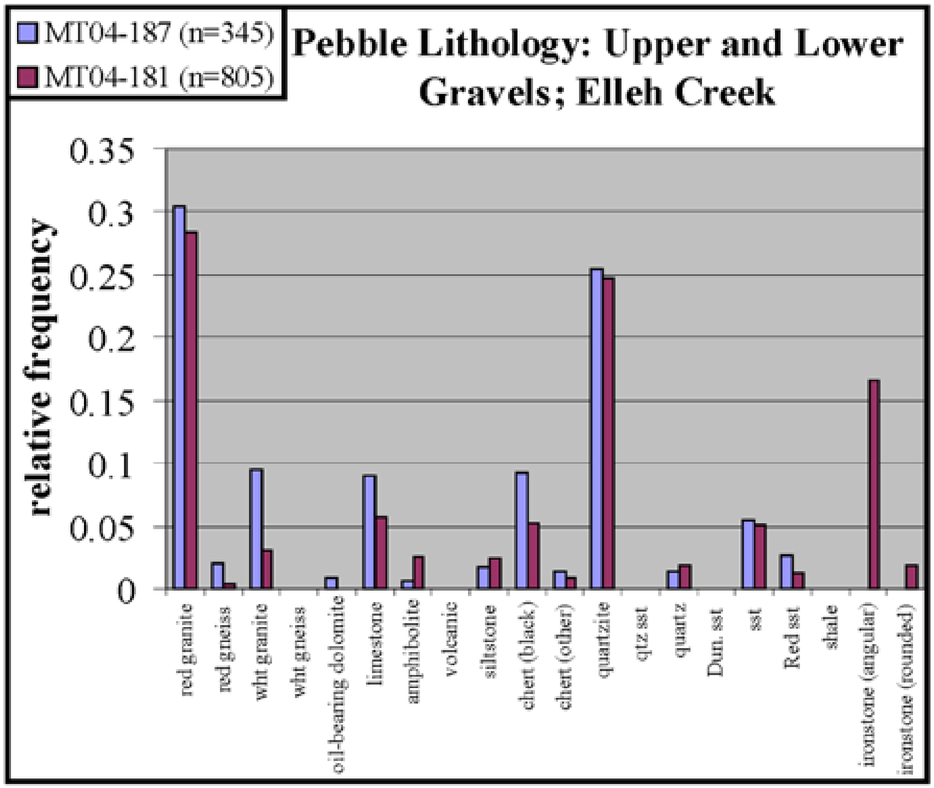

Figure 11. Relative frequency bar graph providing a comparison of pebble lithology for lower MT04-181 (sample 421 m asl) and upper MT04-187 (sample 461 m asl) gravels at the Elleh creek deposit in NTS 094J/09, near the confluence of Elleh Creek and the Fort Nelson River (see Figure 3 for locations). Numbers associated with pebble counts in this report are a summation of size fractions >10 mm and 4–10 mm with no clast larger than 80 mm.

similar to site MT04-181 (except higher ironstone content) and may be part of the same glaciofluvial system. Alternatively, they may represent various stages of deposition within or aligned with a pre-existing channel system. The stratigraphic position of the gravel under till, in conjunction with observations of sheared and deformed (overturned) beds, indicates that the Elleh Creek deposit formed pro-glacially and was then overridden and/or formed subglacially. It is unknown what directly underlies the gravel deposits.

10.2 Prophet River Sections

Three key sections observed along the Prophet River expose very dense clay, silt, sand, gravel, stratified diamict, and massive diamict. Based on preliminary lithology, texture, sedimentary structures, and stratigraphic position, these sections have been separated into six units as described below. For the location and a stratigraphic section of each site discussed, the reader is referred to Figures 3D and 12, respectively.

10.21 UNIT 6

The lowest exposed unit in the Prophet River sections is unit 6, a 2 m thick cobble gravel. This unit occurs only at site MT04-115 (Figure 12), where it is laterally continuous for approximately 30 m. At this site, the cobble gravel is unconformably overlain by massive silt and the lower contact is obscured by modern river level (Figure 13). The gravel is clast-supported with a variable matrix ranging from coarse sand to poorly sorted fine-medium sand. Matrix content increases up-section. Pebble lithologies (n=610) include black chert (43%), sandstone (34%), quartz (11%), tan chert (8%), and minor ironstone and quartzite. Clast size varies from granule to cobble, averaging about 10 cm. The cobbles are dominantly rounded, tabular, and imbricated sandstone clasts. In places within these gravels, deformed lenses of grey silt with small pebbles occur (Figure 14). The lenses are 10 to 40 cm thick and are laterally continuous for 1 to 3 m. Compact and dense, the silt beds exhibit open folding with 10 to 15 cm amplitude.

As this gravel is situated within a modern river valley, overlain by 53 m of sediment, and contains only clasts of local provenance, it is likely pre-glacial and may represent deposition in a paleovalley river system.

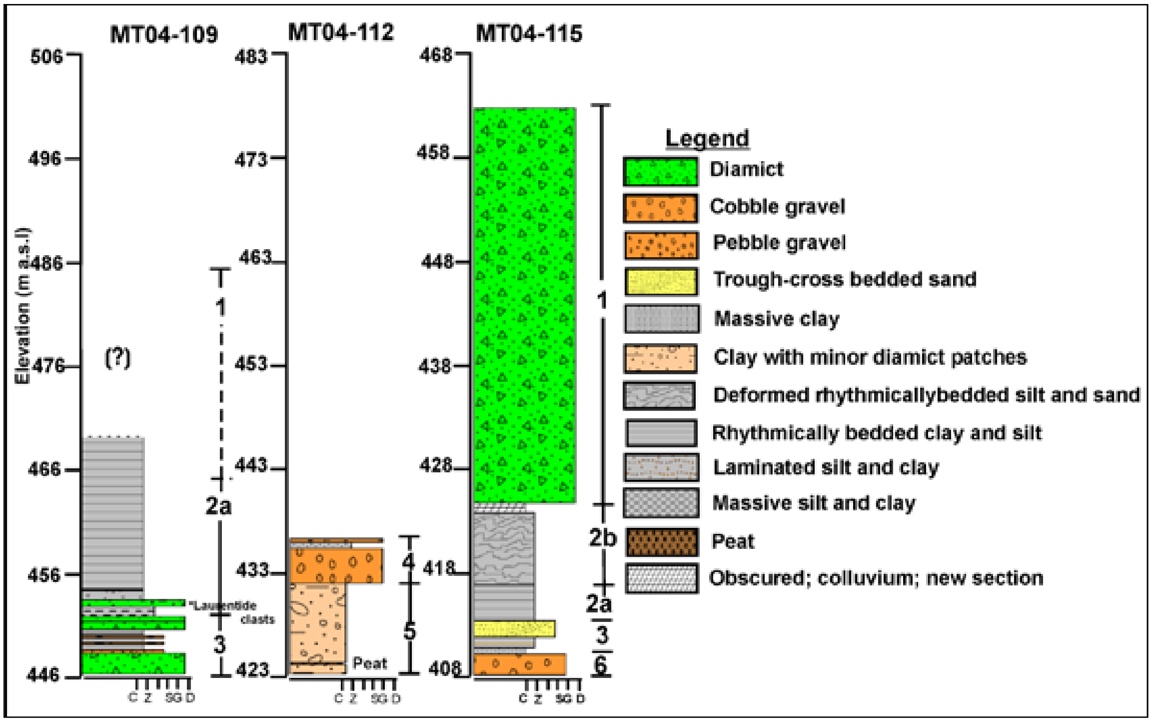

Figure 12. Lithologs of described sections MT04-109, MT04-112, and MT04-115 on the Prophet River (see Figure 3 for locations). 10.3 km separates the first two sections, and 7.35 km separates the last two, with MT04-109 the most southerly section. Numbers 1 though 6 refer to general units correlative between sections (see text.).

10.22 UNIT 5

Unit 5, also exposed at river level, is a 9 m thick massive to horizontally laminated black clay. This unit outcrops only in section MT04-112 (Figure 12), where it is laterally continuous for approximately 500 m. At this site, the clay is unconformably overlain by cobble gravel and the lower contact is below modern river level. Very locally, the black clay grades laterally and vertically into a massive clast-poor diamict. Clasts in the diamict (n=289, 4 to 10 mm size fraction) are rounded to subrounded Dunvegan sandstone, shale, black chert, quartzite, and minor tan chert (one small cobble) and volcanics. Organics are abundant in the clays. A sample of wood occurring 6 m above the section base was dated at more than 44 730 C^{14} years BP (BETA-195754) (Figures 1 and 15). Additionally, a 20 cm thick peat layer, laterally exposed for approximately 20 m, occurs 1 to 3 m above the section base (Figure 16). The peat layer was dated at more than 45 100 C^{14} years BP (BETA-195755) (Figure 1).

This clay with interbedded organics is interpreted as lacustrine sediment deposited in an interglacial pond. The discontinuous diamict beds within this unit may represent debris flows.

Figure 13. Oxidized pre-glacial gravel at modern river level on the Prophet River (site MT04-115). The gravel is overlain by massive grey silt interpreted to be lacustrine deposits.

10.23 UNIT 4

Unit 4 is a cobble gravel that can be found at several sections along the Prophet River valley. It varies from 0.5 to 3.5 m thick and is flat-lying and laterally continuous at most sites. Described in detail at site MT04-112, the unit occurs at the surface and unconformably overlies unit 5. It also overlies bedrock in some sections along the river. The gravel is matrix- to clast-supported with a medium sand matrix. Clasts are rounded to subrounded and field lithology data indicate the presence of quartzite, chert, ironstone, pink granite, white granite, and limestone. Clasts are well- to moderately sorted, and there are a few pebble gravel beds that contain tabular shale clasts in addition to other lithologies. There is a cobble lag at the lower contact. Within the unit, there occurs a 20 to 30 cm thick organic-rich clayey silt bed that is laterally continuous across the section.

As this gravel is flat-lying, unconformably overlies a number of different units at the top of sections along the river, and contains Shield-derived clasts, it is likely a post-glacial fluvial terrace gravel. The organic-rich clayey silt bed is interpreted as a paleosol.

10.24 UNIT 3

Unit 3 varies from 2 to 8 m thick and contains beds of dense silt, clay, sand, gravel, and clast-poor stratified diamict. It outcrops at two key sections, MT04-109 and MT04-115 (Figure 12), along the Prophet River and is laterally continuous for 50 to 100 m at these sections. The unit is overlain (conformably?) by rhythmically bedded clay and silt and unconformably overlies unit 6 at section MT04-115. The unit base is not exposed at section MT04-109. At the latter section, the unit consists of 8 m of dense silt, clay, sand, and horizontally stratified diamict. The thickness of the beds varies laterally and vertically. Gravel occurs as horizontal beds to u-shaped lenses with erosional lower contacts. There are less than 1% clasts within the lower diamict, and lithologies in both the diamict and gravels are shale, sandstone, quartz, and chert. At section MT04-115, unit 3 is a 3 m thick sequence consisting of coarsening-upward clay, silt, and sand. The silts and clays are laminated to rhythmically bedded, and the sand contains horizontal laminations and small-scale climbing ripples (amplitude approximately 0.5 cm). Within the unit, the clay–silt contact is likely conformable, while the sand has a lower erosional contact with the silt and a sharp upper contact with the rhythmically bedded silt and clay.These sediments are probably interglacialor pre-glacial due to the over-consolidated nature, lack of erratic clasts, and stratigraphic position underlying Laurentide till (see section 10.26, Figure 12). They may relate to damming of drainage during the advance of the glaciation, representing pre-glacial valley fill or a transition from valley fill to advance glacial deposits.

10.25 UNIT 2

Unit 2 is a rhythmically bedded clay and silt sequence that varies from 9 to at least 15 m thick. The unit outcrops at MT04-109 and MT04-115 and is laterally continuous for approximately 50 to 100 m at these sections. The clay and silt is unconformably overlain by diamict and underlain (conformably?) by unit 3. The clays and silts are 9 m thick at MT04-115 with a basal silt/clay elevation of 413 m asl. At MT04-109, further upstream, correlative deposits are more than 15 m thick with a basal silt/clay elevation of 454 m asl. The unit is of unknown thickness at this site because a large slump rupture surface occurs within the unit, and the amount of displaced or overlying material is unknown. At both sites, the overconsolidated silt and clay exhibits horizontal rhythmic stratification (1 to 15 mm thick) with small-scale ripples (unit 2a, Figure 12 and Figure 17). Beds are well sorted, and clasts could not be found. The upper 7 m of the unit at site MT04-115 exhibit soft sediment deformation (unit 2b, Figure 12 and Figure 18).

As the silts and clays of unit 2 are overconsolidated and occur stratigraphically below a diamict, these sediments may be part of an advance-phase glaciolacustrine depositional system. The fine-grained well-sorted silts and clays, rhythmic bedding, and thickness of deposits indicate glaciolacustrine deposition over a considerable time period. As such, these sediments were likely deposited when ice moved southward into the Prophet River valley and blocked northward-flowing pre-glacial drainage. This advance-phase interpretation is supported by the sheared and faulted upper silt and clay sediments (unit 2b) within section MT04-115, which may have been deformed by overriding ice. The first appearance of felsic red granites (Shield-derived) in a stratified silty clay diamict just underlying the rhythmically bedded silts and clays at site MT04-109 may indicate a glaciogenic debris flow and further substantiates this interpretation.

Figure 14: Deformed silt and fine sand bed within the lower gravel at site MT04-115.

Figure 15. Wood sampled within grey-black, finely laminated clay, 6 m above the base of section MT04-112. This wood yielded a date of more than 44 730 radiocarbon years BP (BETA-195754).

10.26 UNIT 1

Unit 1 is a massive diamict that varies from less than 1 to more than 40 m thick and is laterally continuous at most sections. The unit outcrops at sections along the Prophet, Fort Nelson, and Fontas Rivers and Klua and Elleh Creeks. Described in detail at section MT04-115 along the Prophet River, the diamict is brown with a silty clay matrix and is matrix-supported with only 2% to 3% granule- to cobble-sized clasts. Clast lithology includes felsic granitic rocks derived from the Canadian Shield. At site MT04-109, a diamict overlying unit 2a is inferred from the presence of abundant felsic granitic and gneissic boulders in a stream cut found above the described section.

As the clasts in both sections include granitoids and gneiss of Shield provenance, the presence of these requires a Shield-derived source; therefore, the till is likely of Laurentide provenance. As this unit occurs at surface (at plateau level), it is likely a record of the last Late Wisconsinan glacial event and can be correlated to the diamict found at many other plateau level sites (see section 9.1).

Figure 16. Peat horizon sampled 1 m above the base of section MT04-112 within a massive to laminated grey-black clay. This peat yielded a date of more than 45 100 radiocarbon years BP (BETA-195755).

11.0 GLACIAL HISTORY

From preliminary studies of surficial field sites and stratigraphic sections, the following glacial history is suggested for the Fort Nelson (NTS 094J/SE) and Fontas River (NTS 094I/SW) map areas.

Quaternary sections on the Prophet River indicate that the modern valley is a re-incision of a paleovalley, at least for a stretch located within the field area between sites 109 and 115 (Figure 3D). This paleovalley contains pebble to cobble gravel consisting of locally derived sandstone, shale, quartz, and chert. Small-scale fluctuations in channel positions and water levels within the valley are suggested by deposits of massive clay, massive silt, bedded sand, gravel beds or pods, and stratified diamict. The stratified diamicts likely represent subaqueous debris flow deposits. Perhaps also within this paleovalley, ponds developed in the valley bottom due to slumping of the valley walls, in a manner similar to modern-day conditions,. This ponding could result in the local deposition of massive to laminated clays. Organics occurring in these clays along the Prophet River have yielded radiocarbon ages of more than 40 000 years BP.

Figure 17. A bedding plane from the rhythmically bedded silt and clay (unit 2a, Figure 12) at site MT04-109 exhibiting small-scale ripples with amplitudes of 1 to 5 mm. Two-dollar coin for scale.

As ice sourced from the Laurentide Ice sheet (from the east) or the Rocky Mountains (from the west) entered the paleovalley, the northward-flowing river was blocked and deposition of a thick, rhythmically bedded silt and clay glaciolacustrine sequence occurred. Minor shears and faults in the upper 7 m of a 9 m outcrop of bedded silts and clays suggest that this unit was overridden by ice as the glaciers continued to expand. At plateau level to the east of the Prophet River in the Elleh Creek area, sands and gravels were deposited either subglacially or ice-marginally. A radiocarbon date (24.4 C^{14} ka BP) of wood found in these sands and gravels indicates that at least the lower portions were deposited during the advance phase of Late Wisconsinan glaciation. The presence of shears and overlying diamict at the Elleh Creek site suggest ice overrode this deposit as well.

The ubiquitous distribution of till at surface throughout the study area suggests there was at least one glacial advance into the region during the Late Wisconsinan. The abundance of Shield-derived clasts suggests that this till was deposited by Laurentide ice. Possible reasons for a lack of distinct Cordilleran Ice Sheet tills in the region include distance from the Rocky Mountains, the lack of a pass (such as the Pine Pass, Peace River, or Athabasca Pass to the south) that would allow Cordilleran ice to flow east into the region, and relative timing of Cordilleran and Laurentide glacier advances.

As ice retreated from the region, flutes and crag and tail features were exposed. Moraines were deposited along ice margins, and meltwater created minor glaciofluvial ridges (eskers). Major and minor meltwater channels were formed, including the 150 km long steep-walled channel that contains the modern Fontas and Fort Nelson Rivers. This large meltwater channel may have been reoccupied by meltwater several times as glacial Lake Hay (east of the study area) drained (Mathews, 1980). Within or near the end of some channels, large hills or plains of glaciofluvial gravel were deposited (e.g., Adsett Creek or Klua Creek deposits).

Regional drainage is northward, and an accumulation of meltwater resulted from short-term ponding due to the presence of northeastward-retreating Laurentide ice. In the stratigraphic record, this is indicated by geographically restricted massive clay to fine sand deposits situated at plateau level along modern river valleys.

As a result of base level adjustment, incision of valleys and development of terraces occurred. Both processes have continued though the Holocene, resulting in deep river valleys with terraces.

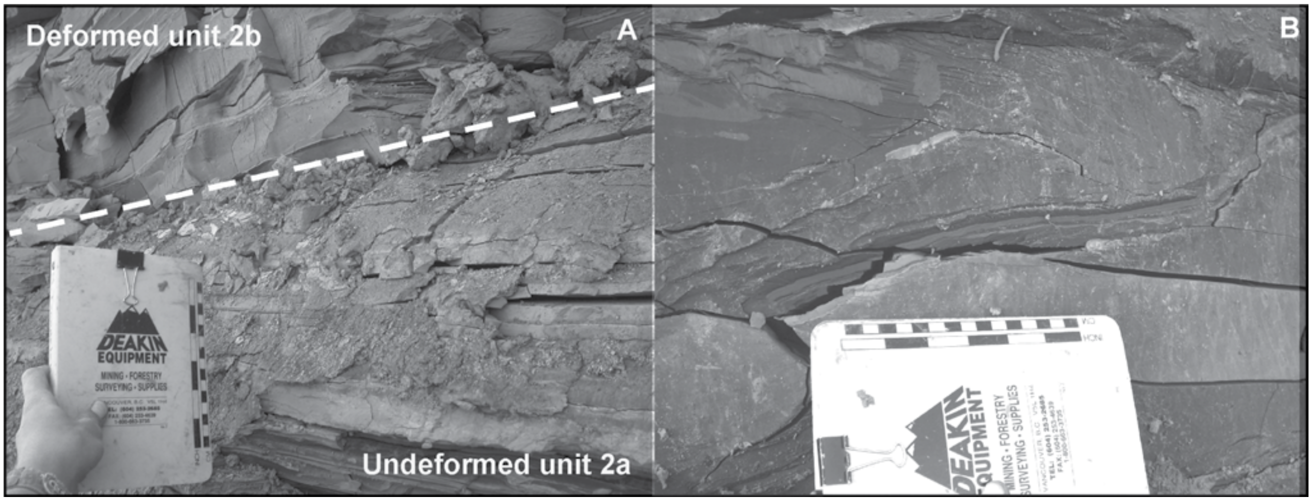

Figure 18. Rhythmically bedded silt and clay at site MT05-115. A: Sheared and faulted unit 2b over undeformed unit 2a. B: Example of folded deformed beds in unit 2b, approximately 11 m above the section base.

12.0 AGGREGATE POTENTIAL

The map region is dominated by the presence of clast-poor diamictons and massive clays and silts unsuited for aggregate use. A very extensive mantle of organics throughout the study area adds difficulty in identifying aggregate resources. Possible aggregate sources include pre-glacial, glaciofluvial, and fluvial gravels as well as Cretaceous pebble conglomerate (Figure 2 for location). Ten gravel pits occur in the study area (Figure 3), including two significantly large ones at Elleh Creek (Figure 3C; section 10.1) and Adsett Creek (Figure 7; section 9.2).

The Elleh Creek deposit is a pebble to cobble gravel covering approximately 2.25 km^2 and ranging in height from 25 to 50 m; it has recently become a critical aggregate resource for the Sierra-Yoyo-Desan (SYD) Road east of Fort Nelson. Through test-pitting, the hill has been separated into regions of predominately gravel, predominately sand, and gravel and predominately sand (Dewar, 2003). Tests completed in the predominately gravel section indicate 6% fines (diameter less than 75 µm), 40% sand (75 µm to less than 4.75 mm), 34% fine gravel (4.75 to less than 25 mm), 18% coarse gravel (25 to 75 mm), and 2% oversize (more than 75 mm). This detailed investigation identified a preliminary granular resource of more than 1 700 000 m.^{3} The reader is directed to Dewar (2003) for the details of this investigation, including test pit logs, laboratory results, and a map of test pit locations. During the winter of 2003, LEDCOR CMI Limited extracted and processed 165 000 m^3 of sand and gravel from the northeast corner of the reserve (site MT04-159, Figure 3C) for use in construction of the Clarke Lake Bypass Road and upgrading of SYD. Blue Canyon Concrete Limited has also opened a smaller pit in the reserve, approximately 1 km west of the LEDCOR CMI Limited pit.

The Adsett Creek deposit is smaller, with an approximate extent of 2 km^2 and height range from 5 to 25 m. The deposit is dissected by the modern Adsett Creek, and several small active gravel pits are located on the south side of the creek. A larger active pit is located on the north side of the creek (MT04-055, Figure 7). Clast sizes within the deposit range from pebble to cobble. The gravels are matrix- to clast-supported in a medium to fine sand matrix. The gravel structure varies from massive to bedded, and matrix content varies from 30% to 80%. Clast lithology is variable, but the dominant lithologies are hard and resistant to weathering (with the exception of Dunvegan sandstone).

By studying the provenance and depositional history of these known aggregate reserves, it is possible to predict where new resources may be found. A new aggregate prospect in the map area is the glaciofluvial outwash deposit at Klua Creek (Figures 5 and 6; section 9.2). This gravel extends approximately 1 km by 0.5 km, and its known thickness at one site is greater than 6 m. Several road construction borrow pits and eight hand-dug pits are located on the deposit. These exposures indicate that the deposit varies from pebble gravel to boulder gravel in a fine sand to silt matrix. The deposit varies from matrix- to clast-supported and is generally poorly sorted. Clast lithology is variable, but the dominant lithologies are hard and resistant to weathering. There is however a significant (approximately 14% at site MT04-141) ironstone component, which is friable and easily breaks down.

When working near the uplands of the Alberta Plateau (Figure 2), Dunvegan pebble conglomerate may provide a source of aggregate and requires further study. It consists of well-rounded, pebble-sized clasts of resistant lithologies (chert and quartz) in a sandy matrix. Other showings, as yet uninvestigated for aggregate potential, include terraces on the Prophet River, terraces on the Fontas River, and small-scale glaciofluvial deposits (eskers, kames, and outwash) and pre-glacial gravel deposits along the Prophet River (see section 10.21).

13.0 CONCLUSIONS

In this paper we present an initial interpretation of the Quaternary history, stratigraphy, and geomorphology of the Fort Nelson (SE) and Fontas River (SW) map areas (NTS 094J/SE and 094I/SW respectively) in northeastern British Columbia. From preliminary work several conclusions can be made:

- Surficial material in the region is predominately silty clay, clast-poor diamict overlain in some areas by massive to rhythmically bedded silt and clay. Bedrock topography defines most of the relief in the region, and Quaternary landforms typically exhibit positive relief of less than 10 m relative to the surrounding area.
- Field investigations of stratigraphy and surficial material suggest at least one episode of glaciation for the map area during the Late Wisconsinan.
- Gravel and diamict pebble lithologies include red felsic granites and gneiss, limestone, oil-impregnated dolostone, and minor mafic and volcanic clasts in addition to local (Cretaceous) sandstone, shale, chert, and quartz. The red igneous and metamorphic rocks are inferred to be Shield-derived, and their abundance within the gravels and diamicts suggests these deposits are of Laurentide provenance.
- The abundance of Shield-derived clasts possibly indicates that the Cordilleran Ice Sheet did not extend into the region, though dilution of Cordilleran-derived clasts by reworking cannot be ruled out. Additionally, inconclusive evidence exists that Rocky Mountain glaciers extended into the map area.
- The Prophet River valley is a re-incised paleovalley

providing valuable pre-glacial to Holocene stratigraphy, including a new pre-Late Wisconsinan interglacial site. Site MT04-112 provided radiocarbon dates of more than 44 000 and more than 41 000 years BP from peat and wood within a massive to laminated clay unit with gradational pods of diamict. The depositional environment is an interglacial pond, possibly formed by slumping of the paleovalley walls, with minor debris flows.

- The map area contains an important aggregate resource for the Sierra-Yoyo-Desan (SYD) Road east of Fort Nelson. This deposit, Elleh Creek, is 2.25 km^2 and is thought to be the result of subglacial or ice-marginal glaciofluvial depositional systems. Several new aggregate showings (economic potential unknown) include outwash surrounding Klua Creek, Prophet River terraces, Fontas River terraces, glaciofluvial deposition, pre-glacial gravel, and outcrops of pebbly Dunvegan conglomerate.

Further field study in 2005 will ground-check potential aggregate resources and surficial map units within remote areas. Detailed work will focus on stratigraphic studies in paleovalley sequences exposed along the Prophet River and delineation of ice-sheet limits within or near the field area.

ACKNOWLEDGEMENTS

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SKEENA AND BOWSER LAKE GROUPS, WEST HALF HAZELTON MAP AREA (93M)

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ABSTRACT

The extent of Skeena Group rocks delineated during the summer of 2004 within the western portion of Hazelton map area (93M) is very similar to patterns currently portrayed on regional-scale maps. Large areas of previously undivided Bowser-Skeena lithologies belong to the Bowser Lake Group. In west Hazelton map area, the Bowser Lake Group can be subdivided into the Ritchie-Alger and Muskaboo Creek lithofacies assemblages, representing submarine fan (or outer shelf)and inner shelf depositional environments, respectively. The Skeena Group is represented by the fluvial Bulkley Canyon Formation. Sedimentary rocks of the Skeena Group (Bulkley Canyon Formation) appear to conformably overlie and intertongue with the Bowser Lake Group (Muskaboo Creek lithofacies assemblage). All these rocks have been deformed into northeast-verging folds and faults and subsequently cut by steep structures.

In the study area, limited surface thermal maturation levels indicate Skeena Group rocks are generally mature to overmature with respect to the oil window and locally extend to the upper gas window. Bowser Lake Group rocks are mature to overmature with respect to the gas window. Skeena Group rocks are rich in Type III kerogen. Delineation of an adequate reservoir rock within Bowser and Skeena sequences is an issue.

KEYWORDS: Hazelton, Bowser Basin, Bowser Lake Group, Skeena Group, Ritchie-Alger, Muskaboo Creek, Bulkley Canyon, Laventie, Kitsuns Creek, Kitsumkalum shale, hydrocarbon potential, petroleum, coal, oil, gas

INTRODUCTION

Regional-scale mapping was carried out within the western Hazelton map area during the summer of 2004 with the objective of delineating the extent of the Skeena Group and identifying its relationship to underlying rocks of the Bowser Lake Group. This mapping project is part of the Integrated Petroleum Resource Potential and Geoscience Studies of the Bowser and Sustut Basins Program, which is a partnership between Natural Resources Canada (Geological Survey of Canada), the B.C. Ministry of Energy and Mines (Resource Development and Geoscience Branch), and Simon Fraser University (Department of Earth Sciences). This four-year, multi-disciplinary program is currently in its second year. During this time, this project has completed regional mapping studies within western McConnell Creek (94D), Bowser Lake (104A), and west Hazelton (93M) map sheets, together with basin-wide thematic studies (Evenchick *et al.*, 2004, 2005; Hayes *et al.*, 2004). The ultimate aim of this program is a better understanding of the geology and hydrocarbon potential of these large, Intermontane Belt sedimentary basins.

Hannigan *et al.* (1995), in their assessment of the Bowser Basin, assigned a higher risk level to Bowser Lake Group sediments than to those of the Skeena Group, based primarily on higher thermal maturities. As a result, potential resources are greater within the Skeena Group, with total mean in-place resources of 7.19x10^{10} m^3 (2.54 trillion cubic feet, TCF) gas and 2.01x10^8 m^3 (1 264 million barrels) oil. In comparison, the Bowser Lake Group is assigned a total mean in-place potential of 5.78x10^{10} m^3 (2.0 TCF) gas and no oil.

A recent geological compilation of the Bowser Basin portrays large portions of the southern parts as undivided Bowser Lake and Skeena Groups (Evenchick *et al.* 2004; Figures 1 and 2). Clearly, an increase in the areal extent of the Skeena Group would increase the overall hydrocarbon resource potential of the Bowser Basin and the number of potential play targets. As a result of this and the overall higher prospectivity of the Skeena Group, the BC Ministry of Energy and Mines, together with the Geological Survey of Canada and Simon Fraser University, initiated a regional mapping program within the western portion of the Hazelton map sheet. The main objectives of this project were to 1) map the extent of Bowser and Skeena Group rocks; 2) examine the relationship between Skeena and Bowser Lake Groups, including preliminary structural interpretations; 3) determine whether lithofacies assemblages de-

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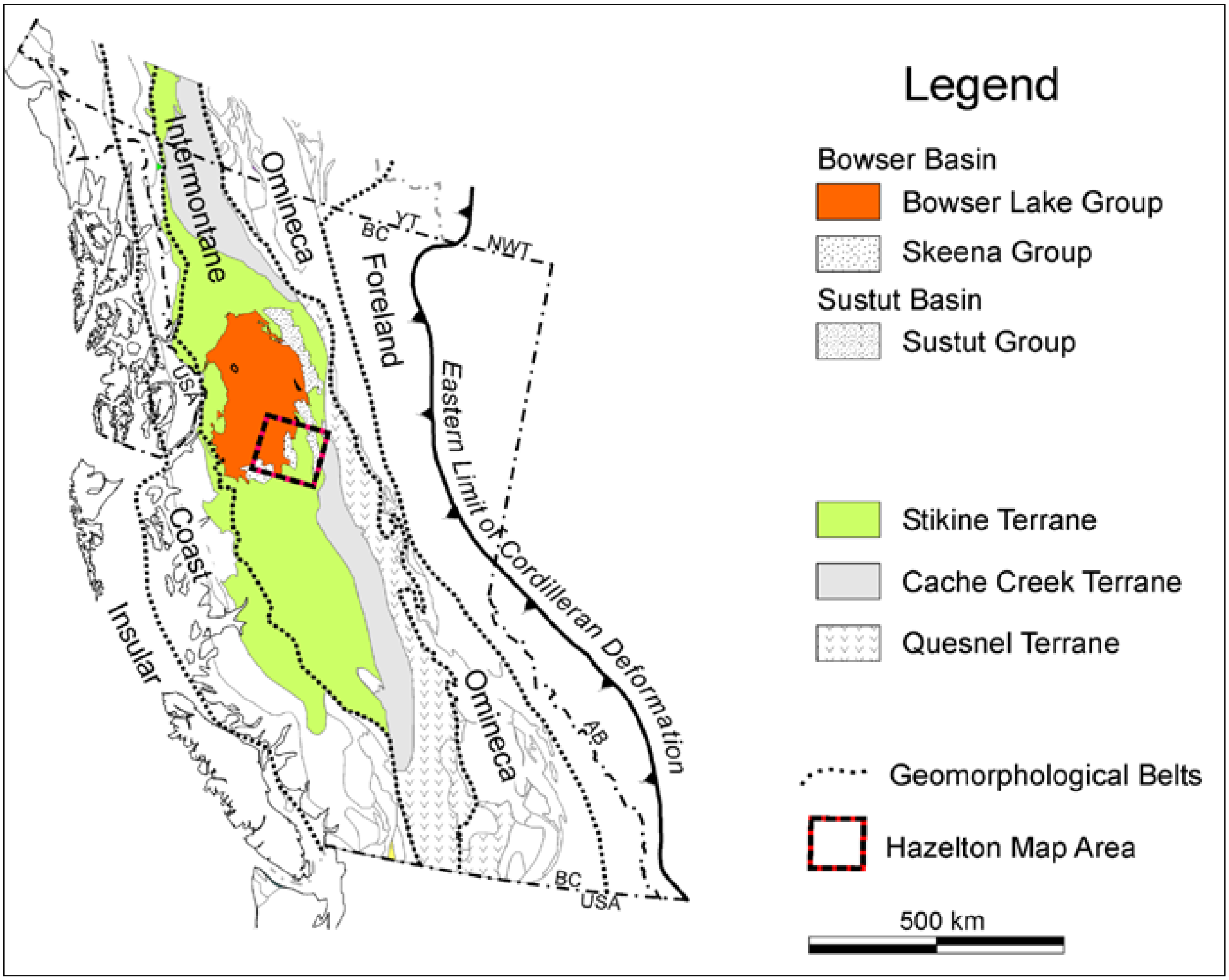


Figure 1. Location of the Bowser and Sustut Basins within the geological framework of the Canadian Cordillera (modified from Evenchick *et al.*, 2004).

lineated for Bowser Lake Group in northern Bowser Basin extend into the southern part of the basin; 4) sample Skeena and Bowser Lake Groups for reservoir characterization; and 5) obtain samples of Bowser Lake and Skeena Groups for determining levels of thermal maturation and source bed potential.

The area examined during the summer of 2004 is roughly centred on the Kispiox River valley and is bounded to the east and west by the Babine and Kispiox Ranges, respectively, and to the south by the Skeena River (Figures 3, 4). The area encompasses the confluence of the Babine, Skeena, and Kispiox Rivers and, except for alpine areas, is easily accessed by an extensive network of logging roads. The town of New Hazelton is located on the Skeena River, at the southern end of the study area, with Smithers roughly an hour's drive to the south along Highway 16, and Terrace some 150 km to the west.

PREVIOUS WORK

Geologic mapping in the Hazelton map area dates back to the early 1900s when Leach (1909) first used the term "Skeena series" to describe the coal bearing sequence that lies above Jurassic volcanic and sedimentary rocks, the latter of which he termed the Hazelton Group (Table 1). The use of the name "Skeena" to describe the coal series was dropped by Armstrong (1944a, b) as he found it difficult to differentiate these rocks from the older Jurassic sedimentary sequence. Tipper and Richards (1976) resurrected the name, raising it to group status, and assigned a Cretaceous age to these sediments. These authors also redefined the Hazelton Group and assigned the intervening sediments and minor volcanics to the Bowser Lake Group, which they believed to be largely Middle to Late Jurassic in age (Table 1). Richards (1980, 1990) mapped and compiled the geology of the entire Hazelton map area and refined Skeena Group and younger stratigraphy. A detailed sedimentologi-

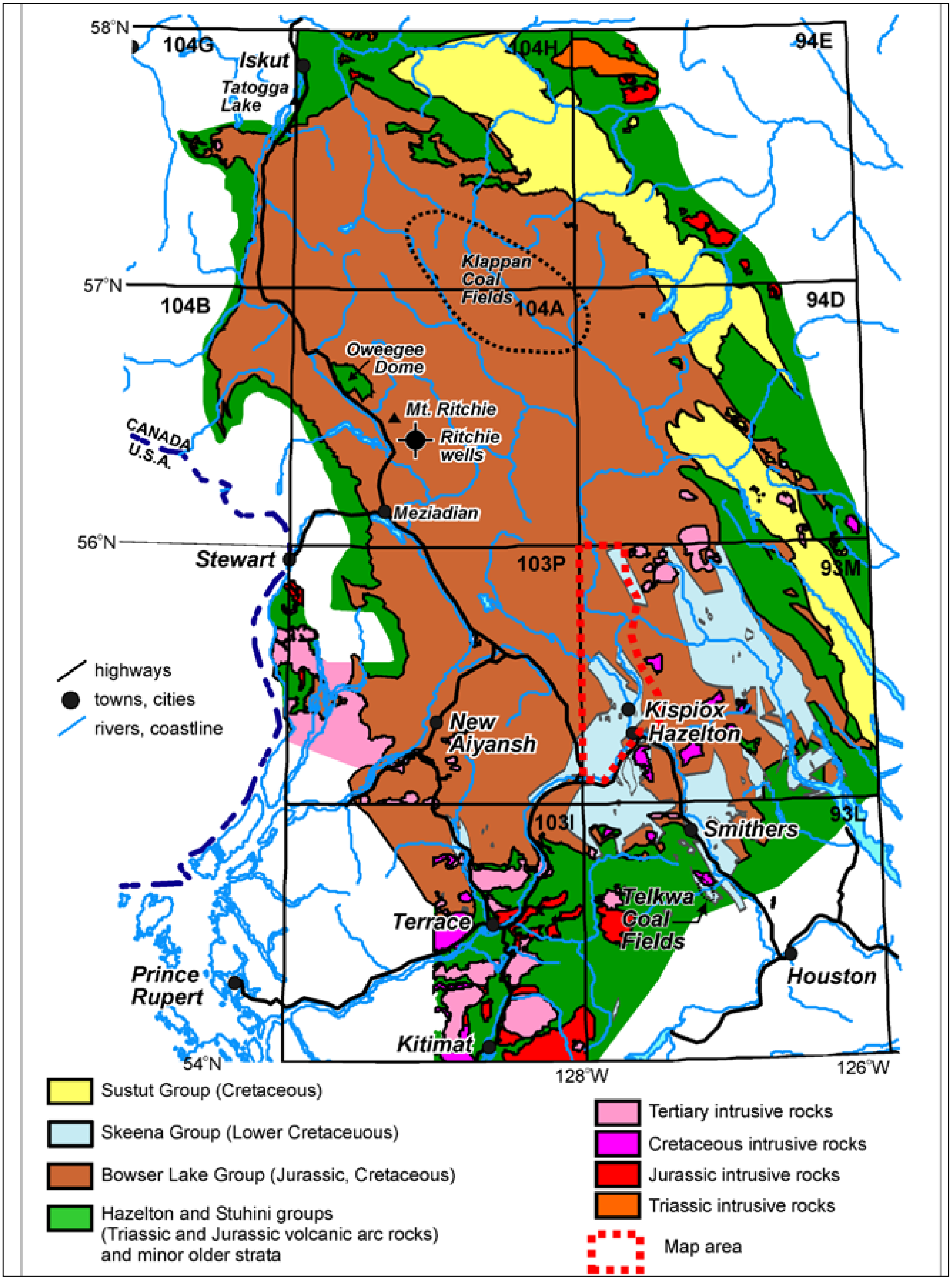


Figure 2. General geology of the Bowser and Sustut Basins, showing the distribution of the Skeena Group (modified from Evenchick *et al*., 2004).

