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Multidisciplinary study of Cretaceous, Neogene, and Quaternary stratigraphy, and bocannes and their associated mineralogy and hydrochemistry, Smoking Hills, Northwest Territories: GEM-2 Western Arctic Project, report of activities 2018

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TABLE OF CONTENTS

page

FORWARD

The Geo-mapping for Energy and Minerals (GEM) program is laying the foundation for sustainable economic development in the North. The Program provides modern public geoscience that will set the stage for long-term decision making related to responsible land-use and resource development. Geoscience knowledge produced by GEM supports evidence-based exploration for new energy and mineral resources and enables northern communities to make informed decisions about their land, economy and society. Building upon the success of its first five-years, GEM has been renewed until 2020 to continue producing new, publically available, regional-scale geoscience knowledge in Canada’s North.

During the 2018 field season, research scientists from the GEM program successfully carried out 18 research activities, 16 of which will produce an activity report and 14 of which included fieldwork. Activities applied a variety of geological, geochemical, and geophysical methods. These activities have been undertaken in collaboration with provincial and territorial governments, Northerners and their institutions, academia and the private sector. GEM will continue to work with these key partners as the program advances.

PROJECT SUMMARY

This report provides a rationale and scientific basis for three multi-disciplinary research projects undertaken during the Smoking Hills fieldwork campaign of July, 2018 (Fig. 1.1). It summarizes their field sample collections and observations and discusses their future research plans. The first activity concerns the age and environment of deposition of Cretaceous strata (145-66 Ma) in the Canadian Arctic mainland. This study will provide new insights into the tectonostratigraphic evolution of the offshore Canada Basin and the regional Mackenzie-Beaufort and Sverdrup basins. This study is also expected to provide insight into Cretaceous climates of the Canadian Arctic. The second activity concerns the study of bocannes, areas of burning shale/mudrock for which the Smoking Hills is aptly named. It aims to collect samples of minerals from within the burning vents and also to study the chemistry of ponds and streams draining from these features and associated bedrock. The final activity is focused on kimberlite (diamond) indicator minerals and tries to draw comparisons between those found in deposits in the Smoking Hills with those previously recovered in related deposits on Banks Island. This activity will also examine sediments from mapped areas of Neogene fluvial Beaufort Formation (<23-2.58 Ma), and from Quaternary glacial deposits (<2.58 Ma).

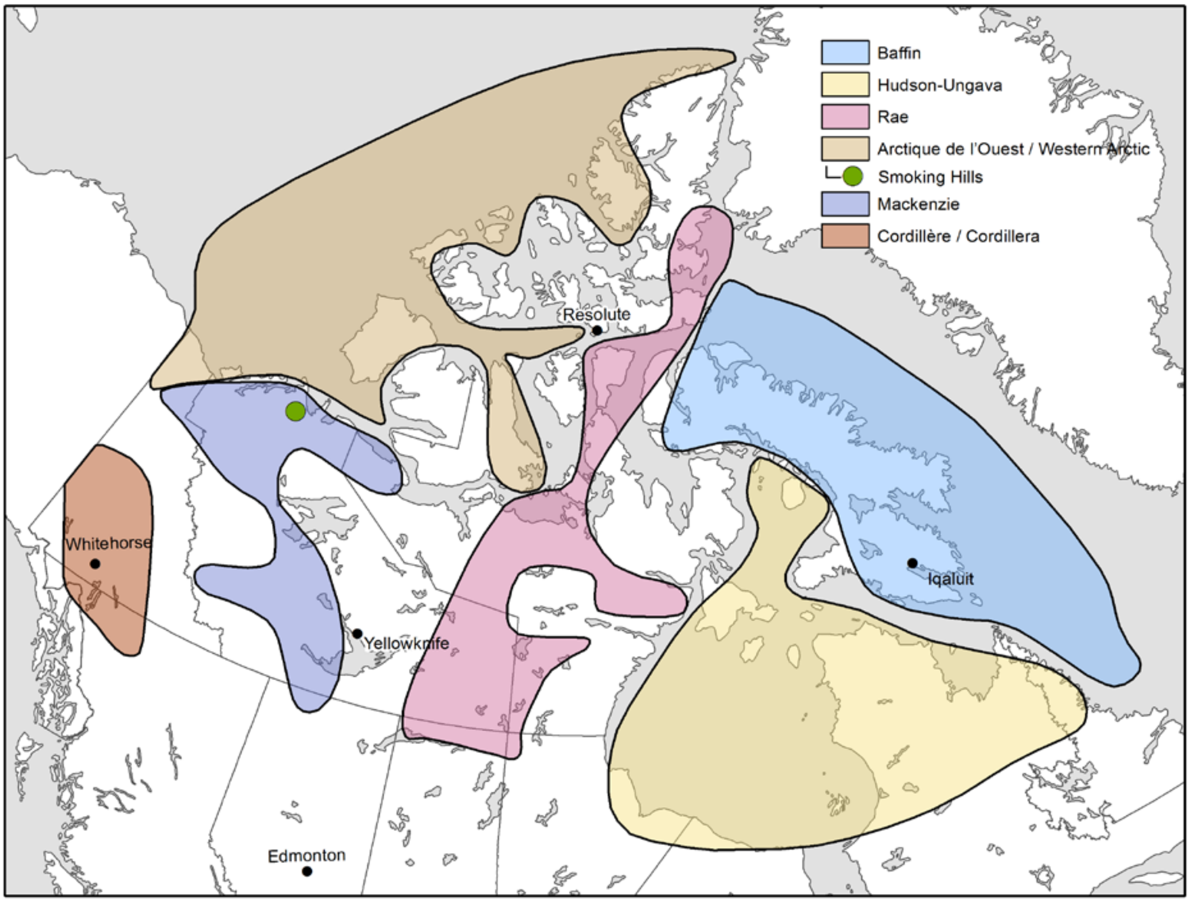

Figure 1.1 Map of the GEM-2 Program project study areas. This activity falls under the Western Arctic Margins Project. The Smoking Hills field area is indicated by the green dot.

Fieldwork for this project was conducted over two weeks (July 18-31, 2018) from a helicopter-supported tent basecamp along the lower Horton River (69°36’19”N; 126°55’03”W; Fig. 1.2). Sample collection locations of the three sub-activities are shown in Figure 1.2. Only one season of fieldwork was planned for this activity. Focus now is on the analysis of samples and interpretation of results.

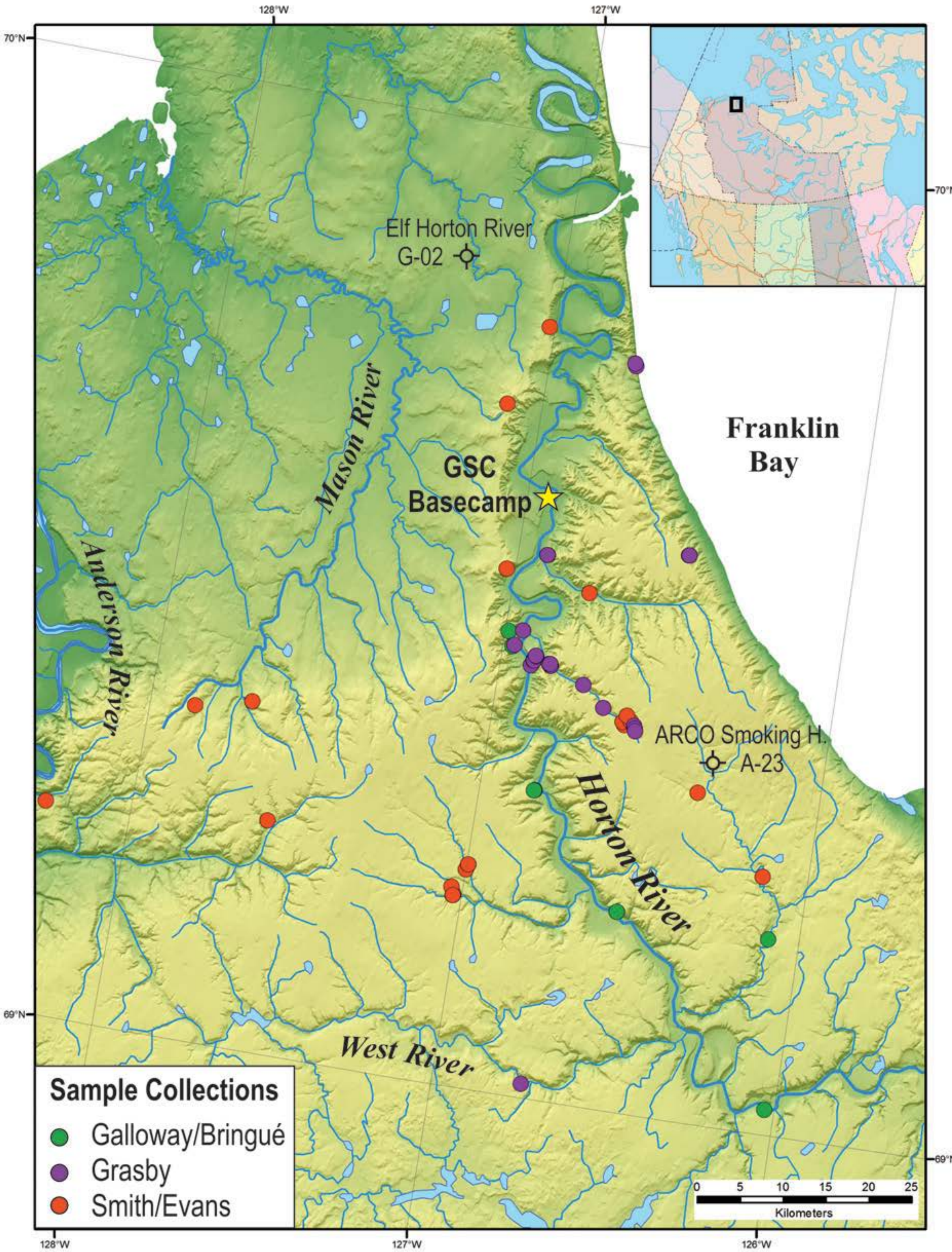

Figure 1.2 Basemap of the Smoking Hills field area. Locations of sample collections from the 2018 field season, classified by collector, are illustrated. Location of the basecamp along the lower Horton River is indicated by the yellow star.

Acknowledgements

These geological research activities are part of the GEM-2 Western Arctic Margins Project, with GSC Management support from Carl Ozyer, Lila Chebab, Guy Buller and Marty McCurdy. Marlene Francis (GSC Calgary) provided excellent project support, as always. Community and Indigenous engagement was organized by Kate Clark (GSC Ottawa). Christine Deblonde (GSC Calgary) provided invaluable GIS, remote sensing imagery, and digital field data collection assistance. We thank the curation staff at GSC Calgary (Rick Fontaine and Ping Tzeng) and the assistance of Jennifer MacQuarrie and Leanne Tingley for sample management. Isabelle Blanchette, Neelam Swarnkar, and Suzanne Twelker provided essential operational and training support. Rebecca Bryant provided able and enthusiastic field assistance to all parties. Diane Ruben and the Paulatuk Hunters and Trappers Committee and Darlene Gruben and the Tuktoyaktuk Hunters and Trappers Committee are thanked for their assistance with community meetings and the planning and approval of this field research program. Helicopter support was provided by Canadian Helicopters, and the excellent piloting of Matt Fricker. Fixed-wing support by Aklak Air was essential to the success of this operation, and thanks are extended to its pilots and Ken Dalton. This research was conducted under NWT Research License #16210, Inuvialuit Land Administration land use permit #ILA17TO028, and Environmental Impact Screening Committee file 08-17-05. Keith Dewing (GSC Calgary) is thanked for his review of this report.

