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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 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 2017 field season, research scientists from the GEM program successfully carried out 27 research activities, 26 of which will produce an activity report and 12 of which included fieldwork (Figure 1). Each activity included geological, geochemical and geophysical surveying. 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.

Activity Summary

This report summarizes results of the Coppermine River Transect activity (Figures 1 and 2) based on fieldwork in 2017 and laboratory analyses in 2018 of samples collected from the Dease Lake area (Northwest Territories), Dismal lakes area (Nunavut) and along the lower Coppermine River (Nunavut) south of the confluence with the Kendall River. This research is in collaboration with scientists at McGill University, Laurentian University, Université de Lorraine and Université de Liège. Research in the Coppermine River area includes a study of the stratigraphy, geochemistry, geochronology and metallogeny of the Coppermine River and lower Rae groups under the GEM program, and an investigation into the nature of eukaryotic organisms in Mesoproterozoic sedimentary rocks of the Dismal Lakes and lower Rae groups funded by the Agouron Institute.

The Coppermine-Dismal Lakes transect study is examining a 7.2-km thick stratigraphic section through the Dismal Lakes, Coppermine River and Rae groups, a section representing an almost continuous record of sedimentation and volcanism from approximately 1.5-1.0 Ga (Figure 2). Older geological maps of this area are being updated in light of new field, geochemical and geochronological data in combination with the interpretation of high-resolution satellite imagery and derived digital elevation models. The new map provides a regional context for studies that explore the controls on basin-scale fluid transport in the formation of uranium deposits in the Hornby Bay Group. Lithogeochemical analyses of the Coppermine River basalts are used to explore the source(s) of mafic magmatism in the Mackenzie Large Igneous province and provide insight into how chemical-stratigraphic changes in the lavas reflect the potential for Ni-PGE and Cu mineralization. The age, provenance and paleoenvironment of clastic sedimentary and interbedded volcanic rocks of the Husky Creek Formation are examined in detail. The Coppermine River exposes the only complete stratigraphic section through the basal Rae Group (Escape Rapids Formation) and these were measured and sampled for geochemistry and micropaleontology to constrain their age, depositional setting and potential for sedimentary-hosted copper. Correlative rocks from the Escape Rapids Formation in the Brock Inlier have yielded exceptionally well preserved eukaryotes (Loron et al. 2018). On a regional scale, work in this area builds on results from previous GSC-GEM projects in Minto Inlier and Brock Inlier by testing recently proposed regional stratigraphic correlations as well as new tectonic reconstructions of northwestern Laurentia during assembly and the break-up of the supercontinent Rodinia.

Introduction

The Hornby Bay Basin comprises Paleo- to Mesoproterozoic sedimentary and volcanic rocks that unconformably overlie metavolcanic, metasedimentary and granitoid rocks of the ca. 1.88-1.84 and 1.74 Ga Wopmay Orogen (Baragar and Donaldson 1973; Hoffman et al. 2011; Figure 2). The Hornby Bay Basin includes continental sedimentary and volcanic strata of the ca. 1.66 Ga Hornby Bay Group (Ross 1983; Bowring and Ross 1985) overlain by transitional marine sedimentary rocks of the <1.6-1.27 Ga Dismal Lakes Group (Kerans 1982; Hahn et al. 2013). The basin is divided by the Leith Line (Kerans et al. 1981) a north-south structural hinge (centered over western Dismal Lakes) across which sedimentary units thicken westward. Hornby Bay Basin is overlain by a 4.2 km thick succession comprised of gently north-dipping continental basalts and clastic sedimentary rocks associated with the 1.27 Ga Mackenzie Igneous event (LeCheminant and Heaman 1989). An angular unconformity separates the Rae Group from the underlying Coppermine River Group. The Rae Group comprises the lowermost units of the Shaler Supergroup, which occupies the Neoproterozoic Amundsen Basin exposed in stratigraphic outliers throughout the western Arctic. Massive sills and dykes of the 0.72 Ga Franklin Igneous event (Heaman et al. 1992) intrude the older Proterozoic strata. Paleozoic sedimentary cover rocks unconformably overlie parts of the western Coppermine River Group and the northern reaches of the Rae Group in Coronation Gulf.

Hornby Bay Group

The Hornby Bay Group is exposed between northern Great Bear Lake and the southern shores of Dismal Lakes. It comprises the Bigbear, Fault River, Lady Nye, East River and Kaertok sedimentary formations, and the Narakay Volcanic Complex (Ross and Kerans 1989).