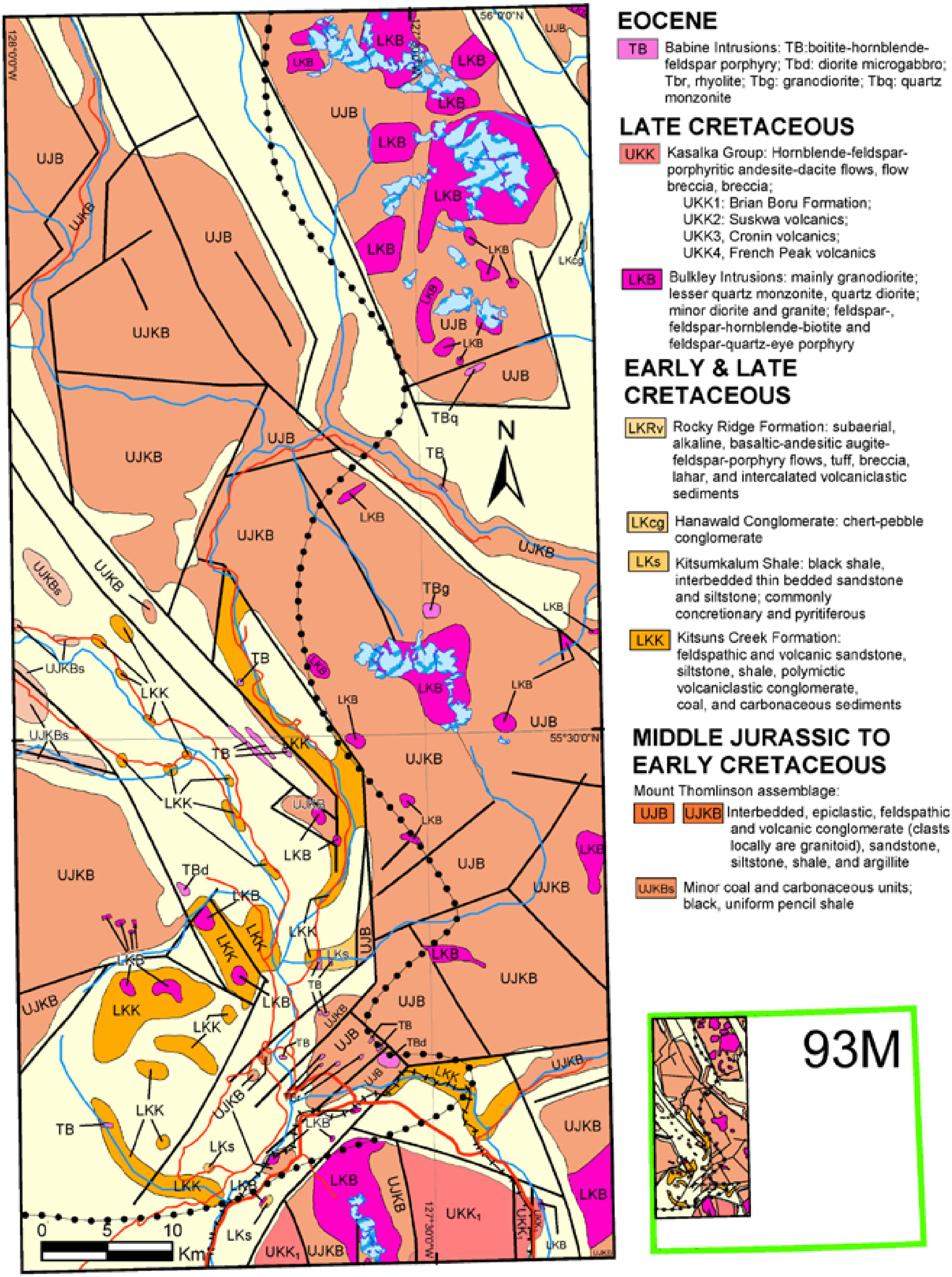


Figure 3. Geology of central and western Hazelton map area (simplified after Richards, 1990). The outline of the current map area is shown by the dashed line.

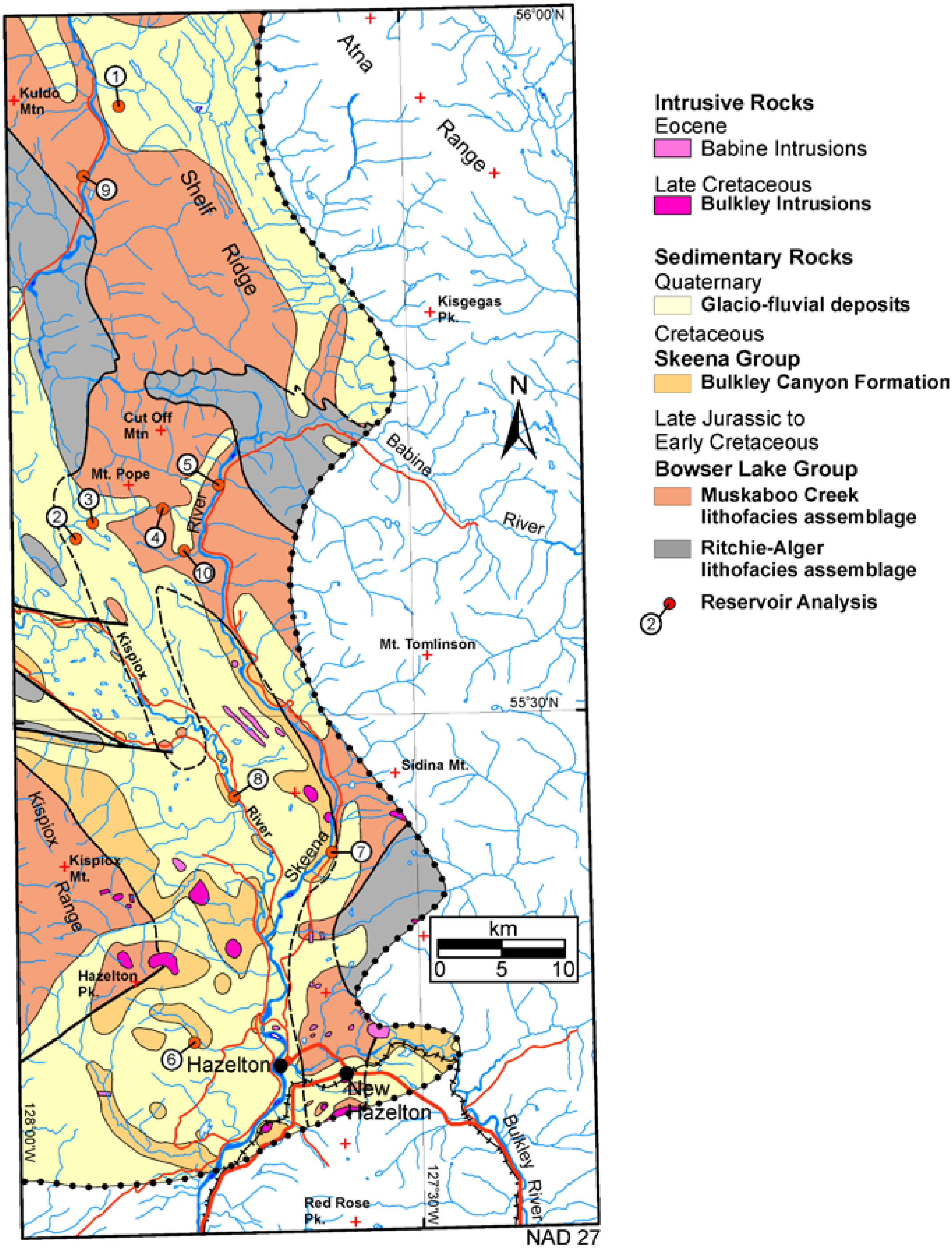


Figure 4. Simplified geological map of the study area. Sample locations for reservoir analysis are also shown.

TABLE 1. EVOLUTION OF STRATIGRAPHIC NOMENCLATURE WITHIN THE HAZELTON MAP AREA, PARTICULARLY WITH RESPECT TO THE BOWSER LAKE AND SKEENA GROUPS.

Dawson (1881) Leach (1908,9)	Leach (1910)	Hanson (1924) Jones (1925)		Armstrong (1944a, b)		Sutherland Brown (1960)	Tipper and Richards (1976)		Richards (1980)		Richards (1990)		Bassett and Kleinspehn (1997)
Porphyrite group	Skeena series		Skeena fm	Hazelton Group	Volcanic Div	Brian Boru fm	Skeena Group	Brian Boru fm		Brian Boru fm	Kasalka Gp	Brian Boru fm Suskwa volcs Cronin volcs French Pk volcs	
									Sustut Gp		Sustut Gp		Sustut Gp
									Skeena Group	Red Rose fm Albian blk shale Rocky Ridge vols	Skeena Group	Red Rose fm Rocky Ridge fm	Rocher Deboule Fm Rocky Ridge Fm
					Sedimentary Div	Red Rose fm		Red Rose fm		Kitsuns Ck seds Black shale Conglomerate		Hanawald cong. Kitsumkalum shale Kitsuns Ck fm	Bulkley Canyon Fm Kitsuns Ck mbr Laventie Fm (Couture Fm; Bassett and Kleinspehn, 1996)
	Hazelton Group	Hazelton Group	Upper Sedimentary Div				Bowser Lake Group		Bowser Lk Gp	Upper to Lower Netalzul Volcs Trout Ck Beds	Bowser Lk Gp	Mt Thomlinson asblge Netalzul Fm Trout Ck Fm Ashman Fm	Mt. Thomlinson asblge Netalzul Fm Trout Ck Fm Ashman Fm
							Hazelton Group	Smithers Fm	Hazelton Group	Smithers Fm	Hazelton Group	Smithers Fm	Smithers Fm Saddle Hill volcanics
			Upper Volcanic Div		Volcanic Div			Nilkitkwa Fm		Nilkitkwa Fm		Nilkitkwa Fm	Nilkitkwa Fm
			Lower Sedimentary Div		Sedimentary Div								
			Lower Volcanic Div		Volcanic Div			Telkwa Fm		Telkwa Fm		Telkwa Fm	Telkwa Fm

cal study of the Skeena Group was carried out by Bassett (1995), which led to a redefinition of Skeena stratigraphy (Table 1, Figure 5; Bassett and Kleinspehn, 1996, 1997). Detailed mapping in the Old Fort Mountain (93M/1) and Nakinilerak Lake (93M/8) map sheet areas (both containing Skeena Group strata) was carried out by MacIntyre *et al.* (1997) and MacIntyre (1998), respectively.

Although a regional-scale geological map of Nass River (103P) does not exist, maps of select parts of the Bowser Basin within 103P were produced by Evenchick (1996a, b, c) and Haggart (1998). To the north of the study area, the geology of the east half of McConnell Creek map area was compiled by Richards (1976). The first compilation at 1:250 000 scale of the west half was completed by Evenchick et al (2001) and based on mapping in the early 1990s (Evenchick and Porter, 1993). As part of this integrated study, this compilation was updated based on mapping in the summer of 2003 (Evenchick *et al.,* 2004). In Bowser Lake map area, (104A) Evenchick *et al.* (2000) delineate preliminary geology, and Evenchick *et al.* (1992) describe the distribution of lithofacies assemblages within Bowser Lake Group strata. The map area was also covered at a regional scale in 2004 as part of the present Bowser-Sustut Basins integrated study, which will lead to a revised geological compilation (Evenchick *et al.*, *in press;* see Evenchick *et al.*, 2004 for a preliminary compilation).

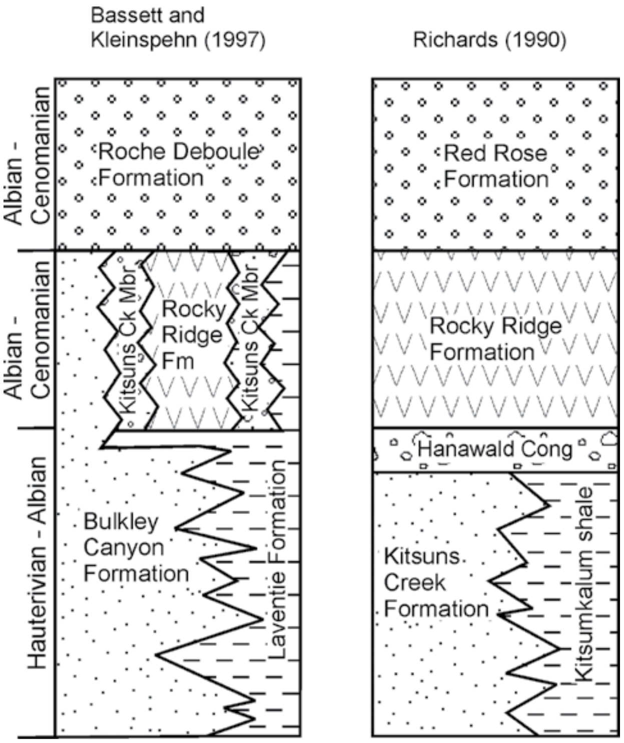


Figure 5. Schematic representation of the stratigraphy of the Skeena Group as depicted by Bassett and Kleinspehn, 1997, and Richards, 1990.

GEOLOGICAL FRAMEWORK

The Bowser and Sustut Basins are located in north-central British Columbia, within the northern part of the Intermontane Belt. These basins represent overlap assemblages deposited after amalgamation of Stikine, Cache Creek, and Quesnel Terranes onto ancestral North America (Figure 1). They primarily overlie Devonian to Jurassic rocks of Stikinia.

Initiation of the Bowser Basin most likely began with thrust-loading of Cache Creek Terrane rocks onto Stikinia in Early to Middle Jurassic times (Toarcian to Aalenian; Ricketts *et al.*, 1992). This is manifested in the stratigraphic record by the deposition of uppermost black clastic deposits of the Hazelton Group and by chert boulder conglomerate in the footwall of the King Salmon Fault (Gabrielse, 1998). The black clastic unit of the upper Hazelton Group in Hazelton map area is referred to as the Nilkitkwa and Smithers Formations (Spatsizi Formation in northern Bowser Basin). The upper part of the Aalenian to Bajocian Smithers Formation records an influx of coarse, chert-rich clastics similar to those of the overlying Bowser Lake Group.

The Bowser Basin contains two main successions: the Middle Jurassic to mid-Cretaceous Bowser Lake Group and the Lower to mid-Cretaceous Skeena Group, although some previous workers have considered the Skeena Group to have been deposited in a separate basin (e.g., Tipper and Richards, 1976). The Sustut Basin is represented by the mid- to Upper Cretaceous Sustut Group. In northern and central Bowser Basin, marine and nonmarine Bowser Lake strata represent a southwestward- and westward-prograding fluvial-deltaic to distal submarine fan sequence (Evenchick *et al.,* 2001). Skeena Group rocks, located along the southern part of Bowser Basin, are inferred to have been deposited in marine to nonmarine deltaic(?) (or estuarine) and fluvial/floodplain environments. The relationship of Skeena to Bowser Lake stratigraphy is uncertain. Previous workers have considered the contact to be either unconformable or conformable, although none have documented an exposed example of this contact (Tipper and Richards, 1976; Bassett and Kleinspehn, 1997). The Sustut Group is interpreted to represent fluvial to lacustrine environments (Eisbacher, 1974) depositing in a foreland basin east of deforming Bowser Lake strata (Evenchick and Thorkelson, 2005).

Bowser Lake, Skeena, Sustut, and underlying Stikine Terrane rocks are deformed into dominantly northwest-trending fold and thrust structures comprising the Skeena Fold Belt (Evenchick, 1991). In eastern Hazelton map area, MacIntyre (1998) shows that rocks as young as Cenomanian were involved in this deformation event. In northern Bowser Basin, oldest Skeena Fold Belt deformation is believed to be bracketed between the latest Jurassic and Albian times, whereas youngest deformation is latest

Cretaceous (Maastrichtian) to earliest Tertiary (Paleocene; Evenchick, 1991).

The youngest period of deformation within the map area is manifested as a series of steep extensional faults and associated horst and graben structures (Richards, 1980, 1990; MacIntyre, 1998; MacIntyre *et al.*, 1997). These features are believed to be Eocene or younger based on cross-cutting relationships. These faults appear to be the main control on the distribution of rock units within the Hazelton map area.

WEST HAZELTON MAP AREA (93M)

In the west part of the Hazelton map area, the distribution of sedimentary rocks encountered during the summer of 2004 broadly corresponds to patterns mapped by Richards (1990). Skeena Group rocks in this area are part of the Bulkley Canyon Formation (Bassett and Kleinspehn, 1997; Kitsuns Creek Formation of Richards, 1990), and we believe that these rocks rest conformably atop those of the Bowser Lake Group (Smith *et al.*, this volume).

The Bowser Lake Group in west Hazelton map area was assigned to the Mount Thomlinson assemblage by Richards (1990), an undivided marine and fluvial sequence of Middle Jurassic to Early Cretaceous age. Mapping of these rocks over the summer of 2004 allowed their subdivision into lithofacies assemblages, as defined within the northern Bowser Basin (Evenchick *et al.*, 2001). The distribution of these lithofacies corresponds to those in the adjoining McConnell Creek and Bowser Lake map areas and include the Ritchie-Alger and Muskaboo Creek assemblages, representing submarine fan (to outer shelf or slope) and inner shelf depositional environments, respectively.

Sedimentary rocks in the Hazelton map area have been intruded by two igneous suites: the Late Cretaceous Bulkley and Tertiary Babine intrusions (Richards, 1990). Bulkley intrusions consist of small to large bodies of dominantly quartz diorite, monzonite, diorite, and granite. These occur along the higher ground of the map area and underlie regions in the Mount Thomlinson, Natlan Peak, Nine Mile Mountain, and Hazelton Peak areas. The Babine intrusive suite comprises porphyritic lithologies including ±biotite±hornblende-feldspar porphyries and lesser diorite, granodiorite, and quartz monzonite. In west Hazelton map area, these rocks forms small plugs in the Four Mile Mountain area, north of New Hazelton and west of Skeena River. In addition, there are numerous small porphyritic dikes and plugs within the map area, which most likely belong to this suite.

Bowser Lake Group

The Bowser Lake Group was subdivided into four packages within the Hazelton map area (Figure 3) by Richards (1990). These are, from oldest to youngest, the Ashman, Trout Creek, and Netalzul Formations, followed by undivided rocks of the Mount Thomlinson assemblage (Figure 3). An overall gross description of this package by Richards (1980), Tipper and Richards (1976), and Richards and Jeletzky (1975) indicates a northwestward progradation of fluvial-deltaic systems into marine environments. Callovian to Early Oxfordian rocks of the Ashman Formation generally record deeper-water marine facies with some fluvial influences (Tipper and Richards, 1976), whereas the Late Oxfordian Trout Creek Formation contains coarser clastics and coal-bearing sequences interpreted as fluvial-deltaic in nature. The Oxfordian Netalzul Formation is composed of intermediate to felsic pyroclastic rocks deposited within specific parts of the Bowser Basin, primarily in the Mt. Netalzul and Ashman Ridge areas of the Hazelton map area (Richards, 1990) and southwest parts of the east half of McConnell Creek map area (Richards, 1976). The Oxfordian to Hauterivian Thomlinson assemblage (Richards, 1990) is the youngest unit of the Bowser Lake Group in southern Bowser Basin and consists of fluvial, marginal-marine, and shallow-marine deposits.

These broad facies relationships support the presence of a paleogeographic high (the Skeena Arch, to the southeast of the map area), which became prominent during late Middle to Late Jurassic times (Tipper and Richards, 1976).

Tipper and Richards (1976) describe a period of faulting, uplift, and erosion that affected Bowser Lake and older rocks between Kimmeridgian and Early Cretaceous (Hauterivian?) times (although Richards [1990] shows the upper part of the Bowser Lake Group extending into the Hauterivian), resulting in Skeena Group rocks appearing to be disconformable to unconformable on older units. This was supported by paleontological evidence suggesting a possible hiatus during this time and by relationships south of the Hazelton map area, where Skeena Group clastics rest unconformably on Hazelton Group volcanics, such as in the Telkwa coal fields (Koo, 1984) and near Tahtsa Lake, where Albian sediments sit unconformably on Middle Jurassic Bowser Lake Group rocks (Woodsworth, 1980). Tipper and Richard (1976) also suggest that the depositional basin represented by the Skeena Group was different from that of the Bowser Basin. Barring the above evidence, the nature of the Skeena-Bowser contact in most areas has been equivocal due to its general lack of exposure and/or stratigraphic control. Although it can be difficult to differentiate between Bowser Lake and Skeena clastics, the latter have commonly been cited to commonly contain mica flakes and are somewhat less indurated.

In the current study area, Bowser Lake Group sedimentary rocks have been subdivided into two units recognized in other map areas to the north: the Ritchie-Alger and Muskaboo Creek lithofacies assemblages (following the terminology of Evenchick *et al.*, [2001] and presented in detail within Evenchick and Thorkelson [2005]). In northern and central Bowser Basin, these lithofacies broadly represent the main marine units of the basin and both underlie and are distal to a southwestward-prograding sequence of deltaic complexes, which locally contain thick sections of coal (Klappan-Groundhog coal fields). In a broad sense, rocks of the Ashman Formation have characteristics similar to those of the Ritchie-Alger assemblage, whereas facies of the Thomlinson Formation are more akin to the Muskaboo Creek lithofacies assemblages.

Fossil data in northern and central Bowser Basin have shown that the age of the Bowser Lake Group is late Middle Jurassic to Early Cretaceous (Bathonian to Albian(?); Evenchick *et al.*, 2001). Fossil collections from the Ritchie-Alger and Muskaboo Creek lithofacies assemblages bracket the late Middle Jurassic (Bathonian) to latest Jurassic (Tithonian) and locally may extend into the earliest Cretaceous.

Ritchie-Alger assemblage

Dark grey to black siltstone (in places slaty) together with grey to beige, thinly to thickly bedded sandstone occur primarily within the northwestern part of the map area. Main areas of exposure include those south of Kuldo Creek, west of Mount Pope and Cutoff Mountain, and north of McCully Creek. These rocks also occur in the vicinity of the Skeena and Babine River confluence and west of the Kispiox-Skeena confluence. Typically, the terrain encompassed by this unit is below tree line and relatively subdued, such that exposures tend to be limited to either stream, road, or quarry cuts. Best outcrops are on the ridge northwest of Cutoff Mountain and along the lower Babine River. Thicknesses are difficult to determine, but are in the order of several hundred metres.

Massive to vaguely laminated siltstone and/or silty mudstone are the dominant lithologies in the northern part of the map area. Commonly, these sections contain thin beds of fine-grained, graded to cross-laminated sandstone that comprise up to 20% of the exposure. Cleavage in finer lithologies is ubiquitous, and rocks locally are slates. Some sections, such as in the vicinity of the confluence of the Babine and Skeena Rivers, can be quite organic-rich and contain small pyritic nodules. Vertical to sub-vertical worm burrows up to 2 cm wide and displaying cuspate infills are well developed in exposures north of the Skeena River near its confluence with the Babine River.

In the vicinity of the Kispiox-Skeena confluence, and as scattered occurrences elsewhere, dark and commonly massive siltstones and silty mudstones contain massive, tabular chert-rich sandstones beds up to a metre or more thick that can comprise up to 50% of exposures. The bases of these sandstone beds commonly contain rip-up clasts of underlying siltstone. Graded bedding and cross-laminations in more thinly bedded, fine-grained sandstone interbeds and siltstone rip-ups and other Bouma sequence features are consistent with turbidite deposition in well-organized sand-rich submarine fan successions. This, together with the overall character of these sections, suggests they are part of the Ritchie-Alger lithofacies assemblage. Notwithstanding the sedimentological attributes that equate it with the Ritchie-Alger lithofacies assemblage, this siltstone-dominated package forms an easily recognizable lithostratigraphic unit within the west part of Hazelton map area.

Although the siltstone- and shale-dominated sequence in the northern part of the map area does not fit the classic description of the Ritchie-Alger lithofacies assemblage (*see* Evenchick *et al.*, 2004), it contains sections and sedimentary features more akin to this assemblage, suggesting it is part of the facies. In areas to the north (Evenchick et al., 2005), the Ritchie-Alger assemblage contains significant amounts of similar siltstone but is characterized by abundant sandstone interbeds (commonly more than 50% by volume) containing classic turbidite features. However, thick sections (more than 100m thick in some places) of mostly massive siltstone to silty mudstone do occur both below and above (and intertonguing with) the sandstone-dominate "classical" Ritchie-Alger assemblage. Some of these siltstone-dominated units are probably distal parts of "off-shelf" submarine fan deposits, but others appear to grade vertically into the shoreface Muskaboo Creek assemblage and thus may represent deep shelf, ramp, or slope depositional environments. In the Hazelton map area, there are several places where the siltstone dominant "member" of the Ritchie-Alger assemblage appears to directly underlie (and rarely can be shown to grade into) the shallow-marine Muskaboo Creek assemblage, thus suggesting an outer-shelf environment for much of this unit in this area (although sandstone-rich submarine fan turbidite successions also are present in some areas)

Muskaboo Creek assemblage

Muskaboo Creek rocks typically underlie the higher parts of the map area, including the Kispiox Range, Shelf Ridge, and the high ground leading down to Cutoff Mountain and Mount Pope. This package is also exposed along road cuts in the low ground between the Skeena and Kispiox Rivers. Thicknesses for this unit are based on observed sections and structural considerations and are at least a few hundred metres and probably greater than a kilometre.

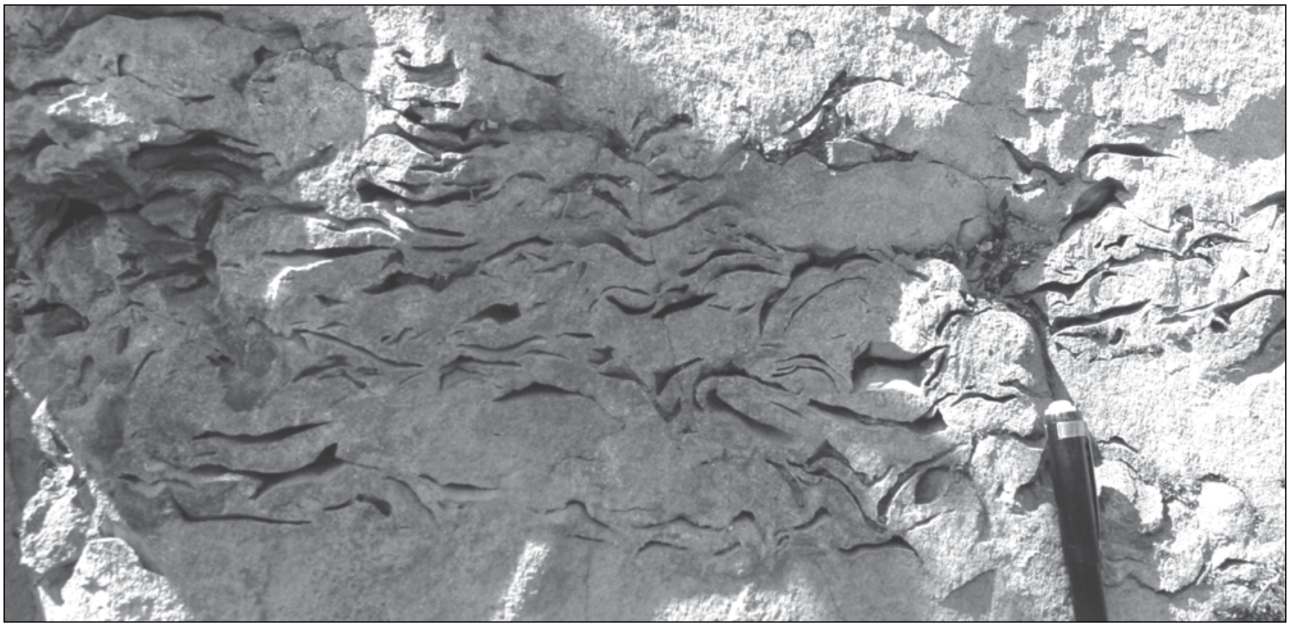


Photo 1. Molds of Ostrea sp. forming a bed 10 to 15 cm thick. These and other bivalves form "coquina" beds within sandstone sections of the Muskaboo Creek lithofacies assemblage.

The Muskaboo Creek lithofacies assemblage is characterized by thinly to moderately bedded, massive to laminated, grey to beige chert-rich sandstone in sections of continuous sandstone in places up to tens of metres thick. Interbedded grey to dark grey siltstone and silty mudstone is subordinate. Sandstone and siltstone is locally characterized by coaly plant fragments or semi-continuous carbonaceous mudstone horizons up to a few centimetres thick. The unit is also characterized by pelecypod-rich horizons up to 1 m thick ("coquinas"; Photo 1). These vary from thin, isolated beds (traceable along strike for tens of metres) to thicker, multiple stacked horizons. The carbonate shells are typically found as molds at surface and produce a distinctive pitted exposure.

The Muskaboo Creek lithofacies represents deposition in various shallow-marine shoreface environments and contains abundant evidence of wave and tidal influences. Common features include lenticular and flaser sandstone-mudstone sets, symmetrical ripples (locally mud draped), bi-directional ripples, and hummocky to swaley cross-bedding. A detailed description of this unit within the map area is given by Smith *et al.* (2005; *this volume*).

The contact between the Muskaboo Creek and Ritchie-Alger lithofacies assemblages is exposed along the main logging road immediately north of the confluence of Kuldo Creek and the Skeena River. The section is roughly 40 m thick with siltstones (greater than 75% of the section) of the Ritchie-Alger occupying the lower 20 m and grading through a thickness of 10 m to sandstones (greater than 75% of the section) and siltstones of the Muskaboo Creek assemblage.

The bulk of the fossil collections made within the study area originated from the Muskaboo Creek lithofacies assemblage. The ages of most of these are inconclusive, being broadly Mesozoic or Jurassic to Cretaceous in age. Only three localities provide more definitive age constraints: 1) a possible Oxfordian age from the top of Cutoff Mountain, 2) a Kimmeridgian to Valanginian (probably) collection along the Skeena River some 7 km southeast of Cutoff Mountain, and 3) a Late Jurassic to Valanginian suite found along Shelf Ridge (T. Poulton, personal communication, 2005).

Skeena Group

PREVIOUS WORK

Richards (1990) subdivided the Skeena Group into several informal units (Table 1). Subsequently, Bassett (1995; see also Bassett and Kleinspehn, 1996, 1997) carried out a detailed sedimentological study of the Skeena Group within the Terrace (103I), Hazelton (93M), Smithers (93L), and Whitesail (93E) map areas and proposed formal type sections and stratigraphic names (Table 1, Figure 5). This new nomenclature partly follows informal designations proposed by previous workers (Richards, 1980, 1990) and also includes new terminology (Table 1). The lithologic subdivision of the Skeena Group proposed by Bassett and Kleinspehn (1997) essentially follows that of Richards (1990), the main differences being that rocks of the Hanawald Conglomerate (even those that clearly underlie the Rocky Ridge Volcanics) have been combined with the

Roche Deboule Formation and Richard's (1990) Kitsuns Creek Formation equates with the Bulkley Canyon Formation (and Kitsuns Creek Member, Figure 5).

Skeena Group rocks represent earliest Early Cretaceous to Late Cretaceous fluvial-deltaic or estuarine sedimentation into lagoonal or restricted marine environments (Bassett and Kleinspehn, 1997). Although the subdivisions of the Skeena Group follow a stratigraphic sequence, many of the units are coeval and interfinger with each other (Figure 5). Rocks of the Bulkley Canyon Formation are over 1 km thick and represent lower delta plain to delta front environments, the latter showing tidal influences. The Laventie Formation of Basset and Kleinspehn (1997) comprises marine siltstone, sandstone, and mudstone, which they considered to represent distal deposits to the deltaic Bulkley Canyon Formation. These authors suggested that this unit is probably greater than 1 km thick.

The Rocky Ridge Formation and Kitsuns Creek Member are related to Albian to Cenomanian volcanism within the Skeena Group. Rocky Ridge Formation represents vent-proximal subaerial or submarine flows to volcanic breccia and tuff of trachybasalt to andesite composition up to 1 km thick. Volcanic-derived conglomerate, up to 500 m thick, of the Kitsuns Creek Member represents coarse fluvial-marine clastics sourced from subaerial volcanic centres.

Greater than 1 km of chert-pebble conglomerate, sandstone, siltstone, and shale of the Roche Deboule Formation represents the youngest formation of the Skeena Group. This unit appears to gradationally overlie other units of the Skeena Group. The repeated upward-fining sections of conglomerate to siltstone are believed to represent laterally migrating fluvial systems. Bassett and Kleinspehn (1997) suggest that these rocks are partially coeval with the basal Sustut Group and possibly with the Devil's Claw Formation of the Bowser Lake Group. As mentioned earlier, conglomerate that evidently underlies the Rocky Ridge Volcanics (Hanawald Conglomerate of Richards, 1990) has been grouped with the Roche Deboule Formation, suggesting that this correlation may be more complicated than proposed by Bassett and Kleinspehn (1997).

WEST HAZELTON MAP AREA

In the study area, Bassett and Kleinspehn (1997) assigned Skeena Group rocks to the fluvial Bulkley Canyon and marine Laventie Formations (the Kitsuns Creek Formation and Kitsumkalum shale of Richards [1990], respectively). Most exposures of Skeena Group rocks encountered during the summer of 2004 were found in the valleys of and between the Kispiox and Skeena Rivers. Skeena Group lithologies are also well exposed on the east flank of Kispiox Mountain and on the southeast flank of Hazelton Peak, where they are likely faulted against rocks of the Muskaboo Creek lithofacies assemblage. The true thickness of this unit in the study area is difficult to determine due to lack of adequate exposure. The section on Hazelton Peak is upwards of a kilometre thick, and Bassett and Kleinspehn (1997) measured some 200 m along railway exposures above the Skeena River several kilometres northeast of New Hazelton. Bassett and Kleinspehn (1997) have shown the Skeena Group (and the Bulkley Canyon Formation) to range in age from Berriasian to Cenomanian (Early to early Late Cretaceous).

Generally, rocks of the Skeena Group appear to be less indurated than those of the underlying Bowser Lake Group, and cleavage is poorly developed, although this may be a reflection of the greater abundance of sandstone in this sequence. Sandstone is generally grey to beige or light yellow-brown. Although chert is the dominant clast type, Skeena sandstones commonly contain trace amounts of muscovite or biotite in addition to appreciable amounts of feldspar and quartz, although in the Hazelton map area muscovite was not common even in undoubted Skeena Group strata. Metamorphic and igneous clasts were also noted in conglomeratic sections. Carbonaceous material, primarily as coaly bits or plant impressions, is very common and can locally form thin coal seams, a few centimetres thick. More extensive coal layers between 15 and 45 cm thick occur within Skeena Group lithologies on the lower slopes east of Kispiox Mountain.

Fining-upwards sequences capped by coal are common in the succession southeast of Kispiox Mountain. Well-exposed east of Hazelton Peak are lenticular, fining-upwards sandstone sections, up to 10 m thick, within grey to brown siltstones. This, together with the coaly material and root casts, is consistent with a fluvial and associated flood plain depositional environment within the 2004 study area.

Rocks along the Shegunia River assigned to the Laventie Formation by Bassett and Kleinspehn (1997) are here mapped as part of the Ritchie-Alger lithofacies assemblage. Structural measurements indicate that these siltstones are below nearby rocks of the Muskaboo Creek lithofacies assemblage, although no contact relationships were observed. Furthermore, the micaceous nature of Laventie Formation, as described by Bassett and Kleinspehn (1997), was not observed in the dark grey to black siltstones in the Shegunia River area. The lithologies of this part of the Laventie Formation are identical to Ritchie-Alger assemblage in other parts of the study area and record deposition by distal turbidites.

Nature of the Skeena-Bowser contact

Mapping along the ridge southeast of Kispiox Mountain delineated a section of Muskaboo Creek lithofacies assemblage, which grades upwards over several metres thickness into rocks of the Skeena Group (Bulkley Canyon Formation; *see* Smith *et al*., 2005; *this volume* for a detailed description). This relationship has influenced our interpretation of Skeena-Bowser contacts within the present map area. Although the juxtaposition of fluvial Skeena rocks against turbiditic Ritchie-Alger assemblage lithofacies along the Kispiox valley is probably best interpreted as a structural relationship, elsewhere within the map area a conformable relationship is permissible, as demonstrated on Kispiox Mountain. This is especially true on the west side of the Skeena River, immediately west of Mt. Thomlinson, where Skeena Group rocks are mapped to within a few hundred metres of Muskaboo Creek assemblage lithologies and bedding attitudes allow a stratigraphic relationship. Furthermore, the shoreface Muskaboo Creek lithofacies is entirely compatible with transition into fluvial environments of the Bulkley Canyon Formation, especially on a wave-dominated coastline where major river deltas have not formed. Bassett and Kleinspehn (1997) also describe current and wave ripples, suggesting a marine influence within parts of the Bulkley Canyon Formation. Thus we suggest that much of the lower Laventie Formation of Bassett and Kleinspahn is actually Muskaboo Creek assemblage of the Bowser Lake Group and is transitional upward and laterally into nonmarine Skeena Group successions.

As Bassett and Kleinspehn (1997) point out, based on age ranges and lithofacies types in the Hazelton map area, it is allowable for rocks of the Bulkley Canyon and Laventie Formations to be conformable with underlying Bowser Lake Group sediments. Applying these inferences and relationships observed as part of this study, together with the mapped distribution of lithofacies in underlying Bowser Lake Group sediments, to the interpretation of contacts within the current map area results in far fewer faults than shown on previous maps.