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CHAPTER 1: PROJECT OVERVIEW

I.R. Smith, M. Bringué, D.J.A. Evans, J.M. Galloway and S.E. Grasby

Introduction

The Smoking Hills represents a unique and important opportunity for furthering geological understanding in Canada's north, including that pursued regionally through the past 10 years of the GEM Program of research. A single season of fieldwork was undertaken in July, 2018, as part of the GEM-2 Western Arctic Margins Activity (Fig. 1.1). The Smoking Hills region contains the southernmost outcrop of Upper Cretaceous strata on mainland Canada, for which age equivalency is being tested with Banks Island and Sverdrup Basin strata to the north, and the Mackenzie-Beaufort Basin to the west (Yorath et al., 1969, 1975; Yorath and Cook, 1981; Embry, 1991, Dixon, 1999). There are numerous sites of combusting shale/mudrock, referred to as bocannes, for which the Smoking Hills region is aptly named. These sites are thought to produce rare mineral forms and relate to acidic pH levels in nearby ponds and streams. These bocannes have relict forms in related strata on Banks Island and in the Sverdrup Basin, and are useful analogues for natural and anthropogenic hyper-acidic environments. The study area also includes extensive outcrop of reported Neogene fluvial Beaufort Formation deposits, considered equivalent to those on northwest Banks Island, which have been shown to contain kimberlite indicator minerals (Smith, 2015; Smith et al., 2016). The region is also said to possess a single Quaternary stratigraphic section with 3-5 tills (Fulton and Klassen, 1969), providing a uniquely long record of glaciation in northwestern mainland Canada.

Project Rationale

This research is the first activity in the area by the Geological Survey of Canada (GSC) examining bedrock since the initial surveys of Yorath et al. (1969). Quaternary glacial work was also part of the original GSC surveys (Klassen in Yorath et al., 1969; Klassen, 1971), and there was some follow-up research focused on the key Quaternary stratigraphic section (Vincent, 1988, 1991, unpublished field notebooks; Matthews and Ovenden, 1990; Duk-Rodkin et al., 2004; Duk-Rodkin and Barendregt, 2011), but there has not been any further field examination of the Beaufort Formation deposits and the regional glacial history since Mathews et al. (1989). And despite their unique and striking character, the bocannes, first identified by Richardson (1828), were studied mostly in their relationship to locally acidified ponds (cf., Havas and Hutchinson, 1983; Mathews and Bustin, 1984), and have otherwise largely remained ignored scientifically. Petroleum-related seismic operations were conducted in the area in 1972-1973 (Smith, 2011), and two exploration wells were drilled in 1969 (Elf Horton River G-02) and 1974 (ARCO Smoking Hills A-23; Fig. 1.2). No evidence of significant petroleum resources was discovered.

Scientific Questions
Each of the three project sub-activities is focused on addressing different scientific questions.

The Cretaceous bedrock project will refine the timing and better characterize the depositional environment of Cretaceous strata of the Canadian Arctic mainland, and provide new insight into the tectonostratigraphic evolution of the Arctic, by:

1. Collecting high stratigraphic resolution samples (approximately every 1.5 m vertical) at all the major sections documented in Yorath et al. (1975) for multi-disciplinary stratigraphic investigations including organic, elemental, and isotopic geochemical, palynological (pollen and spores, dinoflagellate cysts), and micropaleontological analyses (radiolarian and foraminifera);
2. Creating a better understanding of the tectonostratigraphic evolution of the Arctic, specifically through investigation of how the opening of the Arctic Ocean controlled the deposition of source rocks, their depth and timing of burial across the region; and,
3. Reconstructing climatic conditions over the intervals covered by the organic-rich formations, namely the Horton River, Smoking Hills and Mason River formations.

The bocanne mineralogy and hydrochemistry sub-project will test previous models for the origin of bocannes and associated acid ponds as well as to better characterize the associated high temperature acid-minerals found at these sites by:

1. Collecting and analyzing minerals formed at vents of active bocannes.
2. Collecting and analyzing samples of clinker at extinct vent sites.
3. Sampling waters from acid ponds.
4. Characterizing the geochemistry and mineralogy of the Smoking Hills Formation to improve models on natural combustion processes.

The kimberlite indicator mineral (KIM) and Quaternary glacial stratigraphy sub-project will seek to resolve the nature and distribution of KIMs within Beaufort Formation and Quaternary glacial deposits, and reconstruct the regional Quaternary glacial history by:

1. Investigating the sedimentology of mapped Beaufort Formation deposits, and collecting samples for kimberlite indicator minerals recovery.
2. Analyzing the KIMs geochemically and isotopically and comparing results with those from Banks Island and regional kimberlites.
3. Conducting detailed section lithofacies logging of the main Quaternary section and others as discovered through the course of field studies.
4. Dating different lithofacies using the cosmogenic nuclide burial age technique.

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CHAPTER 2. CRETACEOUS STRATIGRAPHY OF THE SMOKING HILLS AREA

M. Bringué, J.M. Galloway, S.E. Grasby, and R. Bryant

Introduction

The Cretaceous Period (~145 to 66 Ma) was a time of profound global change associated with the break-up of Pangea that ultimately led to the opening of the Atlantic and Arctic oceans. Relatively arid conditions of the preceding Jurassic Period gave way to generally warm climate and high relative sea-level in the Cretaceous, even in high northern latitudes. These "hot house" conditions resulted in the deposition of organic-rich sediments in the Canadian Arctic. In Arctic Canada, Mesozoic sediments are well preserved in the Sverdrup Basin of the Canadian Arctic Islands (e.g., Embry, 1991; Embry and Beauchamp, 2008) and were studied during the GEM-1 and previous GSC programs. However, precise age equivalence and linkages of Cretaceous strata from the Sverdrup Basin and localities influenced by the mid- to late Cretaceous Western Interior Seaway (e.g., Interior Plains, Alberta Plains) remains poorly constrained. The Smoking Hills area (NTS Map Sheet 97C; Fig. 1.2) is a key locality for better understanding age equivalence and paleoceanographic connections between the Sverdrup Basin and the Western Interior Seaway.

Our investigations on the stratigraphy of Cretaceous strata from the Smoking Hills area were guided by initial reports and maps of Yorath et al. (1969), Yorath and Balkwill (1970), Balkwill and Yorath (1970) and Yorath et al. (1975) who surveyed the region in the late 1960s. Lower Cretaceous strata in the Horton-Anderson Plains were characterized as the Darnley Bay Group (Yorath et al. 1975), composed of the Langton Bay Formation (Berriasian-Valanginian(?) to early Middle Albian) and the Horton River Formation (Middle Albian). Upper Cretaceous strata were assigned to the Amundsen Gulf Group and comprise the Smoking Hills Formation (Santonian to Campanian) and the Mason River Formation (Campanian to Maastrichtian).

The Darnley Bay Group as a whole rests unconformably on Paleozoic and Proterozoic rocks. The Langton Bay Formation is divided into two members: the lower Gilmore Lake Member is sandstone and coal-dominated with a thickness of 67 m at the type section. It is gradationally overlain by the Crossley Lakes Member, which consists of interbedded siltstone, mudstone and sandstone of 226 m in thickness at its composite type section in the map area (Yorath et al. 1975). The unconformity at the base of the Group (base of Gilmore Lake Member) suggests that only the Aptian portion of the Langton Bay Formation is exposed, whereas subsurface data indicate a Berriasian-Valanginian(?) age for the base of the Gilmore Lake Member based on dinoflagellate cyst data from the Elf Horton River G-02 well (Brideaux in Yorath et al., 1975). The Horton River Formation rests unconformably on mudstones of the Crossley Lakes Member and is overlain unconformably by the Smoking Hills Formation. Yorath et al. (1969) estimated its thickness at 183 m, and it is 235 m thick in the subsurface (Yorath et al., 1975). Upper Cretaceous mudstone of the Amundsen Group are typically organic-rich and possibly constitute excellent potential source rocks for hydrocarbon. Exposures of the Smoking Hills Formation have been actively burning at least since the observations of the second Franklin overland expedition (Richardson, 1828). The thickness of the formation, prone to slumping, is difficult to determine but was estimated between ~ 30 and 51 m (Yorath et al., 1975). The overlying Mason River Formation, sometimes sub-divided into three informal members (all pale grey mudstone-dominated) was estimated to be 183 m in thickness and is disconformably overlain by Paleogene(?) or younger strata.

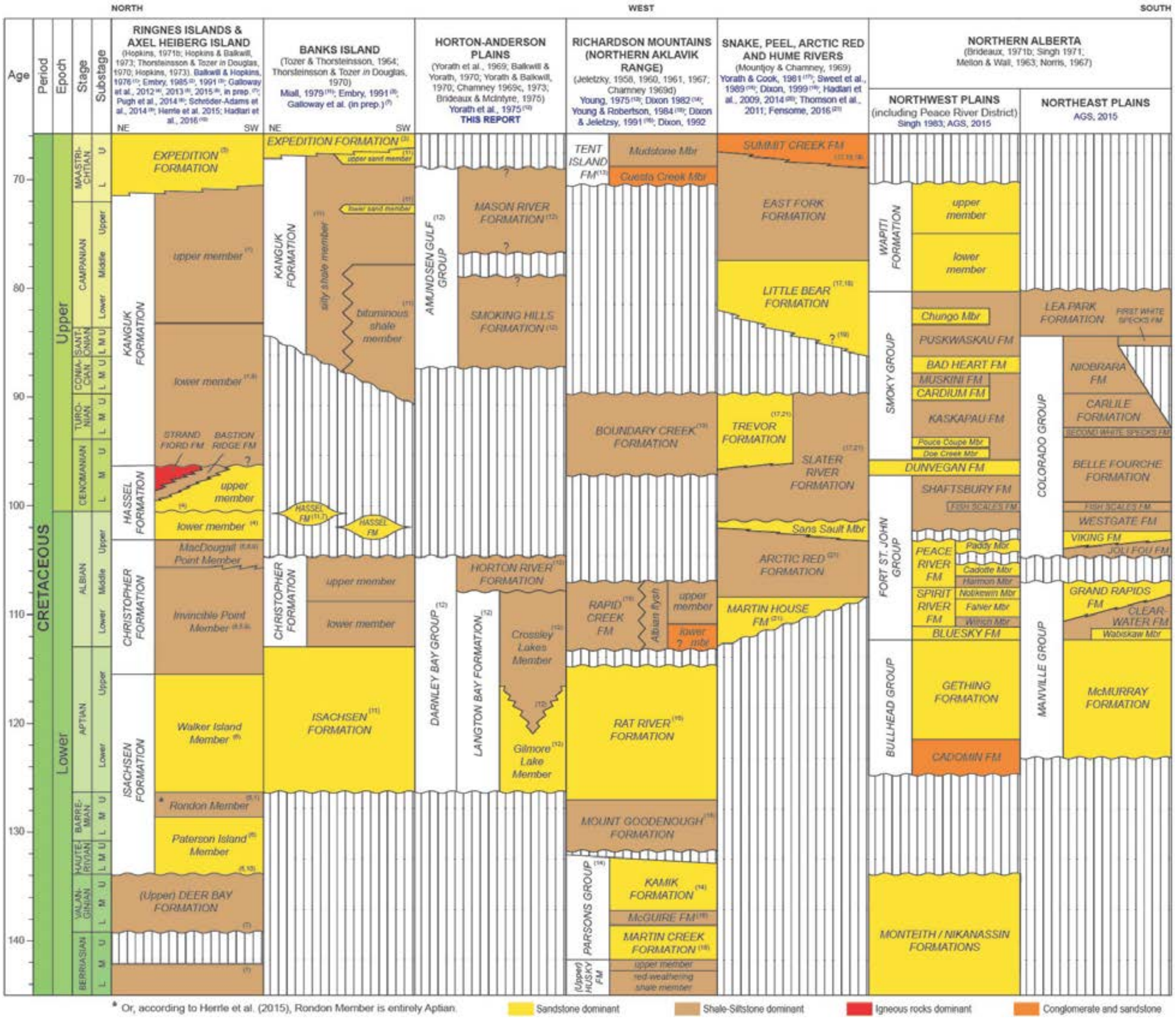

Figure 2.1. Lithostratigraphic correlation chart of the Cretaceous formations of northwestern Canada and northern Alberta.

