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FOREWORD

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 investment in responsible 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 summer of 2015, the GEM program successfully carried out 17 research activities that include geological, geochemical and geophysical surveying. These activities were 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 collaborators as the program advances.

PROJECT SUMMARY

Colville Hills bedrock mapping and stratigraphic studies is a component of the **Shield to Selwyn geo-transect: studying the evolution of sedimentary rocks of the northern mainland NWT to improve exploration success for petroleum resources and base metal deposits (Figure 1).** This activity will initiate the first regional integrated effort to place Proterozoic to Cenozoic strata of Mackenzie Platform, Selwyn Basin, and adjacent regions into a fully modern tectono-stratigraphic and metallogenic framework, and will better enable industry and Northerners to responsibly find and develop energy and mineral natural resources, maximizing their economic and societal impact.

The present report provides a brief account of field activities in the Colville Hills region of the NWT during late July and early August, 2015. Preliminary results are presented that touch upon bedrock geological mapping, structural geology, stratigraphy (with particular focus on Cambrian-Ordovician, Ordovician-Silurian, and Cretaceous units), and oil seeps.

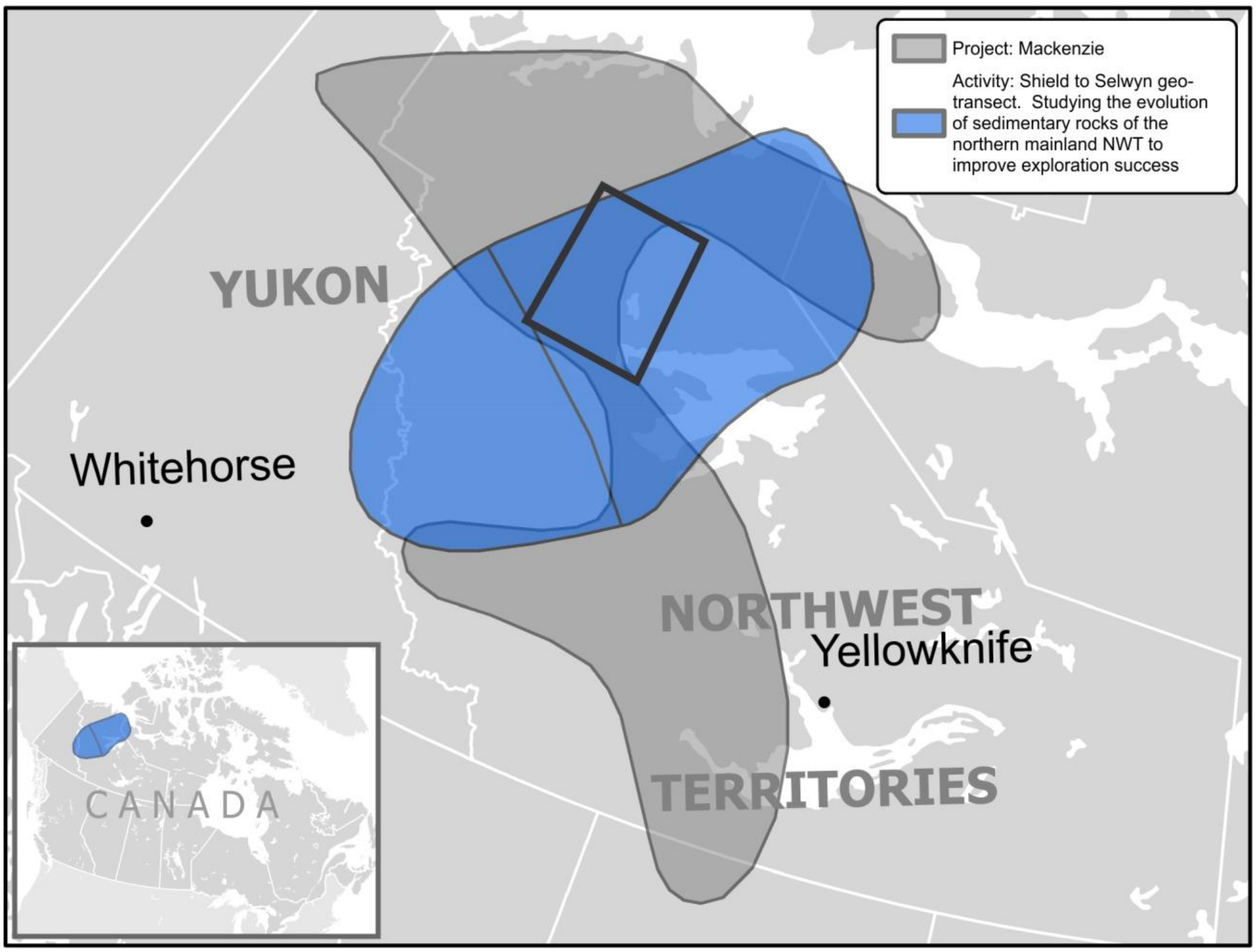

Figure 1. Location of the GEM 2 Mackenzie project area and the Shield to Selwyn geo-transect activity associated with this report. Black box outline shows the location of 2015 field activities.