Structural Geology

The structural style of Bowser Lake and Skeena strata in the map area is dominated by open to closed folds (Skeena Fold Belt). These are well exposed on Shelf Ridge, as well as on Cutoff and Kispiox Mountains, where sandstone ribs of the Muskaboo Creek lithofacies assemblage outline fold structures with wavelengths in the hundreds of metres. The interbedded sandstone-siltstone succession of the Muskaboo Creek assemblage produces folds with sharp hinge lines (chevron-like fold geometries). In many outcrops of the recessive, dominantly siltstone succession of the Ritchie-Alger assemblage, bedding is not discernible, and megascopic folds were rarely observed. Reconnaissance observations immediately west of the northern map area indicate that siltstone strata of the Ritchie-Alger assemblage form megascopic folds. Immediately west of the map area, these folds show marked thickening in hinge zones more akin to similar-type geometries.

Bedding generally strikes to the southeast, especially within the northern part of the map area (Figure 6). In the south, within rocks of the Skeena and Bowser Lake Group, bedding can have an east to northeast attitude. Open to tight, northeast-plunging folds and northeast-southwest striking reverse faults occur locally and are well exposed on the railroad track at Bulkley Canyon. Poles to bedding in the Skeena Group no longer outline a girdle distribution and indicate northwest and northeast fold trends (Figure 6). Two directions of folding were observed in one coal-bearing outcrop along the Skeena River (Photo 2). Northeast- and northwest-trending folds occur locally in the western and northern Bowser Basin (*see* Evenchick, 2001; Evenchick, 1996c; Haggart, 1998). Bedding attitudes observed within rocks of the Skeena Group tended to be somewhat shallower than those within the Bowser Lake Group (Figure 6). This may be a reflection of the very steep to westward northeast limbs developed in folds in the northern part of the map area where the Skeena Group is absent.

In the northwest part of the map area, siltstones of the Ritchie-Alger lithofacies assemblage contain a penetrative to slaty cleavage. In many instances the homogenous nature of the siltstone sequence results in cleavage being the dominant fabric. Cleavage is not as well developed within the more competent sandstones and siltstones of the Muskaboo Creek assemblage and Skeena Group (Figure 6). The average orientation of this fabric within the Bowser Lake Group of the map area is consistent with the predominant northwest trend of fold structures. East- to northeast-trending attitudes are common in the southern part of the map area.

Thrust faulting associated with folding was observed west of Shelf Ridge and at Bulkley Canyon. Incomplete exposure and lack of distinctive markers have likely prevented the recognition of other faults. Structurally disrupted Skeena Group rocks along the west side of the Skeena River suggest faulting parallel or sub-parallel to bedding and may be the result of thrust motion. The juxtaposition of Skeena and Bowser Lake rocks along Hazelton Peak suggests the presence of a northeast-trending fault with southeast-side-down displacement. Skeena rocks are also most likely faulted against Ritchie-Alger assemblage lithologies along the Kispiox River. Although the position of the Skeena Group along river valleys would suggest a structural contact with nearby Bowser Lake sediments, the conformable relationship between the Skeena Group and Muskaboo Creek assemblage suggests that these units need not be separated by faults where direct relationships cannot be observed. The extensional fault systems delineated by Richards (1990; see also MacIntyre, 1998 and MacIntyre *et al.*, 1997) may not be as widespread as currently depicted.

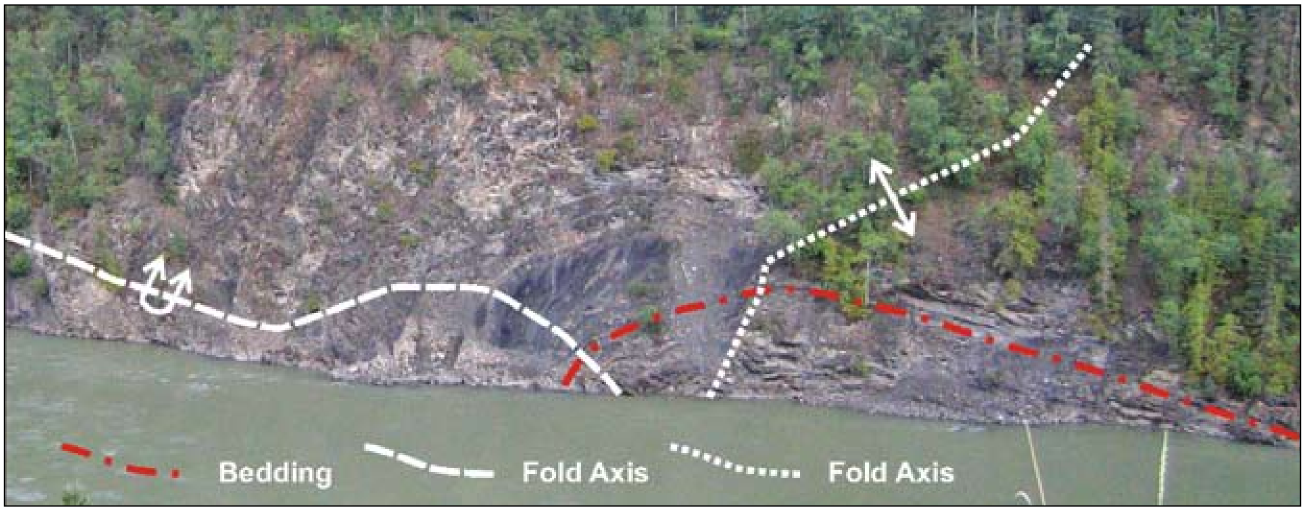


Photo 2. Outcrop of coaly Skeena Group sediments deformed by gently inclined, overturned folds and an upright, northwest-trending open fold exposed along Skeena River approximately 7 km from its confluence with Kispiox River. Bedding attitude shown in the red dashed line.

Petroleum Potential

Determining whether the Bowser and Sustut Basins have the building blocks for the development of economic pools of hydrocarbons (source, reservoir, seal, timing, etc.) will be assessed as part of the integrated program to which this study belongs. The following paragraphs contain a brief overview of the exploration history of the basins together with a short description of relevant geological data. A more in-depth listing of information, detailed exploration history, and pertinent references can be found at www.bowserbasin.com.

Exploration for hydrocarbons within the Bowser and Sustut Basins began in the late 1950s, after reconnaissance mapping in the area by the Geological Survey of Canada documented the presence of a large sedimentary basin. This culminated in the drilling of two exploration wells south of the Oweegee Dome structure by Dome Petroleum Ltd. during 1969 and 1972 (Dome Ritchie a-3-J/104-A-06; Dome Ritchie c-62-G/104-A-06). Although the ultimate target of these wells—the thick Permian carbonate exposed in Oweegee Dome—was not encountered in the subsurface, gas was detected at shallower depths (Koch, 1973). No other conventional hydrocarbon exploration has taken place in the basin.

Shell Canada Ltd. recently acquired extensive tenure in the Klappan coal fields of northern Bowser Basin and drilled several exploratory coalbed gas wells (e.g., Shell Th Ridge c-91-L/104-H-02; Hayes *et al.*, 2005, this volume). These coals are part of the Bowser Lake Group and are anthracite to semi-anthracite in rank. The Skeena Group contains significant thicknesses of coal in the Telkwa coal fields (Koo, 1983; 1984, Ryan and Dawson, 1993). These coal measures are part of the Bulkley Canyon Formation and are generally bituminous (R_o 0.6% to 0.9%) except where locally metamorphosed by intrusions to anthracitic coals (Koo, 1983, 1984). The coalbed gas potential for parts of these coal measures has been examined by Ryan (1990) and Ryan and Dawson (1994; see www.em.gov.bc.ca/Mining/Geolsurv/coal/coalref.htm#Telkwa for a complete reference listing).

Thermal maturity levels at the Klappan and Groundhog coal fields (greater than 2.5% R_o), together with the early exploration efforts, led many to believe that much of the Bowser Basin was overmature with respect to hydrocarbon potential. Recent work by the BC Ministry of Energy and Mines and the Geological Survey of Canada has shown that parts of the northern basin may be in the oil and gas window (Evenchick *et al.*, 2002). Furthermore, oil staining has been found at several surface localities and in the subsurface well cuttings, indicating that petroleum systems have operated within the basin (Osadetz *et al.*, 2003, 2004). Potential oil source rocks have not been identified but may include Mesozoic strata below the basin or intra-basinal horizons (Osadetz *et al.*, 2004; Ferri *et al.*, 2004).

Hannigan *et al.* (1995) assessed the petroleum potential of the Skeena Group and inferred total mean in-place resources of 7.19×10^{10} m^3 (2.54 TCF) gas and 2.01×10^8 m^3 (1264 million barrels) oil. A higher risk level was placed on the Bowser Lake Group due to its higher thermal maturation levels. These authors indicated a total mean in-place potential of 5.78×10^{10} m^3 (2.0 TCF) gas and no oil for the Bowser Lake Group. Data being gathered as part of this integrated project will be used as part of a reassessment of the hydrocarbon potential of the Bowser and Sustut Basins, and these values will undoubtedly be modified. Specifically, surface thermal maturation data indicate that parts of the northern Bowser Basin are in the oil window, implying that a potential oil resource could exist for the Bowser Lake Group.

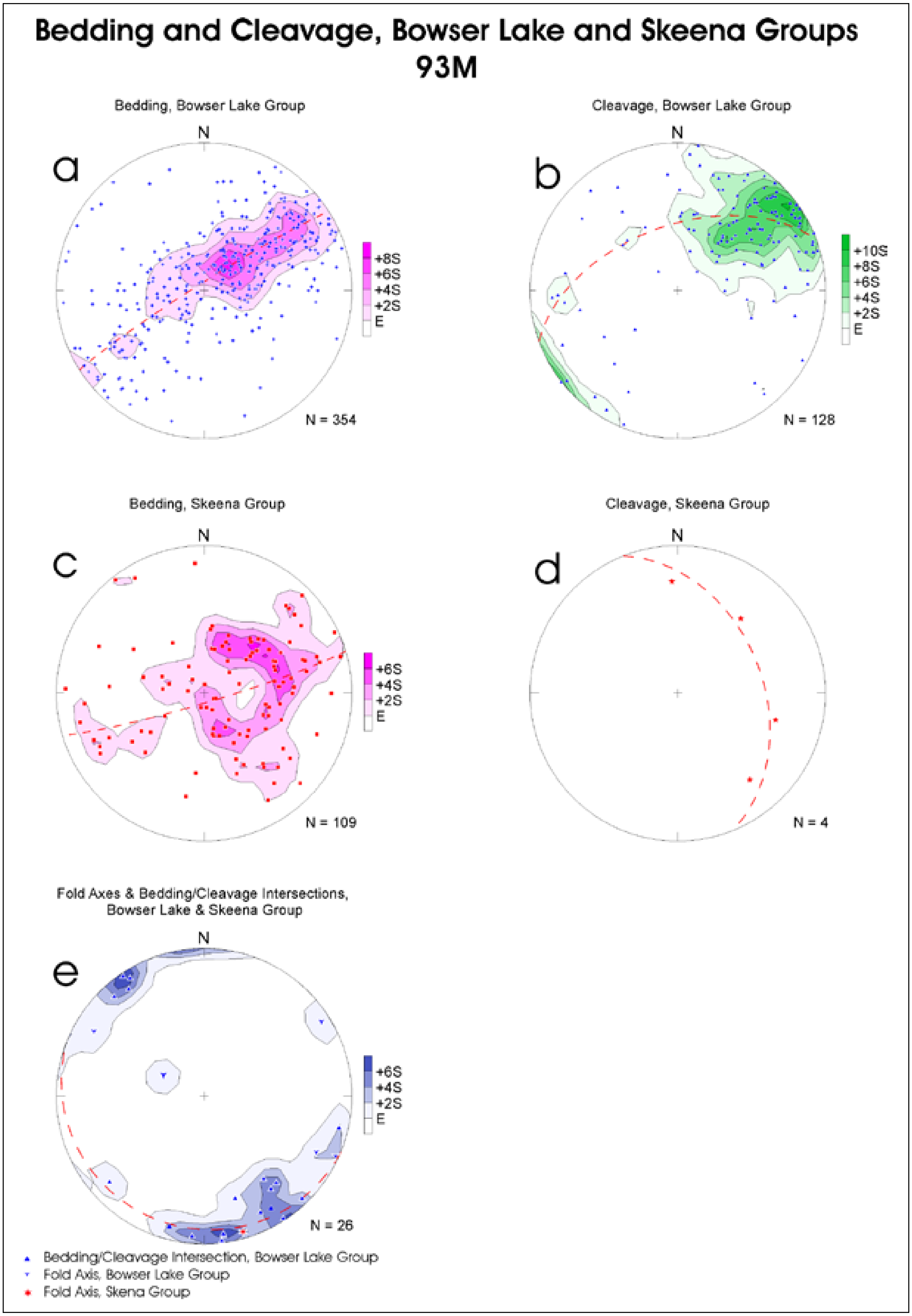
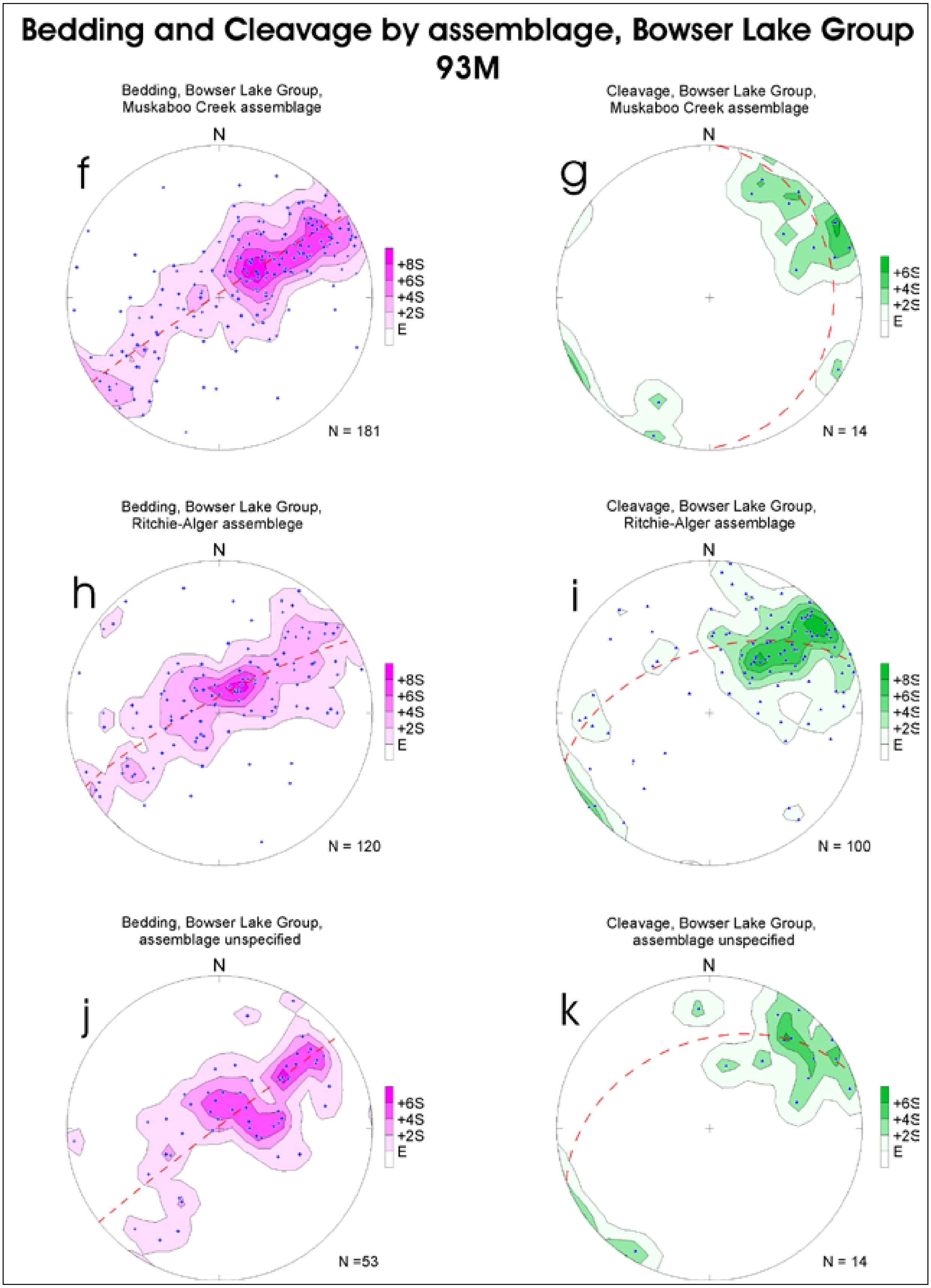


Figure 6. Stereonet diagrams for various lithologies and regions within the current study area.



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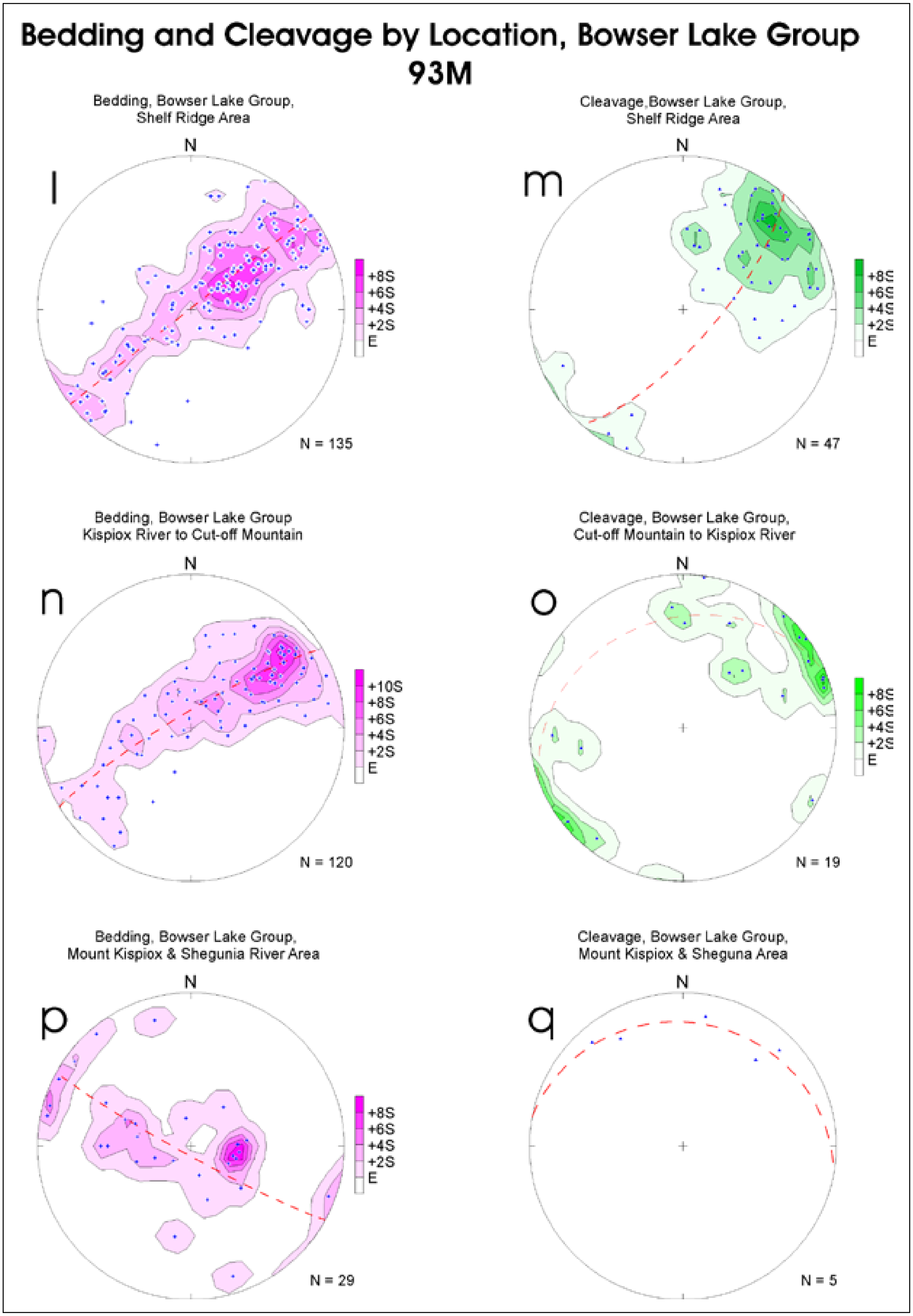

Figure 6 (continued)

Random vitrinite and bitumen reflectance values (R_o) from surface samples of Bowser and Skeena Groups in the Hazelton map area range between 0.8% and greater than 2.5% (Evenchick *et al.*, 2004) and from 0.35% to 5.6% in other parts of southern Bowser Basin (Hunt, 1992; Ryan, 1992; Ryan and Dawson, 1994). Generally, rocks of the Bowser Lake Group have higher values than do Skeena Group strata and are mature to overmature with respect to the gas window (R_o values greater than 1.6%); this is especially true for rocks of the adjoining Nass River and McConnell Creek sheets. Surface thermal maturation levels for the Skeena Group suggest these rocks reached maturation levels between the oil and gas windows, although data are limited from this rock package. The southern Bowser Basin contains numerous plugs and small plutons of Cretaceous and Tertiary age.

In the map area, samples of finer-grained, organic-rich lithologies from the Ritchie-Alger lithofacies assemblage were analyzed for source rock potential (Ferri *et al.*, 2004; Ferri and Boddy, 2005). Although these samples are overmature, the residual organic contents indicate they were originally good to very good source rocks. Considering the marine nature of these sediments, this material was probably Type I or II kerogen. No data are available for the Skeena Group from this study, but regional sampling by Hunt (1992) and Hunt and Bustin (1997) shows low to moderate source rock potential for Type III kerogen—this is entirely consistent with the coaly nature of these fluvial lithologies.

In the northern part of the basin, uppermost marine shales of the Hazelton Group were sampled for source rock potential (Ferri *et al.*, 2004; Ferri and Boddy, 2005). Although presently overmature, the current total organic content (TOC) values suggest that original organic concentrations were likely quite high and that the unit may have acted as an excellent source rock.

The Muskaboo Creek lithofacies assemblage and Skeena Group contain thick sections of clean, well-sorted sandstone, which could, under the proper conditions, develop excellent reservoir characteristics for hosting hydrocarbons. In an attempt at quantifying the reservoir potential, 22 samples of sandstone from the Bowser Lake and Skeena Groups were obtained within the Hazelton and Bowser Lake map areas. Core plugs were either obtained at the outcrop or drilled in the laboratory from large samples collected in the field. Analyses were conducted by AGAT Laboratories and include basic porosity and permeability measurements together with a description of clast lithotypes and characterization of interclast mineralogy. Preliminary porosity and permeability results are shown in Table 2, with locations of samples in west Hazelton map area shown in Figure 4. Although the samples obtained for this study are by no means a thorough representation of all possible lithotypes, the resultant porosity and permeability values indicate that the availability of a suitable reservoir may be an issue with Bowser Lake and Skeena rocks.

DISCUSSION

The conformable nature of Skeena Group with underlying Bowser Lake sedimentary rocks clearly indicates that Skeena Group rocks are part of the Bowser Basin. A logical extension of this relationship would suggest that the Skeena Group, particularly the Bulkley Canyon Formation, is broadly correlative with Early(?) Cretaceous, nonmarine fluvial successions in the northern Bowser Basin, represented by the Jenkins Creek and Endless Creek assemblages (Evenchick *et al.* 2001, 2004). These latter units appear to represent the same broad depositional environments and to be approximately the same age and stratigraphic position as the Skeena Group in southern Bowser Basin; that is, they are fluvial assemblages of roughly Early Cretaceous age that overlie marine assemblages of the Bowser Lake Group. Definitive age constraints are not available for the Jenkins Creek and Endless Creek assemblages, both being approximately Early Cretaceous in age.

Bassett and Kleinspehn (1997) correlated rocks of the Roche Deboule Formation with those of the Devil's Claw Formation and parts of the lower Sustut Group. The absence of Rocky Ridge Volcanics in northern Bowser Basin suggests the volcanics were either localized in the Smithers and Hazelton areas or are not preserved to the north.

Mapping by Richards (1990) places a thick package of conglomerate (the Hanawald Conglomerate) below the Rocky Ridge Formation and above rocks equivalent to the Bulkley Canyon Formation, delineating a sequence of conglomerate separate to those in the Roche Deboule Formation. In the southeastern part of Hazelton map area, MacIntyre (1998) describes thick conglomerate sitting above both the Rocky Ridge Formation and the Bulkley Canyon Formation where the volcanics are missing. MacIntyre (1998) equates these conglomerates with Richards' (1990) Hanawald Conglomerate. These observations suggests a sequence of conglomerate that is older than conglomerate belonging to the Roche Deboule Formation.

Mapping in the upcoming 2005 field season will concentrate on Bowser Basin stratigraphy within the central and eastern portions of Hazelton map area and hopefully will shed light on some of the preceding discussion.

TABLE 2. POROSITY AND PERMEABILITY VALUES DETERMINED FROM SAMPLES OF BOWSER LAKE AND SKEENA GROUPS FROM HAZELTON (93M) AND BOWSER LAKE (104A) MAP AREAS. SAMPLE LOCATIONS FROM THE WESTERN HAZELTON MAP AREA CAN BE SEEN IN FIGURE 4.

Field Number	Map No.	Map Sheet	Easting [1]	Northing[1]	Unit	Lithofacies Assemblage	Rock Type	Grain Size	Porosity	Bulk Density	Grain Density	Per-meability (mD)
EPF-04-13B		093M13	571414	6199356			lithic arenite	medium-coarse	0.01	2694	2713	0.00
EPF-04-57-C		093M12	568008	6165181	Bowser Lk Gp	Muskaboo Ck	arkosic arenite	fine-medium	0.03	2625	2718	0.05
EPF-04-61A		093M12	569345	6166446	Bowser Lk Gp	Muskaboo Ck	arkosic arenite	medium-coarse	0.04	2544	2655	0.34
EPF-04-65B		093M12	574865	6167562	Bowser Lk Gp	Muskaboo Ck	arkosic arenite	medium-coarse	0.03	2571	2657	0.08
EPF-04-69C		093M12	579279	6169445	Bowser Lk Gp	Muskaboo Ck	arkosic arenite	fine-medium	0.01	2691	2727	0.01
EPF-04-95C		093M05	577389	6125433	Skeena Gp		lithic arenite	fine-medium	0.02	2620	2666	0.01
EPF-04-162A		104A14	484578	6292306	Bowser Lk Gp		lithic arenite	fine-medium	0.01	2653	2689	0.00
EPF-04-182A		104A15	505718	6295800	Bowser Lk Gp	Jenkins Ck	conglomerate	pebble	0.04	2543	2642	5.02*
EPF-04-221A		104A07	521294	6254760	Bowser Lk Gp	Muskaboo Ck	arkosic arenite	fine-medium	0.01	2673	2691	0.00
EPF-04-319A		104A15	506972	6298347	Bowser Lk Gp	Groundhog-G[2]	lithic arenite	fine-medium	0.02	2608	2660	0.00
EPF-04-359A		093M05	588218	6140466	Skeena Gp		lithic arenite	medium-coarse	0.01	2664	2690	0.00
EP-04-49A		104A11	482385	6283027	Bowser Lk Gp	Muskaboo Ck	lithic arenite	fine-medium	0.02	2602	2661	0.00
EP-04-90H		104H05	463936	6354585	Bowser Lk Gp	Skelhorne	lithic arenite	fine-medium	0.01	2638	2661	0.00
EP-04-91D		104H12	441927	6385725	Bowser Lk Gp	Todagin	lithic arenite	fine-medium	0.01	2670	2685	0.01
EP-04-92D		104H12	442732	6380523	Bowser Lk Gp	Muskaboo Ck	lithic arenite	fine-medium	0.01	2636	2658	0.00
EP-04-94D		104H04	459229	6322370	Bowser Lk Gp		lithic arenite	fine	0.01	2650	2674	0.00
EP-04-101A		104A14	480712	6298521	Bowser Lk Gp		lithic arenite	fine-medium	0.01	2644	2662	0.00
EP-04-104A		104A11	477128	6278145	Bowser Lk Gp	Muskaboo Ck	lithic arenite		0.02	2624	2668	0.00
EPM-04-201A		104A14	473190	6307941	Bowser Lk Gp		lithic arenite	medium-coarse	0.01	2638	2660	0.00
EPR-04-101A		093M05	580532	6144855	Skeena Gp		lithic arenite	medium	0.04	2578	2673	0.02
EPS-04-MS1-04		093M13	568600	6193814	Bowser Lk Gp	Muskaboo Ck	lithic arenite		0.04	2596	2706	0.18
EPS-04-MS2-09		093M12	576550	6164247	Bowser Lk Gp	Muskaboo Ck	lithic arenite		0.05	2490	2620	0.09

mD: millidarcies

*fractured

[1] NAD27

[2] Groundhog-Gunnanoot

CONCLUSIONS

- In west Hazelton map area, mapping during the summer of 2004 corroborates the distribution of Skeena Group as currently portrayed on regional geology maps.
- Rocks of the Bowser Lake Group are part of the Ritchie-Alger and Muskaboo Creek lithofacies assemblages, representing submarine fan to deep shelf and shallow shelf-shoreface depositional environments, respectively. The distribution of these units is consistent with patterns seen in adjoining map areas to the north.
- In the present map area, the Skeena Group is represented by the fluvial Bulkley Canyon Formation. Strata previously considered part of the Laventie Formation we now consider to be Bowser Lake Group units.
- Rocks of the Muskaboo Creek lithofacies assemblage appear to gradationally change upward to those of the Bulkley Canyon Formation.
- Limited data indicate that Skeena Group rocks are generally less thermally mature than those of the Bowser Lake Group, with R_o values as low as 0.8%. Data from nearby Nass River map area show Bowser Lake sediments are generally mature to overmature with respect to the gas window.
- Organic matter within the Skeena Group has a Type III signature.

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GEOCHEMISTRY OF EARLY TO MIDDLE JURASSIC ORGANIC-RICH SHALES, INTERMONTANE BASINS, BRITISH COLUMBIA

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ABSTRACT

Rock Eval data are presented for Early to Middle Jurassic black clastics belonging to the Spatsizi and Ashcroft Formations. Samples of the Spatsizi Formation originated in northern, northeastern, and northwestern parts of the Bowser Basin and include the Joan Lake, western McConnell Creek, and Oweegee Dome areas, respectively. Samples of Ashcroft Formation and equivalent strata were taken in the Ashcroft area and in the vicinity of the town of Likely. Several sample transects of the Spatsizi Formation were made in the Joan Lake area and multi-element, ICP-MS analyses were also acquired for the purposes of characterizing the formation.

Spatsizi and Ashcroft Formations are, on average, several hundred metres thick. Total organic carbon (TOC) contents for these rocks range up to 6% and average 1.7%. The Abou Member of the Spatsizi Formation averages 30 m in thickness and contains TOC values of approximately 3.6%. Rock Eval (S2 peak) and vitrinite reflectance data indicate that these rocks are mature to overmature in these areas and have little to no remaining generative potential. Due to the high thermal maturation levels, very little can be said about the type of kerogen this organic matter represented, although considering the marine origin of the sediments it was either Type I or II. Assuming that much of the organic material was expelled during maturation of these sediments, the original organic content of these rocks may have been from 2 to 4 times greater, suggesting they were excellent source rocks.

These Early to Middle Jurassic black clastic rocks are regional in extent, underlying the entire Bowser Basin and potentially many of the other Mesozoic Intermontane clastic sedimentary basins. Under the proper conditions, these rocks would act as excellent hydrocarbon source rocks.

KEYWORDS: Source rocks, geochemistry, organic, hydrocarbons, metals, Early Middle Jurassic, Bowser Basin, Spatsizi Formation, Ashcroft Formation, Likely, Oweegee Dome

INTRODUCTION

During the summer of 2003, several localities containing Early to Middle Jurassic black clastic rocks within the Quesnel Trough and northern Bowser Basin were sampled for hydrocarbon source rock potential. This organic-rich succession underlies many of the Jura-Cretaceous clastic Intermontane basins of the Canadian Cordillera and, under the right conditions, would have acted as a hydrocarbon source rock. A description of the general geology around the sample areas, together with a regional perspective, was detailed in a Summary of Activities article by Ferri *et al.* (2004). At the time of publishing, the samples had not been analyzed and no data were available for the article. These analyses have now been performed and the Rock Eval data are included in the following pages. In addition, Rock Eval data for samples of the Spatsizi Formation from its type area are also presented here. These samples were collected during the 2004 field season as part of the Integrated Petroleum Resource Potential and Geoscience Studies of the Bowser and Sustut Basins Program, a partnership between Natural Resources Canada (Geological Survey of Canada), the B.C. Ministry of Energy and Mines (Resource Development and Geoscience Branch), and Simon Fraser University (Department of Earth Sciences). The ultimate aim of this project is a better understanding of the geology and hydrocarbon potential of these large Intermontane sedimentary basins (Evenchick *et al.*, 2004, 2005; Hayes *et al.*, 2004).

Samples collected in 2003 originated in the Ashcroft, Likely, and western McConnell Creek map areas (*see* Ferri *et al.*, 2004; Figures 1 to 7). The intent of this paper is to make this analytical data available, together with new geological and geochemical data for the Spatsizi Formation from both the Joan Lake area of northern Bowser Basin and the north end of the Oweegee Dome structure in western Bowser Lake map area (104A).

RESULTS

Data for samples from the Joan Lake, McConnell Creek, Oweegee Dome, Ashcroft, and Likely areas are shown in Table 1. The locations of the sample sites are shown in Figures 2 to 7. Samples were analyzed with the Rock Eval 6 instrument at the organic petrology labora-

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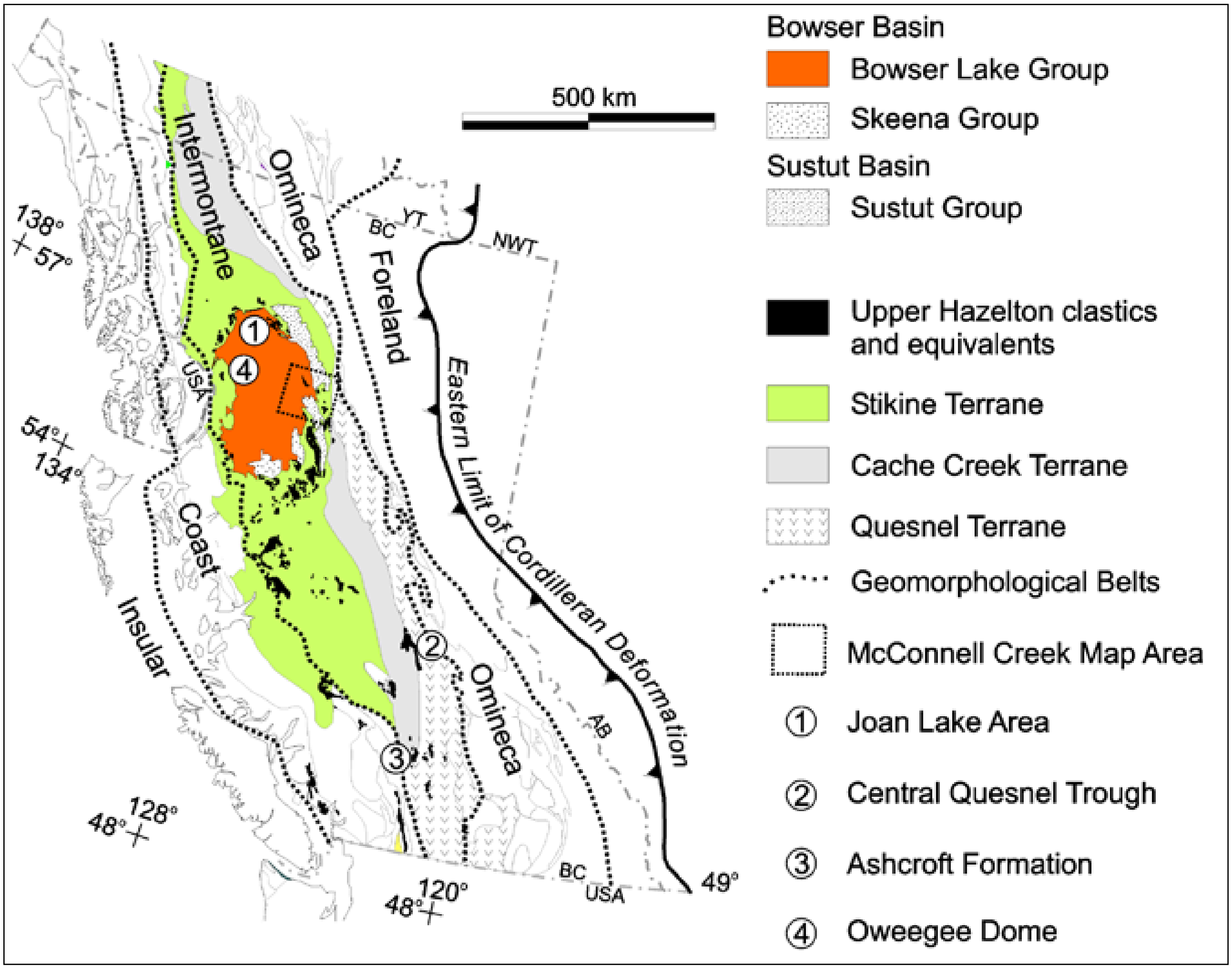

Figure 1. **Location of the Bowser and Sustut basins within the geological framework of the Canadian Cordillera (modified from Evenchick *et al*., 2004).**

tories of the Geological Survey of Canada in Calgary. In addition, multi-element ICP-MS analysis of samples from several transects of the Spatsizi Formation in the Joan Lake area were performed by aqua regia and total acid digestion. These analyses were performed at the laboratories of ACME Analytical Ltd. in Vancouver, BC; a description of these analytical techniques can be found at the ACME website (www.acmelab.com). The rationale behind these analyses was an attempt at geochemically "finger printing" this sequence via trace metal concentrations. It is commonly understood that many metals are precipitated from seawater due to the reducing environment during anoxia, and it is hoped that this chemical signature will be useful in future regional correlations of this unit. The aqua regia digestion would primarily dissolve non-silicate material (e.g., organics and sulphides.) and give a signature of metals precipitated during deposition. Results from the total acid digestion would reflect, in part, composition of clastic source terranes. Due to budgetary restrictions, only a portion of the samples were analyzed by total acid digestion.

Spatsizi Formation

Joan Lake Area

Thomson *et al.* (1986) describe organic-rich shales and siltstones of Pleinsbachian to Bajocian age (Figures 2 to 4) along northern Bowser Basin in the vicinity of Joan Lake. Thomson *et al.* (1986) originally assigned these to the Spatsizi Group, though they were later lowered to formation status by Evenchick and Thorkelson (2005) and made part of the upper Hazelton Group (*see* Ferri *et al.*, 2004).