Despite the thorough assessments by Yorath and co-workers conducted in the 1960s and 70s, large uncertainties regarding contacts and depositional ages remain, which hamper regional correlation of the Horton-Anderson Plains Cretaceous strata with other units in the Canadian Arctic (Fig. 2.1). In the case of the Upper Cretaceous Kanguk Formation, the absence of foraminifera has prompted the recent development of a radiolarian-based zonation for better biostratigraphic age control over that interval in the Sverdrup Basin (Pugh et al., 2014), and to refine the age of equivalent strata in southwestern Saskatchewan (Diaz and Veles, 2018). Our efforts aim to improve regional correlation and biostratigraphic age control of Cretaceous strata, an important stratigraphic interval in the GEM-2 Western Arctic Margins region, by using multiple chronostratigraphic tools.

As part of the Smoking Hills Activity, fieldwork was conducted in the Horton River area to refine the timing and better characterize the depositional environment of Cretaceous strata of the Canadian Arctic mainland, and to provide new insight into the tectonostratigraphic evolution of the Arctic. The specific objectives were:

1. To collect high stratigraphic resolution (approximately every 1.5 m) samples at all the major sections documented in Yorath et al. (1975) for multi-disciplinary stratigraphic investigations including organic, elemental, and isotopic geochemical, palynological (pollen and spores, dinoflagellate cysts), and micropaleontological analyses (radiolarian and foraminifera);
2. To better understand the tectonostratigraphic evolution of the Arctic, specifically investigating how did the opening of the Arctic Ocean control the deposition of source rocks, their depth and timing of burial across the region; and,
3. To reconstruct climatic conditions over the intervals covered by the organic-rich formations, namely the Horton River, Smoking Hills and Mason River formations.

Methods and Preliminary Results

Multiple localities were examined in the Smoking Hills area (Fig. 2.2). A total of four sections were sampled from eight localities (Table 2.1). The Langton Bay Formation (Crossley Lakes Member) was sampled from a composite section across four localities. The Horton River Formation composite section was observed from three different localities, and the Smoking Hills and Mason River Formations were sampled at their type localities.

Structural relationships between exposed strata were established whenever possible, guided by the report of Yorath et al. (1975). At each locality, small mudrock samples (~ 200 g) were collected for paleontological (palynological and other microfossils) and geochemical analyses (C isotopes, bulk whole rock geochemistry, organic geochemistry) along the sections at regular increments of 1.5 m vertical. Additional samples were collected when deemed to be relevant, including rare bentonitic beds, as well as glendonites and macrofossils (e.g., ammonites, fossilized wood), *in situ* when possible otherwise from talus. A total of 290 mudrock samples were collected and transported to the Geological Survey of Canada, Calgary (GSC Calgary Curation Numbers C628779 to C-629066).

All four formations of interest were successfully sampled (Fig. 2.2, Table 2.1) at high resolution (1.5 m vertical), covering the maximum local (temporal) expression of Cretaceous sedimentation in the area. With the exception of the basal conglomerate that marks the base of the Smoking Hills Formation, all formational contacts were observed and sampled.

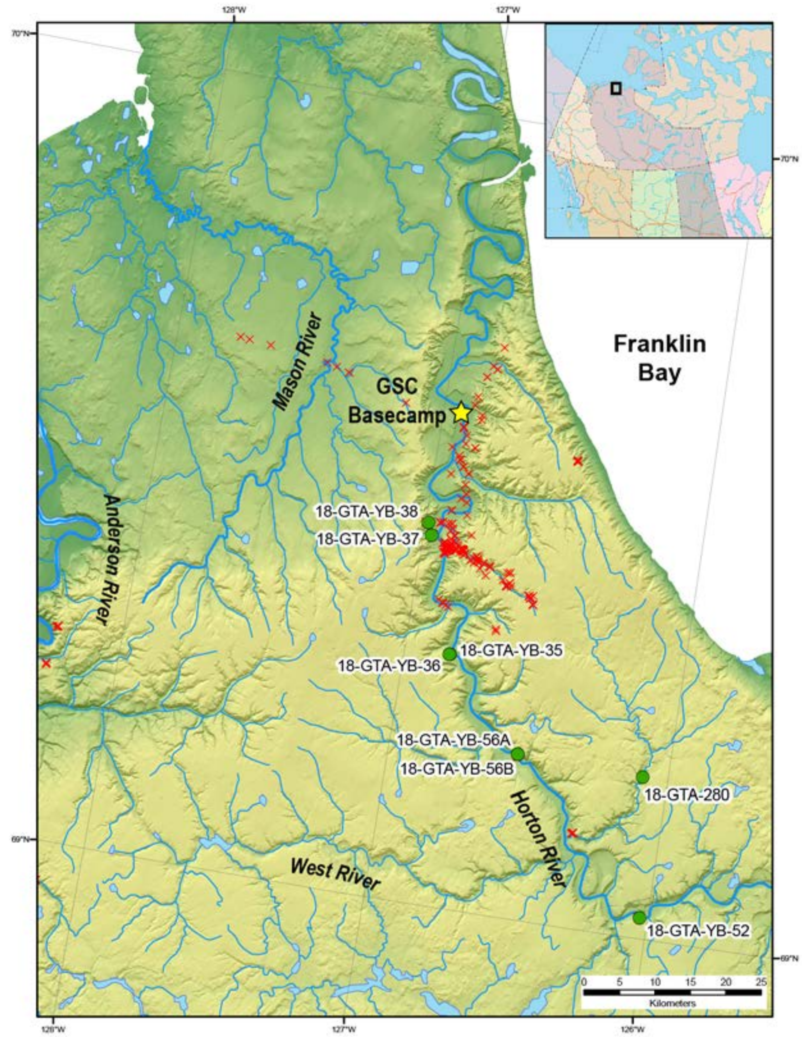

Figure 2.2. Map of the Smoking Hills area showing the locations of basecamp (yellow star), Cretaceous sections sampled (large green circles), and coordinates of pictures taken while surveying the area (red crosses).

Table 2.1 Geographic locations and formation types of bedrock sample collection sites.

Date sampled	Lat. °N	Long. °W	Station	Formation
21-07-2018	69° 01.635'	126° 01.627'	18-GTA-YB-52	Langton Bay
21-07-2018	69° 12.481'	126° 32.440'	18-GTA-YB-56A	Langton Bay
28-07-2018	69° 12.217'	126° 05.400'	18-GTA-280	Langton Bay
26-07-2018	69° 12.481'	126° 32.440'	18-GTA-YB-56B	Langton Bay-Horton River contact
24-07-2018	69° 19.200'	126° 50.200'	18-GTA-YB-35	Horton River
24-07-2018	69° 19.167'	126° 50.267'	18-GTA-YB-36	Horton River
26-07-2018	69° 27.867'	126° 58.217'	18-GTA-YB-37	Smoking Hills
27-07-2018	69° 28.767'	126° 59.333'	18-GTA-YB-38	Mason River

Future work will focus on use of biostratigraphy and chemostratigraphy to refine the age and depositional environment of the examined strata. This information is expected to provide insight into how Smoking Hills area rocks may have formed in relation to other sedimentary strata in the Canadian Arctic. Palynological analysis will be used to better understand oceanographic conditions (dinoflagellate cysts) and terrestrial vegetation (pollen, spores) during development of Cretaceous hothouse conditions in polar latitudes.

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CHAPTER 3. MINERALOGY AND AQUATIC GEOCHEMISTRY ASSOCIATED WITH SMOKING HILLS BOCANNES

S.E. Grasby, R. Bryant, M. Bringué, and J.M. Galloway

Introduction

While long known by Indigenous people, the Smoking Hills on the east side of Cape Bathurst adjacent Franklin Bay, were first recorded in the literature by Sir John Richardson of the second Franklin overland expedition (Richardson, 1828). The name is derived from natural combustion of organic-rich Cretaceous mudstones actively emitting clouds of smoke and are technically known as bocannes (Selwyn, 1877; Crickmay, 1967). In this region they are characterised by emissions of hot sulphuric gases from vent holes with variable but often brightly coloured mineral deposits. Extinct sites that are no longer venting gas are common as well, and are characterised by vividly coloured brick red to orange to yellow clinker deposits. Both burning and extinct sites are observed over a wide area of Cape Bathurst and are directly associated with outcrop of the aptly named bituminous Smoking Hills Formation (Yorath et al., 1975; Yorath and Cook, 1981). Work by Mathews and Bustin (1984) suggest combustion is associated with oxidation of pyrite as well as combustion of organic matter in the shales, with associated calorific heat values up to 4000 kJ/kg. Their detailed work corroborates initial suggestions of Richardson (1828) as well as Dawson (1881). Another feature associated with the Smoking Hills Formation are acid ponds, again first described by Richardson (1828); and later studied by Havas and Hutchinson (1983a) who suggested the acidity is related to fumigation of lakes from bocannes. These and subsequent studies (e.g., Freedman et al., 1990; Havas and Hutchinson, 1983b; Nakatsu and Hutchinson, 1988; Sheath et al., 1982) describe extremophile life that inhabit the acid waters in the region. As such, the Smoking Hills area has been purported to be a natural analogue for the impacts of industrial emissions on the arctic environment and acid mine drainage.

As part of the Smoking Hills activity, work was conducted to test previous models for the origin of bocannes and associated acid ponds as well as to better characterise the associated high temperature acid-minerals found at these sites. The objectives were to:

- Collect and analyse minerals formed at vents of active bocannes.
- Collect and analyse samples of clinker at extinct vent sites.
- Sample waters from acid ponds.
- Characterise the geochemistry and mineralogy of the Smoking Hills Formation to improve models on natural combustion processes.