INTRODUCTION

During the summer of 2015, 1:250 000 scale bedrock mapping was carried out in the Colville Hills region of the Northwest Territories. The purpose of the work was to update the existing 1:500 000 scale map for the region (Aitken and Cook, 1970; Cook and Aitken, 1971), as part of the Shield to Selwyn geo-transect activity of the GEM Program (Figure 1). The region under study comprises NTS map areas 96K, 96L, 96M, and 96N (Figure 2), encompassing the Colville Hills, the northern limit of the Franklin Mountains, and adjacent parts of the interior plains of the mainland Northwest Territories. Large parts of the mapping area are of very low relief and dominated by muskeg and small lakes, but a number of larger lakes are prominent, including the western end of Smith Arm of Great Bear Lake. The region is heavily forested with spruce and brush, but the low, generally elongate ridges that form the Colville Hills locally rise above tree line. The ridges provide some of the best access to bedrock in the area, as do exposures along lake and river banks, along glacial meltwater channels, or around karst sinkholes. Access to isolated outcrops is difficult due to heavy tree cover.

Bedrock map units exposed in the study area range in age from Cambrian to Cretaceous (Figure 3). The region was previously mapped by GSC at reconnaissance scale in 1968, as part of Operation Norman (Aitken et al., 1969; Aitken and Cook, 1970; Cook and Aitken, 1971). The published bedrock geology map for the study area is a GSC Preliminary Map (Aitken and Cook, 1970) that contains large areas for which bedrock geology could not be interpreted due to lack of exposure. Limited modifications to the surface structural and stratigraphic interpretation of the region were published subsequently (Cook and MacLean, 1993), and the region has been included in more recent interpretations of the subsurface geology (e.g., Maclean, 2011).

METHODOLOGY

Field activities took place between July 15 and August 10 (not including time spent in travel to and from the study area). All work was staged from the community of Colville Lake (Figure 2), with the exception of three days at the start of the field season, when work was staged from Norman Wells to study exposures along the southwest edge of the mapping area. In late July, five work days were lost to rain, high winds, and low cloud ceilings.

Bedrock Geological Mapping

Because of limited bedrock exposures, mapping by Fallas, MacNaughton, and Sommers relied heavily on helicopter spot-checking, augmented by foot traverses in areas of better access and exposure. In some parts of the study area, bedrock exposure was so limited by overlying unconsolidated surficial deposits and surface water that large areas could be covered in a single day of flying.

Stratigraphic Studies

A major component of the project focused on producing detailed stratigraphic sections that could support both regional correlations and sedimentological analysis. Reconnaissance-level stratigraphy in the interior plains was documented during Operation Norman (e.g., Balkwill and Yorath, 1970; Cook and Aitken, 1970). Early publications on the study area made use of some stratigraphic terminology that is now obsolete (Figure 3). In particular, strata now included in the Cambrian-Ordovician Franklin Mountain Formation (Norford and Macqueen, 1975; Turner, 2011) were treated as informal subdivisions of the now-abandoned Ronning Group (Aitken and Cook, 1970; Cook and Aitken, 1971). To clarify Franklin Mountain Formation lithostratigraphy within the study area, Turner