Fine-grained siliciclastic lithologies of the Spatsizi Formation record the termination of widespread volcanic activity, represented by the Hazelton Group, and delineate the beginning of Bowser Basin sedimentation (Ricketts *et al.*, 1992). The Spatsizi Formation is up to 900 m thick and subdivided into five members, which are, from oldest to youngest, Joan, Wolf Den, Melisson, Abou, and Quock (Figure 2; Thomson *et al.*, 1986; Evenchick and Thorkel-

TABLE 1. ROCK EVAL DATA FOR SAMPLES OF THE SPATSIZI AND ASHCROFT FORMATIONS, TOGETHER WITH UNNAMED EARLY TO MIDDLE JURASSIC STRATA. UTM COORDINATES IN NAD 27 DATUM.

Sample Number	Rock Unit	Map Num.	Easting	Northing	Tmax	S1	S2	S3	PI	S2/S3	PC %	TOC %	HI	OI
See Figures 2, 3 and 4 for locations														
EPF04-191A	Spatsizi Fm	191A	499192	6373564	-	0.00	0.00	0.39	0.00	0.00	0.00	1.12	0	35
EPF04-191B	Spatsizi Fm	191B	499192	6373564	518	0.00	0.00	1.17	0.00	0.00	0.00	1.91	0	61
EPF04-191C	Spatsizi Fm	191C	499192	6373564	515	0.00	0.00	0.76	0.00	0.00	0.00	1.86	0	41
EPF04-192A	Spatsizi Fm	192A	499147	6373447	-	0.00	0.00	0.30	0.00	0.00	0.00	1.39	0	22
EPF04-192B	Spatsizi Fm	192B	499147	6373447	-	0.00	0.00	0.22	1.00	0.00	0.00	1.87	0	12
EPF04-192C	Spatsizi Fm	192C	499147	6373447	-	0.00	0.00	0.22	1.00	0.00	0.00	1.28	0	17
EPF04-192D	Spatsizi Fm	192D	499147	6373447	-	0.00	0.00	0.34	1.00	0.00	0.01	1.50	0	23
EPF04-193A	Spatsizi Fm	193A	499122	6373305	295	0.00	0.00	0.66	0.50	0.00	0.00	1.40	0	47
EPF04-193B	Spatsizi Fm	193B	499122	6373305	-	0.00	0.00	0.58	1.00	0.00	0.00	2.42	0	24
EPF04-194A	Spatsizi Fm	194A	499107	6373190	-	0.00	0.00	0.42	1.00	0.00	0.00	1.25	0	34
EPF04-194B	Spatsizi Fm	194B	499107	6373190	-	0.00	0.00	0.35	1.00	0.00	0.01	1.28	0	27
EPF04-195A	Spatsizi Fm	195A	499100	6373077	-	0.00	0.00	0.45	1.00	0.00	0.00	1.42	0	32
EPF04-195B	Spatsizi Fm	195B	499100	6373077	-	0.00	0.00	0.49	1.00	0.00	0.00	1.06	0	46
EPF04-195C	Spatsizi Fm	195C	499100	6373077	-	0.00	0.00	0.49	1.00	0.00	0.00	1.12	0	44
EPF04-195D	Spatsizi Fm	195D	499100	6373077	-	0.00	0.00	0.28	1.00	0.00	0.00	0.76	0	37
EPF04-196A	Spatsizi Fm	196A	499110	6372927	-	0.00	0.00	0.21	0.00	0.00	0.00	0.82	0	26
EPF04-196B	Spatsizi Fm	196B	499110	6372927	-	0.00	0.00	0.43	1.00	0.00	0.00	1.09	0	39
EPF04-197A	Spatsizi Fm	197A	499137	6372870	337	0.00	0.00	0.42	0.53	0.00	0.00	0.90	0	47
EPF04-197B	Spatsizi Fm	197B	499137	6372870	433	0.00	0.00	0.15	0.04	0.00	0.00	0.41	0	37
EPF04-197C	Spatsizi Fm	197C	499137	6372870	-	0.00	0.00	0.54	1.00	0.00	0.01	1.41	0	38
EPF04-198A	Spatsizi Fm	198A	499130	6372737	-	0.00	0.00	0.42	1.00	0.00	0.00	1.84	0	23
EPF04-198B	Spatsizi Fm	198B	499130	6372737	-	0.00	0.00	0.30	1.00	0.00	0.00	2.62	0	11
EPF04-198C	Spatsizi Fm	198C	499130	6372737	527	0.00	0.00	1.51	0.00	0.00	0.01	3.03	0	50
EPF04-198D	Spatsizi Fm	198D	499130	6372737	517	0.00	0.01	2.18	0.06	0.00	0.01	4.60	0	47
EPF04-199A	Spatsizi Fm	199A	499472	6372793	391	0.00	0.01	1.25	0.05	0.01	0.01	0.55	2	227
EPF04-200A	Spatsizi Fm	200A	500666	6373358	426	0.00	0.00	0.34	0.19	0.00	0.00	0.71	0	48
EPF04-200B	Spatsizi Fm	200B	500666	6373358	587	0.00	0.00	0.44	0.91	0.00	0.00	0.24	0	183
EPF04-201B	Spatsizi Fm	201B	500625	6373340	345	0.00	0.00	0.40	0.57	0.00	0.00	1.01	0	40
EPF04-201C	Spatsizi Fm	201C	500625	6373340	322	0.00	0.00	0.34	0.88	0.00	0.00	0.79	0	43
EPF04-201D	Spatsizi Fm	201D	500625	6373340	522	0.00	0.00	0.88	0.86	0.00	0.00	1.18	0	75
EPF04-202A	Spatsizi Fm	202A	500586	6373235	352	0.00	0.00	1.04	0.21	0.00	0.01	0.99	0	105
EPF04-202B	Spatsizi Fm	202B	500586	6373235	420	0.00	0.00	0.46	0.72	0.00	0.00	0.76	0	61
EPF04-202C	Spatsizi Fm	202C	500586	6373235	-	0.00	0.00	0.37	1.00	0.00	0.01	1.02	0	36
EPF04-202D	Spatsizi Fm	202D	500586	6373235	362	0.00	0.00	0.59	0.47	0.00	0.00	1.27	0	46
EPF04-203A	Spatsizi Fm	203A	500527	6373166	-	0.00	0.00	0.51	1.00	0.00	0.00	1.16	0	44
EPF04-203B	Spatsizi Fm	203B	500527	6373166	-	0.00	0.00	0.46	1.00	0.00	0.01	1.19	0	39
EPF04-203C	Spatsizi Fm	203C	500527	6373166	522	0.00	0.00	1.04	0.16	0.00	0.00	1.28	0	81
EPF04-203D	Spatsizi Fm	203D	500527	6373166	329	0.00	0.00	0.65	0.44	0.00	0.00	1.12	0	58
EPF04-204A	Spatsizi Fm	204A	500472	6373038	-	0.00	0.00	0.57	1.00	0.00	0.00	1.26	0	45
EPF04-205A	Spatsizi Fm	205A	500364	6372621	606	0.00	0.00	0.74	0.23	0.00	0.00	4.92	0	15
EPF04-205C	Spatsizi Fm	205C	500364	6372621	602	0.00	0.00	0.36	0.81	0.00	0.01	4.20	0	9
EPF04-205D	Spatsizi Fm	205D	500364	6372621	607	0.00	0.00	0.45	0.87	0.00	0.00	4.62	0	10
EPF04-205E	Spatsizi Fm	205E	500364	6372621	519	0.00	0.01	1.72	0.01	0.01	0.01	3.65	0	47
EPF04-206A	Spatsizi Fm	206A	500291	6372595	314	0.00	0.00	0.78	0.84	0.00	0.00	4.78	0	16
EPF04-207A	Spatsizi Fm	207A	500253	6372571	605	0.00	0.00	1.23	0.09	0.00	0.00	4.40	0	28
EPF04-207C	Spatsizi Fm	207C	500253	6372571	-	0.00	0.00	0.38	1.00	0.00	0.01	3.72	0	10
EPF04-207E	Spatsizi Fm	207E	500253	6372571	-	0.00	0.00	0.64	1.00	0.00	0.00	4.03	0	16
EPF04-208A	Spatsizi Fm	208A	500189	6372496	522	0.00	0.02	2.45	0.16	0.01	0.01	2.88	1	85
EPF04-209A	Spatsizi Fm	209A	500068	6372471	524	0.00	0.01	1.70	0.00	0.01	0.01	1.74	1	98
EPF04-210A	Spatsizi Fm	210A	499972	6372463	572	0.00	0.00	1.03	0.04	0.00	0.00	3.45	0	30
EPF04-257B	Spatsizi Fm	OD	460587	6283817	-	0.00	0.00	0.23	1.00	0.00	0.00	0.38	0	61
EPF04-258A	Spatsizi Fm	OD	460562	6283813	-	0.00	0.00	0.27	1.00	0.00	0.00	0.23	0	117
EPF04-259A	Spatsizi Fm	OD	460540	6283886	606	0.00	0.00	0.70	0.00	0.00	0.00	1.47	0	48
EPF04-260A	Spatsizi Fm	OD	460529	6283956	606	0.00	0.01	0.18	0.03	0.06	0.01	1.69	1	11
EPF04-261A	Spatsizi Fm	OD	460489	6284094	521	0.00	0.01	0.44	0.00	0.02	0.01	0.87	1	51

TABLE 1, CONTINUED

Sample Number	Rock Unit	Map Num.	Easting	Northing	Tmax	S1	S2	S3	PI	S2/S3	PC %	TOC %	HI	OI
See Figure 5 for locations														
EPF03-091-1	Bowser Lk Gp	1	599419	6273768	-	0.00	0.00	0.44	1.00	0.00	0.00	0.57	0	77
EPF03-095-1	Spatsizi Fm	2	617036	6223010	441	0.00	0.12	0.51	0.01	0.24	0.02	1.58	8	32
EPF03-135-1	Spatsizi Fm	3	605196	6285736	606	0.00	0.00	0.43	0.60	0.00	0.01	1.75	0	25
EPF03-139-1	Spatsizi Fm	4	604749	6286114	525	0.00	0.05	1.06	0.00	0.05	0.01	1.57	3	68
EPF03-139-3	Spatsizi Fm	4	604749	6286114	440	0.01	0.03	1.03	0.18	0.03	0.01	1.11	3	93
EPF03-139-4	Spatsizi Fm	4	604749	6286114	531	0.00	0.01	0.74	0.38	0.01	0.00	1.49	1	50
EPF03-140-1	Spatsizi Fm	5	604661	6286652	600	0.00	0.00	0.65	0.12	0.00	0.01	1.39	0	47
EPF03-142-1	Spatsizi Fm	6	604317	6287363	295	0.00	0.00	1.27	0.54	0.00	0.01	3.12	0	41
EPF03-161-1	Spatsizi Fm	7	600946	6286619	-	0.00	0.00	0.33	1.00	0.00	0.00	0.81	0	41
EPF03-165-1	Spatsizi Fm	8	601148	6285998	-	0.00	0.00	0.20	1.00	0.00	0.00	0.59	0	34
EPF03-166-1	Spatsizi Fm	9	601192	6285337	606	0.00	0.00	1.11	0.42	0.00	0.01	3.87	0	29
EPF03-167-3	Spatsizi Fm	10	608444	6292880	604	0.00	0.00	0.34	0.32	0.00	0.00	0.62	0	55
EPF03-168-1	Spatsizi Fm	11	608257	6292354	606	0.00	0.01	0.38	0.03	0.03	0.00	1.15	1	33
EPF03-171-1	Spatsizi Fm	12	608301	6291561	607	0.00	0.03	0.27	0.00	0.11	0.00	0.86	5	31
EPF03-173-1	Spatsizi Fm	13	608915	6291068	605	0.00	0.02	0.32	0.00	0.06	0.00	0.93	2	34
EPF03-177-1	Spatsizi Fm	14	608594	6289218	606	0.00	0.00	0.43	0.33	0.00	0.00	0.66	0	65
EPF03-180-3	Spatsizi Fm	15	598939	6293063	-	0.00	0.00	1.87	1.00	0.00	0.01	6.01	0	31
EPF03-184-1	Spatsizi Fm	16	598577	6292977	446	0.00	0.01	0.96	0.02	0.01	0.01	1.37	1	70
EPF03-184-2	Spatsizi Fm	16	598577	6292977	-	0.00	0.00	0.56	0.97	0.00	0.00	2.23	0	25
EPF03-191-1	Spatsizi Fm	17	605103	6285081	539	0.00	0.04	0.07	0.00	0.57	0.00	0.27	15	26
EPF03-205-1	Spatsizi Fm	18	607857	6279674	605	0.00	0.02	0.27	0.01	0.07	0.01	0.91	2	30
EPF03-224-2	Spatsizi Fm	19	648880	6247807	469	0.01	0.04	0.69	0.21	0.06	0.02	0.18	22	383
EPF03-228-1	Spatsizi Fm	20	596444	6298903	382	0.00	0.02	1.47	0.13	0.01	0.04	1.04	2	141
EPF03-231-1	Spatsizi Fm	21	595830	6297891	315	0.01	0.00	0.45	0.96	0.00	0.00	3.34	0	13
See Figure 7 for locations														
FF04-01A	Ashcroft Fm	B	619543	5613654	606	0.00	0.00	0.28	0.16	0.00	0.00	1.10	0	25
FF04-01B	Ashcroft Fm	B	619543	5613654	-	0.00	0.00	0.15	1.00	0.00	0.00	0.60	0	25
FF04-01E	Ashcroft Fm	B	619543	5613654	606	0.00	0.01	1.21	0.11	0.01	0.01	5.09	0	24
FF-03-1A	Ashcroft Fm	A	621033	5620414	475	0.00	0.04	0.43	0.00	0.09	0.01	1.32	3	33
FF-03-2A	Ashcroft Fm	A	621066	5620479	-	0.00	0.00	0.36	1.00	0.00	0.00	1.58	0	23
FF-03-2B	Ashcroft Fm	A	621066	5620479	315	0.00	0.00	0.24	0.91	0.00	0.00	1.17	0	21
FF-03-3A	Ashcroft Fm	A	621073	5620505	490	0.00	0.00	3.95	1.00	0.00	0.01	0.73	0	541
FF-03-4A	Ashcroft Fm	A	621106	5620590	-	0.00	0.00	1.90	1.00	0.00	0.00	1.65	0	115
FF-03-4B	Ashcroft Fm	A	621106	5620590	606	0.00	0.00	1.16	1.00	0.00	0.00	1.42	0	82
FF-03-5A	Ashcroft Fm	A	621140	5620636	-	0.00	0.00	1.30	1.00	0.00	0.00	0.73	0	178
FF-03-6A	Ashcroft Fm	A	621147	5620691	607	0.00	0.00	1.01	1.00	0.00	0.00	2.85	0	35
FF-03-8A	Ashcroft Fm	A	621046	5620363	324	0.00	0.00	0.55	1.00	0.00	0.01	1.29	0	43
See Figure 6 for locations														
FF-03-13A	E-M Jurassic	C	589945	5833905	606	0.00	0.13	0.49	0.02	0.27	0.02	5.50	3	9
FF-03-13B	E-M Jurassic	C	589945	5833905	605	0.00	0.12	0.39	0.02	0.31	0.02	5.05	3	8

OD - Oweegee Dome

son, 2005). The formation is characterized by dark grey to black, organic-rich, fine-grained siliciclastics, which record deposition in anoxic water conditions. The Spatsizi Formation, particularly the upper Abou and Quock Members ("Pyjama Beds"), and its equivalents can be traced around the base of the Bowser Basin and found within structural windows, suggesting it underlies the entire basin. The high organic content of Spatsizi shales and siltstones would suggest that, under the proper conditions, this unit may have acted as a hydrocarbon source bed for potential reservoirs in succeeding clastics of the Bowser Lake and Sustut Groups.

At Joan Lake, Spatsizi lithologies sit atop rhyolites of the Cold Fish Volcanics, which are exposed in the core of a doubly plunging anticline. The Spatsizi Formation displays considerable lithologic and thickness variation around this structure. Rocks of the Joan Member are developed only locally along the top of the Cold Fish Volcanics, and the Melisson Member is commonly absent due to removal or non-deposition below the sub-Abou unconformity. In the vicinity of Joan Lake, the Spatsizi Formation varies in thickness from 400 to over 900 m. Although the increased thickness seen at the northwest end of the anticline may in part be structural, cross-sections indicate that the variation is probably a reflection of removal or non-deposition of lithologies below the Abou Member (see sections in Figure 3).

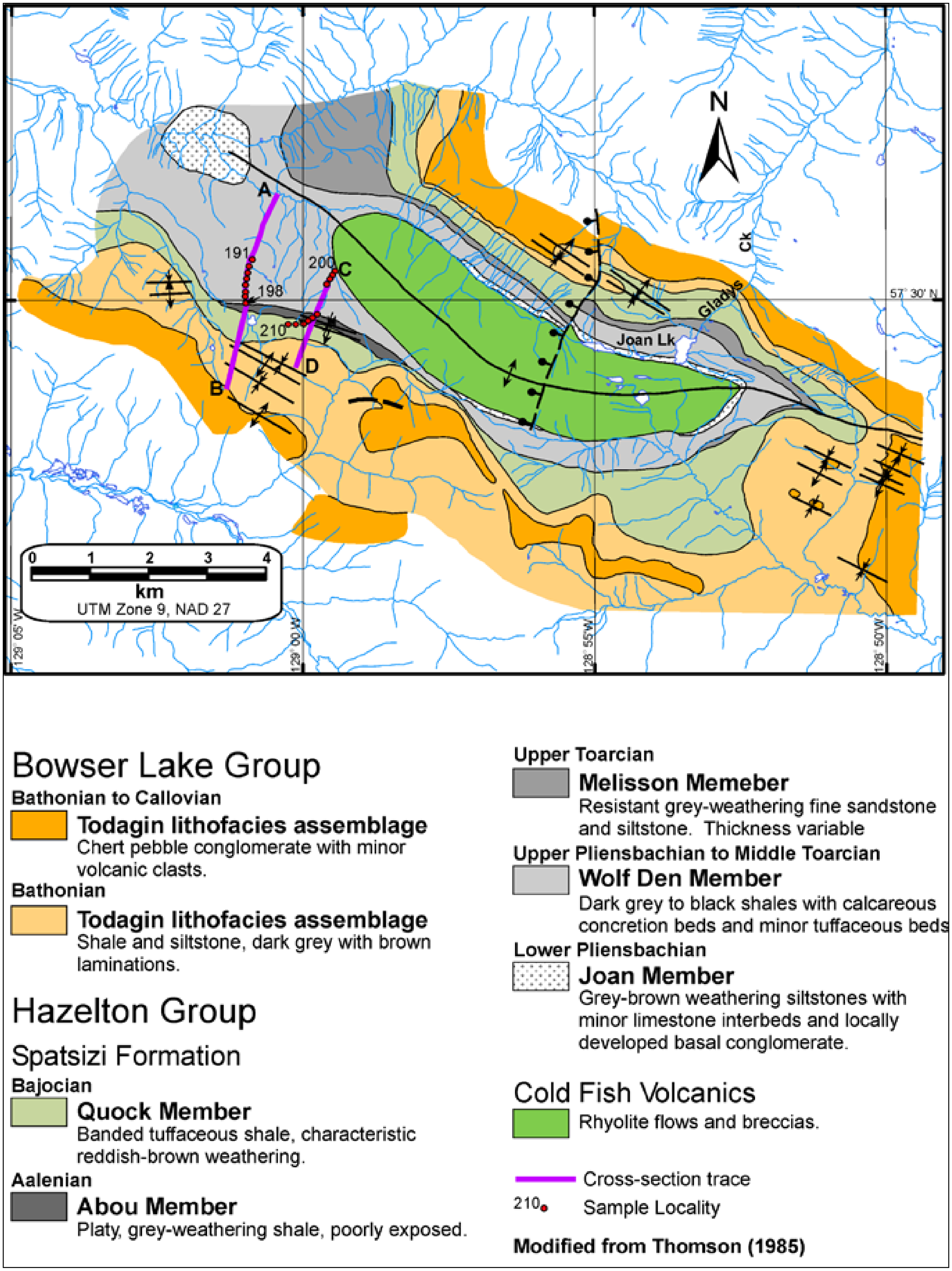

Figure 2. Geological map of the Joan Lake area, showing location of sampling transects and structural cross-section lines shown in Figure 3. Adapted from Thomson et al., 1986.

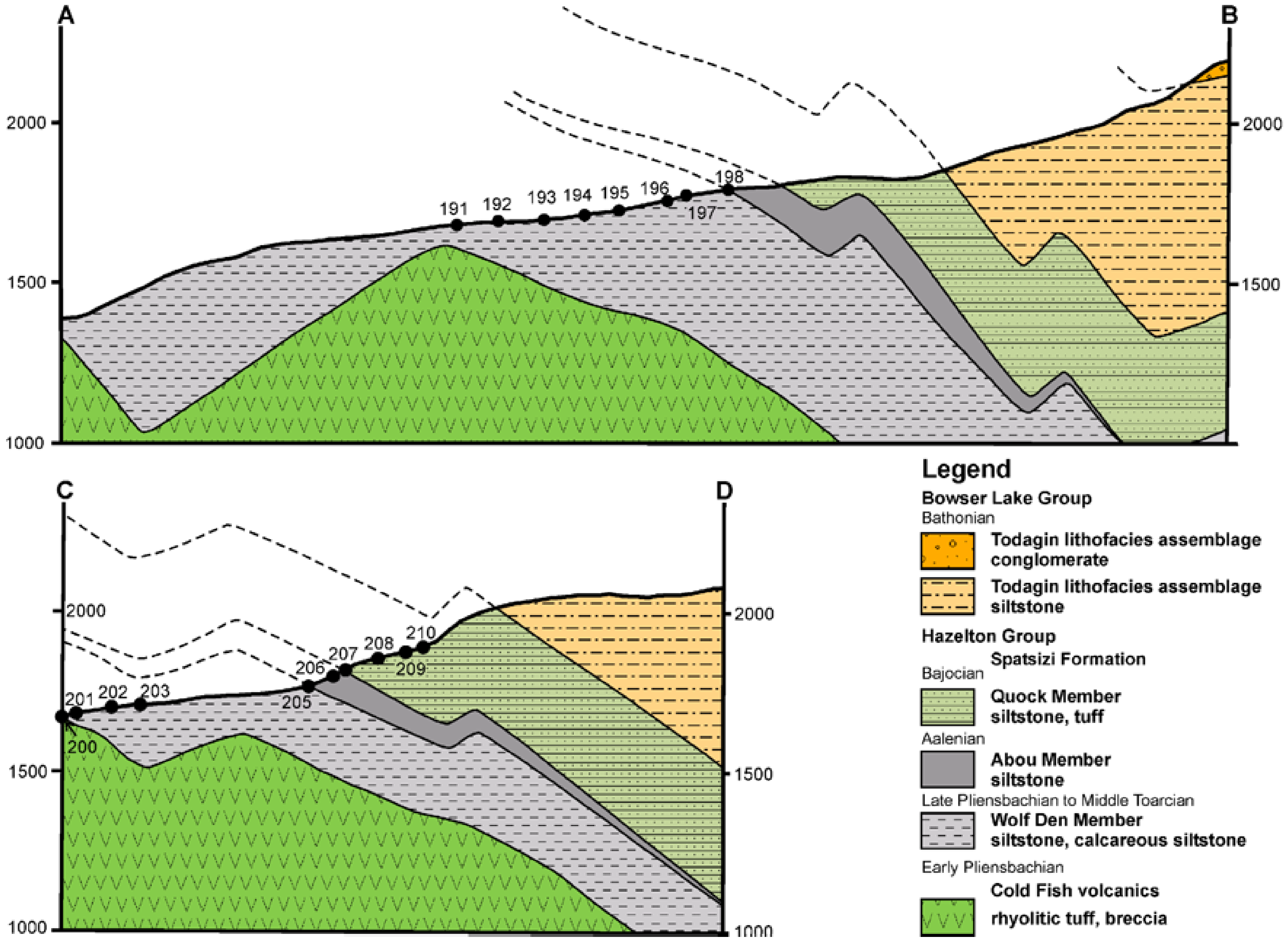

Figure 3. Structural cross-sections along sampling transects in the Joan Lake area. Sample locations refer to data in Tables 1, 2 and 3.

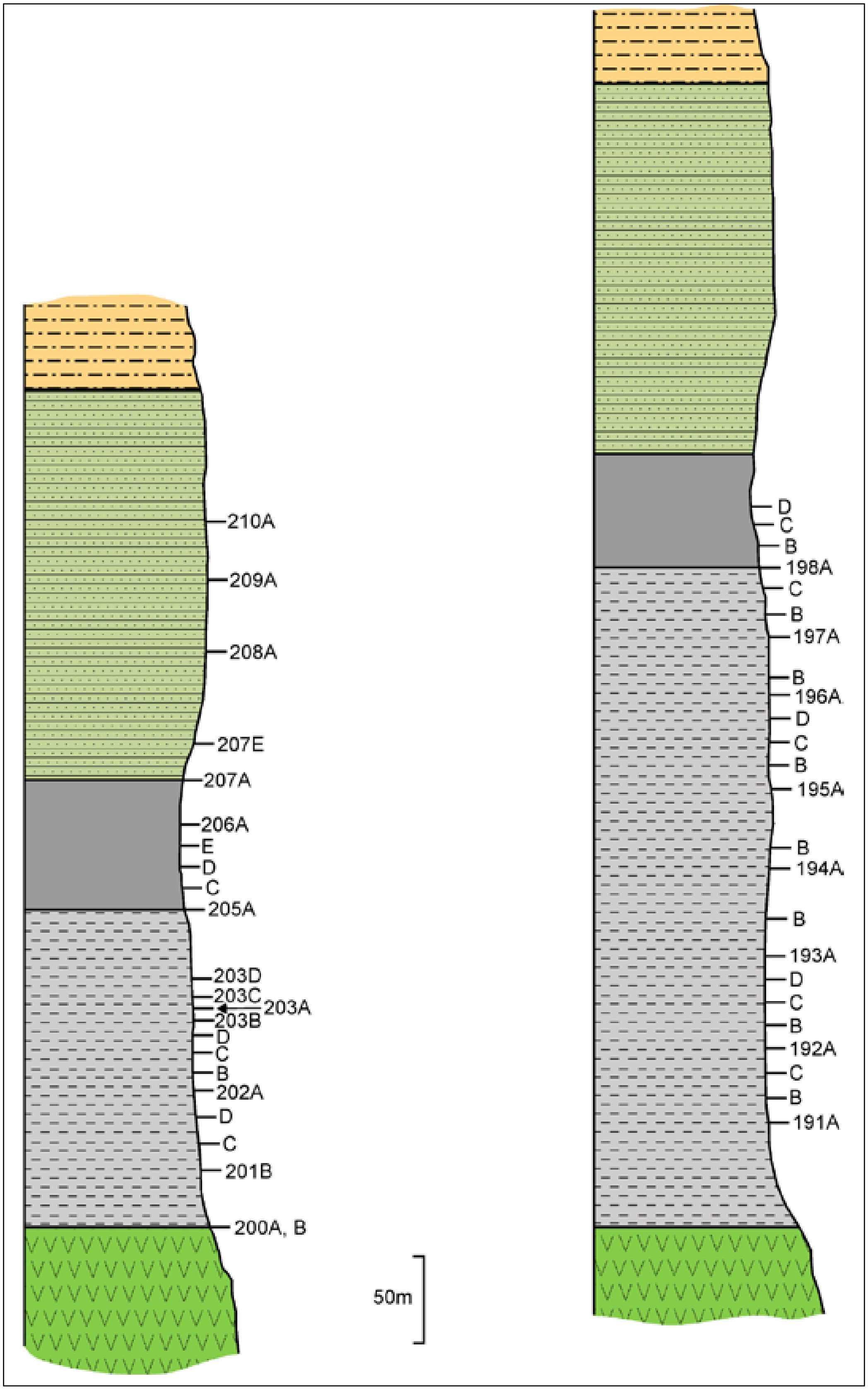

Figure 4. Simplified stratigraphic sections of the Spatsizi Formation, as seen along sampling transects. Sample locations refer to data in Tables 1, 2, and 3.

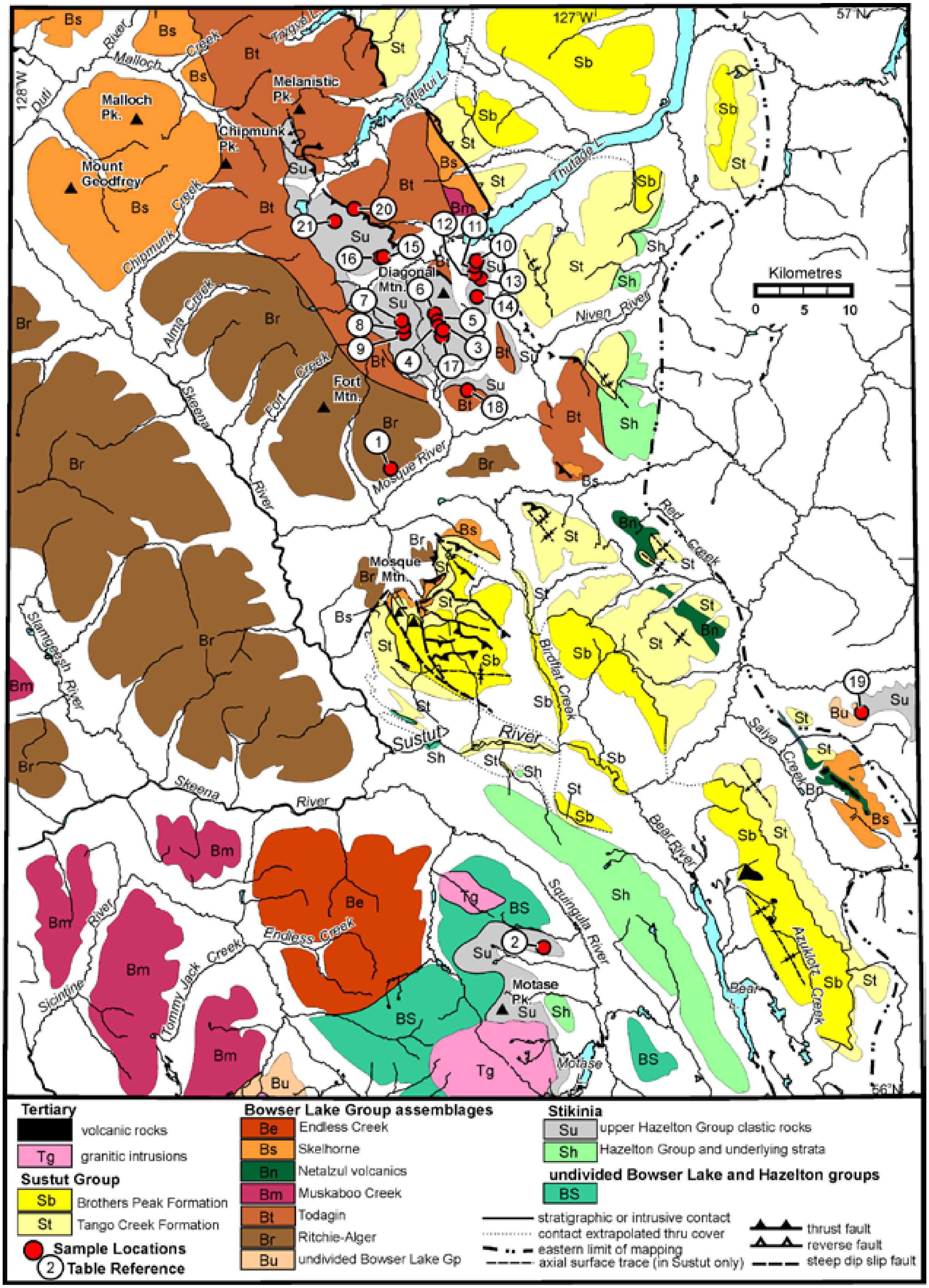

Figure 5. General geology map of the west part of McConnell Creek map area, showing the locations of Spatsizi Formation samples listed in Table 1. Modified from Evenchick et al., 2004.

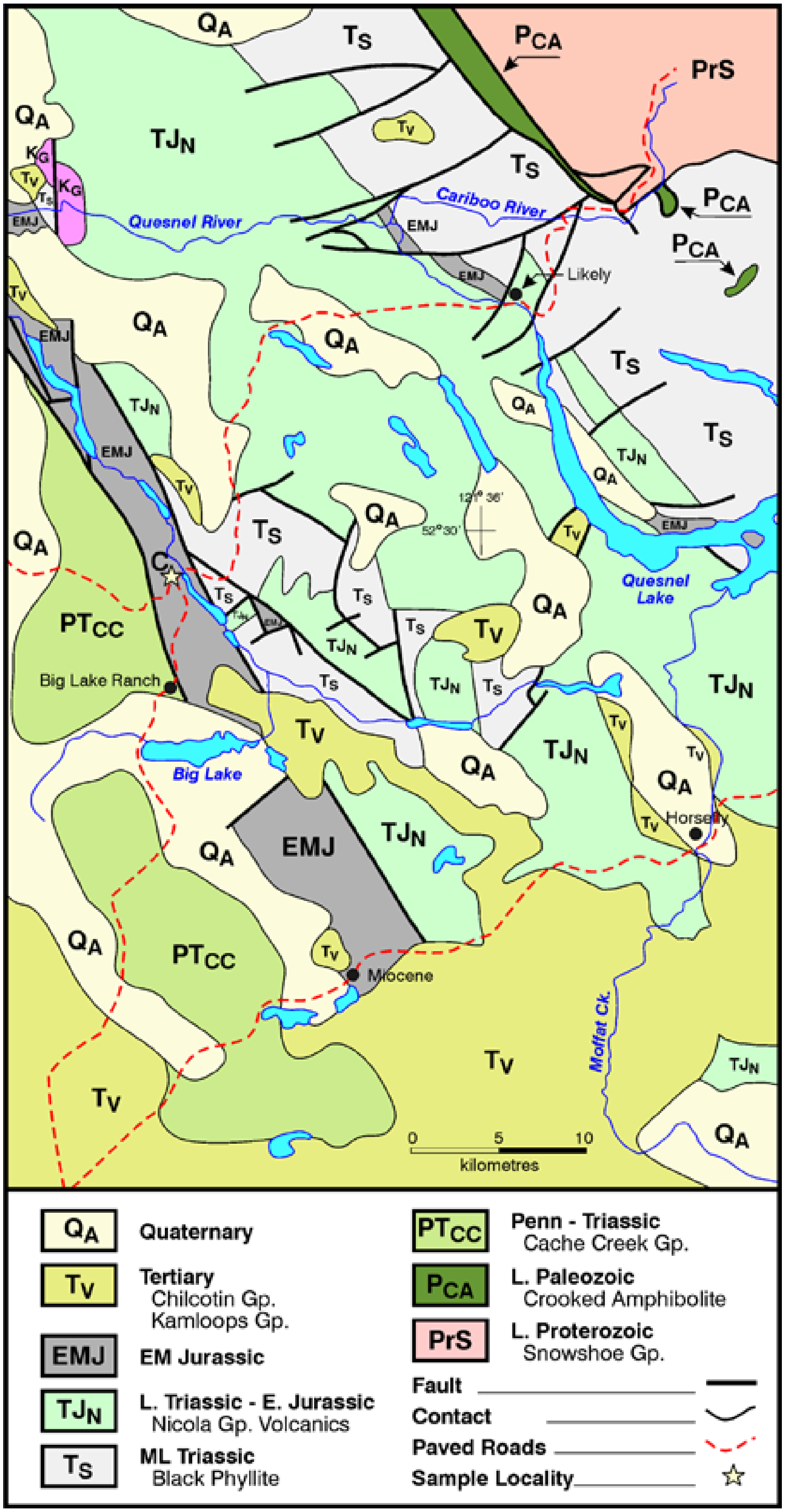

Figure 6. General geology of the Likely area, showing the location of unnamed Early to Middle Jurassic samples listed in Table 1. Modified from Panteleyev et al., 1996.

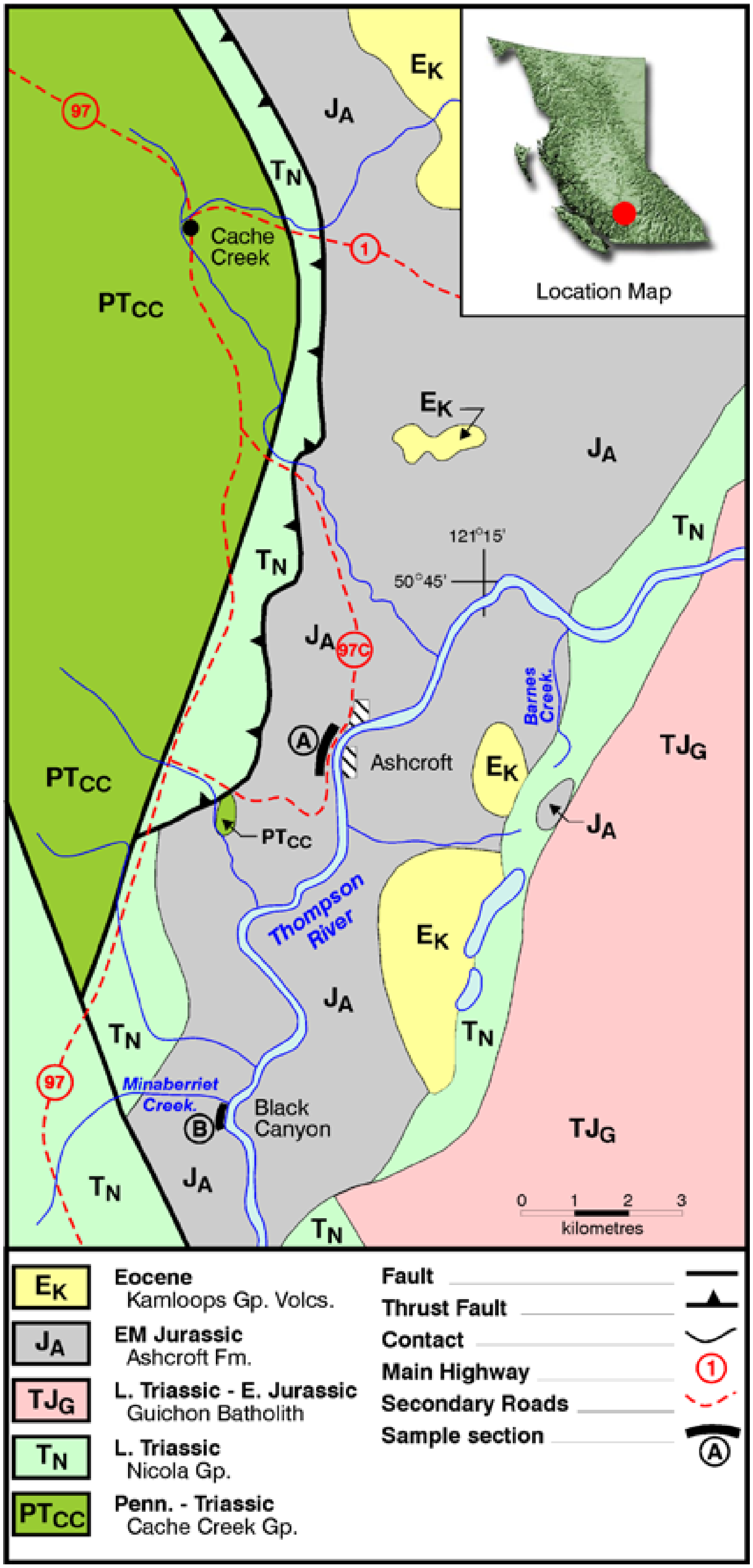

Figure 7. General geology of the Ashcroft area, showing the location of Ashcroft Formation samples listed in Table 1. Modified from Travers (1978).