Methods

Five actively burning sites were visited using respirators and eye covering to provide protection from sulphuric acid fumes, as well as working only in the upwind direction. Random collection of minerals at various vent sites were made in Falcon™ tubes. In some cases minerals were high enough temperature to melt the tube and samples had to be transferred to a new container once cooled. Previous work has shown that these minerals are hydrous and will actively dehydrate and alter to other mineral phases. To prevent this, vent minerals were stored in mineral oil. Seven extinct burn sites were also visited and samples of clinker were collected from around the sites in plastic sample bags and with no preservation agents added.

Water samples were collected from 18 sites, including acid ponds occurring within the Smoking Hills Formation, ponds on the overlying Mason River Formation, and a profile down an unnamed creek that has a source area within the Mason River Formation and cuts progressively down-section through the underlying Smoking Hills Formation. Complete water samples were collected for measurement of anions, cations, stable isotopes of oxygen and deuterium in water, and stable isotopes of dissolved sulphate in water. All samples were first filtered through a 0.45 μm membrane before being placed into HDPE Nalgene™ bottles. Dissolved sulphate was precipitated in the field by addition of barium chloride to reach $BaSO_4$ saturation. The pH, temperature, and conductivity of waters were measured in the field using a Thermo Orion 5-Star multiprobe calibrated daily.

Results

Boccanes were observed at numerous locations along the sea cliffs of Franklin Bay where they were originally described and also inland throughout the outcrop area of the Smoking Hills Formation, as far west as the Anderson River valley. Actively burning sites all appear to occur in areas of recent slumping that have exposed fresh surfaces of the bituminous shale. Sites were characterised by active emission of smoke and multi-coloured minerals around the vent surface (Fig. 3.1). Mineral colours varied from yellow, white, purple, as well as vitreous green crystals. Attempts were made at each site to collect a representative suite of mineral species present.

Figure 3.1 Actively burning bocannes formed in the Smoking Hills Formation, showing clouds of sulphurous emissions along with multi-coloured minerals formed at vents.

Extinct burning sites, identified by clinker deposits, were more numerous than active sites, and again occurred throughout the outcrop area of the Smoking Hills Formation. These clinker sites stand out on the landscape as typically brick red colouration of the shales as well as pale yellow, in contrast to the otherwise black appearance of the Smoking Hills Formation (Fig. 3.2). As with active vents, a suite of samples were collected at each site. The thermally altered shale was hardened and brittle but still maintained a bedded appearance. In one locality paralava was also observed. The colourful minerals observed at the active bocannes were not seen at extinct sites. Interestingly, with one exception, it was only in slumped material that combustion appears to be initiated, as the fresh slump bedrock faces exposing the same materials did not combust. Also, bocannes form not only directly below the failure faces, but within debris flow lobes extending well down-slope of the initial failure. This suggests that there is some mechanism in the slumping that is critical to the process, either reflecting the degree of oxidation required, or the intermixing of strata.

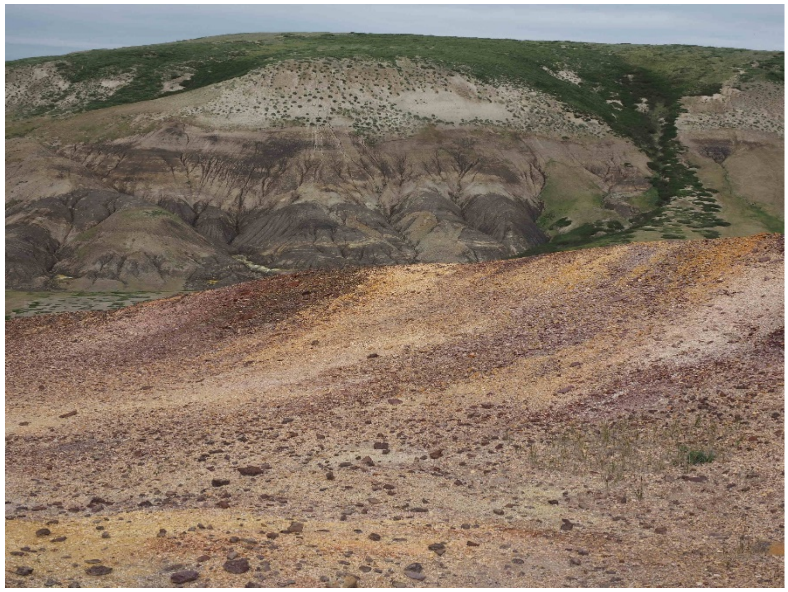

Figure 3.2 Photograph showing clinker deposits at an extinct combustion site (in foreground). The background shows outcrop of the black shales of the Smoking Hills Formation overlain by light grey sediments of the Mason River Formation.

Ponds sampled in the area show distinct differences in geochemistry as a function of what formation they are found in. Ponds sampled on the Mason River Formation typically had near neutral pH and are characterised by a clear appearance and low conductivity (< 0.6 mS/cm), even in ponds that are being actively fumigated by acid smoke of nearby bocannes. In contrast, ponds formed within shales of the Smoking Hills Formation have a characteristic ruby red colour (Fig. 3.3), extremely low pH (as low as -1.44) and very high conductivity (up to 40 mS/cm). These ponds are found both near as well as far from active bocannes. As well, the stream sample transect showed that in the headwaters in the Mason River Formation, stream waters have consistent geochemistry to ponds on the same formation. However, as the stream cuts down stratigraphic section into the underlying Smoking Hills Formation, the water rapidly changes from clear to red in colour, pH drops to <2, and conductivity increases from 0.6 to 10 mS/cm.

Figure 3.3 Acid ponds with characteristic ruby red colour formed in outcrops of the Smoking Hills Formation.

Discussion and Future Work

Results based on field observations demonstrate that active burning sites of the Smoking Hills Formation appear to be favoured in areas of recent slumping activity. However, discovery of extinct burn sites in normally bedded outcrops suggest that slumping itself may not be critical for auto-ignition. Other factors such as lightning strikes could also play a role. Once burning, localised areas of unusual minerals form around the vent site. Rapid desiccation of these samples indicate that they are likely hydrous minerals that form in high temperature acid environments. Ongoing mineral x-ray diffraction work will aid mineral identification. Once extinct, conditions at the vents return to normal background temperatures and environmental conditions, acid minerals at the sites likely alter or dissolve in meteoric waters as they are not visually observed at inactive sites. Instead these sites are characterised more simply by thermally altered shales. The degree of thermal alteration and mineral composition will also be the focus of further study.

Observation of acid ponds in the region brings question to previous models of these ponds being associated with acid fumigation from bocannes. There was a clear association of water geochemistry with bedrock type and no association with proximity to active bocannes. This suggests that the acidity is most likely associated with water-rock interaction of fresh waters with the Smoking Hills Formation. Further laboratory study and experiments will be conducted to verify this hypothesis. Results of water geochemical analyses will also be forthcoming.

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CHAPTER 4. KIMBERLITE INDICATOR MINERALS AND GLACIAL RECONSTRUCTIONS IN TERTIARY BEAUFORT FORMATION AND QUATERNARY GLACIAL DEPOSITS, SMOKING HILLS, NT.

I.R. Smith and D.J.A. Evans

Introduction

The Smoking Hills region of Cape Bathurst is notable, among other reasons, for including the reported southernmost occurrences of the Tertiary Beaufort Formation (Yorath et al., 1969, 1975), and a section of Quaternary glacial deposits spanning 3 to 5 glacials which is unique in northern mainland Canada outside of Yukon and the Mackenzie Mountains (Fulton and Klassen, 1969; Duk-Rodkin et al., 2004; Duk-Rodkin and Barendregt, 2011).

Field investigations conducted as part of this study focused on collecting sediment samples to recover kimberlite (diamond) indicator and other heavy minerals within identified Beaufort Formation and Quaternary glacial deposits. This work stems from past research on Banks Island (Smith, 2015; Smith et al., 2016), and was designed to test models and observations developed there, and provide an improved regional understanding of kimberlite indicator mineral (KIM) dispersal histories in northwestern Canada.

Beaufort Formation

The Beaufort Formation is a Tertiary fluvial deposit, variously described as dating from Miocene to Pliocene-Pleistocene time. It forms a prominent accretionary wedge of unconsolidated sediment fringing the western islands of the Canadian Arctic Archipelago, and thickens westwards into the Beaufort Sea (Fig. 4.1; Tozer, 1956, 1960; Craig and Fyles, 1960, 1965; Thorsteinson, 1961; Thorsteinson and Tozer, 1962; Hills, 1969; Miall, 1979; Vincent, 1983, 1990; Fyles, 1990, Devaney, 1991; Fyles et al., 1994; Williams et al., 2008). The type section of the Beaufort Formation is located on Prince Patrick Island, and was described by Tozer (1956) as comprising cross-bedded quartz sand and well-rounded fine to medium gravel, and containing much unlithified and uncarbonized fossil wood. Elsewhere it has been characterized by an abundance of orange and brown chert, in contrast to underlying Eureka Sound Formation strata which has more grey and black chert and which also contains noticeably more carbonized and compressed fossil wood. On Banks Island, two deposits are distinguished: the formerly “lower Beaufort” (Hills, 1969; Kuc and Hills, 1971; Fyles, 1990) now recognized as the Miocene Ballast Brook Formation (Fyles et al., 1994), and the “upper Beaufort” (Fyles, 1990 and references therein) which lithostratigraphically and paleontologically correlates with the type Beaufort Formation section on Prince Patrick Island. No other Ballast Brook Fm. equivalents are recognized on land within the Arctic Archipelago. There are, however, several other terrace gravels, interbedded silt, and organic detritus-rich and peat bed sites on numerous islands including Melville, Meighen, Axel Heiberg and Ellesmere that are considered Tertiary “Beaufort-equivalents” *sensu lato* (Thorsteinsson, 1961, Tozer, 1970, Balkwill and Bustin, 1975; Wilson, 1976, Bustin, 1982; Hodgson et al., 1984; Fyles, 1989; Davies et al., 2014).

South of the Canadian Arctic Archipelago, late Tertiary outliers of sand and gravel were identified by Norris (1981) and Yorath and Cook (1981) northeast of Inuvik, bordering the Mackenzie River. Further east, in the Horton River area, Yorath et al. (1969, 1975) were the first to report unconsolidated gravel and sand deposits, 8-10 feet thick, on plateau surfaces between the Anderson and Horton rivers and between the Horton River and Smoking Hills (Fig. 4.2; curiously these deposits are not identified on Klassen’s (1971) surficial geology map of the area). They describe low-angle foreset bedding in sand units (with a wide range of azimuth directions, but generally indicating a northwesterly transport direction), with mainly quartzite, dolomite and black chert pebbles and cobbles, and small wood fragments and humic materials. These plateau-cap deposits were reported to form a flat, featureless plain, with exposures along a north to south transect at elevations between 180 and 335 m above sea level (asl; Yorath et al., 1975). Based largely on lithological and sedimentological comparisons with descriptions of the Beaufort Formation on Banks Island (Thorsteinsson and Tozer, 1962), Yorath et al. (1969, 1975) suggest that the units they describe are probably correlative, but caution that in the absence of detailed palynological studies their age remains unconfirmed. As discussed below, based on the 2018 fieldwork, we questions the assignment of the plateau-cap gravels to the Beaufort Formation.