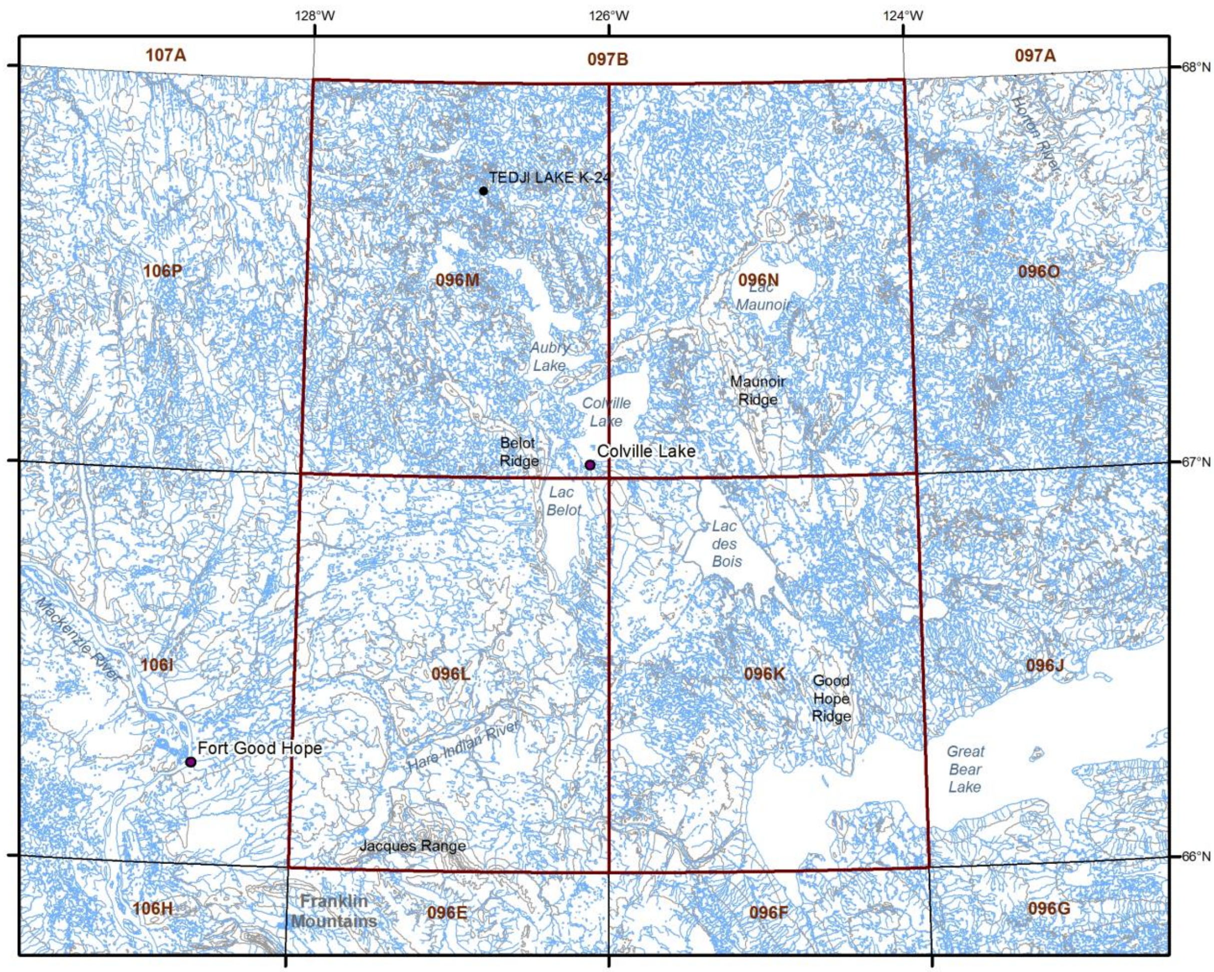

Figure 2. Location map showing the Colville Hills area with labelled topographic features for locations mentioned in the text.

<table>
<tr><th></th><th>Cook and Aitken (1971)</th><th>Cook and MacLean (1993)</th><th>This study</th></tr>
<tr><td>UPPER CRETACEOUS</td><td rowspan="2">Unnamed shale</td><td rowspan="2"></td><td>Slater River Formation / Smoking Hills Formation</td></tr>
<tr><td rowspan="3">LOWER CRETACEOUS</td><td>Arctic Red Formation / Horton River Formation</td></tr>
<tr><td rowspan="2">Unnamed sandstone</td><td rowspan="2">Langton Bay Formation</td><td>Martin House Formation, Tukweye Member sandstone / Langton Bay Formation, Gilmore Lakes Member</td></tr>
<tr><td>Martin House Formation, Tukweye Member shale / Langton Bay Formation, Gilmore Lakes Member</td></tr>
<tr><td colspan="4">Regional Unconformity</td></tr>
<tr><td rowspan="3">MIDDLE DEVONIAN</td><td>Ramparts Formation</td><td></td><td>Ramparts Formation</td></tr>
<tr><td>Hare Indian Formation, locally includes Cretaceous shale</td><td></td><td>Hare Indian Formation</td></tr>
<tr><td>Hume Formation</td><td>Hume Formation</td><td>Hume Formation</td></tr>
<tr><td>LOWER DEVONIAN</td><td>Bear Rock Formation</td><td>Landry Formation
Arnica Formation
Tatsieta Formation</td><td>Bear Rock Formation / Landry Formation
Arnica Formation
Tatsieta Formation</td></tr>
<tr><td colspan="4">Regional Unconformity</td></tr>
<tr><td>LOWER SILURIAN
UPPER ORDOVICIAN</td><td>Ronning Group, Mount Kindle Formation</td><td>Mount Kindle Formation</td><td>Mount Kindle Formation</td></tr>
<tr><td colspan="4">Regional Unconformity</td></tr>
<tr><td>LOWER ORDOVICIAN</td><td>Ronning Group, unit 2b</td><td>Franklin Mountain Formation, cherty member</td><td>Franklin Mountain Formation, upper member</td></tr>
<tr><td rowspan="2">UPPER CAMBRIAN</td><td>Ronning Group, unit 2a</td><td></td><td>Franklin Mountain Formation, middle member</td></tr>
<tr><td>Ronning Group, unit 1</td><td></td><td>Franklin Mountain Formation, lower member</td></tr>
</table>

Figure 3. Historical stratigraphic nomenclature for Colville Hills and preliminary correlations from 2015 field work. Diagonal lines denote units occurring outside the study area of Cook and MacLean (1993).

studied the Franklin Mountain Formation at localities along the Hare Indian and Horton rivers and on Maunoir Ridge.