The Joan Member is Pliensbachian in age and composed of dark siltstone, mudstone, limestone, and locally a thin basal conglomerate. This unit is not developed everywhere above the Cold Fish Volcanics and is missing on the south side of the large anticline. It is succeeded by upper Pliensbachian to middle Toarcian dark grey to black, fissile to slaty shale, siltstone, or calcareous siltstone of the Wolf Den Member. Thomson *et al.* (1986) describe tuffaceous beds locally. Bedding is typically developed as colour banding, and the rock locally has a slightly fetid odour when broken. Some horizons are characterized by abundant small (5 to 10 mm) bivalves of the genera *Bositra* and *Pseudomytiloides*. This is the thickest and most aerially extensive member of the Spatsizi Formation. These rocks are conformably overlain by middle to upper Toarcian, grey-brown resistive siliceous siltstone to fine sandstone of the Melisson Member. The Melisson Member records shallowing conditions, although interbedded siltstone and shales are dark and organic-rich. Unconformably above this and the Wolf Den Member is the Aalenian Abou Member, a sequence of dark grey to black, organic-rich siltstone to slightly siliceous siltstone up to 100 m thick. It is usually well-cleaved and platy, although it produces blocky rubble where siliceous. These rocks grade into the succeeding Bajocian Quock Member, which is composed of distinctive dark, rusty-weathering, blocky, siliceous siltstone and is characterized by interbeds of thin to moderate bands of beige, white to pinkish fine- to medium-grained tuff. Regionally, this member is informally referred to as the "Pyjama Beds" due to its characteristic striped nature. This unit locally contains sections of grey- to light grey-weathering, dark grey to black, fissile calcareous siltstone up to several metres thick. The contact with the overlying Bowser Lake Group occurs over several metres and Quock siltstones lose their siliceous nature and tuffaceous interbeds and become brown-grey to grey, crumbly, and recessive.

Fine clastic rocks of the Spatsizi Formation are invariably high in organic material. The purpose of this investigation was to attempt a systematic quantification of the amount and nature of this organic material through a series of transects across the formation. Two sections were sampled some 6 and 7.5 km west of Joan Lake, where a thick section of Abou shales and siltstones have been delineated (Figures 2 to 4). The Abou has been noted by Thomson *et al.* (1986) as having the highest organic content within the formation. The sections and sampling scheme were arranged so that as much as possible of the Abou section could be sampled. In addition, rocks of the Wolf Den and Quock Members were sampled. The Joan and Melisson Members were not developed within the transect areas. Samples were taken roughly every 25 m with a total of 50 samples analyzed. Structural sections were drawn across the sampling lines and, together with geological control from field observations and unit distributions, the samples were placed in an approximate stratigraphic position.

Rock Eval data results shown in Table 1 suggests that little if any hydrogen (HI) remains in the samples due to either oxidation and/or high thermal maturities. Considering these samples were collected from outcrop, oxidation is a likely possibility. Thermal maturation levels are high in this region, with R_o values in nearby (within 10 km) Bowser Lake sediments ranging between 1.86 and 2.67 (Evenchick *et al.*, 2005), suggesting that these samples are in the upper end of the gas window. Due to the lack of an S_2 peak (HI), very little can be inferred about the original type of organic material, although considering the marine nature of these sediments, it was probably Type I or II. Notwithstanding this, the current levels of total organic carbon (TOC) seen in some sections, particularly across the Abou Member, indicate that it was once a very rich source bed. If one assumes that most of the organic material was expelled during oil and gas generation, then original levels of TOC may have ranged between approximately 1% and 20%, assuming only a quarter of the original organic matter remains. The Abou Member currently has TOC values between 3.65% and 4.92%, suggesting original levels of approximately 15% to 20%. Considering this unit appears to be upwards of 100 m thick in this area and 30 m on average, it had the potential to generate considerable amounts of hydrocarbons. Current TOC levels are 0.24% to 2.42% in the Joan Lake Member and 1.74% to 3.45% in the Quock Member, indicating that these too were respectable source beds.

ICP-MS analytical results are shown in Table 2. Concentrations of various elements, (e.g., Zn, Cu, Ni, Mo) increase within the Abou Member, probably reflecting the more anoxic water conditions that facilitated metal precipitation. One sample from this horizon has elevated Ba levels (approximately 1400 ppm or 0.14%). The Abou Member is time-equivalent to the horizon hosting the Eskay Creek mine, a syngenetic silver-rich massive-sulphide deposit.

TABLE 2. MULTI-ELEMENT ICP-MS DATA FOR SPATSIZI FORMATION SAMPLES FROM THE JOAN LAKE AREA. THESE WERE ANALYZED USING AN AQUA REGIA DIGESTION. UTM COORDINATES IN NAD 27 DATUM.

	Sample	EPF04-191A	EPF04-191B	EPF04-191C	EPF04-192A	EPF04-192B	EPF04-192C	EPF04-192D	EPF04-193A	EPF04-193B	EPF04-194A	EPF04-194B	EPF04-195A
	easting	499192	499192	499192	499147	499147	499147	499147	499122	499122	499107	499107	499100
	northing	6373564	6373564	6373564	6373447	6373447	6373447	6373447	6373305	6373305	6373190	6373190	6373077
Mo	ppm	0.5	0.4	0.6	0.4	0.5	0.3	0.5	0.4	0.7	0.5	0.5	0.7
Cu	ppm	29.6	36.8	32.1	28.7	36.5	25.4	35.3	35.5	38.2	26.8	27.4	33.5
Pb	ppm	9.3	7.7	7.9	10.5	8.5	9.4	11.2	9	8.6	11.3	13.6	10.4
Zn	ppm	120	98	96	83	102	107	107	103	110	77	92	98
Ag	ppm	0.1	0.1	<.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Ni	ppm	21.1	21.6	18.2	14.9	19.3	21.3	21.6	18.6	22.3	17.7	24.4	18.5
Co	ppm	9.6	8.4	6.5	5.7	8	9.8	9.1	8.5	7.5	7	12.9	8
Mn	ppm	351	325	196	240	266	352	325	414	243	664	496	451
Fe	%	4.86	4.07	4.55	4.38	4.51	4.47	5.22	4.02	4.45	3.13	4.1	3.81
As	ppm	7.6	6.6	5.4	13.7	10.1	7.9	10.1	5.6	4.9	6.6	7	4.6
U	ppm	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Au	ppb	<.5	<.5	0.7	<.5	<.5	<.5	0.7	<.5	<.5	<.5	<.5	<.5
Th	ppm	1.4	1.4	1.6	1.6	1.6	2.1	1.8	1.7	1.8	1.5	1.7	1.8
Sr	ppm	65	40	17	32	33	81	43	61	25	206	180	141
Cd	ppm	0.1	0.1	0.1	0.1	0.1	0.1	<.1	0.1	<.1	0.2	0.1	0.1
Sb	ppm	0.4	0.8	0.5	2.5	1.9	0.9	1	0.5	0.6	0.4	0.5	0.4
Bi	ppm	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.1	0.1	0.1	0.1	0.1
V	ppm	49	43	44	41	47	36	44	40	48	25	30	35
Ca	%	1.82	1.66	0.23	0.78	0.81	2.1	1.19	1.95	0.52	5.87	4.39	3.39
P	%	0.078	0.105	0.084	0.082	0.088	0.091	0.092	0.08	0.106	0.062	0.096	0.081
La	ppm	6	9	9	7	8	8	8	8	9	8	8	7
Cr	ppm	61.9	40.5	49.4	38.3	45.3	33.4	35.7	39.1	42.7	27.9	32.8	36.3
Mg	%	1.3	1.1	1.18	1.07	1.11	1.06	1.39	0.96	1.05	0.82	0.97	0.97
Ba	ppm	131	110	115	130	132	141	146	183	154	150	119	144
Ti	%	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
B	ppm	7	6	8	7	6	7	5	7	5	7	6	7
Al	%	2.76	2.33	2.39	2.32	2.43	2.27	2.9	2.22	2.35	1.79	1.99	2.08
Na	%	0.024	0.015	0.02	0.018	0.019	0.017	0.015	0.018	0.014	0.013	0.013	0.014
K	%	0.25	0.17	0.2	0.21	0.2	0.2	0.18	0.23	0.2	0.19	0.18	0.22
W	ppm	<.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1
Hg	ppm	0.05	0.04	0.04	0.04	0.04	0.03	0.05	0.04	0.05	0.03	0.04	0.03
Sc	ppm	7.8	7.4	7.3	7.2	7.1	6.2	7.2	7.1	7.2	7.5	7.2	7.2
Tl	ppm	0.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1
S	%	0.68	0.17	0.06	0.39	0.34	0.67	0.43	0.23	0.14	0.29	0.39	0.22
Ga	ppm	6	5	6	5	5	5	6	5	5	4	5	5
Se	ppm	0.8	1.1	0.7	0.9	0.9	0.7	0.7	0.7	1.5	0.6	0.7	0.8

TABLE 2, CONTINUED

	Sample	EPF04-195B	EPF04-195C	EPF04-195D	EPF04-196A	EPF04-196B	EPF04-197A	EPF04-197B	EPF04-197C	EPF04-198A	EPF04-198B	EPF04-198C	EPF04-198D
	easting	499100	499100	499100	499110	499110	499137	499137	499137	499130	499130	499130	499130
	northing	6373077	6373077	6373077	6372927	6372927	6372870	6372870	6372870	6372737	6372737	6372737	6372737
Mo	ppm	0.7	0.4	0.3	1.1	0.3	0.3	0.1	0.6	1.5	1.4	12.5	28.8
Cu	ppm	29.8	24.9	23.9	31.5	27.6	34.2	23.7	25.8	27.6	19.9	15.6	67.7
Pb	ppm	3.5	9.4	7.5	6.9	5.8	6.5	5.3	7.9	8.1	5	6	3.5
Zn	ppm	97	90	93	99	91	108	100	76	99	45	100	270
Ag	ppm	<.1	0.1	<.1	<.1	<.1	<.1	<.1	0.1	0.1	0.1	0.4	0.2
Ni	ppm	18.7	16.2	13.5	13.9	12.9	16.1	11.7	17.1	17.9	9.8	11.7	46.5
Co	ppm	10	12	8.3	8.4	7.5	10.4	8.1	9.6	6.4	1.5	0.9	2.5
Mn	ppm	426	498	602	415	389	440	366	643	282	113	38	339
Fe	%	4.47	3.99	4	3.56	4.49	4.84	3.58	3.15	2.93	1.74	0.92	1.42
As	ppm	4.6	4.8	3.5	2.5	3.5	3.6	2.2	6.8	5.4	3.9	7.7	8.5
U	ppm	0.2	0.2	0.1	0.1	0.2	0.2	0.1	0.2	0.3	0.2	0.6	1.4
Au	ppb	<.5	<.5	<.5	<.5	<.5	<.5	<.5	<.5	<.5	<.5	<.5	<.5
Th	ppm	1.8	1.8	1.1	1	1.5	1.5	1.1	1.2	1.1	0.8	0.5	1.2
Sr	ppm	103	124	218	129	88	89	114	220	41	14	19	131
Cd	ppm	0.1	0.1	0.1	0.1	0.2	0.1	0.1	0.1	0.2	0.1	0.7	3.5
Sb	ppm	0.1	0.3	0.3	0.3	0.3	0.3	0.2	0.4	0.5	0.9	1.6	1.7
Bi	ppm	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
V	ppm	42	31	27	27	37	40	32	27	32	27	33	79
Ca	%	2.76	3.6	4.62	2.62	2.15	1.83	2.17	5.5	0.97	0.2	0.21	5.05
P	%	0.1	0.089	0.053	0.06	0.073	0.084	0.075	0.101	0.121	0.077	0.044	0.072
La	ppm	8	8	5	5	6	7	5	8	9	6	5	7
Cr	ppm	38.3	37.1	27.3	28.6	33.7	39.5	34.4	35.3	31.7	53.4	59.5	36.3
Mg	%	1.12	0.95	0.96	0.82	1.08	1.13	0.86	0.63	0.5	0.26	0.1	0.22
Ba	ppm	152	124	110	138	121	191	163	167	202	204	144	1434
Ti	%	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.047
B	ppm	6	7	4	4	5	7	7	6	6	5	6	6
Al	%	2.4	2.08	1.96	1.78	2.17	2.4	1.98	1.44	1.37	1.02	0.49	0.68
Na	%	0.014	0.015	0.013	0.012	0.015	0.019	0.018	0.014	0.018	0.022	0.034	0.013
K	%	0.19	0.19	0.15	0.19	0.16	0.24	0.22	0.16	0.19	0.18	0.13	0.16
W	ppm	<.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1	0.2
Hg	ppm	0.02	0.03	0.03	0.02	0.03	0.03	0.02	0.04	0.05	0.03	0.04	0.03
Sc	ppm	6.7	6.8	6.7	6.3	6.6	7.3	5.4	6.6	7.2	4.2	2.2	5.1
Tl	ppm	<.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1	0.1	0.1	0.5	0.5
S	%	<.05	0.23	0.43	0.33	0.24	0.14	0.4	0.29	0.31	0.12	0.11	0.14
Ga	ppm	6	5	5	4	6	6	5	4	3	3	1	2
Se	ppm	<.5	<.5	<.5	<.5	<.5	<.5	<.5	0.7	1.5	2.6	4.5	4.5

TABLE 2, CONTINUED

	Sample	EPF04-199A	EPF04-200A	EPF04-200B	EPF04-201B	EPF04-201C	EPF04-201D	EPF04-202A	EPF04-202B	EPF04-202C	EPF04-202D	EPF04-203A	EPF04-203B
	easting	499472	500666	500666	500625	500625	500625	500586	500586	500586	500586	500527	500527
	northing	6372793	6373358	6373358	6373340	6373340	6373340	6373235	6373235	6373235	6373235	6373166	6373166
Mo	ppm	0.7	0.8	1.6	0.4	0.4	0.5	0.4	0.3	0.5	0.5	0.6	0.6
Cu	ppm	24.7	11.7	12.4	29.6	29.3	38.3	31.2	34	19.8	32.8	27.3	27.5
Pb	ppm	6.6	4.3	1.8	3.2	4	7.5	8.5	9.4	12.4	10.6	10.6	10.1
Zn	ppm	85	25	30	100	135	105	95	102	56	90	88	82
Ag	ppm	0.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1	0.1	0.1	0.1	0.1
Ni	ppm	12.4	3.6	2.7	13.8	11.2	15.2	16.6	18.4	5.9	19.9	16.9	16.3
Co	ppm	5.8	0.8	4.5	5.3	5.2	9.1	9.1	15.1	3.2	10.2	10.7	10.1
Mn	ppm	315	108	6358	365	349	135	584	415	55	258	413	362
Fe	%	3.17	2.27	2.29	4.86	4.76	3.83	4.32	5.31	2.87	4.24	4.35	4.13
As	ppm	5.7	4.9	2.6	4	2.6	3.7	4.2	5	5.8	4.8	6	5.8
U	ppm	0.2	0.1	0.2	0.1	0.1	0.1	0.2	0.1	0.1	0.2	0.2	0.2
Au	ppb	<.5	<.5	<.5	0.8	<.5	<.5	0.5	<.5	<.5	0.8	<.5	<.5
Th	ppm	1.5	0.7	0.5	1.6	1.4	1.7	1.4	1.2	1.4	1.6	1.8	1.8
Sr	ppm	88	10	317	63	86	27	140	84	10	78	170	126
Cd	ppm	0.1	<.1	0.1	0.1	0.1	0.1	0.2	0.2	<.1	<.1	0.1	0.1
Sb	ppm	0.3	0.3	0.1	0.1	0.2	0.3	0.3	0.3	0.5	0.3	0.4	0.3
Bi	ppm	0.1	0.1	<.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
V	ppm	25	17	39	44	35	35	38	57	31	37	32	30
Ca	%	2.32	0.08	25.16	1.8	1.98	0.73	2.98	1.81	0.09	2.04	3.96	3.13
P	%	0.069	0.029	0.04	0.085	0.07	0.066	0.088	0.084	0.077	0.088	0.108	0.089
La	ppm	8	3	7	4	3	2	3	4	2	3	4	3
Cr	ppm	31.8	38.9	13.5	38.7	28.8	26.2	39.7	32.5	32.4	29.9	29.4	28.6
Mg	%	0.59	0.39	0.36	1.22	1.21	0.85	0.9	1.05	0.53	0.92	0.89	0.85
Ba	ppm	175	73	42	98	130	152	354	99	142	145	111	101
Ti	%	0.001	0.001	0.002	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
B	ppm	6	3	1	7	6	5	7	6	8	6	6	8
Al	%	1.48	1.11	0.53	2.57	2.54	2.07	2.33	2.43	1.93	2.07	2.12	1.88
Na	%	0.016	0.024	0.012	0.018	0.013	0.014	0.021	0.019	0.017	0.017	0.015	0.015
K	%	0.2	0.1	0.01	0.2	0.21	0.19	0.31	0.15	0.27	0.21	0.23	0.2
W	ppm	<.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1
Hg	ppm	0.03	0.04	0.01	0.02	0.02	0.03	0.03	0.03	0.03	0.03	0.02	0.04
Sc	ppm	7.3	3.5	6.4	7.5	7.3	8.4	10.7	10.3	9.6	10	9.7	9
Tl	ppm	0.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1
S	%	0.18	<.05	0.36	0.17	0.28	0.15	0.21	0.54	<.05	0.19	0.65	0.39
Ga	ppm	4	5	2	6	6	5	6	6	5	5	5	5
Se	ppm	0.9	<.5	0.8	0.6	<.5	0.5	0.5	<.5	0.6	0.8	0.5	0.5

TABLE 2, CONTINUED

	Sample	EPF04-203C	EPF04-203D	EPF04-204A	EPF04-205A	EPF04-205C	EPF04-205D	EPF04-205E	EPF04-206A	EPF04-207A	EPF04-207C	EPF04-207E	EPF04-208A
	easting	500527	500527	500472	500364	500364	500364	500364	500291	500253	500253	500253	500189
	northing	6373166	6373166	6373038	6372621	6372621	6372621	6372621	6372595	6372571	6372571	6372571	6372496
Mo	ppm	0.7	0.7	0.5	18.7	39.6	21.5	27.4	26.1	34.9	6.1	30.9	15.3
Cu	ppm	29.6	30.6	22.4	46.9	6.4	57.2	42.1	50.9	21.1	6.4	33.3	28.7
Pb	ppm	10.3	11.1	10.6	5.5	9.2	6.2	5.7	8.9	6.6	5.3	7.7	4.5
Zn	ppm	114	98	60	439	58	407	288	358	69	25	144	173
Ag	ppm	0.1	0.1	0.1	0.4	0.5	0.3	0.2	0.3	0.3	0.3	0.2	0.2
Ni	ppm	18.3	21.6	7.6	49.3	8.4	52.9	44.7	54.3	12.3	3.6	18	23.2
Co	ppm	10.3	10.2	3.2	3.5	0.8	5	3.4	4	1.4	0.4	1.8	1.3
Mn	ppm	204	380	100	373	6	537	250	210	35	15	46	168
Fe	%	4.87	4.25	3.64	1.55	0.44	1.89	2.12	1.97	1.05	0.52	1.73	1.6
As	ppm	5.3	4.2	4.3	10.6	16.5	15.3	12.1	17.4	14.6	7.9	17.3	9.1
U	ppm	0.2	0.1	0.1	1	0.3	1.3	1.1	0.9	1.3	0.3	0.7	1.1
Au	ppb	<.5	<.5	0.5	0.8	0.8	<.5	<.5	0.7	0.7	<.5	1.3	<.5
Th	ppm	1.8	1.7	1.6	0.9	0.3	0.8	1	1.7	0.8	0.5	0.8	1
Sr	ppm	29	69	23	93	8	278	41	39	16	7	10	30
Cd	ppm	0.1	0.2	<.1	9.1	<.1	7.6	3.5	4.6	0.3	<.1	0.3	2.1
Sb	ppm	0.4	0.4	0.5	1.6	2.1	1.5	1.9	1.7	2.2	1.3	2.2	1.6
Bi	ppm	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
V	ppm	37	36	33	83	52	56	59	63	66	21	36	75
Ca	%	0.4	2.17	0.22	3.77	0.05	6.88	1.77	1.53	0.22	0.05	0.1	0.59
P	%	0.103	0.085	0.081	0.064	0.009	0.072	0.075	0.044	0.089	0.044	0.059	0.071
La	ppm	4	3	3	9	2	10	7	8	6	6	6	8
Cr	ppm	34.5	35.5	39.2	35.3	37.9	38.4	28.8	32.4	34.9	44.9	23	39.2
Mg	%	0.89	0.87	0.72	0.26	0.03	0.16	0.32	0.3	0.18	0.06	0.25	0.28
Ba	ppm	144	137	174	184	155	153	148	169	161	152	187	250
Ti	%	0.001	0.001	0.001	0.001	0.001	0.001	0.001	<.001	0.001	0.001	<.001	0.001
B	ppm	5	7	5	5	3	4	4	6	4	3	4	5
Al	%	2.2	2.16	1.92	0.74	0.38	0.5	0.88	0.85	0.62	0.37	0.69	0.94
Na	%	0.015	0.013	0.014	0.013	0.025	0.016	0.014	0.014	0.015	0.019	0.015	0.013
K	%	0.22	0.24	0.25	0.16	0.15	0.13	0.13	0.19	0.14	0.13	0.17	0.18
W	ppm	<.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1
Hg	ppm	0.04	0.04	0.03	0.06	0.09	0.07	0.06	0.07	0.08	0.07	0.07	0.05
Sc	ppm	10.5	8.7	6.9	6.8	3.1	8.7	6.1	5.8	4.4	2	4.6	5.5
Tl	ppm	<.1	<.1	<.1	0.6	1.1	0.5	0.7	0.7	0.5	0.3	0.6	0.5
S	%	0.14	0.23	<.05	<.05	0.09	0.78	0.07	0.13	<.05	0.06	<.05	<.05
Ga	ppm	5	5	5	2	1	2	2	2	2	1	3	2
Se	ppm	0.6	0.6	0.7	8.4	8.7	5.2	5.9	7.1	3.4	3.8	5.1	3.8

TABLE 2, CONTINUED

	Sample	EPF04-209A	EPF04-210A	FF04-1A	FF04-1B	FF04-1E	FF03-1A	FF03-13A	FF03-13B	FF03-15A	FF03-15B	FF03-15C	FF03-2A
	easting	500068	499972	619543	619543	619543	621033	589945	589945	600523	600523	600523	621066
	northing	6372471	6372463	5613654	5613654	5613654	5620414	5833905	5833905	5566989	5566989	5566989	5620479
Mo	ppm	6.1	13.7	4.2	0.6	0.3	7.9	43.5	17.8	1	1.3	0.2	11
Cu	ppm	18.4	23.2	86.6	72.1	1.3	14.7	91	86.8	46.1	24	58.4	44.9
Pb	ppm	3.6	8.9	13.7	4.9	<.1	12.2	7.4	6.1	5	5.2	6.8	10.6
Zn	ppm	122	118	173	135	2	25	441	354	59	60	83	154
Ag	ppm	0.1	0.2	0.2	0.1	<.1	0.1	0.5	0.5	<.1	<.1	0.1	0.1
Ni	ppm	23.9	16.3	44.8	34.7	0.8	4.3	175.4	75.9	15.4	21.5	30.8	28.8
Co	ppm	1.1	1.3	12.9	8.2	0.1	1.4	7.2	5.1	9.1	10.1	13.2	10.4
Mn	ppm	1092	88	548	504	2854	20	347	570	841	914	374	421
Fe	%	1.31	1.8	3.62	3.25	0.48	0.74	2.08	2.03	3.9	3.19	2.81	1.81
As	ppm	5.3	12	18.5	5	0.8	16.8	27.5	21.2	10.3	10.3	1.3	11.7
U	ppm	0.6	0.5	0.5	0.4	0.1	0.7	3.7	1.4	1.2	0.3	0.2	0.9
Au	ppb	1.1	1	1.4	0.5	1.3	1.4	1	0.8	0.8	1.6	0.8	<.5
Th	ppm	0.8	0.8	2.6	2.7	<.1	4.6	1.1	0.9	1.1	1.3	0.8	2.8
Sr	ppm	354	10	207	167	3138	37	743	753	366	262	91	205
Cd	ppm	2	0.4	1.4	1	0.1	0.1	4.9	4	0.3	0.2	0.2	1.6
Sb	ppm	0.8	1.3	2	0.4	0.1	1	2.9	3.3	0.6	0.8	0.1	1.5
Bi	ppm	0.1	0.1	0.1	0.2	<.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2
V	ppm	70	60	78	71	4	10	195	180	67	41	47	17
Ca	%	8.03	0.15	3.35	2.99	31.82	0.33	9.84	14.66	11.11	10.24	1.6	4.13
P	%	0.038	0.037	0.118	0.118	0.022	0.036	0.156	0.091	0.436	0.109	0.06	0.056
La	ppm	7	4	9	10	<1	20	6	5	28	13	9	7
Cr	ppm	63.3	60.5	50.2	51.5	11.5	53.3	40.6	42.9	25.7	31.9	30.3	15.5
Mg	%	0.5	0.6	1.31	1.43	0.48	0.05	0.31	0.36	1.07	0.81	0.88	0.1
Ba	ppm	140	117	148	123	225	238	75	95	389	195	132	54
Ti	%	0.001	0.001	0.003	0.003	<.001	0.002	0.001	0.001	0.056	0.067	0.092	0.002
B	ppm	2	2	17	19	1	11	16	9	5	6	6	11
Al	%	0.75	0.95	2.17	2.12	0.03	0.51	0.59	0.43	2.36	1.89	2.37	0.39
Na	%	0.021	0.03	0.016	0.038	0.009	0.059	0.027	0.018	0.015	0.015	0.014	0.038
K	%	0.09	0.13	0.5	0.49	0.01	0.43	0.23	0.16	0.18	0.24	0.29	0.36
W	ppm	<.1	<.1	<.1	<.1	0.1	<.1	<.1	<.1	0.7	0.2	0.1	<.1
Hg	ppm	0.02	0.06	0.13	0.03	0.01	0.03	0.15	0.15	0.11	0.06	0.02	0.08
Sc	ppm	4.1	4.1	7.9	6.5	0.3	1.5	8.3	6.2	4.8	5.4	7.1	4.3
Tl	ppm	0.4	0.3	0.2	0.1	<.1	0.1	0.5	0.2	<.1	<.1	0.1	0.3
S	%	<.05	<.05	0.28	0.09	0.14	0.26	1.93	1.8	0.06	0.51	<.05	1.72
Ga	ppm	2	3	7	7	<1	2	2	2	5	4	6	1
Se	ppm	1.4	3.1	2.2	1.1	0.6	1.3	14.2	11.7	1.1	0.8	<.5	2.3

TABLE 2, CONTINUED

	Sample	FF03-2B	FF03-3A	FF03-4A	FF03-4B	FF03-5A	FF03-6A	FF03-8A
	easting	621066	621073	621106	621106	621140	621147	621046
	northing	5620479	5620505	5620590	5620590	5620636	5620691	5620363
Mo	ppm	8.7	10.4	12.7	11.8	24.7	36.9	10.1
Cu	ppm	30.6	43.1	41.9	41.8	49.2	64.5	40
Pb	ppm	9.7	10.1	9.4	9.1	7.5	8.6	10.5
Zn	ppm	111	128	141	132	304	437	129
Ag	ppm	0.1	0.1	0.1	0.1	0.2	0.2	0.1
Ni	ppm	18.7	26.8	26.2	23.1	55.9	78.9	23.7
Co	ppm	8	9.1	9.6	8.6	9.6	12.6	9.1
Mn	ppm	914	379	670	674	460	409	592
Fe	%	1.42	1.61	2.43	3.4	1.99	2.56	2.28
As	ppm	10.1	10.1	11.7	11.8	14.7	19.5	12.1
U	ppm	0.9	0.7	0.9	0.9	1.1	1.4	0.8
Au	ppb	<.5	<.5	<.5	0.7	0.6	<.5	<.5
Th	ppm	2.8	2.3	2.8	2.6	2.1	2	2.6
Sr	ppm	224	236	265	300	313	311	265
Cd	ppm	1.1	1.5	1.6	1.4	3.1	4.6	1.3
Sb	ppm	1	1.3	1.1	1.1	2.9	3.7	1.2
Bi	ppm	0.1	0.2	0.2	0.1	0.2	0.2	0.2
V	ppm	12	14	14	13	36	39	16
Ca	%	6	4.61	7.66	7.13	8.39	7.34	5.4
P	%	0.047	0.055	0.059	0.053	0.064	0.068	0.054
La	ppm	10	5	5	7	3	2	8
Cr	ppm	14.9	15	12.4	12.5	15.7	16.2	16.2
Mg	%	0.12	0.18	0.22	0.2	0.58	0.33	0.1
Ba	ppm	152	83	83	79	101	85	95
Ti	%	0.001	0.001	0.001	0.001	0.001	0.001	0.002
B	ppm	10	9	10	9	12	7	9
Al	%	0.45	0.4	0.4	0.39	0.41	0.4	0.44
Na	%	0.033	0.703	0.776	0.268	0.44	0.071	0.023
K	%	0.43	0.35	0.29	0.38	0.26	0.21	0.4
W	ppm	<.1	<.1	<.1	<.1	<.1	<.1	<.1
Hg	ppm	0.05	0.08	0.08	0.08	0.09	0.14	0.06
Sc	ppm	4	3.9	4.5	4.4	5.8	6.8	4.2
Tl	ppm	0.2	0.5	0.3	0.3	1.5	0.7	0.3
S	%	1.31	1.77	2.28	3.62	2.85	3.07	2.18
Ga	ppm	2	1	1	1	1	1	1
Se	ppm	1.5	5.4	6	6.1	5	6	2.2

TABLE 3. MULTI-ELEMENT ICP-MS DATA FOR SPATSIZI FORMATION SAMPLES FROM THE JOAN LAKE AREA. THESE WERE ANALYZED USING A TOTAL ACID DIGESTION. UTM COORDINATES IN NAD 27 DATUM.

	Sample	EPF04-191A	EPF04-192C	EPF04-194B	EPF04-196A	EPF04-198A	EPF04-200A	EPF04-202A	EPF04-203B	EPF04-205C	EPF04-207C	EPF04-210A	FF04-01B	FF03-001A	FF03-015C	FF03-004B
	easting	499192	499147	499107	499110	499130	500666	500586	500527	500364	500253	499972	619543	621033	600523	621106
	northing	6373564	6373447	6373190	6372927	6372737	6373358	6373235	6373166	6372621	6372571	6372463	5613654	5620414	5566989	5620590
Mo	ppm	1	0.7	0.7	1.3	2	1	0.4	0.8	43.1	6.6	14.1	0.9	9.3	0.3	13.3
Cu	ppm	31.7	28.4	29.5	34.5	28.1	12.4	31.9	30.3	7.1	6.4	24.9	78.1	16.5	62.6	44.6
Pb	ppm	9.9	11.2	13.4	7.4	7.6	5.1	8.4	10.6	8.9	4.8	8.1	6.3	12.8	7.9	9.4
Zn	ppm	133	116	99	114	111	32	107	97	61	28	130	171	35	104	168
Ag	ppm	<.1	0.1	0.1	0.1	0.1	0.1	<.1	0.1	0.8	0.4	0.3	0.1	0.1	0.1	0.2
Ni	ppm	23	22.1	28.2	15.7	19.7	5.1	15.6	18.5	13.5	6.1	16.7	42.1	6.2	38.2	25.8
Co	ppm	9	10	13	8	6	1	8	11	1	<1	1	8	1	15	8
Mn	ppm	370	386	528	472	281	131	564	372	11	18	89	588	50	488	747
Fe	%	5.35	5.3	4.59	4.17	3.39	2.87	4.5	4.48	0.59	0.63	1.94	4.02	1.57	3.89	4.4
As	ppm	8	10	7	3	5	6	5	6	17	8	12	5	20	3	16
U	ppm	0.9	1.5	1.1	0.9	0.9	1	0.8	1	4.2	2.8	2.9	2.2	5.2	0.6	3.4
Au	ppm	<.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1
Th	ppm	3	4.5	3.2	2.6	2	2	2.8	3.3	1.2	1.3	1.7	5.4	9.8	2.3	5.1
Sr	ppm	139	155	244	200	87	127	184	195	48	42	46	214	90	150	332
Cd	ppm	0.2	0.2	0.1	0.3	0.1	0.1	0.1	0.1	0.3	0.3	0.7	1.3	0.3	0.3	1.5
Sb	ppm	1	1.9	0.9	0.6	1	0.8	0.7	0.8	4	2.3	1.8	0.9	1.9	0.4	2
Bi	ppm	0.1	0.1	0.1	0.1	0.1	<.1	0.1	0.2	0.1	0.1	0.1	0.1	0.2	0.2	0.1
V	ppm	148	127	118	116	111	46	115	120	383	164	127	196	61	144	126
Ca	%	2.1	2.5	4.94	3.04	1.15	0.13	3.04	3.42	0.06	0.06	0.13	3.49	0.39	2.04	8.03
P	%	0.086	0.125	0.109	0.075	0.134	0.039	0.093	0.108	0.013	0.05	0.037	0.133	0.045	0.081	0.057
La	ppm	12.1	14	15.8	15.8	17	4.1	8.1	7.5	5.6	12.2	4.2	20.5	24.8	16.9	13.2
Cr	ppm	97.5	68.1	65.5	60.7	58.8	67.6	68.1	64	66.5	77.8	84.3	113.3	92.9	66.8	37.3
Mg	%	1.38	1.33	1.17	1.11	0.65	0.53	1.01	1.01	0.2	0.23	0.69	2.09	0.3	1.43	0.54
Ba	ppm	910	686	928	1080	686	401	1074	823	968	982	498	551	1019	528	31
Ti	%	0.476	0.442	0.416	0.451	0.337	0.255	0.424	0.428	0.336	0.271	0.208	0.434	0.198	0.394	0.243
Al	%	8.56	8.43	7.69	7.75	6.08	4.87	7.73	7.79	5.19	4.46	3.93	7.59	7.22	7.31	5.28
Na	%	1.239	1.315	1.276	1.275	1.401	1.501	1.151	1.431	1.964	1.388	1.457	1.428	3.599	0.404	1.569
K	%	1.91	1.84	1.73	1.82	1.3	0.75	1.85	1.85	0.97	0.94	0.61	2.42	1.87	1.48	1.91
W	ppm	0.7	0.9	0.7	0.7	0.7	0.4	0.6	0.7	0.5	0.5	0.4	1	1	0.4	0.8
Zr	ppm	34.6	46	42.4	31	40.1	36.8	33.4	38.1	66.4	57.7	48.9	70.8	111	59.1	75
Ce	ppm	23	25	28	30	27	7	17	16	10	20	8	37	48	35	31
Sn	ppm	1.4	1.4	0.9	1	0.9	0.8	1	1.1	0.8	1	0.7	1.5	1.8	0.9	1.2
Y	ppm	18.1	19.5	19.9	17.2	23.8	8.2	16.3	16	9.6	8.9	10.3	22.1	22.8	15.6	22.3
Nb	ppm	6.3	6	5.9	5.5	3.8	2.9	5.7	6.4	2.4	2.5	2	6.7	7.1	3.2	4.5
Ta	ppm	0.4	0.6	0.4	0.3	0.3	0.2	0.3	0.4	0.1	0.1	0.1	0.5	0.6	0.2	0.4
Be	ppm	1	1	1	1	1	<1	1	1	1	<1	<1	1	2	1	1
Sc	ppm	21	18	16	19	17	11	18	17	11	10	9	15	7	15	8
Li	ppm	48.3	50.4	36.1	32.3	20.4	22.1	30.1	32.9	1.2	1.7	6.9	58.1	4.7	35	8.6
S	%	0.7	0.9	0.5	0.4	0.4	0.1	0.2	0.5	0.2	0.1	<.1	<.1	0.4	<.1	3.7
Rb	ppm	74.5	72.8	69.3	68.2	44.4	28.4	70.2	70.9	28.1	26.6	15.3	91.3	72.5	52	64.5
Hf	ppm	1.4	1.8	1.4	1.2	1.2	1.5	1.1	1.5	2	1.9	1.7	2.8	4.8	2	3.1

McConnell Creek and Oweegee Dome Areas

In western McConnell Creek, rocks of the Spatsizi Formation show similar compositional trends to those in the Joan Lake area, suggesting effects from oxidation and thermal maturation (Figure 5; Table 1). Surface thermal maturation levels (based on vitrinite reflectance data) for Spatsizi rocks in McConnell Creek range from 1.6% to greater that 2.4% (V. Stasiuk, personal communication). Current TOC levels are similar to those seen in the Joan Lake area, ranging from 0.27% to 6.01% (*see* Table 1).

Oweegee Dome (see Figure 1 for approximate location) is believed to represent a structural window exposing Jurassic and older basement to the Bowser Lake Group. The Spatsizi Formation is exposed below Bowser Lake Group sediments around the entire structure and is several hundred metres in thickness. As in the McConnell Creek area, it is not possible to differentiate all the members defined by Thomson *et al.* (1986) in the Joan Lake area. Lithologically, the section appears most similar to the Wolf Den Member. The upper half of the Spatsizi section in the northern Oweegee Dome area does not contain well-developed tuffaceous horizons of the Quock Member. Instead, the dark siltstones are punctuated by distinctive brown-weathering feldspathic chert sandstone sheets up to several metres thick which, together with features in thinner beds, suggest deposition as turbiditic flows. Intervening siltstone may be siliceous and contains thin tuffaceous horizons. This section passes upwards into crumbly siltstone and grey-brown sandstones typical of the Ritchie-Alger lithofacies assemblage.