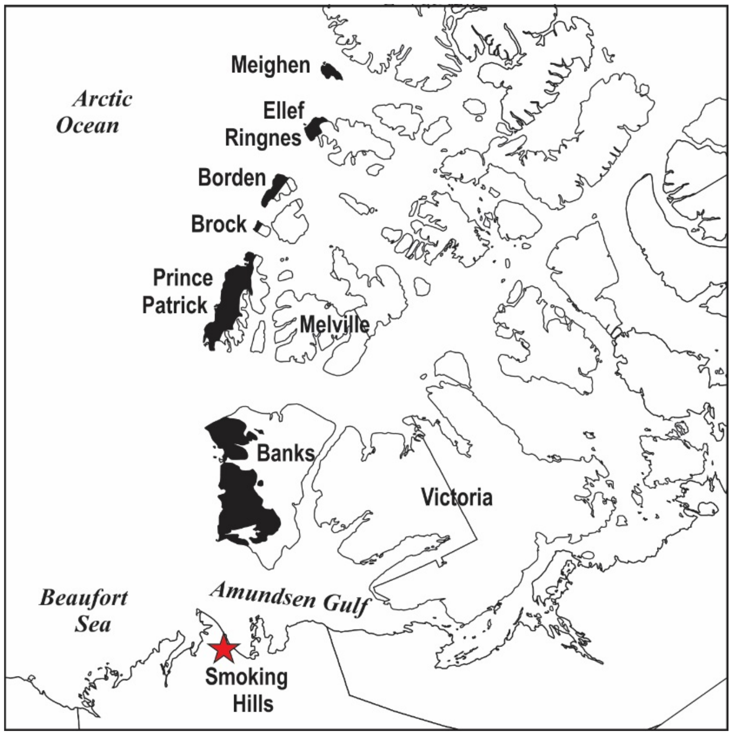

Figure 4.1. Extents of Beaufort Formation deposits (shaded) on islands in the western Canadian Arctic Archipelago.

A 32 m thick Quaternary sequence along an unnamed tributary of the Horton River was first reported by Klassen in Yorath et al. (1969) and Fulton and Klassen (1969). It is situated 18 km north of the West River (69°13'N, 127°03'W), and to simplify matters in this report, hereafter will be referred to as the Klassen section (Fig. 4.2). The section was reported to contain at least 3 tills, which lay beyond moraines they attributed to the last glacial advance (from the south). Overlying bedrock at the base of this section was a sand and gravel deposit characterized by an abundance of black chert and quartzite pebbles, along with clusters of well-preserved wood, which they suggested may be equivalent to the Beaufort Formation (seemingly on the basis of pebble lithology). This sand and gravel unit is overlain by the 3 tills. A peat bed above the lower two tills and below at least one till is indicated to be in the same stratigraphic position as a peat bed in a near-by section dated at >38,100 ^{14}C yr BP (GSC-576; Lowden et al., 1971).

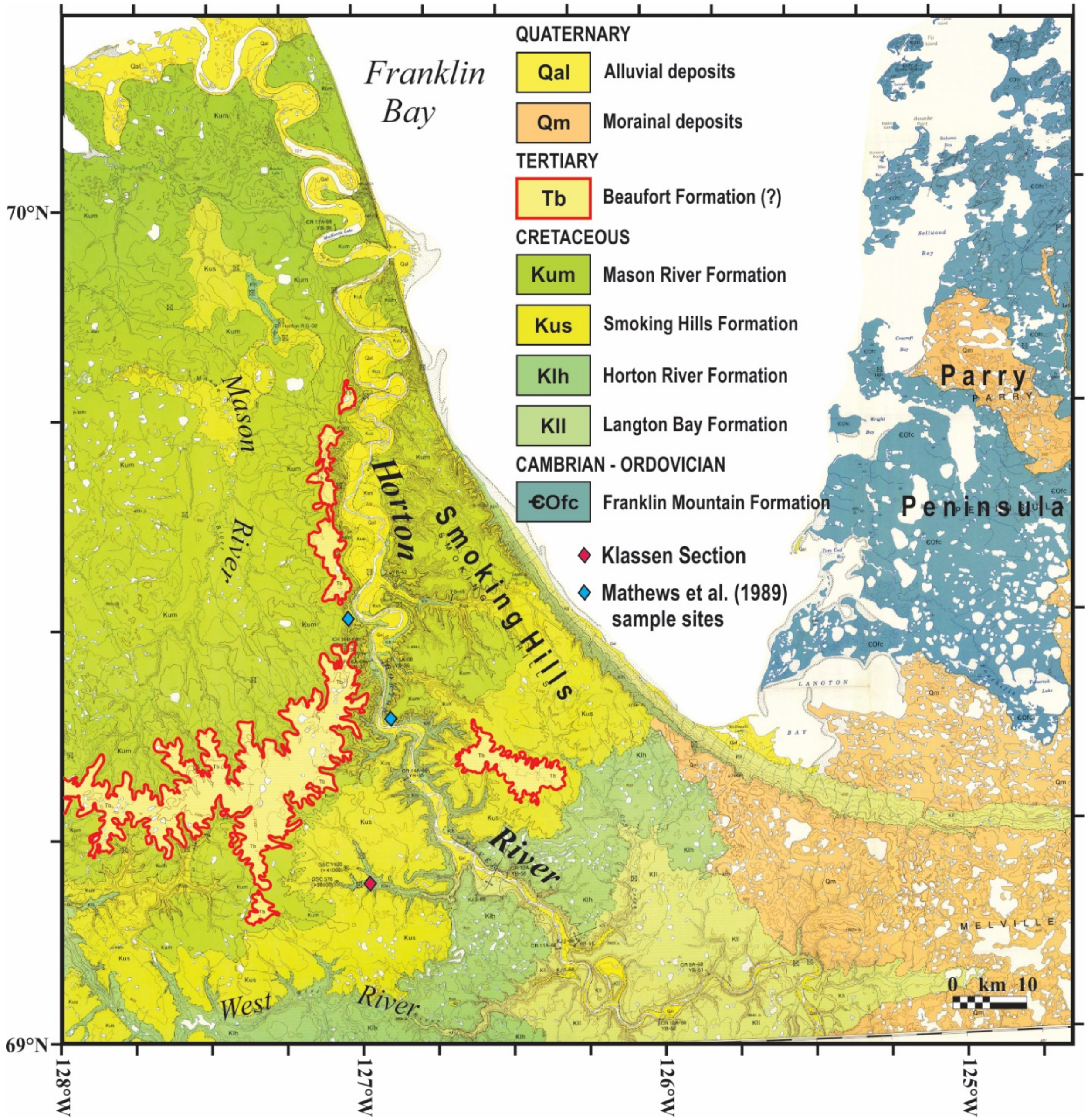

Figure 4.2. Western part of Yorath et al.'s (1975) bedrock geology Map 1403A illustrating the Smoking Hills study area. Extents of their mapped Beaufort Formation highlighted in red. The Quaternary (Klassen) section is marked by a red diamond.

A clear distinction must be made, however, between the lower sand and gravel deposit in the Klassen section, situated in the base of the valley at 172-175 m asl, and the possible Beaufort Formation plateau-cap gravel terraces described by Yorath et al. (1969, 1975) situated 15-20 km west and northwest of this site at 280-340 m asl (Fig. 4.2). While both were conjectured to be possible Beaufort Formation deposits, no stratigraphic or otherwise correlation, beyond pebble lithologies, was made (Fulton and Klassen, 1969; Yorath et al., 1969, 1975).

W. Mathews et al. (1989) further investigated the Pleistocene geology and geomorphology of the Smoking Hills area. Examining the plateau-cap gravels identified by Yorath et al. (1975), they noted the conspicuous rusty-weathering pebble-gravels were mostly clasts of dolostone, quartzite and chert such as occur in Paleozoic and Proterozoic rocks 50 km and more to the south and east. Clasts of ironstone and conglomerate derived from underlying Cretaceous beds were present but uncommon, and Canadian Shield-derived granite, diabase, gabbro, and gneiss were present, but rare. They indicate that clast imbrication demarks a northward paleoflow, while local trough-cross bedded sand indicates north to northwest transport. Palynological analysis of two sample localities in the plateau-cap gravels led W. Mathews et al. (1989) to conclude that they represented Pleistocene interglacial deposits, and were devoid of the hardwood-bearing Beaufort Formation sediments in the Arctic Islands (Hills, 1969; Vincent, 1983). Further, they characterized the plateau-cap gravels as either reworked Beaufort Formation or glaciofluvial deposits by virtue of their comparatively low quartzite content.

Vincent conducted field investigations in the Smoking Hills area in 1988 and 1991 (unpublished GSC field notebooks), and collected samples for pollen analysis from a section of the basal sand and gravel deposit, 900 m upstream of the Klassen section. Vincent's collection site (VH-88-017, 69°12.4'N; 127°02.5'W; cited in J. Matthews and Ovenden (1990) is considered to be the same as which occurs at the base of the Klassen section. However, this basal sand and gravel deposit is incorrectly identified by J. Matthews and Ovenden (1990) as being part of the "Plateau Cap Gravels" which they state occur beneath the Smoking Hills uplands along the West River. The plateau-cap gravels identified by Yorath et al. (1969, 1975) and W. Mathews et al. (1989) are instead situated atop the Smoking Hills uplands, while the section being described by J. Matthews and Ovenden (1990) is in the base of the valley, 900 m upstream of the Klassen section (Fig. 4.2). Palynological analyses by J. Matthews and Ovenden (1990) reveal a taxa suggestive of a Tertiary age. Similarly, analysis of wood remains from the sand and gravel deposit are considered to be the *Pinus strobus* type (Jetté, 1988), which J. Matthews and Ovenden (1990) considered to be uncorrelated with known Quaternary sediments from the region. They argue that were this sand and gravel deposit to be of Quaternary age there should have been a mix of both well-preserved fossil taxa typical of northern taiga species, and a smaller abundance of poorly-preserved "old" forms, reworked from older deposits. Their analysis revealed an assemblage consisting entirely of "old" forms, from which they conclude it is "almost certainly pre-Quaternary" (J. Matthews and Ovenden, 1990).

Duk-Rodkin and Hughes (1994) in their reconstruction of Tertiary-Quaternary drainages perpetuate the stratigraphic error of J. Matthews and Ovenden (1990) regarding the Smoking Hills plateau-cap gravels. They describe the Smoking Hills uplands as an erosional remnant capped by Tertiary gravels, and repeat the argument of J. Matthews and Ovenden (1990) that the presence of only "old" pollen macrofossils dismisses the Pleistocene interglacial interpretations of W. Mathews et al. (1988), despite the fact that the two deposits studied are clearly different, and not stratigraphically linked. This also compounds the local Tertiary-Quaternary drainage evolution argued by Duk-Rodkin and Hughes (1994) as while the Smoking Hills upland may well be a post-Cretaceous fluvial remnant (age-unconstrained) it is seemingly not capped by Tertiary-aged fluvial deposits, which instead may only exist in the base of one minor drainage system (the Klassen section), 100-150 m below the actual plateau surface.