Also included in the Ronning Group was the Mount Kindle Formation, which was considered to preserve the Ordovician-Silurian boundary, based on limited macrofossil collections (Cook and Aitken, 1971). In hopes of further refining the position and stratigraphic context of this important boundary, MacNaughton studied Mount Kindle Formation sections at the headwaters of Hare Indian River and on Good Hope Ridge; Turner also contributed to studies at the latter location.

Early workers encountered difficulties in consistently subdividing and mapping Cretaceous strata in the study region (Cook and Aitken, 1971). A notable problem was the distribution of a unit of Cretaceous sandstone that is deeply weathered and generally poorly exposed across the area. MacNaughton made observations at several problematic localities, and Sommers and MacNaughton measured a section through an exposure of oil-saturated Cretaceous sandstone on the western flank of Belot Ridge.

Petroleum Seeps

The presence of oil seeps in the Colville Hills was part of First Nations traditional knowledge, oil from the seeps having been used to waterproof canoes (Fred John Barnaby, personal communication, 2015). During Operation Norman, Cook and Aitken (1971) documented the presence of oil saturated sands at Lac des Bois and on the west flank of Belot Ridge. These localities were revisited for sampling during the present work.

RESULTS

Bedrock Geological Mapping

New bedrock geology maps will be prepared for NTS map areas 96K, 96L, 96M, and 96N (Figure 2). Mapping in 2015 yielded new observations that, when combined with stratigraphic data obtained from petroleum wells drilled since 1971, will allow the updating of the Paleozoic and Cretaceous stratigraphic terminology for the four map areas.

The oldest map unit found at surface is the Franklin Mountain Formation (Upper Cambrian to Lower Ordovician). Franklin Mountain Formation is a thick and monotonous dolostone (Figure 4A). Where previously described in detail, near and in the Mackenzie Mountains, it consists of three informal members. The uppermost member contains conspicuous chert (Figure 4B), making it easy to identify, even in areas of poor outcrop (Norford and Macqueen, 1975; Turner, 2011). In the study area, only the middle and upper members can be recognized at surface. Franklin Mountain Formation is overlain unconformably by grey dolostone of the Mount Kindle Formation (Upper Ordovician to Lower Silurian), which commonly contains abundant silicified fossils (Figures 4C-D).

Another unconformity separates Mount Kindle Formation from an overlying conformable succession of Devonian strata. Early workers (Aitken and Cook, 1970; Cook and Aitken, 1971) assigned the lower part of this succession entirely to the Bear Rock Formation (a mixture of bedded carbonates and carbonate solution-collapse breccia, commonly petroliferous; Figure 5A). Cook and MacLean (1993) later indicated that Bear Rock Formation may be underlain by limestone and shale of the Tatsieta Formation (Figure 5B). Additionally, those authors suggested that, where Bear Rock breccia textures are not developed, strata correlative with Bear Rock Formation may be assigned, in ascending order,

Figure 4. A) Pale orange bedded dolostone of the middle member of the Franklin Mountain Formation. B) Silicified stromatolite typically found in the upper member of the Franklin Mountain Formation. C) Grey-weathering dolostone in the upper part of the Mount Kindle Formation, showing typical bedding style. D) Silicified fossils are commonly found in Mount Kindle Formation.

Figure 5. Devonian strata. A) Brecciated carbonate of the Bear Rock Formation. B) Laminated carbonate possibly belonging to the Tatsieta Formation. C) Fossiliferous Hume Formation. D) and E) Contact between Hume Formation limestone and overlying shale of the Hare Indian Formation. F) Close-up of Hare Indian Formation shale.

to Arnica Formation (laminated dolostone), and Landry Formation (pelletal limestone). Our field observations generally support the suggestions of Cook and MacLean (1993) and we collected a number of samples from the Devonian interval for conodont analysis in hopes of further clarifying these stratigraphic issues. In the western portion of the study area, Bear Rock Formation (or its equivalents) is overlain by the Middle Devonian Hume Formation, which consists of rubbly, fossiliferous limestone (Figure 5C) that locally is shaly. Hume Formation is overlain with a sharp but conformable contact (Figures 5D-E) by dark-weathering shale of the Hare Indian Formation (Figure 5F), which in turn is overlain by fossiliferous limestone of the Ramparts Formation.