Several samples were acquired along the northern part of Oweegee Dome, returning TOC levels between 0.23% and 1.69%. Surface R_o levels for Spatsizi and Bowser rocks in the vicinity of the sample localities are between 1.53% and 5%

Unnamed Early Middle Jurassic Rocks

Likely Area

In the Likely area, Early to Middle Jurassic organic-rich shales and calcareous shales were also sampled for determining organic content (Figure 6; Ferri *et al.*, 2004). TOC values shown in Table 1 are 5.5% and 5.05%. Thermal maturities, based on vitrinite reflectance, at this locality are on the order of $R_o = 2.11$ (V. Stasiuk, personal communication, 2005), which would explain the low HI levels.

Ashcroft Formation

Ashcroft Area

Sampling in 2003 took place along Highway 97C, which leads into the town of Ashcroft (Figure 7). Possible oil shales described along Minaberriet Creek (Macauley, 1984) were sampled during the summer of 2004. Analyses of these samples are shown in Table 1. Thermal maturation levels, based on vitrinite reflectance data, indicate Ro levels of 1.96% to 2.73% (V. Stasiuk, personal communication, 2005). As in samples from other regions, S_2 values are 0 or less than 0.2, although TOC values range from 0.6% to 5.09%.

DISCUSSION

The compositional and lithological similarities of Early to Middle Jurassic black clastic sequences observed in Bowser Basin and the southern Intermontane region suggest widespread deposition (Ferri *et al.*, 2004). In addition, Rock Eval data indicate these horizons are rich in organic matter, containing approximately 1% to 6% TOC. In all areas sampled, thermal maturation levels were high—either at or exceeding the upper end of the gas window. These high temperatures, together with possible surface oxidation, probably explain the low S_2 (HI) levels observed in the analysis.

Assuming that a considerable amount of the organic matter was driven off during thermal maturation, it is conceivable that these rocks originally had a much higher organic content. As surmised earlier, original TOC may have ranged from 1% to 20% with some zones having contents between 15% and 20%.

Although all areas examined as part of this study are overmature, it is possible that in other regions, equivalent horizons may occur in the proper thermal window and act as effective source beds. These fine clastic sequences are temporally and lithologically equivalent to the Fernie Group of the Western Canada Sedimentary Basin. TOC levels for the Fernie Group, particularly the Nordegg and equivalent members, are similar to original levels postulated for rocks of this study (Riediger, 2002).

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THE SOUTHERN CONTACT OF THE BOWSER LAKE AND SKEENA GROUPS: UNCONFORMITY OR TRANSITION?

Gareth T. Smith[1] and Peter S. Mustard[1]

ABSTRACT

New geologic mapping in the west Hazelton map area and immediately adjacent areas has clarified both Bowser Lake Group (BLG) stratigraphy in this area and the relationship of these strata to the overlying Cretaceous Skeena Group. The upper unit of the BLG in this area is a sandstone-dominated shallow-marine succession that can be lithostratigraphically correlated to the Muskaboo Creek assemblage known from central and northern Bowser Basin. In at least one area, this shallow-marine succession appears to gradationally change upward into a nonmarine unit which has previously been considered as a stratigraphic unit of the Cretaceous Skeena Group. This suggests that, at least in this area, the Skeena Group is gradational from Bowser Lake Group and represents a southern nonmarine component of an originally continguous Jura-Cretaceous Bowser Basin.

KEYWORDS: sedimentology, stratigraphy, Muskaboo Creek Assemblage, Skeena Group, Bowser Lake Group, Cretaceous, Jurassic

INTRODUCTION

Recent efforts have been made by the BC Ministry of Energy and Mines (BCMEM) and the Geological Survey of Canada (GSC) to improve the structural and geological knowledge of the Jurassic-Cretaceous Bowser Basin of northeast BC (Figure 1) as well as to assess its integrated petroleum resource potential (Hayes *et al*., 2004, Evenchick *et al*., 2003). During the summer of 2004, this research focused on the southern and central parts of the extensive Bowser Basin NTS map sheets 93M and 104A (summarized in Ferri *et al*., 2005, Evenchick *et al*., 2005 respectively).

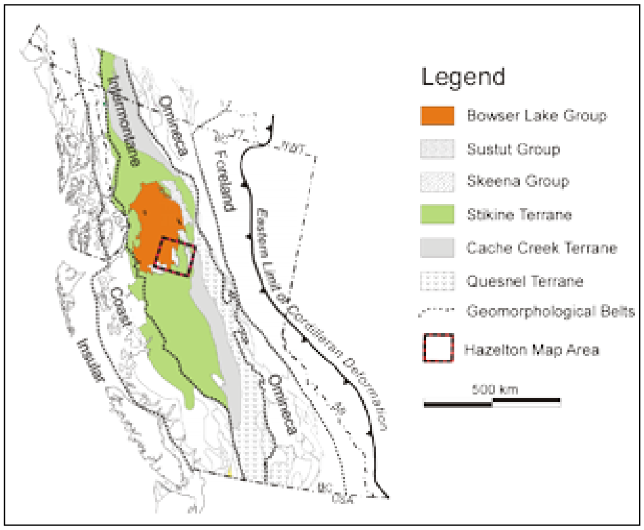

Figure 1. Location of the Bowser, Sustut, and Skeena Groups within the geological framework of the Canadian Cordillera (modified from Ferri et al., 2005 and Evenchick et al., 2003).

The Bowser Lake Group (BLG) consists of sedimentary rocks of late Middle Jurassic to mid-Cretaceous age and is the oldest of three major stratigraphic successions that comprise the Bowser Basin and related sedimentary rocks (Figure 2). The southernmost region of the BLG in the Hazelton map sheet (NTS sheet 93M) is dominated by shallow-marine siliciclastics, which on extant geologic maps are defined as "undivided Bowser Lake Group" (e.g., Richards, 1990). Outcropping south of the BLG, a second stratigraphic succession of Lower to Upper Cretaceous rocks is generally termed the Skeena Group (SG). This unit has been interpreted as predominantly deposited in nonmarine fluvial/floodplain and shallow-marine environments with localized volcanic influence (e.g., Bassett and Kleinspehn 1997). The stratigraphic relationship between the undivided Bowser Lake Group and the nonmarine sedimentary rocks of the Skeena Group in the southernmost region of the Bowser Basin remains unclear. Previous workers have suggested that the contact is unconformable or a fault contact (Tipper and Richards, 1976) or that the Skeena Group sediments represent the Cretaceous continuation of Bowser Basin deposition (Bassett and Kleinspehn 1997). Ferri et al. (2005) summarize previous studies in this area and the complex evolution of stratigraphic terms involving the stratigraphy now termed Skeena Group and Bowser Lake Group in this region.

PROJECT GOALS

This project aims to characterize the shallow-marine siliciclastic unit that appears to be the upper stratigraphic unit of the BLG within the Hazelton map area and immediately adjacent regions. The aim is to describe this unit in terms of its sedimentological make-up and depositional

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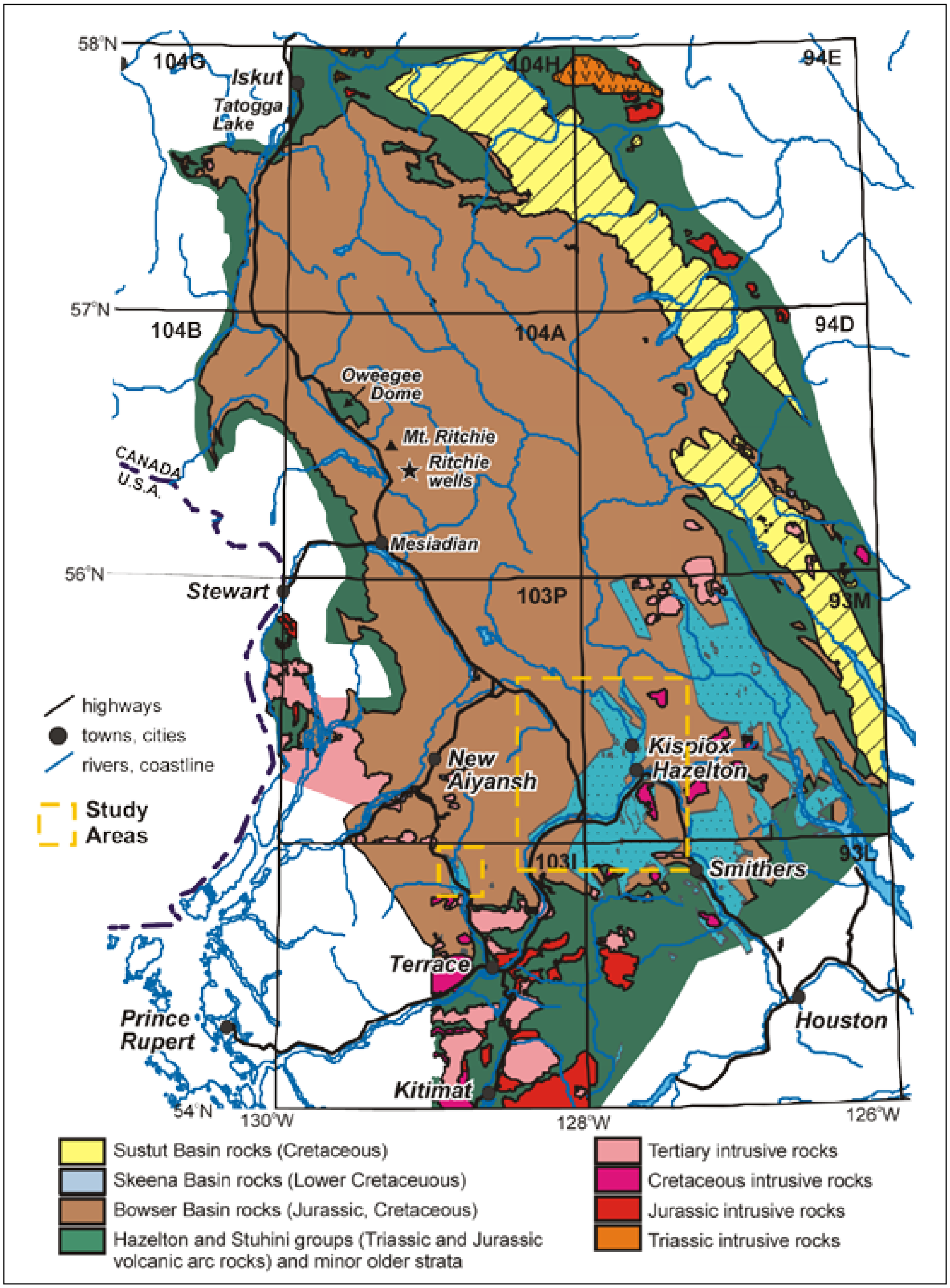

Figure 2. General geology of the Bowser Basin region, showing the distribution of the Skeena Group and the main areas of study for this project (modified from Ferri et al., 2005 and Evenchick et al., 2003).

history. This unit will be compared to previous studies of similar lithostratigraphic units in the BLG and Skeena Group to try to discern whether they are correlative. A second major goal of this project is to more clearly define and differentiate the nature of the BLG contact with the overlying Skeena Group.

WORK TO DATE

Much of the initial part of this project involved assisting in regional mapping of the west half of the Hazelton map area to define local and regional stratigraphic relationships as well as to view the lateral variance of the undivided BLG and their regional interrelationships. New geologic

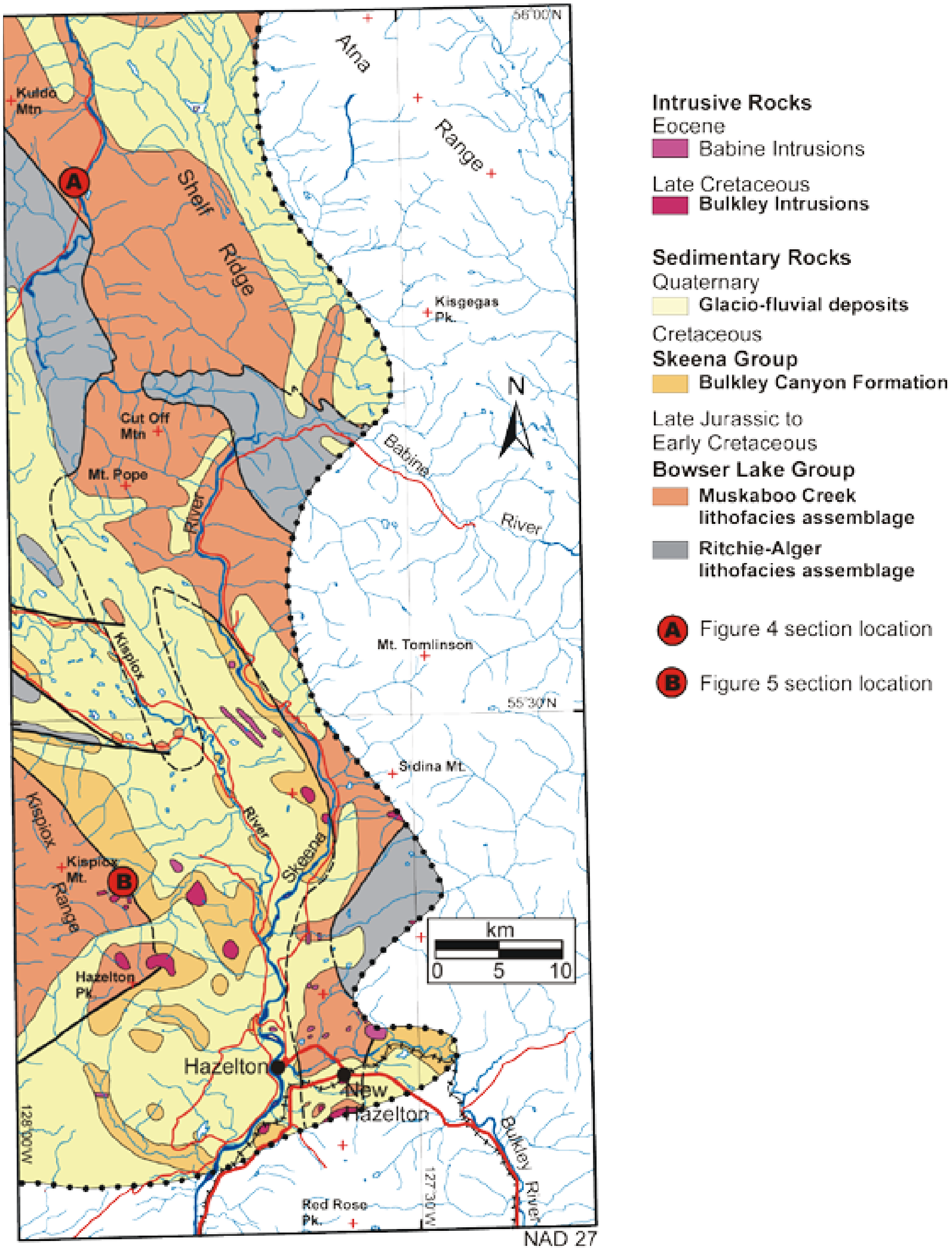

Figure 3. Simplified geological map of the study area with approximate location of measured sections shown in Figures 4 and 5 (modified from Ferri et al., 2005).

insights from this regional study are summarized in Ferri et al. (2005) with a simplified version of the new geologic mapping provided in Figure 3.

In conjunction with (and in part as a result of) the geologic mapping, eight stratigraphic section localities were chosen, most within the study areas located on Figure 2. Our selection of the localities was restricted to areas that were previously mapped as undivided Bowser Lake Group or Skeena Group or to areas that have been mapped to show transitional characteristics from possible BLG into Skeena Group. These selections were made as a result of the new geologic mapping and from reference to previous work documented by Bassett (1995) and Tipper and Richards (1976).

At each location, a detailed measured stratigraphic section was constructed. In the majority of cases, a basal contact was not identified; therefore, measurement began from the clearest exposed surface and thus the sections do not represent the total thickness of the stratigraphic unit. Each measured section comprises a detailed lithostratigraphic description, identification of internal sedimentary structures and internal gradational relationships, and inference of sediment type and depositional nature. Suitable hand samples were taken at each site to allow for petrographical identification and thin-section analysis; maturation and palynology samples were also taken from the more carbonaceous layers to assist in age determination and reservoir potentiality. Figures 4 and 5 illustrate two of these sections.

Hazelton map area Muskaboo Creek Assemblage

In the Hazelton map area, the upper BLG consists of a shallow-marine siliciclastic unit greater than 250 m thick and thought to be Late Jurassic to Early Cretaceous in age. This unit is dominated by medium- to fine-grained lithic arenite with lesser siltstone and mudstone (Figure 4). The sandstones are generally well sorted and contain abundant

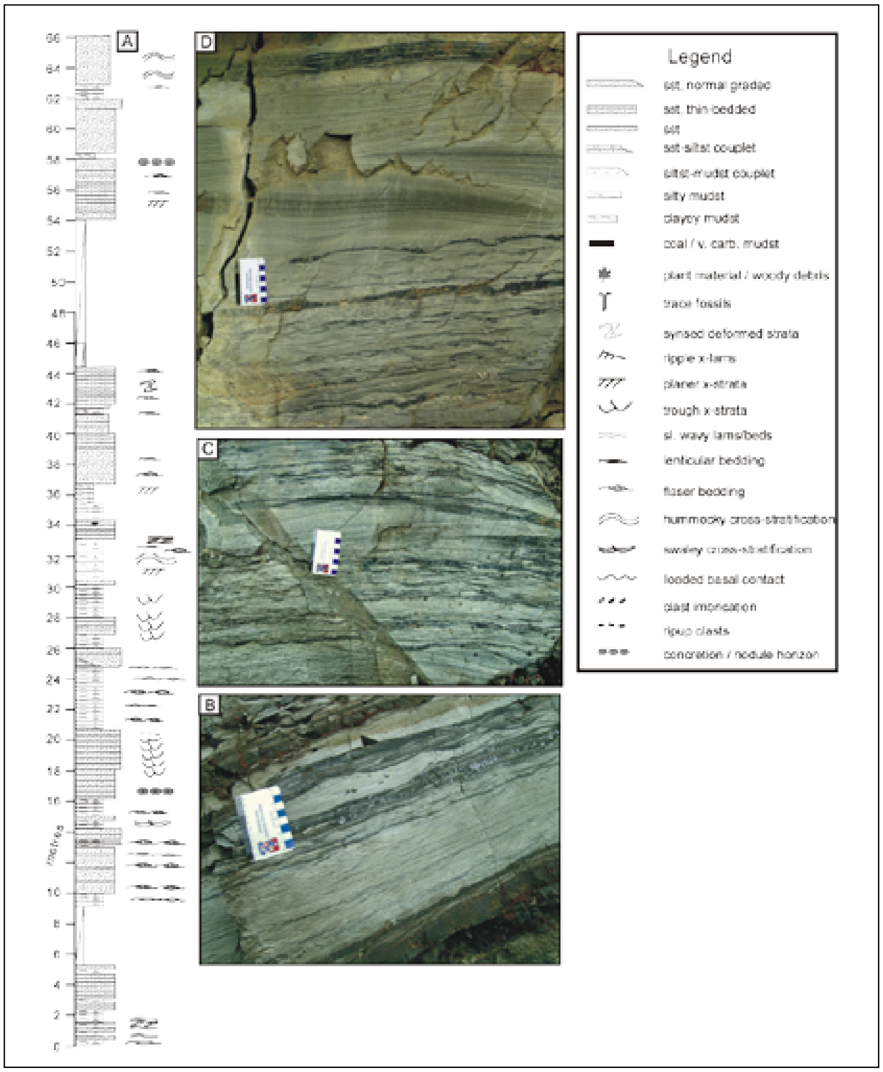

Figure 4. A. Simplified measured section through typical Muskaboo Creek assemblage in Hazelton map area (location A on fig. 3). B. Intercalated sandstone and siltstone showing variations in planar cross-stratification types, combined flow ripples, plus minor flaser and lenticular ripple forms (scale in cm) C. Typical complex heterolithic stratification, including flaser bedding forms, minor draped ripple laminaton, and minor remnant swaley cross-stratification (immediately above cm scale). D. Sandstone and minor silty mudstone showing lower wavy stratification and rippled sandstone with minor mud drapes changing upward to overlapping hummocky cross-stratified sets (above cm scale). Legend is common for this figure and Figure 5.

sedimentary structures indicative, in general, of tidal and shoreface marine environments. These structures include extensive hummocky, swaley, and trough cross-stratification, flaser and lenticular bedding features, syn-sedimentary ball and pillow structures, as well as minor units of chaotic shell debris and coquina layers.

This assemblage is very similar to (and we correlate it with) the Muskaboo Creek (MBC) assemblage of the BLG, an extensively exposed lithofacies assemblage in map areas north and northeast of the Hazelton area (Evenchick and Thorkelson, 2005 and Evenchick *et al.,* 2003, 2005).

In several places, this MBC unit gradationally overlies a siltstone-dominated sedimentary unit, which somewhat resembles the Ritchie Alger assemblage of the BLG. However, this siltstone unit lacks the abundance of sandstone turbidite beds typical of Ritchie Alger assemblage in other map areas. It is possible this is a transitional unit from the shallow-marine (wave-dominated) MBC unit through deeper marine shelf and slope environments into the submarine fan complexes typical of the Ritchie Alger assemblage (also discussed in Ferri *et al.,* 2005, Evenchick *et al.,* 2005)

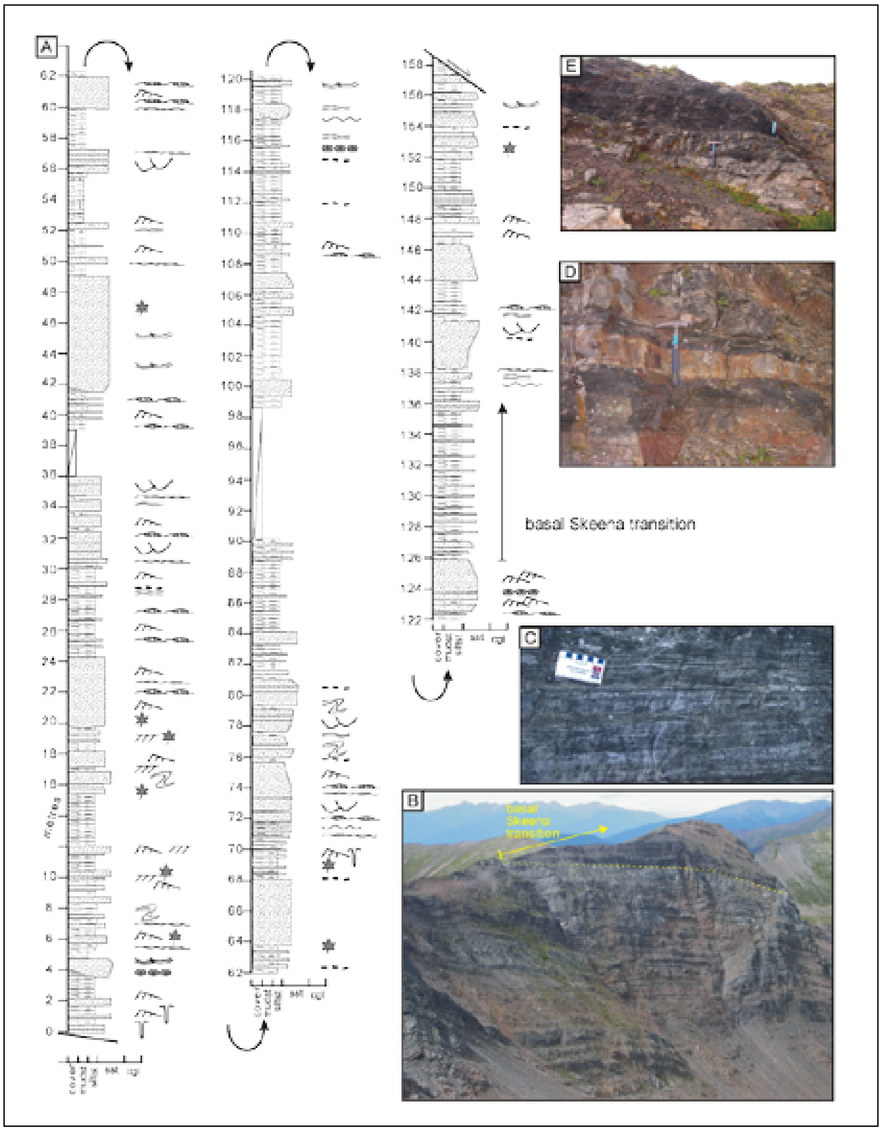

Figure 5. A. Simplified measured section through possible Muskaboo Creek assemblage transition into marginal to nonmarine facies of basal Skeena Group (location B on fig. 3). See Figure 4 for legend. B. Looking NW at cliff and ridge of measured section. C. Typical Muskaboo Creek assemblage displaying wavy to heterolithic stratification of sandstone and silty mudstone from this section (scale in cm). D. Brown weathering siltstone and minor sandstone in transitional zone at about 130 m in measured section (hammer is about 25 cm length) E. Near top of section, illustrating dark grey-brown, plant-bearing siltstone with intercalated sandstone of possible basal Skeena Group lithofacies (hammer is about 25 cm length).

In at least one place, this BLG unit grades upward into nonmarine fluvial and minor deltaic strata previously mapped by Richards (1990) as part of the lower Skeena Group (Figure 5). A preliminary conclusion derived from this observation is that, at its southern extent, the Skeena Group is gradational, both laterally and vertically, from the underlying Bowser Lake Group. In turn this may imply that both units belong to a single continuous sedimentary basin deposited during the latest Jurassic and Early Cretaceous time.

Hazelton map area Skeena Group

In the southern part of the Hazelton map area, fluvial to nonmarine Skeena Group sedimentary units have been identified by several previous workers. The most common strata consist of nonmarine sandstone, mudstone, and minor coal layers, which Bassett (1995) considered to be part of her proposed Bulkley Canyon Formation, previously referred to as the Kitsuns Creek Formation by Richards et al. (1990).

The Bulkley Canyon Formation consists of micaceous sandstones with lesser conglomeratic beds, which grade upward into coal, with a rich abundance of macroflora and pollen. (Bassett 1995). A basal section of this unit appears to conformably overlie the Muskaboo Creek assemblage exposed on Kispiox Mountain (Figure 3, location B). As shown in Figure 5, at this locality a gradational change is suggested from shallow-marine sandstone into finer fluvial siltstone containing repeated thin sandstone units lacking in marine sedimentary structures. Further up-section, this unit appears to interfinger back and forth between marine and fluvial characteristics, suggesting periods of transgression and progradation of a shoreline succession. This unit as it occurs in the Hazelton map area is described in more detail in Ferri *et al*. (2005).

CONCLUSIONS AND CONTINUED STUDY

The evidence from the 2004 field season indicates that the Muskaboo Creek Assemblage known from northern parts of the Bowser Basin can also be recognized in southern areas. In addition, in at least one place, this assemblage appears to gradationally change upward into nonmarine strata typically considered part of the Skeena Group, suggesting a conformable contact between these major successions. To support this preliminary conclusion, more examples of this contact need to be identified and documented. In addition, detailed sampling of both the existing contact section and any new examples of this contact for palynologic and other paleontologic constraints will be undertaken to try to define the age relationships of the transition.

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CUMULATIVE COAL THICKNESS AND COALBED GAS POTENTIAL IN THE COMOX COAL BASIN, VANCOUVER ISLAND

Barry Ryan[1], Gwyneth Cathyl-Bickford[2] and Martin Niemann[3]

ABSTRACT

This paper presents desorption, isotherm, and coal thickness data for the Comox Basin on Vancouver Island, British Columbia. Cumulative coal thicknesses are presented as contours on a number of maps that together cover the Comox Basin. Cumulative coal thicknesses are greatest in the Cumberland to Tsable River areas. Based on coal rank and isotherms, the potential gas capacity of the coal increases to the south. Carbon isotope data from the northern part of the basin indicate a biogenic origin for the gas.

KEYWORDS: Comox Basin, coalbed gas, desorption, cumulative coal thicknesses, carbon isotopes, isotherms.

INTRODUCTION

The eastern side of Vancouver Island is underlain by two major coal basins, the Nanaimo Basin in the south and the Comox Basin in the north, each of which is subdivided into coalfields. Further north, there is also an area referred to as the Suquash Coalfield and a number of coal occurrences (Figure 1). The Suquash Coalfield has limited potential, and the Nanaimo Basin has largely been mined out; however, the Comox Basin has significant potential for coal mining and extraction of coalbed gas (CBG), also referred to as coalbed methane (CBM).

It should be noted that in previous literature there is no consistency in the use of the terms basin, coal basin and coalfield; however, in this paper it is convenient to use the term Comox Basin and then subdivide it into a number of coalfields.

The coal measures on Vancouver Island are contained in the Late Cretaceous Nanaimo Group, while those in the Comox Basin are largely restricted to the Comox Formation, which is divided into three members. The lowest Benson Member tends to be coarse-grained and devoid of coal; the overlying Cumberland Member contains at least two coal seams; and the uppermost Dunsmuir Member, which is sandier that the Cumberland Member, also in some places contains a single seam. Bickford and Kenyon (1988) described the coal geology of the Comox Basin, and Cathyl-Bickford and Hoffman (1998) mapped the Comox and Nanaimo basins on a 1:2000 scale.

This paper utilizes a drillhole database developed by Cathyl-Bickford to contour cumulative coal thickness in the Comox Formation within the Comox Basin. This is a preliminary study, and depth and rank data are not contoured, so that a detailed CBM resource estimate is not included. This paper also includes some new data that will aid in an assessment of the CBM potential of the basin. Desorption, carbon isotope, and gas composition data were collected from samples obtained during 2004 exploration in the Quinsam area (Figure 1). Isotherm data were collected both from core samples from exploration holes drilled in the summer 2004 in the Quinsam area and from samples collected from drilling in the Comox area in 2001.

COAL RANK IN THE COMOX BASIN

In the literature, rank data is quoted as mean maximum (Rmax%) or mean random (Rran%) reflectance of vitrinite. Recently, the literature generally uses mean random reflectance, which is quicker to measure in terms of microscope time than is mean maximum reflectance. Older literature sometimes used mean maximum reflectance. The relationship between the two measurements is empirical, but most equations indicate that Rmax is about 5% greater than is Rran for ranks in the Comox Basin (Table 1). Data in this paper are all corrected to Rran% of vitrinite.

It is important to have an overview of coal rank variation in the Comox Basin. Most of the coal in the basin is high-volatile A bituminous with ranks in the 0.65% to 0.9% range. Kenyon and Bickford (1989) provide Rmax measurements for many locations within the basin. Rank tends to increase from north to south, with some areas of high rank adjacent to Tertiary intrusions. Rank in the north at the Quinsam Mine ranges from 0.61% to 0.64% Rran (0.64% to 0.67% Rmax) (Ryan and Dawson, 1993) and in the area averages 0.66% with a range of 0.50% to 0.80% (recalculated to Rran from Matheson *et al*., 1994). The coal contains about 80% vitrinite on a mineral-matter-free basis (mmfb), and high vitrinite contents are generally characteristic of Comox coals. In the Cumberland area, rank is variable—increasing to 1.7% in the vicinity of Tertiary

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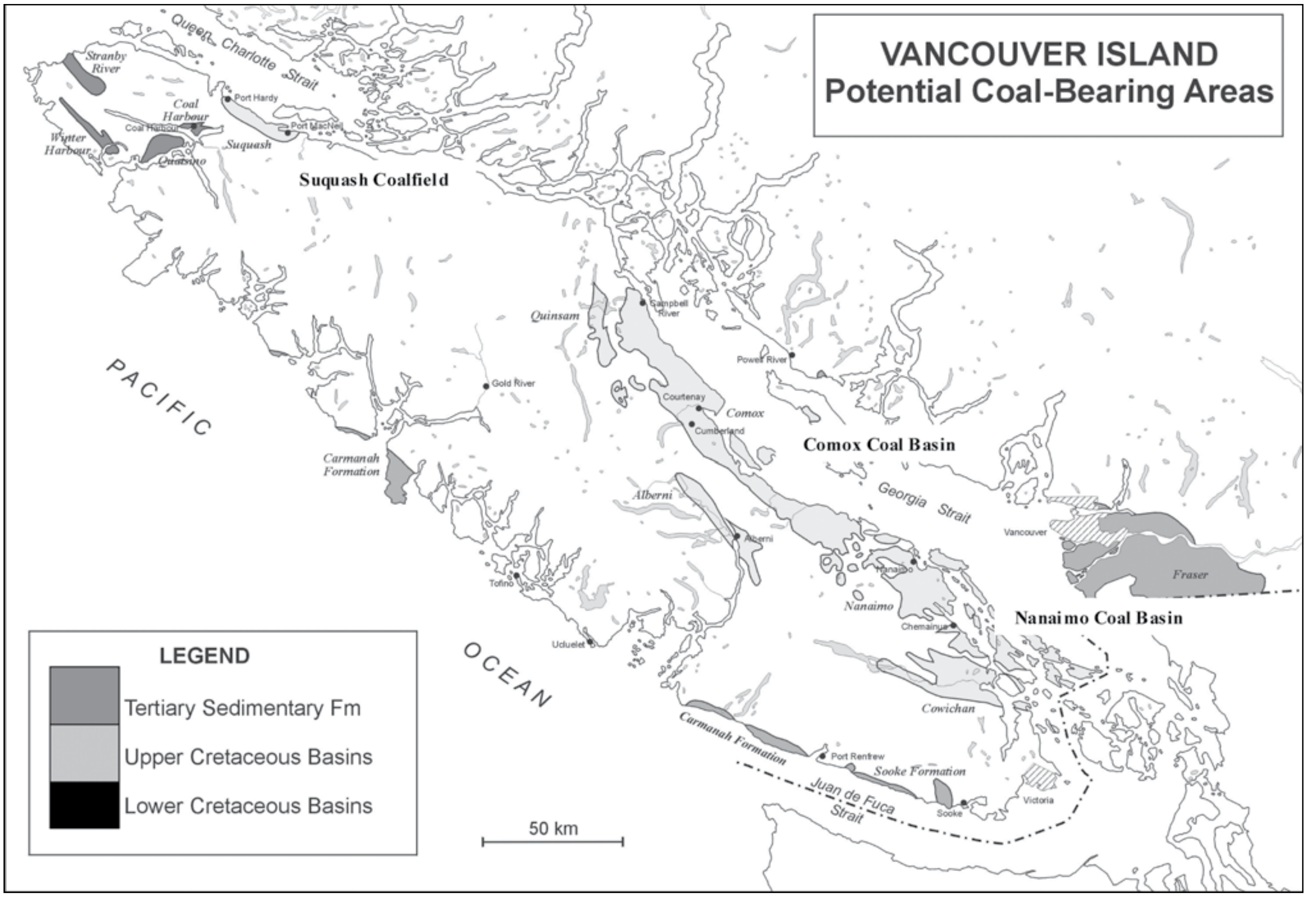


Figure 1. Regional map of coalfields on Vancouver Island.

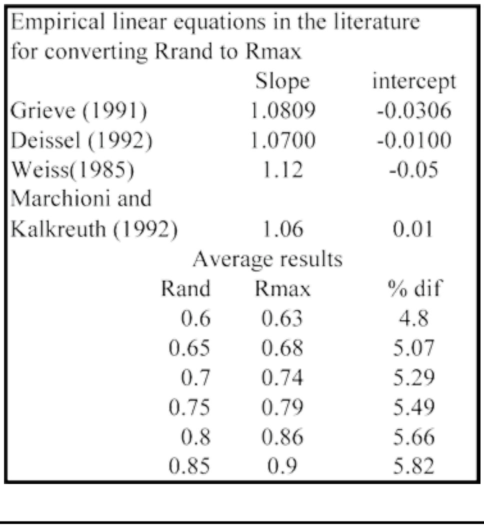
intrusions in the Browns River area (Kenyon and Bickford, 1989) but generally in the range 0.75% to 0.85% (Kenyon and Bickford, 1989 and Ryan, 2002). In the southern part of the Comox Basin in the Tsable River area, Rran rank is 0.80% (Ryan, 1997) to 0.83% (Kenyon and Bickford, 1989).

GAS DESORPTION DATA ON VANCOUVER ISLAND

There are very limited desorption data for coals on Vancouver Island. Novacorp obtained some of the earliest data when the company drilled 8 holes in 1985. Geophysical logs and hole locations are in reports filed with the Ministry of Energy and Mines in Victoria. Desorption data from this program have been referenced by a number of authors (Cathyl-Bickford, 1992), but little detail is published. Ryan (1997, 2002) has published limited desorption data for coal from Tsable River and Cumberland areas, and Ryan and Dawson (1993) have published data for coals from the Quinsam Mine. Samples from the last study came from depths ranging from 100.9 to 145.7 m, and gas contents (dry ash-free basis, dafb) ranged from 1 to 1.6 cc/g.

In this study, advantage was taken of a four-hole exploration program conducted west of the present Quinsam mine by the Quinsam mine personnel. Eight samples were collected from hole 2004-4 from depths ranging from 134.25 to 156.4 m (Table 2). The samples generally consisted of inter-layered bright coal and mudstone with high ash con-

TABLE 1. CONVERSION OF MEAN RANDOM REFLECTANCE TO MEAN MAXIMUM REFLECTANCE OF VITRINITE.125



Empirical linear equations in the literature for converting Rrand to Rmax

	Slope	intercept
Grieve (1991)	1.0809	-0.0306
Deissel (1992)	1.0700	-0.0100
Weiss(1985)	1.12	-0.05
Marchioni and Kalkreuth (1992)	1.06	0.01

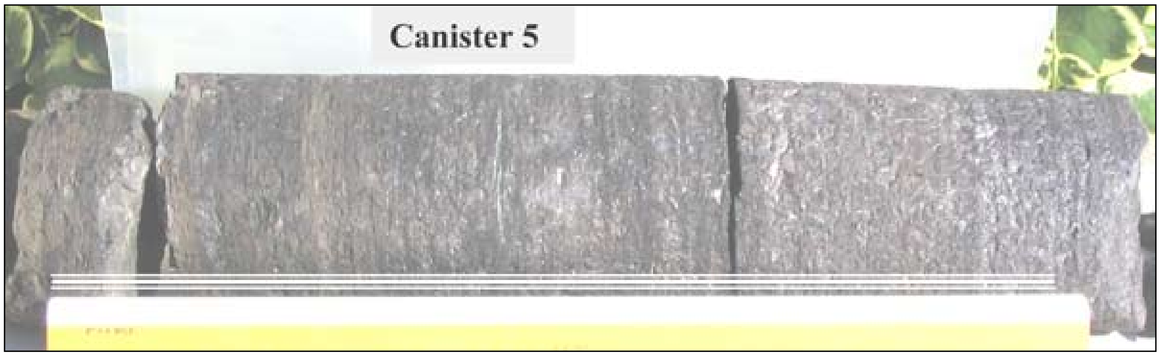
Average results

Rand	Rmax	% dif
0.6	0.63	4.8
0.65	0.68	5.07
0.7	0.74	5.29
0.75	0.79	5.49
0.8	0.86	5.66
0.85	0.9	5.82

TABLE 2. DESORPTION DATA FROM HOLE 2004-4 QUINSAM AREA.