Glacial History

Mackay (1958, 1963) was the first to study the glacial history of the region, and indicated that most of the broader Anderson River region had been glaciated, likely by the last [Late Wisconsinan] glaciation with the possible exception of Cape Bathurst and the region west of the Smoking Hills (~126°W). Ice advanced westward down Amundsen Gulf, impinging on the outer edge of the Smoking Hills, and northward from the Great Bear Lake region (Fig. 4.3). He also commented on the nature of the regional fluvial systems, noting that Pleistocene ice sheets advanced across areas of pre-existing broad, deep bedrock valleys, enlarging or blocking some, and creating new channels where meltwater was diverted along ice margins. He suggests that while the upper Horton River is situated in a Pleistocene valley, the lower course is only recent in age. Klassen in Yorath et al. (1968, 1975) identifies what is herein being described as the Klassen section north of the West River where 3 or more tills provide evidence of multiple glaciations, the lowest till of which is suggested to be an early or pre-Wisconsinan age. Klassen (1971) delineates an approximate limit of Late Wisconsinan ice that shows it wrapping around the Smoking Hills from the south and east, but not overtopping them, or covering the Klassen section (Fig. 4.3). For some time it was agreed that the Smoking Hills uplands remained unglaciated by Wisconsinan ice (Prest, 1984; Vincent, 1984, Dyke and Prest 1987, Hughes, 1987, Rampton, 1988). W. Mathews et al. (1989) argued that based on their reconstruction of the modern and ancient Horton River drainage courses relating to progressive ice diversions, evidence of glaciotectonized bedrock, and rare diamictons on the plateau-cap, that the Smoking Hills upland was fully glaciated during a mid-Pleistocene or earlier glaciation. They envisaged ice encroaching upon the upland from both the east and the west, but concur with other authors that there remained an absence of evidence for subsuming the uplands during both Early and Late Wisconsinan advances.

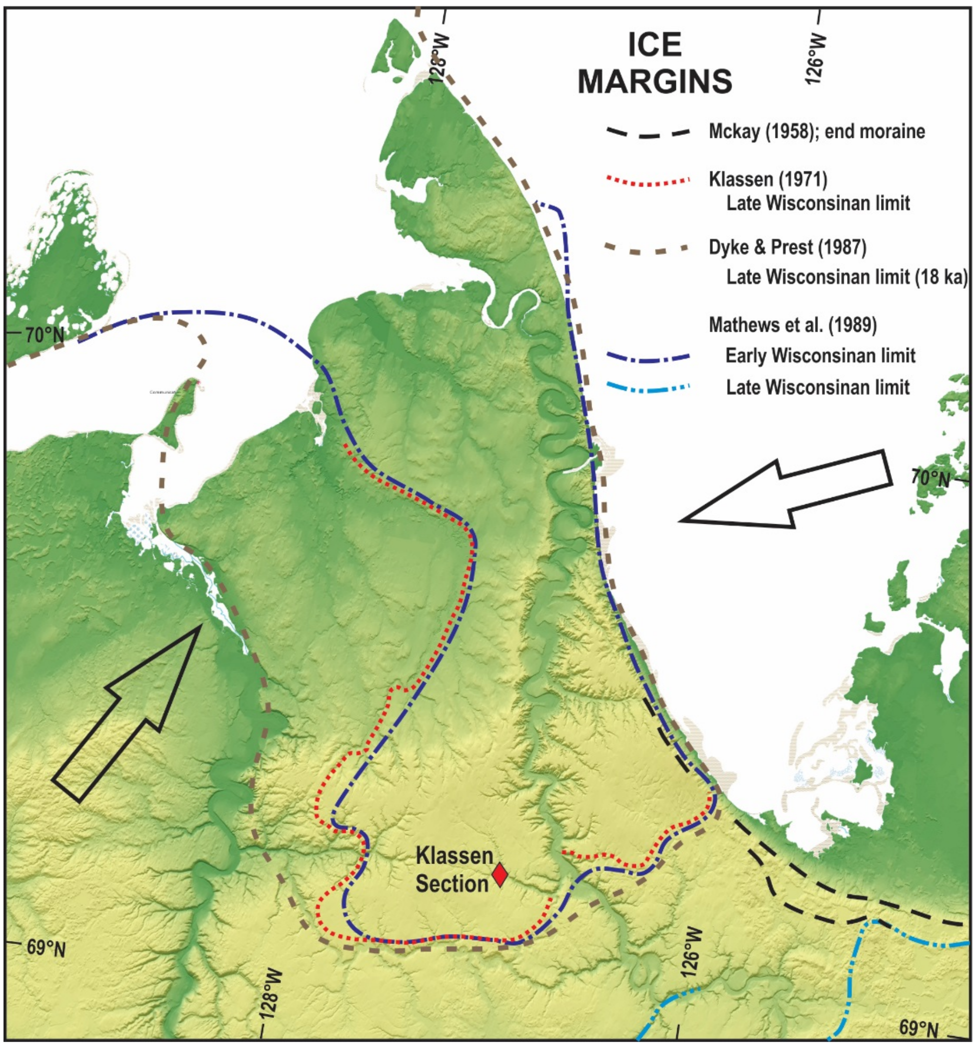

Figure 4.3. Historical glacial ice margin reconstructions in the Smoking Hills, NT, area. Generalized ice flow directions shown by open arrows.

Regionally glaciotectonized bedrock was also noted by Yorath et al., (1975) and Yorath and Cook (1981), wherein they described small, tight disharmonic folds within Upper Cretaceous Smoking Hills and Mason River rocks, likely detached above highly ductile Lower Cretaceous bentonitic shales; fold axes in all but one observed site was in a northerly direction. W. Mathews et al. (1989) describe structural deformation and rare faults affecting Cretaceous bedrock, including one site that extends through the plateau-cap gravels. Fold amplitudes range from a few tens of metres to 100 m, and exhibit tight to locally overturned bedding. While fold axes tend to trend northerly, vergence, where detected, are westerly-directed at sites on the east side of Horton Valley, and easterly-directed at sites west of Horton Valley.

Duk-Rodkin et al. (2004, p. 329) report exploratory paleomagnetic measurements (Vincent and Barendregt, unpublished field notes, 1989 [?1988]) based on Vincent's detailed stratigraphic interpretations of till and inter-till sediments from the Klassen section (1988, unpublished field notebook; his site VH-88-015). Based on stratigraphic logs (Duk-Rodkin et al., 2004, their Figure 18), and magnetic characterizations, it is suggested that the sedimentary record of the Klassen section spans the late Pliocene Matuyama Chron (<2.58 Ma) and/or the late Gauss Chron (3.04-2.58 Ma; Barendregt and Duk-Rodkin, 2004; Duk-Rodkin et al., 2004). The lower normal magnetized till depicted by Duk-Rodkin et al. (2004) is Vincent's Unit 3, and overlies the presumed Beaufort Formation gravel deposit, for which no paleomagnetic measurements were made (Vincent, 1988, unpublished field notebook). In 2004, Duk-Rodkin and Barendregt returned to the Klassen section and conducted detailed sampling for paleomagnetism (Duk-Rodkin and Barendregt, 2011). They indicate that the lower sand and gravel deposit overlying Cretaceous bedrock is reversely magnetized, and that this is overlain by three magnetically reversed tills, which are capped by magnetically normal lacustrine, paleosol and overbank deposits, which in turn are capped by an upper magnetically normal till (Duk-Rodkin and Barendregt, 2011). Vincent's former normal magnetized basal till (cf., Duk-Rodkin et al., 2004; their Figure 18) is now indicated to be reversely magnetized, removing the possible temporal extension to the Gauss Chron, and suggesting the section may instead date only as far back as the Matuyama Chron (<2.58 Ma). Vincent (1988, unpublished field notebook) identified the presence of granites in his Unit 3 dark till (equivalent to Duk-Rodkin and Barendregt's (2011) units 2 through 6) and rare granites and gabbro erratics within his upper Unit 6 brown till which is equivalent to Duk-Rodkin and Barendregt's (2011) units 9 and 10. Duk-Rodkin et al (2004), Barendregt and Duk-Rodkin (2004) and Duk-Rodkin and Barendregt (2011) indicated, however, that Canadian Shield-derived erratics were not found anywhere in the stratigraphy, and only occurred as a scattered boulder lag on the surface at the top of the section, which they considered as additional support of their hypothesized Horton Ice Cap as the source of the underlying till stratigraphy.

Ongoing Quaternary glacial research, including field, remote sensing and modelling-based studies, now argues that during the Late Wisconsinan glaciation, ice from the Keewatin Sector of the Laurentide Ice Sheet flowed both west down Amundsen Gulf, and north and east from Great Bear Lake, subsuming the Smoking Hills and Bathurst Peninsula (Dyke, 1996; Dyke et al., 2002, 2003; Stokes et al., 2006, 2008, 2012; England et al., 2009). Hence the uppermost normally magnetized tills at the Klassen section and the surface boulder lags are likely the deposits of Late Wisconsinan glaciation.

Kimberlite Indicator Minerals

Drift sampling for recovery of KIMs for geochemical analysis were carried out under one of two focusses. The first of these was designed to target the areas of suggested Beaufort Formation upland-cap gravel deposits delineated by Yorath et al. (1975). Previous studies on Banks Island (Smith, 2015;

Smith et al., 2016) had identified both the presence, and in one case a significant abundance (n=101), of KIMs in Beaufort Formation deposit samples. These were the first studies to identify the Beaufort Formation as a potential source of KIM bedrock inheritance. Fluvial dispersal of KIMs within the Beaufort Formation thus represented a further complexity in trying to resolve dispersal of KIMs from potential kimberlite sources beyond simply trying to reconstruct palimpsest glacial flow histories. Samples from Beaufort Formation deposits on the Smoking Hills are to be compared and contrasted with the Banks Island mineral populations to see if they are related, and in so doing, constrain aspects of their fluvial dispersal trajectory. A second focus of KIM study were the multiple tills identified in the Klassen section (Fulton and Klassen, 1969; Duk-Rodkin et al., 2004; Duk-Rodkin and Barendregt, 2011). The idea being tested is that previous glacial advances could entrain and redeposit KIMs from potentially different kimberlite sources, and in turn, successive glaciations would rework pre-existing deposits, homogenizing different dispersal records. Deciphering these KIM dispersal histories would further help constrain and inform regional KIM exploration. There are 13 kimberlites known to occur on Parry Peninsula, immediately east of the study area, and numerous others to the south and further east on Victoria Island (Kolebaba et al., 2003; Davies and Davies, 2013; Liu et al., 2018). While extensive drift sampling programs have been conducted in the broader region (Fig. 4.4; Talmora Diamond Inc., 2018), to our knowledge, the area of the Smoking Hills where we were working has not been subject to KIM exploration.