Cretaceous rocks (shale and sandstone) are present throughout much of the study area (Figure 6) but, as was also noted during Operation Norman (Cook and Aitken, 1971), the strongly recessive weathering character of these strata makes them difficult to find, study, or subdivide. Along the western edge of the study area, the lowest Cretaceous unit is a succession of soft, grey shale interbedded with well-cemented, tan sandstone (Figure 6A) with abundant soft-sediment deformation and trace fossils (Figure 6B). A unit of Lower Cretaceous quartz sandstone (Figures 6C-D) is widely distributed. In some regions the quartz sandstone unit lies unconformably upon Devonian strata, and it is locally overlain by Lower Cretaceous marine shale (Figure 6E). In the eastern part of the study area, dark grey, shale-dominated strata (Figure 6F) are considered to belong to the Upper Cretaceous (Cook and Aitken, 1971). Clarification of Cretaceous stratigraphic relationships will be an important element of the work during map compilation, and a number of field samples were collected for biostratigraphic analysis to support these efforts.

Although many structural relationships in the study area are unclear due to the limited outcrop, a few better exposed structures at the northern edge of the Franklin Mountains are being revised based on 2015 mapping. For poorly exposed structures, data from reflection-seismic lines on record with the National Energy Board help constrain the location and style of structures. Folding in the area consists of a few anticlines rising out of an otherwise flat plateau to form topographic highs (Figure 7A). A preliminary assessment of these structures suggests that more reverse faults (Figure 7B) and thrust faults (Figure 7C) underlie the major topographic ridges than were shown on the map of Aitken and Cook (1970), in general agreement with MacLean and Cook (1992) and Cook and MacLean (1993). Field relationships on the flanks of major structures show that Lower Cretaceous outcrops within the Colville Hills are tilted in association with folding and faulting (Figure 7D), indicating the development of these structures after the Early Cretaceous. The timing of this deformation overlaps with the structural development of the Franklin Mountains during the latter phases of mountain building (Late Cretaceous to Eocene) at the northeastern edge of the Foreland Belt of the Canadian Cordillera.

Stratigraphic Studies—Franklin Mountain Formation

Exposures of Franklin Mountain Formation described here are hundreds of kilometres from the type area of the formation in the Franklin Mountains (Williams, 1922, 1923). Five sections of Franklin Mountain Formation were measured within the study area during the 2015 field season. All of the sections are in the upper, chert-bearing dolostone unit (see above). None of the sections exposed contacts with other stratigraphic units.

Two overlapping sections in the Hare Indian River valley span approx. 120 m of the upper member. The lowest 5 m of the lower section (total thickness = 40 m) contain bright green clay seams and are overlain by burrowed, ripple cross-laminated dolostone, which may be a correlatable combination of