Hole location Elevation 260, Easting 322796, Northing 5536095 metres										
sample	wt g adb	Seam	from metres	to metres	ash% adb	adm	gas cc/g adb	gas cc/g dmmfb	slope lost gas line	tau Hours
5	2829	2	134.25	134.65	39.39	1.56	0.585	1.10	0.065	35
6	2544	1R	138.11	138.5	21.32	1.44	1.332	1.80	0.106	150
8	3877	1	143.9	144.31	66.87	0.96	0.227	1.23	0.046	12
9	3331	1	144.45	144.85	67.70	0.87	0.450	2.11	0.050	125
7	3220	1	144.85	145.24	54.91	0.93	0.531	1.48	0.066	30
10	3109	1	146.43	146.84	60.92	1.05	0.533	1.84	0.061	120
11	3216	1	148.51	148.89	68.38	0.96	0.292	1.43	0.039	20
12	3646	1L	155.98	156.4	68.89	1.13	0.237	1.21	0.028	70

Photo 1. Core sample canister 5.



tents (Photo 1). Gas contents on an air-dried basis ranged from 0.2 to 1.3 cc/g and, on a dry mineral-matter-free basis, range from 1.1 to 2.1 cc/g. The mmfb calculation was made using a mineral-matter-to-ash ratio of 1.15 as supported by the specific gravity data discussed in the "correction to mmfb" section that follows. A plot of gas content (mmfb) *versus* ash does not reveal any trend, indicating that there is no obvious bias in the correction to mmf basis. Based on an isotherm for the sample from seam 1R (Figure 2, Table 3), seams are under-saturated at the shallow depth of about 150 m. The degree of under-saturation may reflect a low and fluctuating water table. If the effective long-term water table is 50 m below surface, then on average the samples appear to be saturated.

The ash content of the samples is variable and high, and some samples are mainly mudstone with coal stringers. There is no apparent correlation of gas content (dry mineral-matter-free basis, dmmfb) with ash content. However, sorption time, Tau (time to 0.632 total desorbed gas), correlates weakly with gas content (mmfb), possibly indicating that high mmfb gas contents correlate with larger particle sizes, which control diffusion. However, there is no correlation of coal particle size with the total ash content in samples. Whatever is influencing coal grain size is not related to the amount of mudstone in samples and is variable with depth.

Diffusivity is related to the slope of the lost-gas plot (gas *versus* $t^{1/2}$) (Smith and Williams, 1984) and to the sorption time, Tau (Gas Research Institute**,** 1995). However, the latter determination assumes that the calculation uses the shape factor and the first that the actual radius of particles is the radius controlling spherical diffusion. The values of diffusivity calculated by the two methods differ, but the difference is minimized if spherical diffusion, with a shape factor of $15/r^2$, is used (Figure 3). It appears that even in fairly solid core, it is broken into particles approaching spherical shape rather than cylindrical shape. This is also suggested by the fairly short Tau times, because long Tau times probably correlate with cylindrical diffusion. Sample 8 (Table 1), which has high ash content and is mainly mudstone with stringers, appears not to conform with spherical diffusion; however the Tau time constant is short.

TABLE 3. ISOTHERM DATA; CANISTER 6, SEAM 1R; DEPTH CALCULATED ASSUMING NORMAL HYDROSTATIC GRADIENT.

temperature	20ºC
ash %	20.37
EQ moisture%	4.82
SG	1.472
wtlos	1.15
Rran	0.68
Lang vol AR cc/g	34.09
Lang P Mpa	4.6

depth m	MPa	AR	DAF	mmfb
37	0.366	0.39	0.52	0.54
72	0.709	0.91	1.21	1.26
118	1.155	1.45	1.94	2.02
170	1.668	1.92	2.57	2.68
221	2.164	2.33	3.12	3.25
273	2.682	2.62	3.5	3.65
386	3.787	3.27	4.37	4.56
522	5.122	3.79	5.06	5.28
671	6.577	4.08	5.45	5.68
821	8.05	4.34	5.8	6.05
938	9.196	4.69	6.27	6.54
1111	10.9	4.92	6.57	6.85
1214	11.906	5.08	6.79	7.08

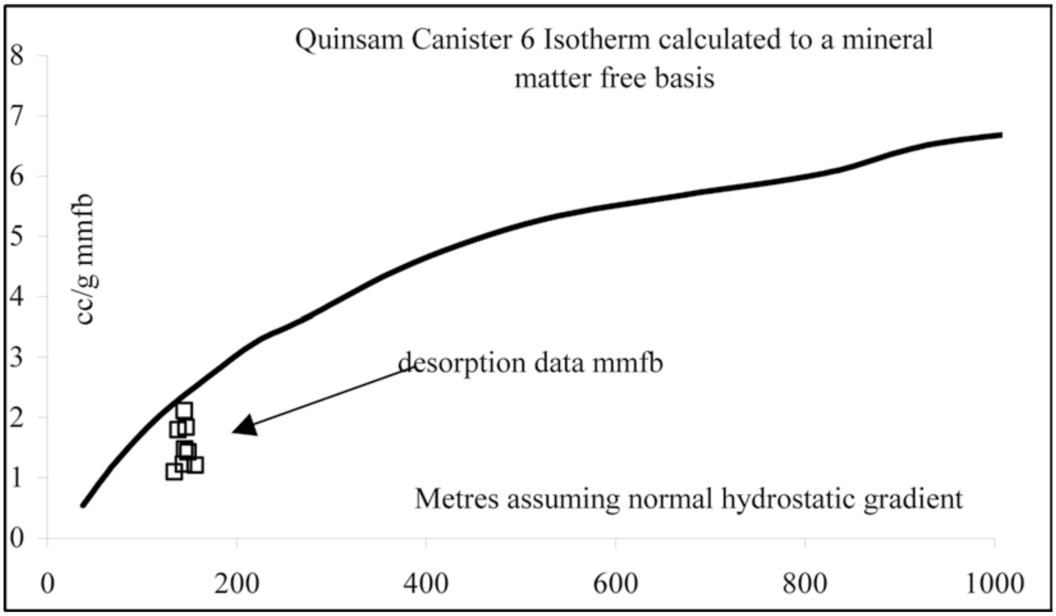


Figure 2. Isotherm plot; Canister 6, seam 1R Quinsam area with desorption data all calculated to a mineral-matter-free basis using a mineral-matter-to-ash ratio of 1.15.

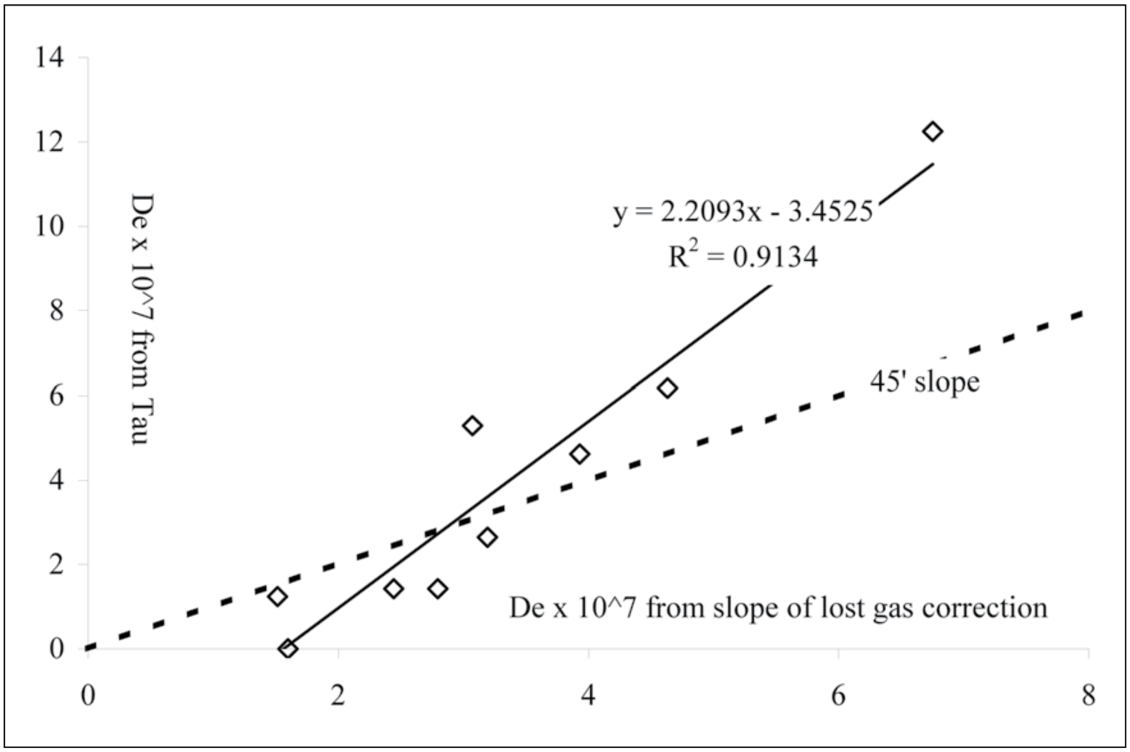


Figure 3. Diffusivity calculated from lost-gas plots and from the time to 63.2% desorbed gas for each sample.

CARBON ISOTOPE RATIOS AND GAS COMPOSITION DATA FOR QUINSAM GAS SAMPLES

Gas samples from canisters 5 to 12 (Table 2) were taken during desorption and analyzed for chemical composition and isotopic composition. Analyses were performed at the Biogeochemistry Facility of the University of Victoria using a gas chromatography–isotope ratio mass spectrometer (GC-IRMS).

Concentrations of hydrocarbons and carbon dioxide were measured over a period of time from each canister. Prior to collecting gas samples, the sampling line was purged with argon. Consequently samples contained a mixture of desorbed gas and argon (Table 4). If it is assumed that samples contain only CH_4, C_2H_6, CO_2, and argon, then the average composition of the gas desorbed from the canisters is about 97% CH_4, 2% CO_2, and less than 0.2% C_2H_6.

Carbon isotope values ($\delta^{13}C$-C_1 methane) for the samples change over time during desorption (Table 5), as does the gas composition of the samples. The isotope values (Table 5) are given in the delta (δ) notation with reference to the PDB-standard. A modified Bernard plot (Figure 4, gas wetness vs. $\delta^{13}C$-C_1 plot) is commonly used to differentiate between biogenic and thermogenic gases. Biogenic gases are generally characterized by “light” methane isotope compositions, with $\delta^{13}C$ values more negative than −55‰, whereas thermogenic gases generally have $\delta^{13}C$ values less negative than −55‰ (Schoell, 1980). Compared to biogenic gases, thermogenic gases are also characterized by higher concentrations of heavier hydrocarbons (wet gas). Biogenic activity does not generally generate heavier hydrocarbons, and heavier hydrocarbons are adsorbed more strongly onto coal than is methane.

Almost all $\delta^{13}C$ values for the samples are “lighter” than −55‰ (Figure 4) and in terms of gas composition are considered to be dry, indicating biogenic gas generation. The data are divided into two sets—one representing initial samples and a second representing samples collected later during desorption. The wetness increases with desorption (Figure 4), but there is little change in $\delta^{13}C$ values. The increase in wetness is due to stronger adsorption of higher hydrocarbons and not due to mixing of biogenic gas with thermogenic gas, which would create $\delta^{13}C$ values in the range –50‰ to –30‰ (Figure 4).

CORRECTION TO MINERAL-MATTER-FREE BASIS

It is important to reduce all data to a common basis when comparing gas content results. This is often done by reducing data to a dry ash-free basis (dafb), which is a simple correction using the measured moisture contents (or a constant equilibrium moisture content) and ash contents. Alternatively, a mineral-matter-free correction is used that requires ash and sulphur contents and generally uses the Parr equation. Both approaches have problems derived

TABLE 4. ISOTOPIC COMPOSITION AND VARIATION OVER TIME OF METHANE RELEASED FROM CANISTERS DURING DESORPTION.

	actual concentations				calculated to 100%		
Canister No.	[CH_4] [%]	[C_2H_6] [%]	[CO_2] [%]	A %	[CH_4] [%]	[C_2H_6] [%]	[CO_2] [%]
5	14.7	0.1	0.3	84.9	97.4	0.7	2.0
6	14.9	< 0.02	0.2	84.9	98.5	0.1	1.3
7	13.1	< 0.04	0.3	99.7	97.5	0.3	2.2
8	10.9	< 0.007	0.2	88.9	98.1	0.1	1.8
9	10.5	< 0.01	0.2	89.3	98.0	0.1	1.9
10	5.8	0	0.1	94.1	98.3	0.0	1.7
11	2.7	0	0.1	97.2	96.4	0.0	3.6
12	3.1	0	0.1	96.8	96.9	0.0	3.1

TABLE 5. AVERAGE CONCENTRATIONS OF METHANE, ETHANE, AND CARBON DIOXIDE RELEASED FROM CANISTERS DURING DESORPTION.

Time Steps	$\delta^{13}C-CH_4$ Can. 5 [‰]	$\delta^{13}C-CH_4$ Can. 6 [‰]	$\delta^{13}C-CH_4$ Can. 7 [‰]	$\delta^{13}C-CH_4$ Can. 8 [‰]	$\delta^{13}C-CH_4$ Can. 9 [‰]	$\delta^{13}C-CH_4$ Can. 10 [‰]	$\delta^{13}C-CH_4$ Can. 11 [‰]	$\delta^{13}C-CH_4$ Can. 12 [‰]
1	-75.9	-81.1	-65.3	-74.7	-79.3	-69.0	-77.6	-66.4
2	-73.0	-77.2	-61.4	-67.7	-65.9	-65.5	-76.9	-64.5
3	-67.2	-68.2	-60.7	-63.9	-66.4	-65.0	-72.9	-64.6
4	-67.5	-64.1	-63.3	-66.5	-64.6	-68.5	-71.6	-71.3
5	-70.3	-63.6	-65.6	-66.1	-66.3	-68.4	-69.8	-72.1
6	-70.6	-69.7	-67.5	-67.6	-66.5	-68.8	-70.4	-72.3
7	-72.6	-70.7	-67.7	-67.6	-66.9	-69.8	-70.7	-73.5
8	-72.3	-70.8	-67.4	-67.5	-66.5	-69.2	-70.5	-72.7
9	-72.2	-70.2	-66.9	-66.9	-66.1	-70.3	-71.8	
10	-73.4	-71.1	-67.7	-68.1	-66.7	-71.1	-70.6	
11	-72.9	-71.6	-67.9	-65.8	-67.4	-70.9		

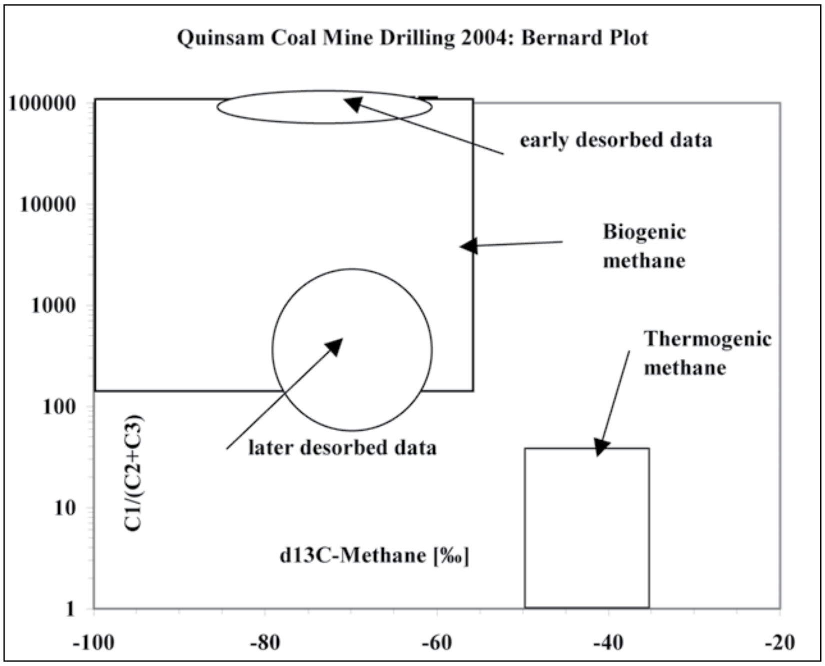


Figure 4. Simplified Bernard plot showing gas wetness (C1/C2+C3) on the y axis vs. the carbon isotope composition of methane on the x axis. Separate fields indicate biogenic and thermogenic gas generation (modified from Whiticar, 1986)

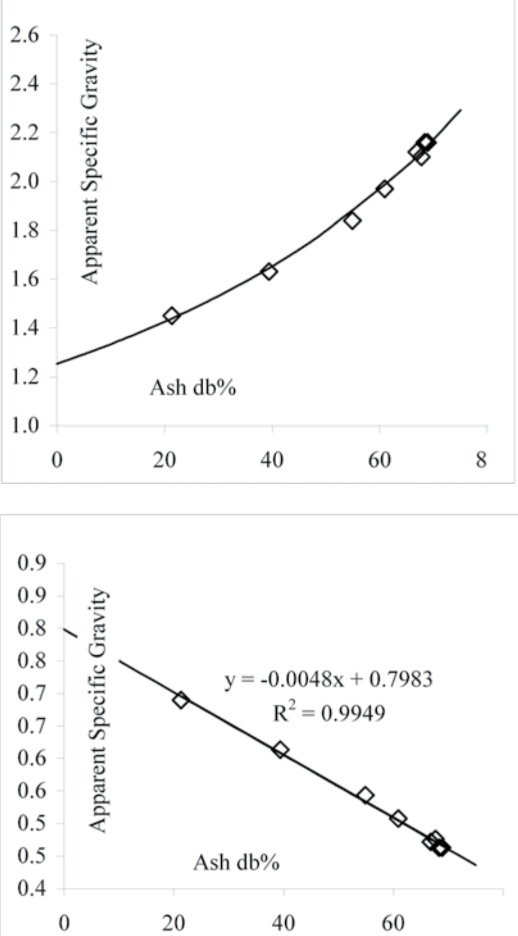
from the fact that the ratio of mineral matter to ash varies, is not 1, and is not always adequately accounted for using the Parr equation. An alternative approach uses Apparent Specific Gravity (ASG) analyses performed on air-dried samples.

The relationship of ASG to ash has the form

$SG=1/(A-B*ash)$ (1) (Ryan, 1993)

which can also be expressed as

$1/ASG=A-B*ash$ (2)



slope(0.481)=(DMM-DC)/(DMM*DC)*WTLOS

DMM SG mineral matter

Intercept= 1/SG zero ash coal (DC=1.253)

WTLOS	DMM
1.12	2.715
1.13	2.688
1.14	2.661
1.15	2.635
1.16	2.61
1.17	2.586

Figure 5. Quinsam desorption data; measured apparent specific gravity values (ASG) versus ash content and calculation of mineral-matter-to-ash ratio (WTLOS).

The constant A equals 1/DC (where DC is the density for zero-ash coal), and the constant B incorporates the density of rock (DMM) and the ratio mineral-matter-to-ash (WTLOS). Plotting ash-*versus*-ASG data using Equation 2 allows for solving for DC and for generation of a table of possible pairs of DMM and WTLOS values. Correction of data to a mmf basis is easy using the expression

gas mmfb= gas/(1−ash*WTLOS)

once a value of WTLOS is determined. The Quinsam data set is plotted in Figure 5 and illustrates how to obtain a solution for WTLOS.

A plot of gas content *versus* ash content (dry basis) (for saturated samples) should provide a straight line, which intersects the *y* axis at the *gas content (mmfb)* and has a slope of *gas content (mmfb) x WTLOS* (Figure 6). The imaginary data in Figure 6 are calculated assuming a gas content of 10 cc/g (mmfb). Unfortunately many data sets do not plot on a straight line, in part because coal petrographic composition varies with ash content. Correcting data,with varying ash contents back to gas contents (dafb) produces considerable error when there is a range of ash contents (Figure 6). In fact for the data set used in Figure 6, with ash contents ranging from 20% to 70%, calculated gas values (dafb) range from 6.7 to 9 cc/g when the actual gas (mmfb) is 10 cc/g.

It is apparent that when there is a wide range of ash content corrections, using daf basis produces errors that will make it difficult to compare data and to determine whether samples are saturated. Use of ASG data and a linear plot to determine the WTLOS factor allows calculation of the mmfb gas content in a simple and cost-effective way.

ISOTHERM DATA PETROGRAPHY AND RANK OF CANISTER 6

A number of isotherms exist for the Comox Basin. This paper presents new isotherms for the Quinsam and Dove Creek areas (Figure 2, Table 3). An isotherm was measured for the sample Canister 6 seam 1R, which has a rank of 0.65% Rran. The sample is vitrinite-rich and contains about 13% by volume mineral matter (Figure 7). Two isotherms, previously unpublished, were obtained from samples collected during the drilling at Dove Creek in 2001. The rank of these samples is somewhat higher but they also contain a high percentage of vitrinite on a mineral-matter-free basis (Figure 7).

Isotherm data already exist for coals at Tsable River (Bustin, personal communication, 2003) and Quinsam (Ryan and Dawson, 1993). All isotherm data are plotted in Figure 8. The isotherms reflect the decreasing rank from north to south, and at 500 m, saturated-gas contents are predicted to range from 6.6 cc/g (daf) to 10.9 cc/g (daf). Ranks are highest in the Dove Creek area, though this may be the

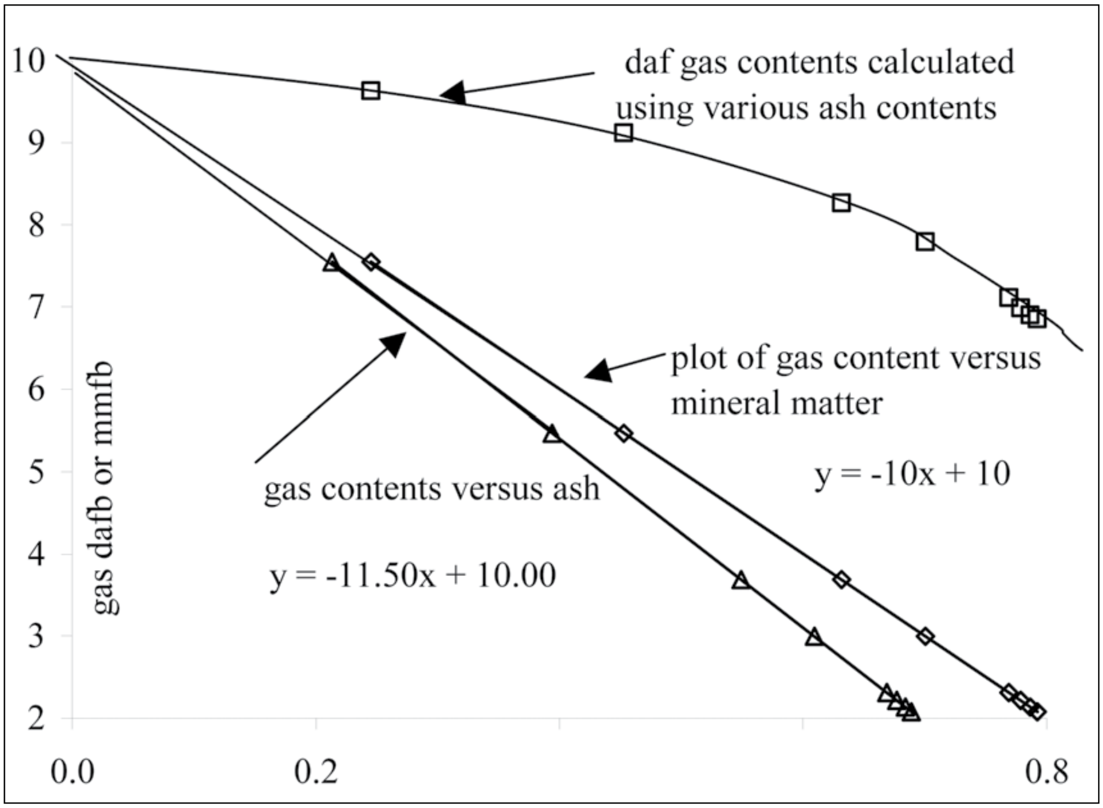


Figure 6. Plot of ash or mineral matter *versus* gas content. The slope of the ash db *versus* gas content plot is the WTLOS factor.

result of local Tertiary intrusions. The composition of gas desorbed from the 3 holes at Dove creek (Ryan, 2002) included a moderate amount of nitrogen that might originate from Tertiary intrusive activity.

COAL THICKNESS ISOPACHS

A database containing formation and coal picks from approximately 1300 holes was generated by Cathyl-Bickford and made available for this study. The database includes depths and thicknesses of net coal in seams and thicknessess of seams in the Comox Formation. An estimate of the cumulative thickness of seams, including in-seam splits in each hole, provides a starting point for estimating the potential CBM resource in the Comox Basin. Because it neither considers individual seam thicknesses and depths nor excludes splits, it does not provide an estimate of that part of the coal resource that might be available for underground or surface mining.

The cumulative coal thickness data for holes was contoured to provide isopachs. Contouring was limited by the subcrop of the Comox Formation and by the coastline to the east. In addition, contours were not extended into areas where holes did not contain coal, irrespective of whether this was because there was not coal in the section or because the hole was not drilled deep enough. The gridded file used to produce the contours was also used to calculate the tonnage represented by the contour values and area covered by the contours. Tonnage calculations are made assuming an average specific gravity of 1.5 g/cm^3. The value derived is an estimate of coal resource, including splits and seams too thin to be of interest for mining; it is therefore an estimate of the resource available for CBM exploration.

The Comox Basin is subdivided into 8 areas (Figure 9). These areas tend to outline local areas of more intense drilling (Figure 10) and therefore in a loose way tend also to outline areas previously described as coalfields. The area referred to as Ash River (Figure 9) is actually in the Alberni Coalfield but is included here for completeness. It should be noted that there are no accepted outlines nor standardized names to coalfields. Maps for each of the sub-areas outlined in Figure 9 provide contours of cumulative coal thickness and plots of drill holes, indicating which holes intersected coal and which did not.

Data in each area are kriged using 250 m by 250 m cell sizes. Search areas were set as circles with radii of 2.5 km. No attempt is made in this preliminary study to tailor the kriging to recognize anisotropy in the geology. Seam development is probably most consistent in a northwest-southeast direction with a shoreline to the west-southwest and a hinterland to the northeast.

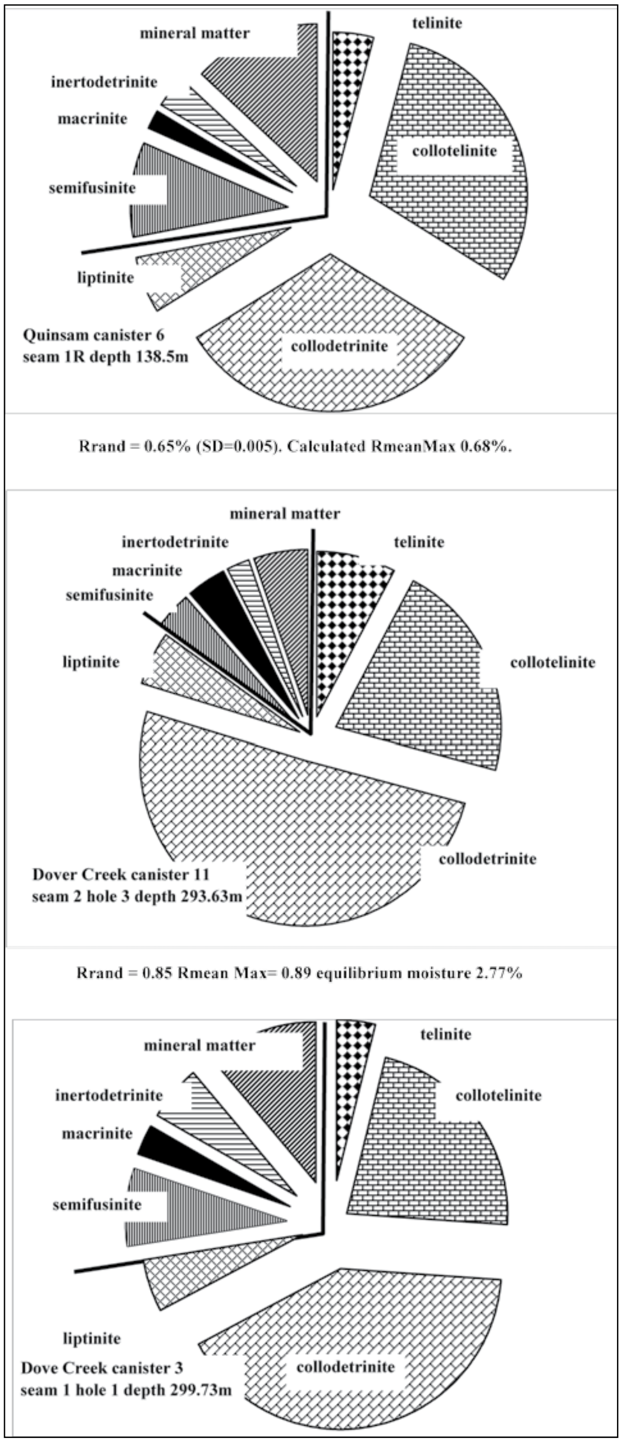


Figure 7. Petrography and rank for isotherm samples Quinsam canister 3, Dove Creek canister 3 and Dove Creek canister 11.

In the south (Figure 11), a number of holes were drilled in the Ash River area (Alberni Coalfield), but none intersected coal.

The southernmost area of interest in the Comox Basin is Cowie River, where 47 holes were drilled (circles Figure 12a) with 33 intersecting coal (circles filled with a cross Figure 12a). Some of this area overlaps with the Tsable River area to the north. The drilling was not successful in extending the coal measures south of Wilfred Creek. The Comox Formation subcrops along the western margin of the area and dips at between 5° and 20° to the northeast. Coal is restricted to the northern part of the area where cumulative thicknesses range from less than 3 m to over 10 m (Figure 12b). An area of about 30 km^2 is underlain by about 250 x 10^6 t of resource (Table 6).

Over the years there has been a lot of interest in the Tsable River area. A small underground mine operated from 1945 to 1966, and in the 1990s Hillsbourgh explored the area hoping to develop an underground coalmine. Exploration outlined an underground potentially mineable resource of about 100 x 10^6 t (Gardner, 1999). There is a large area underlain by more than a cumulative 6 m of coal, and data indicate that coal probably extends under Georgia Strait, though ash content of the seams may increase to the east (Cathyl-Bickford, 1992). More recently, there has been interest in the CBM potential of the area.

The southern part of the Tsable River area overlaps with the Cowie River area and this is accounted for when calculating the tonnage attributed to the Tsable River area. There are 151 holes in the area, of which 126 intersect coal (Figure 13a). The contoured area (Figure 13b), which is about 71 km^2, is underlain by 454 x 10^6 t of resource. Some CBM desorption data were collected in 1996 (Ryan, 1997); generally samples appeared to be under-saturated, and as-received gas contents ranged from 1.6 to 5.5 cc/g for samples collected over a depth range of 127 to 376 m. Ash content of samples ranged from 14% to 55%.

In the Cumberland area, there is a long history of mining, which lasted from 1869 to 1947. During this period, 14.5 x 10^6 t of high-volatile A bituminous coal were extracted. The mines in the area were gassy, and over the years at least 300 people were killed. Based on emission rates (Cathyl-Bickford, 1992), gas contents vary from 7 to 14 cc/g on an as-received basis. In 2001 Priority Ventures drilled 3 holes in the Dove Creek area (Figure 14a) north of the Cumberland mines. Hole D3 (Table 7) is about 2 km from the underground workings and from the other 2 holes further to the north. Some desorption work was performed on the core from these holes (Ryan, 2002). Gas contents of the samples range from 3.5 to 11.5 cc/g on a daf basis. Ash contents are high, but some of the samples appeared to be gas-saturated.

A report on the exploration at Dove Creek was submitted to the government (Cathyl-Bickford, 2001). Data in coal exploration reports is confidential for three years following the exploration program, but data in this report are now public, and Table 7 provides information on the cumulative coal in the three holes. Net coal data is extracted from the report and gross coal thicknesses are estimated

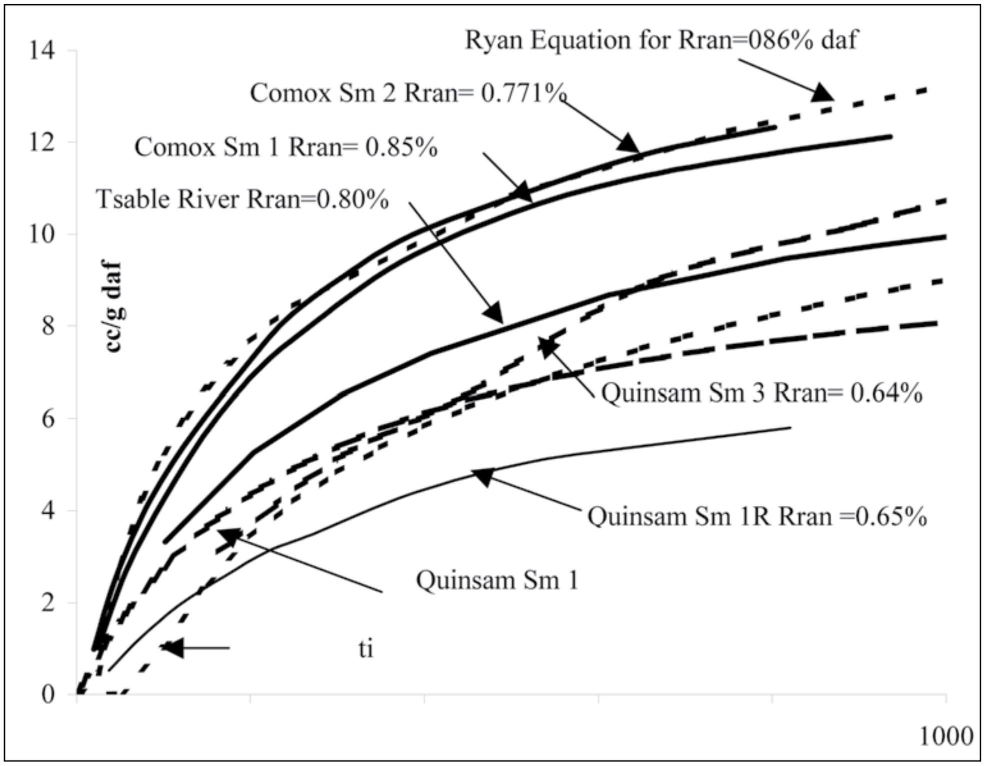


Figure 8. Isotherms for seams from the Comox Basin.

from geophysical logs in the report. There is considerable difference between net coal thickness and seam width (Table 7). The 3 holes have cumulative coal thicknesses of 12, 11, and 5 m and net coal thicknesses of 4.9, 6.1, and 2.3 m. Ash contents generally appear to be high and in the range 35% to 50%.

A total of 245 holes were drilled in the Cumberland area, with 174 holes intersecting coal (Figure 14a). A lot of these holes were shallow and drilled in the area of the underground mines, which are located on Figure 14a. These areas were excluded from resource calculations. The area contoured (Figure 14b) is 125 km^2 and it contains 1820 x 10^6 t. Much of this resource underlies existing communities and may not be available for CBM exploration. Cumulative coal thicknesses in much of the area are over 10 m, though in the east the contours are not supported by much drill data (Figure 14a). Gardner (1999) estimates that there might be a potential coal resource of about 70 x 10^6 t available for underground mining in the area.

The Trent River area, also referred to as the Hamilton Lakes area, (Figure 15) consists of two outliers and an ill-defined area of coal-bearing rocks to the east that dip off to the northeast. Within these areas there are 35 holes, of which 16 intersect coal (Figure 15, in which cumulative thickness data are posted next to hole location). The northeastern outcrop area, which is about 4.5 km^2, contains a resource of about 32 x 10^6 t (Figure 15). No resource is assigned to the southern area. Gardner (1999) calculates a coal resource in these areas of 6.4 x 10^6 t in the north and 2.6 x 10^6 t in the south. The amount of data east of the main subcrop line (Figure 15) is limited, and the tonnage estimate is restricted to two areas where holes intersected coal (outlined by small circles in Figure 15); these two areas cover about 6.5 km^2 and represent a potential resource of about 100 x 10^6 t.

There are 30 holes in the Tsolum River area, and only 7 intersect coal (Figure16). The cumulative coal is posted next to the holes in Figure 16. There are only 3 holes in the south, with cumulative coal thicknesses between 6 and 14 m. Tonnage calculation restricted to the area where holes intersected coal resulted in a potential resource of 130 x 10^6 t in an area of 16.5 km^2. A number of companies have drilled in the area and intersected thin seams 1 to 1.5 m thick with limited mining potential; however, the rank in the area is high—in some places reaching semi-anthracite (Gardner, 1999).

The coal potential of the Oyster River area, which is east and south of the Quinsam mine, is discussed by Bickford *et al*. (1990) and by Gardner (1999), who refers to it as the Quinsam East area and outlined a surface mineable resource of 8.2 x 10^6 t. There are 87 holes in the area, and 49 intersect coal (Figure 17a). The potential resource in the area contoured (Figure 17b) is 360 x 10^6 t, which underlies an area of 41.5 km^2.