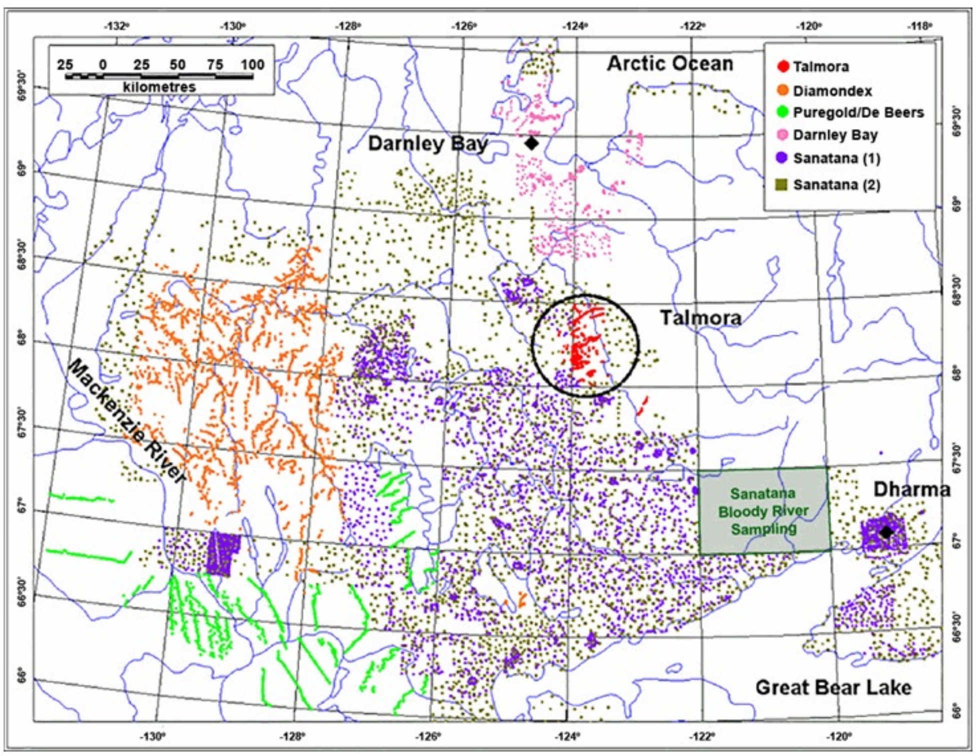

Figure 4.4. Distribution of historical kimberlite indicator mineral exploration activity by different companies in northwestern Canada south of the Smoking Hills region. Areas of known kimberlite occurrences identified by black diamonds. Figure reproduced from ***http://www.talmoradiamond.com/project.html***

Methodology

Kimberlite Indicator Mineral Drift Sampling

Eight samples from the suggested Beaufort Formation upland-cap gravels were collected from bluff faces and prominent terraces. In bluff sections, the faces were excavated back until all potential slumped material had been removed and the sediments thereby considered in situ. In terraces, small pits were excavated ~50 cm deep, and then sediments below this were collected. Holes were refilled after sampling. Samples were either collected in bulk (discarding only larger cobbles), or were dry-sieved through a sieve nest consisting of a coarse ½ inch (12.7 mm) and finer #8 mesh (2.38 mm) sieve sizes in order to concentrate the sand fraction within which KIMs and other heavy minerals are recovered. In those samples which were sieved, a representative sample of >50 pebbles were included in the pail for clast shape and lithological study. Total sample weights ranged from 20-30 kg, and were stored in clean 5 gallon plastic pails.

Two KIM samples were collected from the basal sand and gravel deposit in the Klassen section, and from an extension of what is interpreted to be this same deposit at a site 4 km to the northeast. Five KIM samples were also collected from various identified till/diamictic deposits overlying the basal sand and gravel at the Klassen section. Smaller bag samples of till/diamict matrix materials were collected for geochemical analysis.

All KIM samples have been submitted to Overburden Drilling Management Ltd. for processing and picking of both KIMs and other heavy minerals. Returned KIMs will be analyzed geochemically, including trace element and isotopic analyses, at the University of Alberta's Arctic Resources Laboratory. Results will be presented in Open File reports when analyses and interpretations are completed.

Quaternary Studies

A landsystem approach (cf. Dyke and Evans, 2003) was used to investigate and document the regional glacial geomorphology, sedimentology and glaciotectonic history, whereby the spatial arrangement of landform-sediment assemblages was combined with intensive sedimentological and stratigraphic data to compile a holistic analysis of the dominant glacial process-form regimes in the area over time. At targeted and newly discovered exposures throughout the field area, detailed stratigraphic and lithofacies logs were made. Bluff sections were cleaned using hand shovels, and an overlapping sequence of ~75 cm steps were dug vertically in alternating fashion or diagonally across faces in order to reveal primary sedimentological and structural character. Detailed lithofacies logs were constructed for each site investigated, and will be presented in future publications. Individual lithofacies were identified based on bedding, texture, lithology and sedimentary structures and then described and classified according to the modified scheme of Eyles et al. (1983) proposed by Evans and Benn (2004). Clast macrofabrics and forms were measured based upon 50 clasts per sample where possible, although a minimum of 30 clasts were sampled in sedimentary units where clasts were more sparsely distributed and to ensure that data collection was confined to small areas and thereby reflected local variability in till properties (cf. Evans and Hiemstra, 2005; Evans et al. 2016). Macrofabric measurements of the dip and azimuth (orientation) of the A-axes of clasts were taken using a compass clinometer, aiming to use predominantly clasts in the range of 30-125 mm (A-axis length) to allow comparison with other studies (Benn, 1994a, b; 1995; Evans, 2000; Evans and Hiemstra, 2005; Evans et al., 2007). The A-axes of clasts will tend to rotate to parallelism with the direction of shear in a shearing Coulomb plastic medium like till (cf. March, 1932; Ildefonse and Mancktelow, 1993; Hooyer and Iverson, 2000). Fabric data were plotted on spherical Gaussian weighted, contoured lower hemisphere stereonets, using Rockware™ software. Statistical analysis was also undertaken using eigenvalues (S1 - S3), based on the degree of clustering around three orthogonal vectors (V1-V3), presented in fabric shape ternary diagrams (Benn, 1994b). This identifies end members as being predominantly isotropic, girdle or cluster fabrics (see Evans 2018 for a full discussion of the technique). To further ascertain strain histories, fabric data has been classified according to five modal groups (un-unimodal, su-spread unimodal, bi-bimodal, sb-spread bimodal and mm-multimodal) and plotted against isotropy in a modality-isotropy template, based on the modification of Hicock et al.'s (1996) modality-isotropy plot (Evans et al., 2007).

In order to assess the operation and impacts of debris transport pathways inherent within the clast forms of the various lithofacies, especially potential subglacial tills, (Boulton, 1978), clast form was assessed by measuring the three principal axes (A, B and C) of clasts and the results plotted in ternary diagrams, based on the C:A axial ratio (blockiness) and B:A axial ratio (elongation). This facilitated the calculation of the C40 index (the percentage of clasts with a C:A axis ratio of <0.4), which determines the relative proportion of slabby to blocky clasts within a sample (Benn and Ballantyne, 1993). The roundness of clasts was classified according to Powers (1953), and was used to calculate the RA summary index (percentage of angular and very angular clasts within a sample; Benn and Ballantyne, 1993) and the mean roundness (cf. Spedding and Evans, 2002; Evans, 2010). These data are compared to available datasets on different glacigenic materials through the use of co-variance plots (Benn and Ballantyne, 1994; Evans, 2010; Lukas et al. 2013). Finally the morphological characteristics of clasts indicative of subglacial transport, including striae, facets and stoss/lee forms, were noted (cf. Sharp, 1982; Krüger, 1984; Benn, 2004b) and presented as percentages for each sample.

Within the Klassen section (Fulton and Klassen, 1969), samples of bulk, quartz-rich sand and individual quartzite cobbles and pebbles were collected from the basal sand and gravel deposit, and in overlying till/diamict units. These are being submitted for cosmogenic nuclide burial dating (cf., Gosse, 2012) in order to constrain their age of deposition.

Discussion

Plateau-Cap Gravel Deposits

The palynological analysis reported by W. Mathews et al. (1989) at two sites along the Horton River (one site comprising two stratigraphic samples) clearly questioned the correlation of the Smoking Hills plateau-cap gravels as possible Beaufort Formation equivalents. Sample locations provided by them actually place their sites outside the mapped Beaufort Formation extents of Yorath et al. (1975; Fig. 4.2), but field investigations this past summer confirm their identification as plateau-cap gravel deposits, identical to those delineated by Yorath et al. (1975).

Numerous field observations from this past summer further question the Beaufort Formation classification of the plateau-cap gravels.

1. All of the plateau-cap gravel deposits within the mapped extents contain both faceted and rare striated clasts (Fig. 4.5). At the very least, they require an antecedent glaciation, but as first suggested by W. Mathews et al. (1989) are quite likely glaciofluvial deposits.

Figure 4.5. Striated and faceted quartzite clast from deposits mapped by Yorath et al. (1975) as Beaufort Formation (sample 18SUV522; 69°47’57”N, 127°0’56”W). Clast morphology suggests that these are instead glaciofluvial deposits.

2. The mapped extents of plateau-cap gravels do not capture all such deposits in the field area, and in the case of the mapped western and eastern extensions, greatly exaggerate their aerial extents. It appears that the basis for mapping conforms to textural properties on the air photographs, rather than actual surficial geology and outcrop. It is noted that Yorath et al. (1975) delineate the boundaries of their Beaufort Formation (?) deposits with “approximate” and “assumed” line types, and indicate that some bedrock contacts were extended by air-photo interpretation.

3. The plateau-cap gravel sections immediately bordering the west side of the Horton River valley typically have steep bluffs facing the river valley, and topographic profiles that decline northwestward (Fig. 4.6). Assuming these are in fact glaciofluvial deposits, they would represent outwash terraces or kames from an eastward retreating ice mass presumably occupying Amundsen Gulf and the Horton River valley. The low-angle foreset and clast imbrication directions generally align with their northwestward descending topographic profiles.

Figure 4.6. Orange-stained upland-cap gravel deposits (Beaufort Formation of Yorath et al. (1975)) unconformably overlying pale Mason River Formation sandstone along west side of Horton River (69°35’20”N, 127°04’7”W). Unit thickness up to 5 m. Gravel deposit inclined to northwest; photo view to northeast.

4. The broad southern expanse of mapped Beaufort Formation deposits that extend to the east and west appear morphologically distinct from those to the north, bordering the Horton River. Instead of steep bluffed expanses, there are areas of broad, discontinuous, cryoturbated outwash deposits and washed till connecting to prominent staircase, outwash terraces that extend radially southwards into adjacent valleys and tributaries (Fig. 4.7). Lateral accordance in terraces suggests that in some cases these may be deltas formed within ice-dammed lakes, but in all cases a glacial and/or glaciofluvial origin is interpreted. It is most conceivable that the extent of these deposits mirror an arcuate ice margin flowing from the north and northeast (Fig. 4.1).

Figure 4.7. View looking west across a southward descending staircase of outwash terraces into unnamed valley north of West River (69°14’32”N, 127°35’53”W). Graveled surface in foreground (sample 18SUV519) match those in the distant terraces, and lie within the bounds of Yorath et al.’s (1975) mapped Beaufort Formation plateau-cap gravels.

With respect to the basal sand and gravel deposits in the Klassen section, it has already been discussed that the apparent confusion within the literature that these are part of the Smoking Hills plateau-cap gravels should be corrected. There is no stratigraphic linkage between these two deposits, and similarities based on clast lithologies is a weak correlative tool, especially given the greater range of lithologies identified by W. Mathews et al. (1989) in the plateau-cap gravels, and confirmed by our field campaign. Also, similar to the plateau-cap gravel deposits, these basal sand and gravel deposits in the Klassen section contain both faceted and rare striated clasts, suggesting that they could represent a glaciofluvial deposit, or at least post-date a local glaciation. A paleocurrent based on gravel sheetflow bedding was measured at 344° (declination corrected), and based on regional exposures of this deposit, a buried channel system trending northwestward is proposed. As a means of further testing the age equivalency of this basal sand and gravel deposit, samples of organic detritus within the upper sand facies of this lithofacies assemblage were collected for palynological and other plant macrofossil analysis. Results will test that of J. Matthews and Ovenden (1990) and their single sample collected from what is interpreted to be the same deposit, 900 m north of the Klassen section. Samples collected for cosmogenic nuclide burial age dating hopefully will provide an independent age estimate.