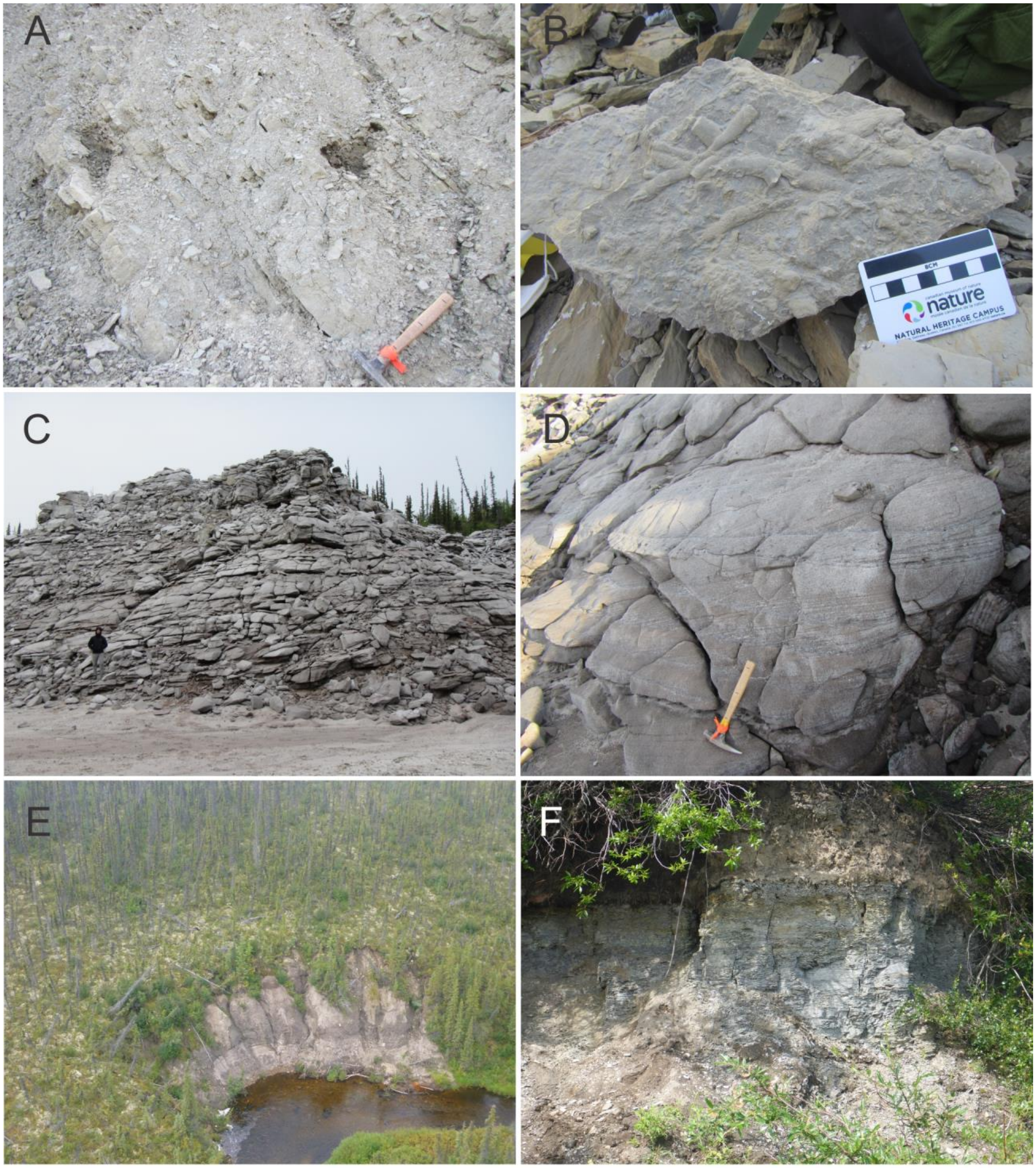

Figure 6. Cretaceous units. A) Lowermost marine shale and interbedded sandstone. These are the lowest Cretaceous strata found in 2015 and occur along the western edge of the study area. B) Trace fossils preserved on a sandstone bedding plane from interval shown in A. C) General bedding character of conglomeratic, cross-bedded, fluvial sandstone which overlies interval shown in A. Photograph shows oil-saturated sandstone strata exposed immediately west of Belot Ridge. D) Close-up view of cross-bedded sandstone. E) Lower Cretaceous marine shale found above sandstone in shown C and D. F) Upper Cretaceous marine shale found at Lac des Bois.