The Quinsam area represents an outlier isolated from the Comox Basin by faults that bring to surface an area of basement. The area has been explored extensively by a number of companies over the years (Kenyon *et al*., 1991),

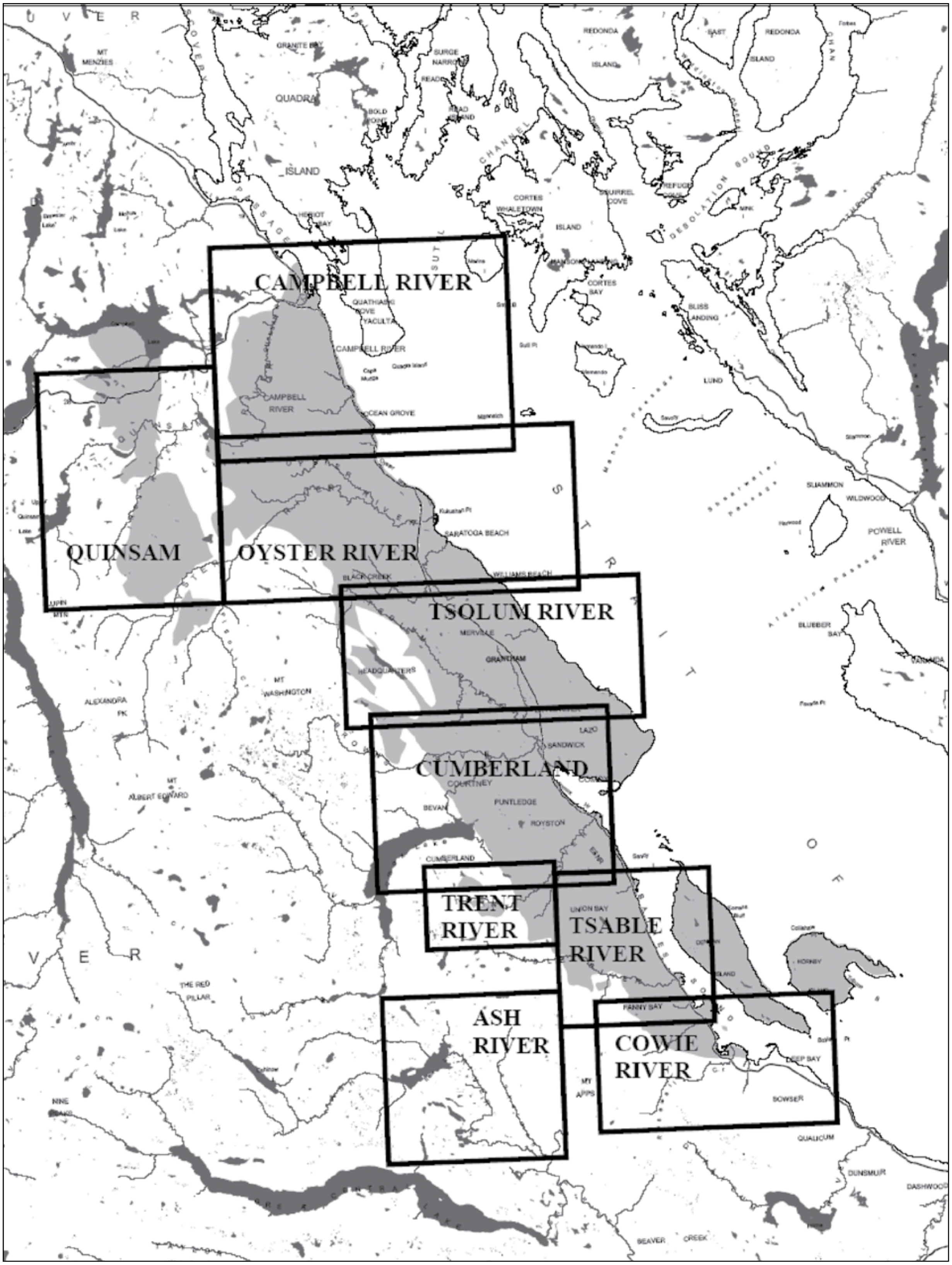


Figure 9. Location of subbasins of the Comox Basin in which cumulative coal thickness is contoured.

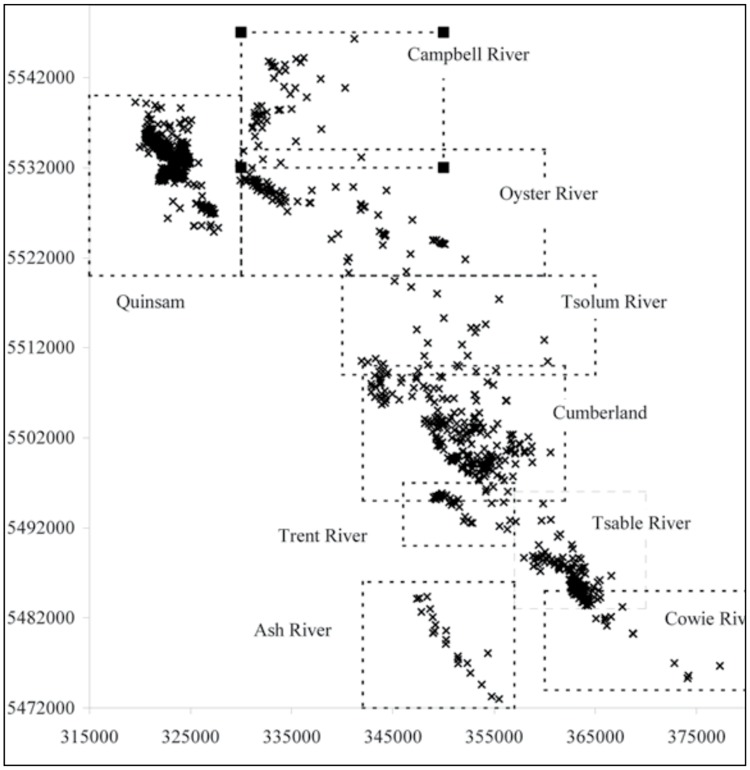


Figure 10. Drill distribution in the Comox Basin.

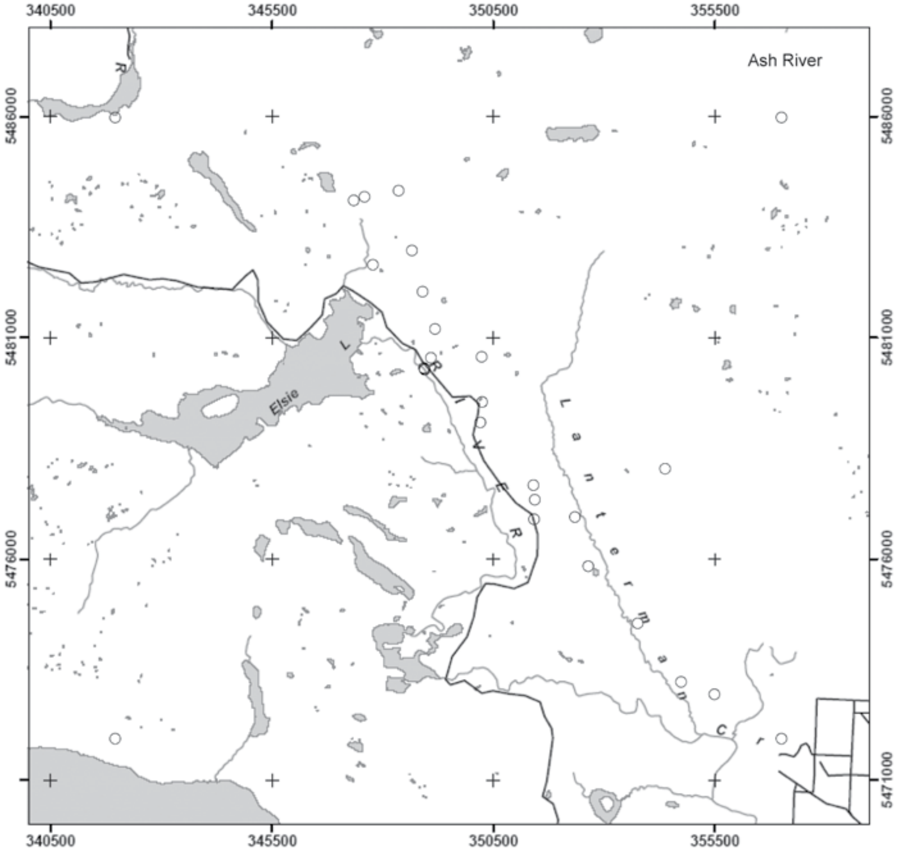


Figure 11. Drill holes—Ash River area, Alberni Coalfield.

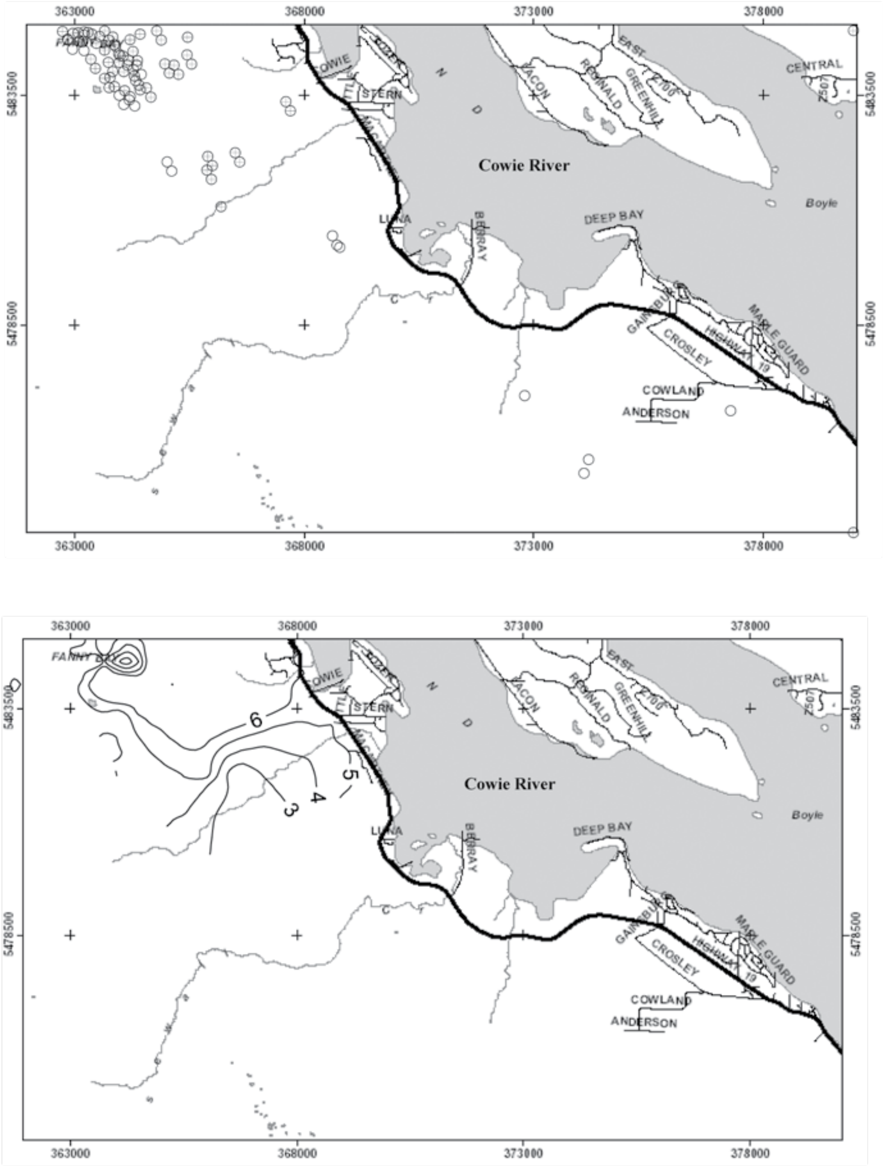


Figure 12. Cowie River area; (a) all holes drilled and holes intersecting coal and (b) cumulative coal thickness contours.

TABLE 6: COMOX BASIN; COAL-BEARING AREAS AND ESTIMATED COAL RESOURCE BY AREA.

Area from Figure 9	mil tonnes	area Km^2	av thick	gas cc/g	resource bcf
Campbell River	245	46.2	3.5	4.0	31.3
Quinsam	112	26.1	2.9	4.0	14.4
Oyster River	332	49.1	4.5	4.0	42.5
Tsolum River	87	16.6	3.5	8.5	23.7
Cumberland	1287.2	124.2	6.9	8.5	350.5
Trent River N area	32	4.4	4.9	6.0	6.1
Trent River NE area	83	5.3	10.6	6.0	16.0
Trent River SE area	15	1.3	7.6	6.0	2.9
Tsable River	587	84.5	4.6	6.0	112.9
Cowie River	246	29.3	5.6	6.0	47.3
totals	3026.9	386.8			647.8

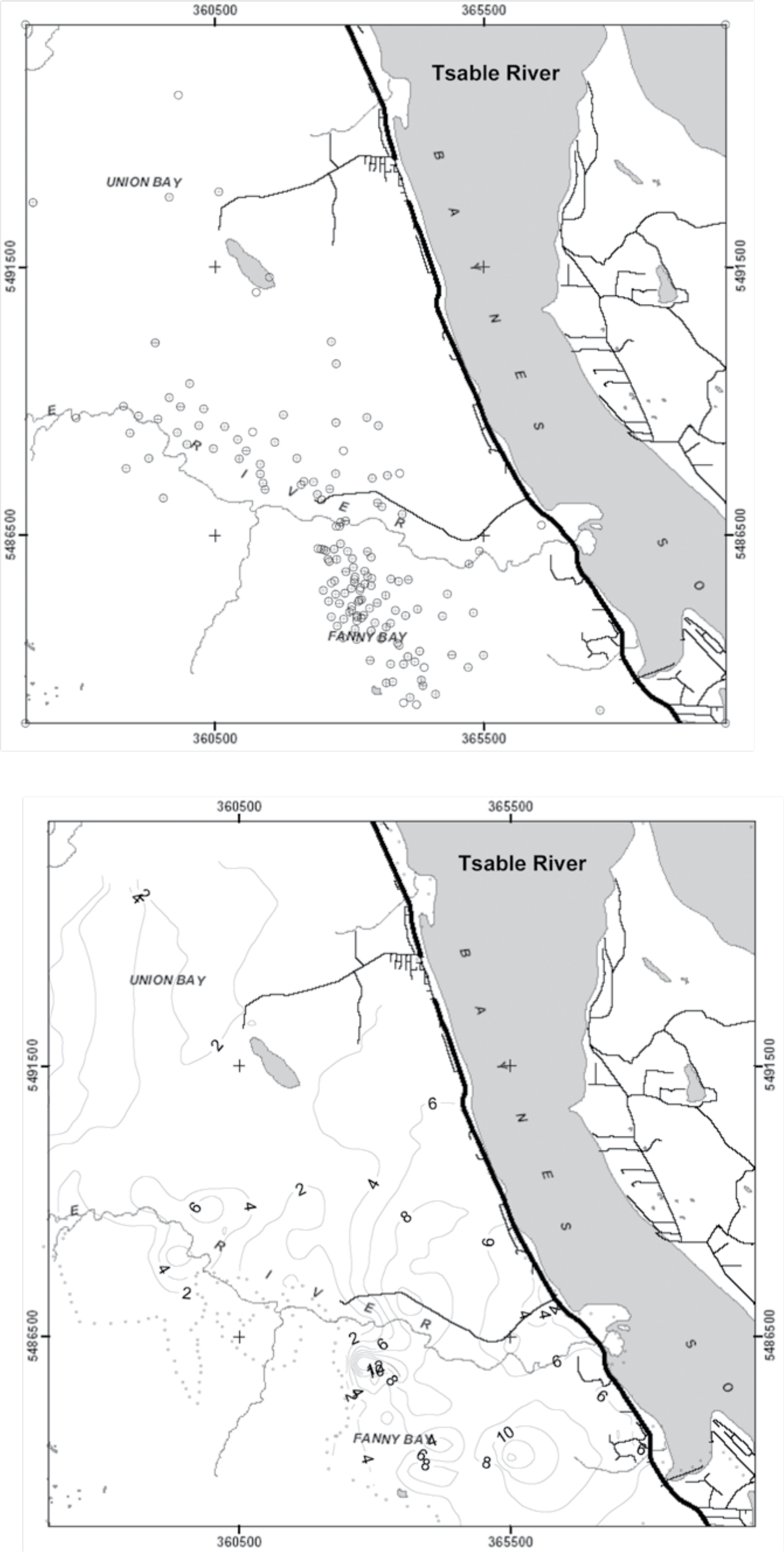


Figure 13. Tsable River area; (a) all holes drilled and holes intersecting coal and (b) cumulative coal thickness contours.

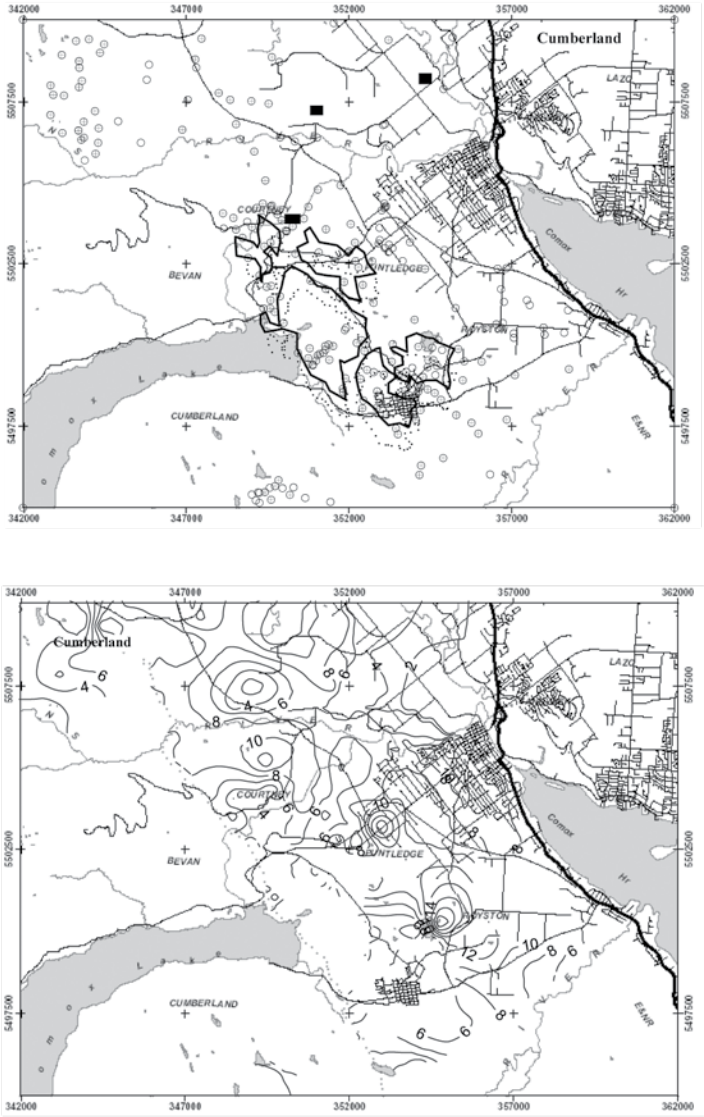


Figure 14. Cumberland area; (a) drill holes with outline of underground mining and location of the 3 Priority Ventures holes; (b) contours of cumulative coal thickness.

TABLE 7. COAL THICKNESSES BY SEAM IN THE DOVE CREEK AREA.

seam	hole D1				hole D2A				hole D3		
	depth metres	coal net	coal gross	ash	depth metres	coal net	coal gross	ash	depth metres	coal net	coal gross
X	206.0	0.01			416.4	0.48	1.6		236.1	0.52	1.4
XL	211.6	0.03	0.8		424.8	0.55	0.8				
Y	230.6	0.305	1		443.0	0.53	0.6		255.5	0.12	0.4
YL	235.6	0.33	0.7		448.3	0.03	0.5		260.0	0.27	0.4
Z	254.1	1.09	1.8	45.85	460.4	0.98	2.2	46.5	271.5	0.15	0.3
1R	274.1	0.54	1.2		477.1	1.08	1.4		296.0	0.6	1.2
1	276.2	0.22	0.6		484.7	1.19	2		297.5	0.51	0.9
1L					490.7	0.47	0.5		298.9	0.35	0.9
2R	291.0	0.35	0.4		504.0	0.55	0.6		309.4	0	
2	298.9	0.9	1.8	35.14	512.4	0.28	0.6		314.5	0.315	1.1
2A	325.3	0.51	1.8								
3	347.5	0.6	2.2								
cumulative coal		4.885	12.3			6.14	10.8			2.315	5.2

Data from Cathyl-Bickford (2001).

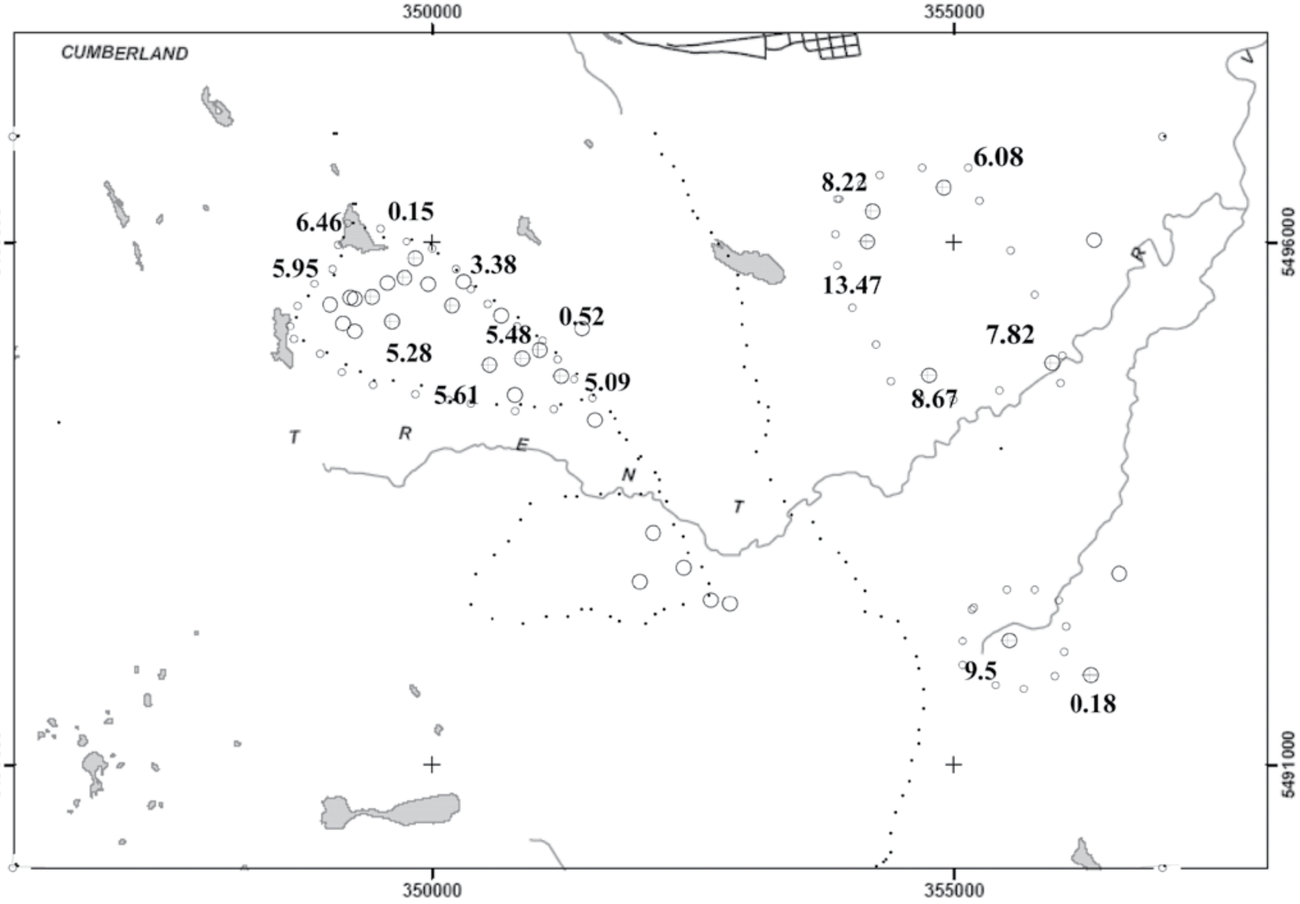


Figure 15. Trent River area; (a) all holes drilled and holes intersecting coal; (b) contours of cumulative coal thickness.

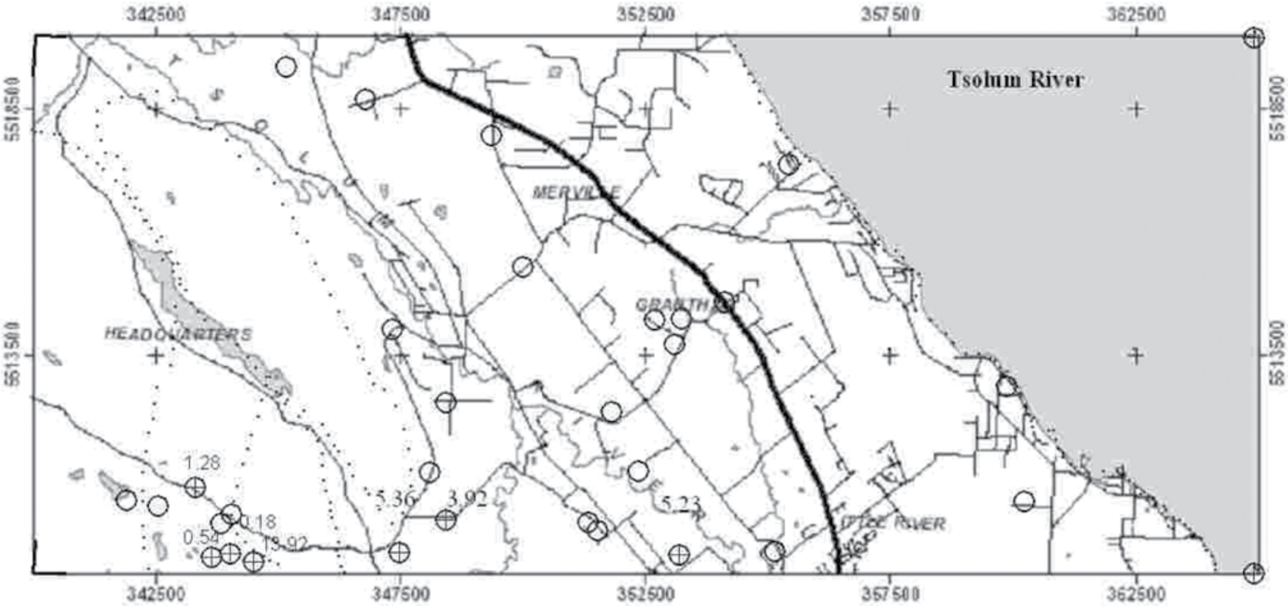


Figure 16. Tsolum River area; plot of drill holes and posted cumulative coal thickness contours.

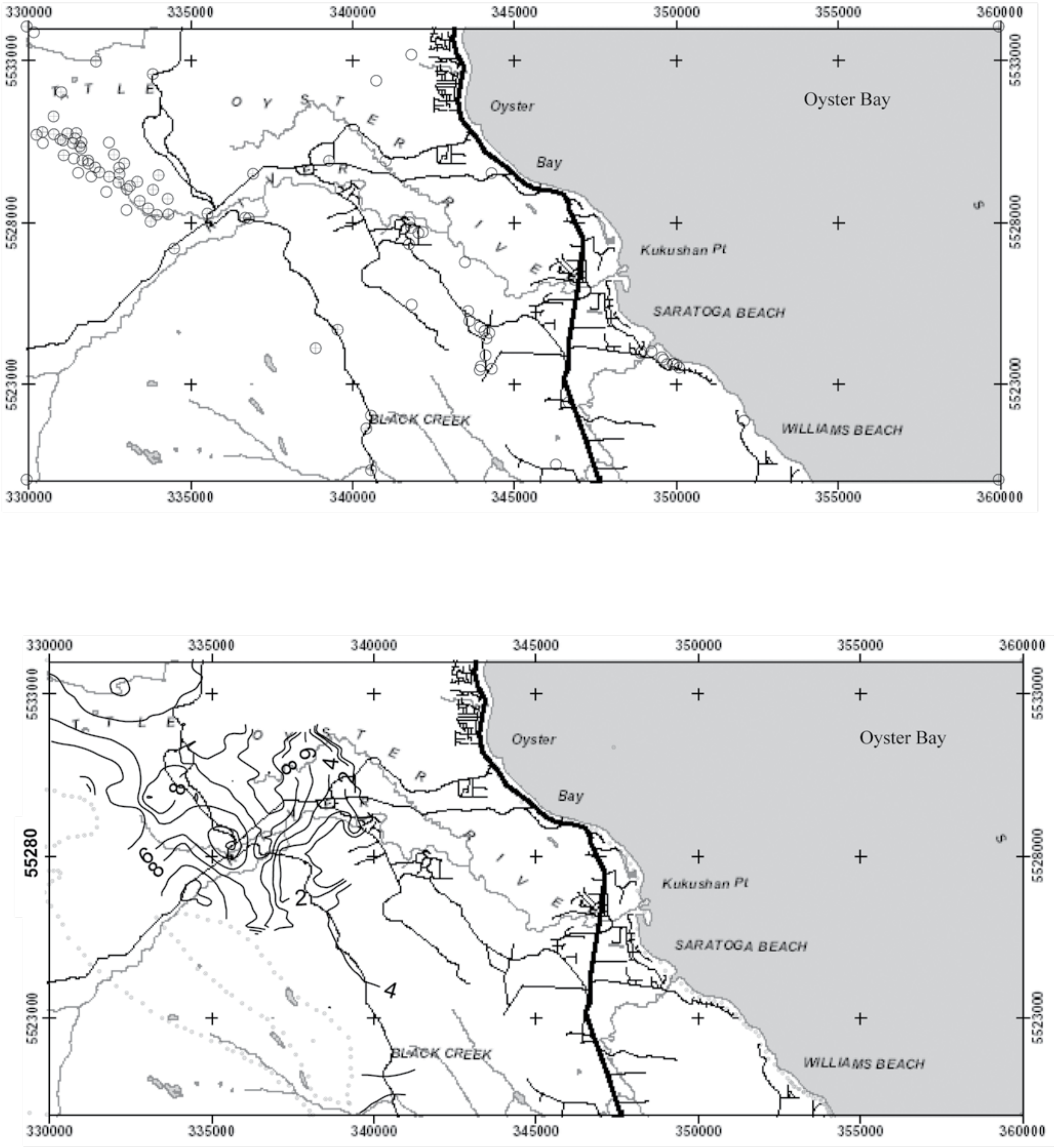


Figure 17. Oyster River area; (a) all holes drilled and holes intersecting coal; (b) cumulative coal thickness contours.

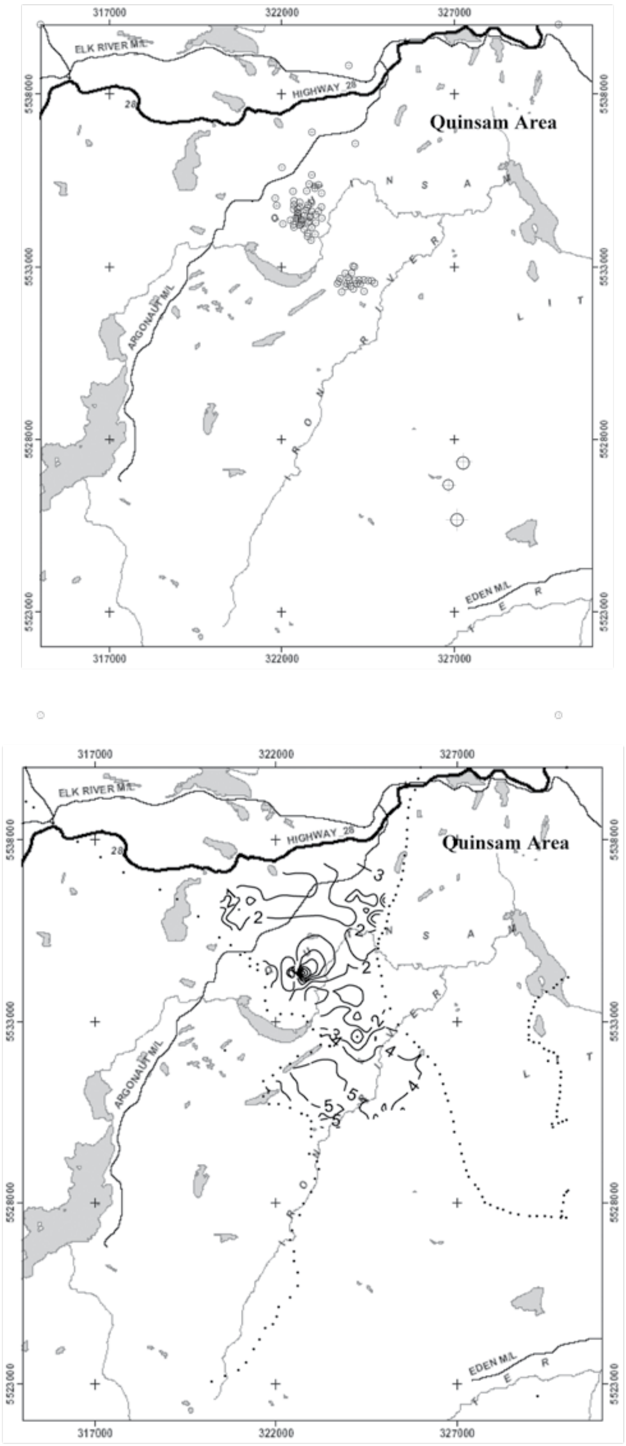


Figure 18. Quinsam River area; (a) all holes drilled and holes intersecting coal; (b) cumulative coal thickness contours.

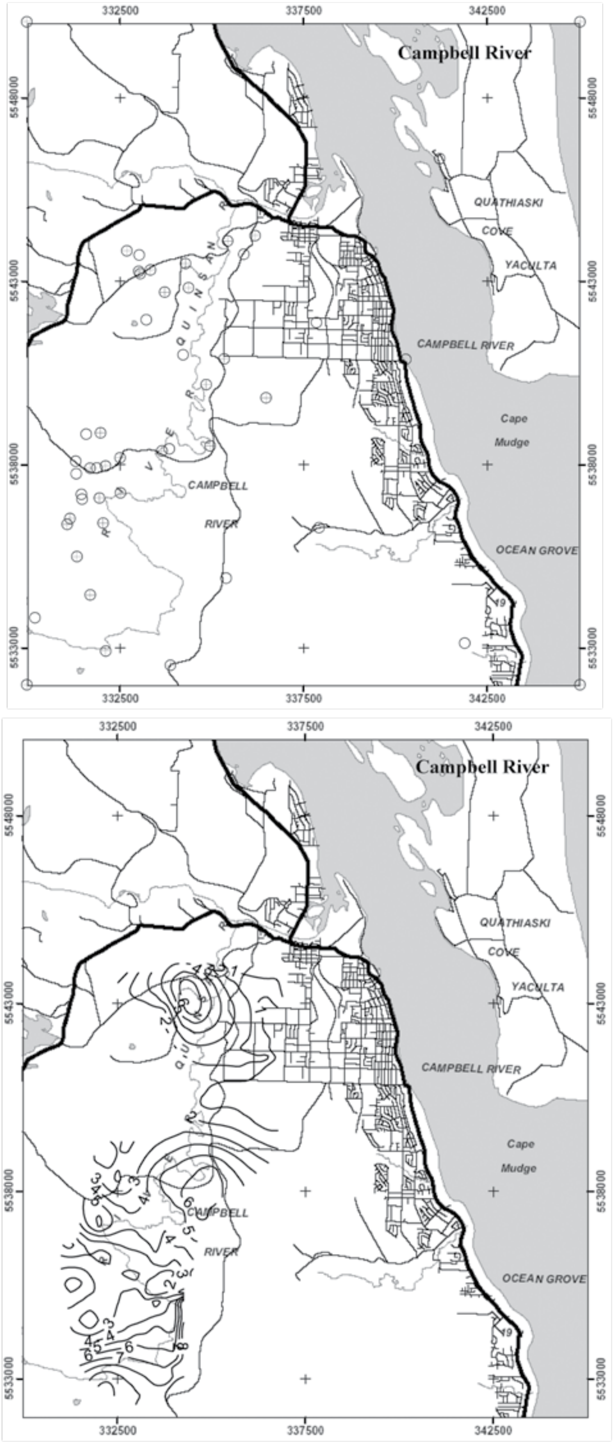


Figure 19. Campbell River area; (a) all holes drilled and holes intersecting coal; (b) cumulative coal thickness contours.

and 768 holes are represented in the database, of which 77 intersected coal (Figure 18a). Many holes were drilled to outline shallowly buried coal and did not reach the coal seams. Figure 18a only plots holes that intersected coal. The estimated resource in the area contoured (Figure 18b), which is 26 km^2, is 112 x 10^6 t. Gardner (1999) estimates a potential resource of 77 x 10^6 t available for underground mining. Chute Creek is a small deposit south of the Quinsam mine that was explored in the 1980s when a number of holes were drilled and an addit constructed. At least 3 holes intersected thin seams in the area (Figure 18a) and a resource of about 5 x 10^6 t is documented, of which Gardner (1999) considers about 2 x 10^6 t to be surface mineable.

The Comox Basin extends for some distance north to the town of Campbell River, but there has been very little exploration in the area. In the Campbell River area, 45 holes were drilled and 27 intersect coal (Figure 19a). The area contoured (Figure 19b) is 46 km^2 and is underlain by an estimated 245 x 10^6 t of resource. The area south of Campbell River is referred to as the Airport area; Gardner (1999) outlines a potential underground mineable resource of about 45 x 10^6 t in this area and to the north.

The total coal resource in the Comox Basin is in the range of 3 x 10^9 t (Table 6), and this resource underlies an area of about 400 km^2. Based on the isotherms in Figure 8, approximate gas contents at an average depth of 300 m are assigned to each area (Table 6), and an estimate of the in situ gas resource of about 0.65 trillion cubic feet (tcf) is calculated. There have been numerous estimates of the gas resource on Vancouver Island, and most are in the range of 0.5 to 1.5 tcf. These are only estimates of what might be in the ground and are in no way estimates of what might be produced in the future.

CONCLUSIONS

There is very little desorption data available for coals in the Comox Basin, and that which does exist is generally from shallow coals, so it is not surprising that results often indicate under-saturation. In the north, where ranks are in the range of high-volatile B bituminous, the gas has a biogenic carbon isotope imprint and contains less than 3% carbon dioxide. The isotopic composition of the gas in the Dove Creek area was not checked, but composition data indicate a moderate amount of nitrogen in some of the samples.

Isotherms now exist for samples from Quinsam, Dove Creek, and Tsable River areas, providing information about the potential saturated-gas contents for Comox Formation coals.

The Comox Formation contains a number of coal seams, with one or two of mineable thickness in some areas. The overall impression is that there is not a lot of coal in the formation. Initial CBM resource assessments should use hanging-wall to footwall estimates of seam thicknesses even when this includes splits, because splits are often carbonaceous and may generate and retain CBM. In this study, the cumulative gross coal seam thicknesses are contoured. The thickness values and tonnages calculated are not appropriate for assessing coal mining potential but do provide the basis for a CBM resource assessment.

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