Quaternary Field Investigations

In summary, the field data record multiple glacial advances over the study region as recorded by several tills, coherent and deformed glacial rafts of unconsolidated to weakly-consolidated bedrock, and associated glaciotectonically disturbed bedrock outcrops. Detailed lithostratigraphic logs and broader outcrop architectures of the investigated Quaternary sections will be presented in future publications. We confirm Vincent's (1988, unpublished field notebook) observations of granite erratics in the upper brown till at the Klassen section (Vincent's unit 6; units 9 and 10 of Duk-Rodkin and Barendregt, 2011), but did not, through the course of step excavation up the section, observe any granites as reported by Vincent (1988, unpublished field notebook) within the lower dark till unit #3. We note Duk-Rodkin and Barendregt's (2011) "scattered Laurentide (Shield) boulder erratics" on the top of the section and would characterize our own observations of these as rare. However, we equate the surface presence of these with the underlying normally magnetized brown till and regard both to be the product of the same, likely Late Wisconsinan glaciation.

At the landform/landscape scale, conspicuous patterns of lakes in the broader Anderson River map area were noted by Mackay (1958) and were used to deduce their formative mechanisms, including aspects of glacial, fluvial, and periglacial geomorphology. Interestingly, one site highlighted by Mackay (1958, p 73; his Figure 16D), is situated in the southeastern Smoking Hills, east of the Horton River (Fig. 4.8). Mackay (1958) describes these as "dry" valleys with underfit streams and sinuous lakes that he suggests occupy deeper parts of old river channels, or are old channels that became partly dammed by alluvial fans, deltas and slumping. Further, he suggests that many dry channels in the area mark marginal flow of glacial meltwater. Based on field investigations this past summer, we now recognize the patterns of these lakes and dry channels as demarcating ice-thrust ridges, from southward flowing glaciers. Although best developed on the east side of the Horton River, they also conform to the lake patterns on the west side of the Horton River, north of West River (Fig. 4.8). In both localities, numerous slumps and retrogressive thaw flow slides along steep lake shorelines expose large areas of buried ice which could be both periglacial or glacial in origin. Abundant exposures of buried glacial ice were noted in tributary valleys and upland regions bordering the lower Anderson River.

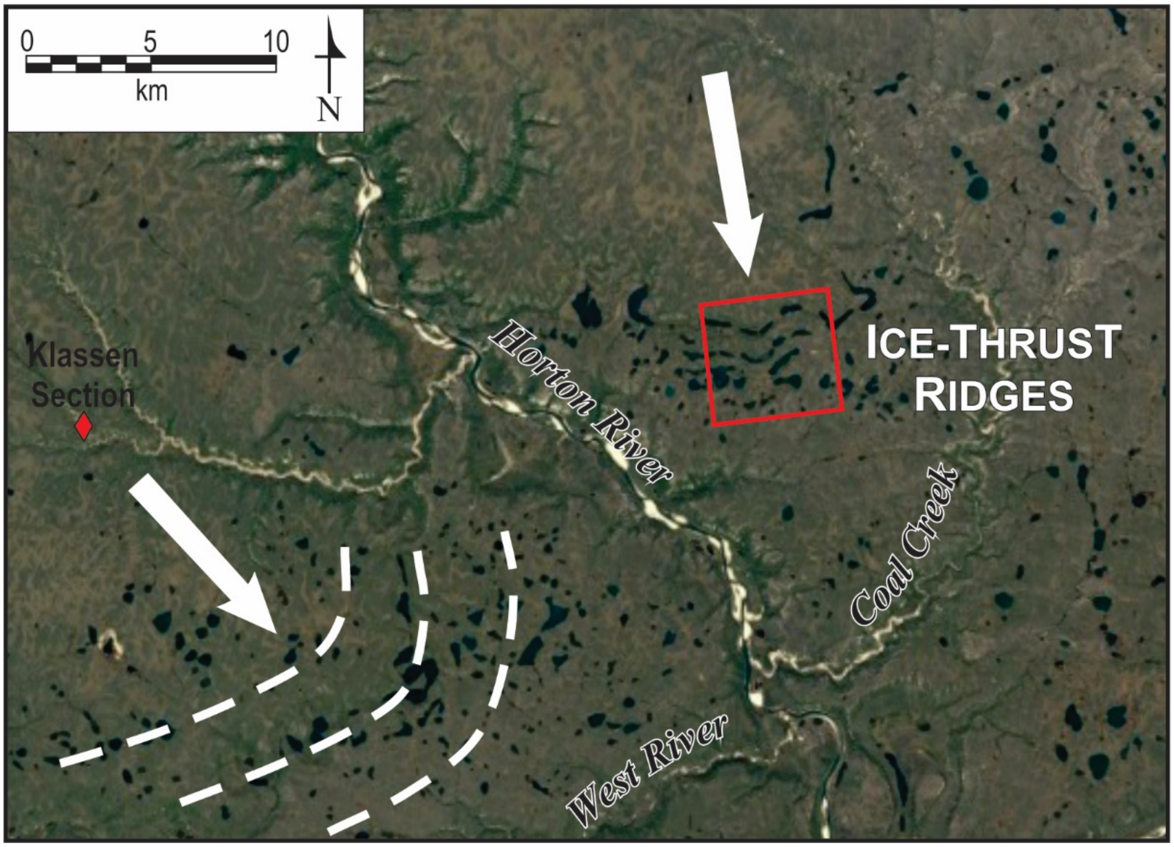

Figure 4.8. Lake-bound traces of ice-thrust ridges north of West River and Coal Creek, Smoking Hills, NT. "Dry valley" area identified by Mackay (1958, his Figure 16D) shown in red box. White arrows shows direction of ice flow. Ice-thrust ridge pattern west of Horton River mirrored by white dashed lines; those east of Horton River are more obviously bound by chain lake patterns.

One site discovered this past summer presented a unique glacial raft of bedded forest, marl and fluvial deposits (Fig. 4.9). Situated at the top of a >40 m bluff are 3 m of diamictic sediments interpreted to be a till from what was likely the Late Wisconsinan glaciation. These overlie 2 m of laminated to massive silty-sands of either lacustrine or glaciolacustrine origin. Below this are 3 successive layers of forest-type vegetation remains containing tree stumps, up to 18 cm in diameter, rooted in place. Each layer of forest has a stratigraphy of tree stumps and large woody debris, buried in up to 10 cm of dense leaf litter, capped by up to 15 cm of marl, overlain by poorly sorted, muddy sand and gravel. Below the forest layer deposits are 5-8 m of deformed and tectonized ripple-laminated sand, cobble beds and muddy sand, which in turn overlies 20+ m of diamicton and associated stratified sediments. Assuming these forest layers to be an internally continuous deposit (as opposed to a thrust and stacked sequence), it most likely resembles a forested floodplain/small oxbow lake-type environment that must have formed in a carbonate-rich terrain (accounting for the marl). The successive forest layers would represent an aggradational floodplain sequence. The geographic position of this deposit in relation to the deeply incised valleys it sits atop and within argues that it cannot be in place. Also, none of the local surface bedrock contains sufficient carbonate and associated groundwater to generate the marls. It is hypothesized that these forest layers represent a single, largely internally undisturbed glacial raft from an unknown locality to the east (possibly the dolomitic terrain of Parry Peninsula). A sample of one of the in situ tree stumps submitted for radiocarbon dating, returned a non-finite age (>46,500 ^{14}C yr BP; UOC-7312). While it doesn't discount the interpretation that the overlying till (and presumed mechanism of glacial rafting of the underlying forest layers) was a Late Wisconsinan advance, it perhaps reinforces the deduction that there is an abundance of very well preserved "old" wood, of likely various ages (possibly up to and including Tertiary) found in various deposits throughout the area. Additional analyses will be required to constrain the potential age of this deposit.

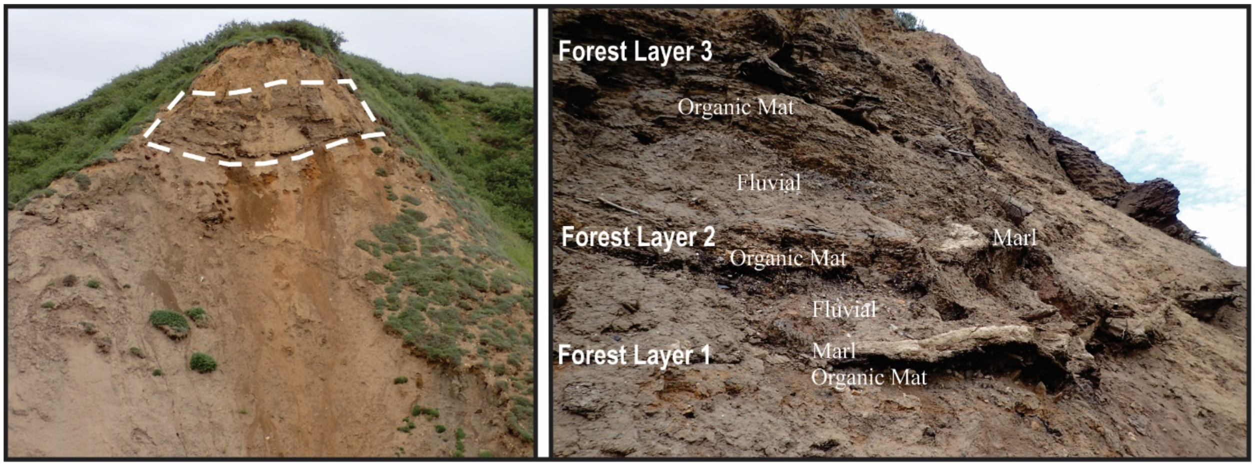

Figure 4.9. Glacial raft of buried forest layers consisting of organic mats, rooted trees and large woody debris, marl, and fluvial deposits. Upper 20 m of section shown at left where forest layers are capped by 3 m of till. Detail of buried forest layers shown at right. Radiocarbon sample 18SUV531 (>46,500 ^{14}C BP; UOC-7312) came from Forest Layer 1.

Conclusions

The Smoking Hills field area yielded significantly more scientific complexity and intrigue than had been expected. Sampling and recovering KIMs from the deposits mapped by Yorath et al. (1975) as Beaufort Formation was a priority of this activity. Our investigations challenge their Beaufort Formation classification, so it may not be possible to make the intended comparisons with Banks Island Beaufort Formation-derived KIMs. Nevertheless, the potential to recover KIMs from the basal gravels at the Klassen section, and from overlying tills, should help refine and inform regional KIM exploration. The discovery and analysis of complex glacigenic deposits and associated glaciotectonic structures, developed in both Quaternary and pre-Quaternary materials, will facilitate the compilation of a glacial landsystems model for the region and the reconstruction of ice sheet dynamics in an area of permafozen soft bedrock terrain.

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