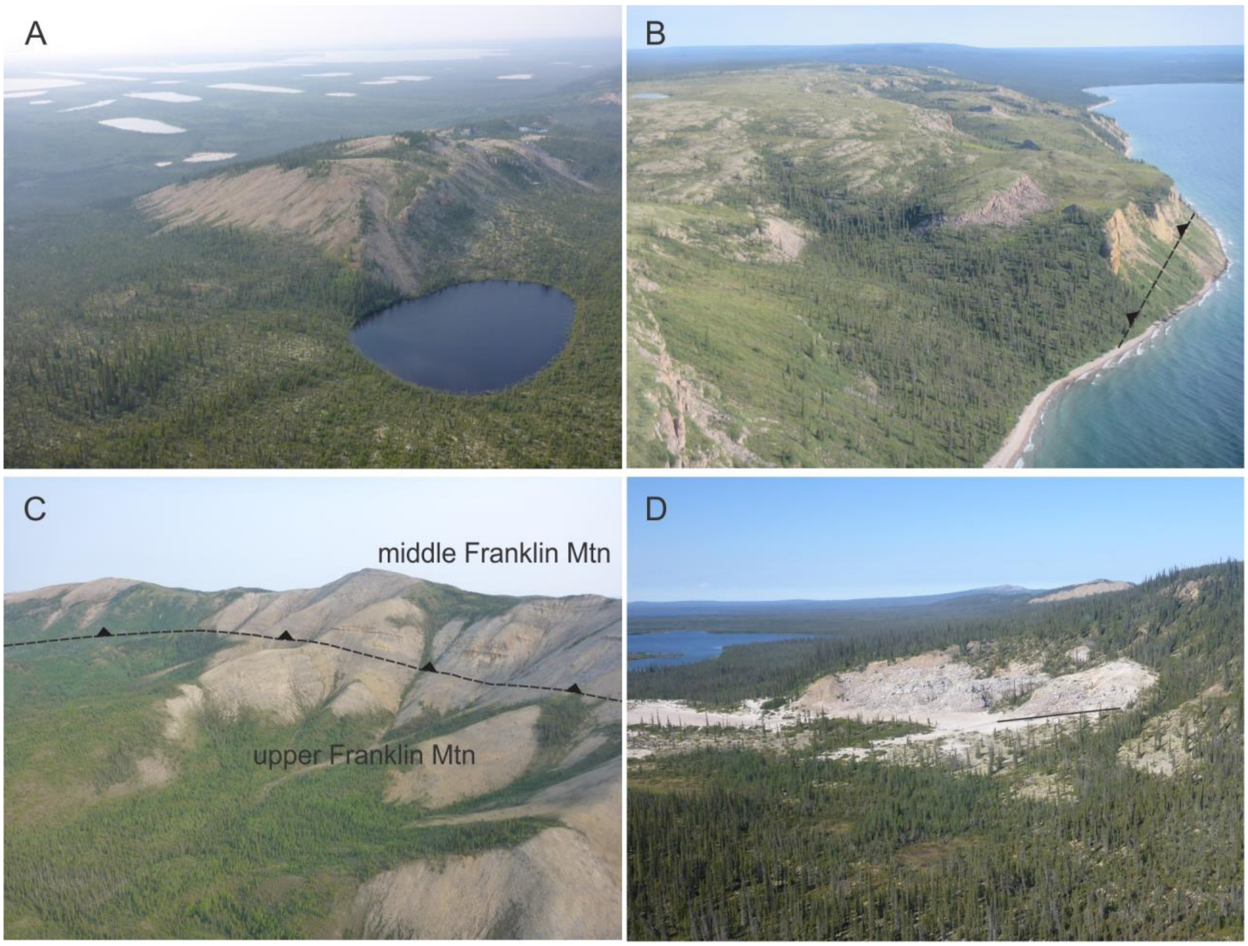

Figure 7. A) Anticlinal shape typical of the major ridges in the Colville Hills seen in exposure of Bear Rock breccia on Belot Ridge. B) Gently west dipping panel of Mount Kindle Formation at Good Hope Ridge. Panel is uplifted along a fault at right-hand side of photo. A previously interpreted anticline along the ridge is not present. C) Newly recognized fault on the Jacques Range placing the middle member of the Franklin Mountain Formation over the upper member. D) Tilted Cretaceous sandstone on the west flank of Belot Ridge suggesting involvement of Lower Cretaceous strata in deformation - black line is parallel to bedding.

features. The upper section (total thickness = 90 m) overlaps the lower by 15 m and contains minor white chert. Turbinate to columnar unbranching stromatolites are present in the middle of the upper section. Fractures and vugs lined with a rind of colourless to brown quartz are common throughout both sections.

A section measured at Maunoir Ridge (total thickness = ~70 m) contains significant covered intervals and consists mainly of fabric-destructive dolomite. Columnar, unbranching, unwalled stromatolites are preserved in white chert in at least two stratigraphic levels.

Almost identical sections of Franklin Mountain Formation were measured on each side of Horton River in the northernmost part of the study area (total = 60 and 90 m, respectively). White chert intervals are conspicuous throughout these sections, and commonly contain turbinate to columnar, unbranching stromatolites. Relict ooids, intraclasts, and cross-lamination are abundant. One unidentifiable gastropod was documented in a cherty stromatolitic unit. The upper part of the two sections consists of complexes of poorly preserved, metre-scale, thrombolite mounds with inter-mound oolite. Fractures and vugs lined with a rind of colourless to brown quartz are common throughout both sections.

These sections were documented, together with another measured in the Hornaday River canyon (Rainbird et al., 2015), to add to a linear transect through the Franklin Mountain (Turner, 2011) and laterally equivalent formations in the Misty Creek Embayment (Turner 2015). Collectively, these sections will form a transect approximately 700 km long from the Arctic mainland coast through the cratonic interior and Mackenzie Mountains, to Selwyn Basin, for a significant slice of the lower Paleozoic. During the time of Franklin Mountain Formation deposition, deep-water settings in the Selwyn Basin were the sites of SEDEX mineralization, which is known to be associated with movement of oxygenated crustal brine that was originally generated in laterally equivalent, shallow-water environments.

Stratigraphic Studies—Mount Kindle Formation

The study area includes part of the northeastern erosional edge of the Mount Kindle Formation (as mapped previously; Aitken and Cook, 1970). Regionally, erosion associated with the sub-Devonian unconformity has led to highly varied preservation of the Silurian-aged upper part of the unit (e.g., Pope and Leslie, 2013; Leslie et al., 2013). Limited macrofossils collected during Operation Norman suggested that exposures of Mount Kindle Formation at Good Hope Ridge were likely to preserve the Ordovician-Silurian boundary (Cook and Aitken, 1971). In an effort to constrain regional sub-Devonian erosion patterns, two overlapping sections were measured at Good Hope Ridge, one through the entire exposed thickness (approx. 132 m) and another through the uppermost 32 m of exposure. An additional section was measured through an exceptionally well exposed succession of Mount Kindle Formation at the headwaters of Hare Indian River (total thickness = 43 m). All sections were collected for stable isotope chemostratigraphy and conodont biostratigraphy. None of the sections exposes the upper or lower contact of the Mount Kindle Formation. The two shorter sections were documented in detail for future sedimentological analysis but, due to time constraints, the longer section at Good Hope Ridge could only be documented at reconnaissance scale.

In the measured sections, the Mount Kindle Formation is dominated by grey-weathering dolostone (Figure 4C) that is commonly silicified, including chert masses. Dolowackestone to dolopackstone with irregular bedding and abundant silicified macrofossils (including solitary rugose corals, colonial tabulate corals, orthocone cephalopods, large brachiopods, and stromatoporoids) is prevalent at many levels (Figure 4D). Such intervals presumably reflect open-marine deposition in warm, well-oxygenated water. There also are numerous intervals within the Mount Kindle Formation that lack obvious fossils but preserve sedimentary features suggestive of distal shelf settings (e.g., rubbly mottled dolostone) or of intertidal environments (parallel lamination, microbial lamination, hummocky cross-lamination).

Stratigraphic Studies—Cretaceous sandstone

In addition to opportunistic sampling of Cretaceous outcrops in an effort to constrain the age relationships of Cretaceous units, particular focus was placed on the Cretaceous sandstone previously documented by Cook and Aitken (1971; the Kss map unit of Aitken and Cook, 1970). This unit is quartz-rich but poorly cemented. As a result, outcrops are rare and Cook and Aitken (1971, p. 12) noted that ". . . many exposures consist of unconsolidated white sand." Outcrops observed during 2015 all were dominated by cross-bedded sandstone. Sommers and MacNaughton were able to measure a section through an oil-saturated exposure of the unit on the western flank of Belot Ridge (Figure 6C), and thus help to constrain the sandstone's depositional setting. The section (total thickness = 24 m) does not expose the top or bottom of the sandstone unit. It preserves at least two upward-fining packages from conglomeratic sandstone to cross-bedded sandstone, with thin shale beds locally separating the packages (Figure 6D), features consistent with fluvial deposition. Sedimentological and biostratigraphic analysis of data and samples from the measured section is planned.

Petroleum Seeps

During the present work, two petroleum seeps previously noted by Cook and Aitken (1971) were revisited. The first consists of oil-saturated deposits of sand overlying modern shoreline gravel on Lac des Bois (Figures 7A-B). The second is the Cretaceous sandstone on the west flank of Belot Ridge (Figure 6C) where Sommers and MacNaughton measured the Cretaceous stratigraphic section referred to above. At both localities, samples of the oils were collected for geochemical analysis, in particular to determine likely source rocks and migration paths. Field relationships suggest that the seeps may be due to migration of oil along faults.

Economic interest in the Colville Hills focuses on oil and gas exploration. In 1974, gas was discovered in sandstone of the Mount Clark Formation (Cambrian) at Tedji Lake K-24 (Anonymous, 1974) and additional discoveries of gas, gas-condensate, and oil have been documented from the same unit (Hamblin, 1990; Janicki, 2004; Price and Enachescu, 2009). Hannigan et al. (2011) included the Colville Hills discoveries in their 'Cambrian Clastics play', which they estimated contains nearly one billion barrels of oil and 10.7 TCF of gas. New data from the studied oil seeps may clarify aspects of the petroleum system that produced these occurrences of oil and gas.

Figure 8. Oil seep on west shore of Lac des Bois. A) Saturated sand forming black deposit on shoreline cobbles, cliff of Devonian carbonate on left. B) Oil oozing out of saturated sand shown in A.

CONCLUSIONS

Preliminary reassessment of stratigraphic units in the Colville Hills area suggests that updated regional terminology for the Cambrian to the Cretaceous can be applied. In particular, an improved understanding of the stratigraphic relationships in the Cretaceous bedrock suggests that these units can be related to units known from the Mackenzie or Anderson plains. The structural interpretation of the region is modified by the identification of new faults along major folds, along with possible minor faulting in intervening plateaus. These faults influence the modern petroleum system and point to possible active fluid migration pathways.

Ongoing work on Colville Hills geology will focus on integration of laboratory results with structural and stratigraphic analysis. Field mapping observations will be combined with publicly available subsurface data from petroleum wells and reflection-seismic data to generate new and improved bedrock maps for NTS map areas 96K, 96L, 96M, and 96N. Detailed stratigraphic information collected from measured sections will be used along with biostratigraphic information and stable isotope geochemistry to refine regional correlations and tectono-stratigraphic history. Oil samples collected from oil seep localities are being analysed for their geochemical characteristics with the aim of matching these oil deposits with known sources to identify migration pathways. Each of these elements will form an important link in the Shield to Selwyn geo-transect aimed at improving the regional understanding of petroleum and mineral systems across northern mainland Northwest Territories.

ACKNOWLEDGEMENTS

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