The Bigbear Formation (Figure 2) is separated by an unconformity from metamorphic and plutonic rocks of the Wopmay Orogen. It comprises (Ross and Kerans 1989) a lower monomict breccia and conglomerate, pebbly sandstones and mudstones (member b1). These are overlain by crossbedded feldspathic sandstone and quartz arenite, pebbly sandstone and polymict conglomerate (members b2 and b3). Overlying these are red quartz arenite with large-scale crossbedding (eolian) and rare mudstone (members b4 and b5). Intraformational boulder conglomerate and red quartz arenite overlie these units (member b6) and is capped by buff quartz arenite, vein quartz pebbly arenite and rare mudstone (member b7). The Fault River Formation comprises a lower polymict conglomerate and red mudstone overlain by a polymict intra-basinal conglomerate (member f1). These are overlain by quartz arenite and volcanic granulestone (member f2). The top of the formation comprises sublitharenite with volcanic-rich pebbly beds (member f3). The Lady Nye formation includes a lower red feldspathic quartz arenite with quartz cobble/boulder beds (member l1). These are overlain by a polymict intrabasinal-derived conglomerate, crossbedded quartz arenite and glauconitic arenite (member l2). The upper part of the formation consists of crossbedded quartz arenite with rare mudstone and quartz-pebble lag (member l3), quartz arenite and green-black, locally evaporitic mudstone (member l4). The East River Formation includes a lower stromatolitic dolostone, oolitic grainstone, intraclastic conglomerate, quartz arenite and mudstone (member e1). These are overlain by calcareous arenite, oolitic packstone, intraformational conglomerate and digitate stromatolite bioherms (member e2). The uppermost unit is a laminated to domal stromatolitic dolostone, oolitic and intraclastic dolostone, and minor red and green mudstone (member e3). The Kaertok Formation consists of feldspathic quartz arenite, red and green mudstone and mudchip breccia. The Narakay Volcanic Complex includes lithic-vitric, locally crystal-rich mafic lapilli tuff and tuff breccia, overlain by lithic-rich, felsic ash-flow tuff, rhyolite lava and felsic porphyry. Bowring and Ross (1985) reported an age of 1663 +/- 8 Ma from a rhyolite porphyry in the Narakay Volcanic Complex. Hahn et al. (2013) suggest that the Narakay Volcanic Complex may be contemporaneous with the East River Formation.

Dismal Lakes Group

The LeRoux Formation (Kerans 1982; Ross and Kerans 1989; Hahn et al. 2013) is separated by an angular unconformity from the underlying Hornby Bay Group east of the Teshierpi fault, and a disconformity west of the fault (Figure 2). The LeRoux Formation includes a local basal conglomerate overlain by quartz arenite with tabular-planar and trough crossbedding, planar bedding, and laminated to massive mudstone and siltstone (Figure 3A). The Fort Confidence Formation consists of interbedded mudstone/siltstone/fine-grained sandstone, and trough- to planar cross-stratified sandstone (Figure 3B).

The Dease Lake Formation (Kerans 1982; Ross and Kerans 1989) is best exposed in the western half of the map area (Figure 2). We logged incomplete stratigraphic sections northwest of Dease Lake (DL-1 in Figure 2) spanning from the lower Dease Lake (member d1) into upper Dease Lake (member 3). Member d1 of the Dease Lake Formation consists of: wave- and current cross-laminated sandy dolostone containing synaeresis cracks, healed synsedimentary microfaults, scours and loads; doloarenite with occasional ooids; cryptalgal dolostone (microbiolaminite) with silicified tepee structures; broad domal stromatolites. Member d2 consists of red siltstone, sandstone and mudstone (Figure 3D) with halite casts (Figure 3C), fine-grained sandstone with wave-ripple cross-lamination, and increasing dolostone and sparse desiccation-cracked dolomudstones up section. The contact with member d3 is defined by a chaotic, intraclast breccia that is up to 2 m-thick, contains angular dolostone and mudstone clasts, and shows evidence of fluid escape. The lower contact of the breccia is sharp and slightly erosive in places into intraclastic dolarenites. The upper surface is also sharp, but undulatory. The remainder of member d3 consists of moderately well-developed cycles of dolomitic mudstone and siltstone, capped by beds of dolarenite that are locally intraclastic. At Dease Lake, the contact between the Dease Lake Formation and overlying Kendall River Formation (Ross and Kerans 1989; Kerans 1982) is sharp and defined by red, dolomitic marl below and grey, recrystallized cherty dolostone above. The lower Kendall River Formation comprises 5–6 m of wavy-bedded dolarenite with minor low relief stromatolitic domes and abundant, bedding parallel white to dark grey chert. This lower dolomitic member of the Kendall River Formation is bounded by a karstic upper exposure surface and overlain by red rippled siltstone. We measured a 60 m section (DL-1 in Figure 2) of the upper Kendall River Formation from which we collected approximately seventy carbonate samples for geochemistry and approximately a dozen chert samples for micropaleontology. This section comprises shallow-water dolostone, with abundant microbial and crinkly dololutite and minor dolarenite and interbedded dolomitic mudstone. White to tan-colored chert nodules and lenses are common throughout the section, and locally black chert occurs as irregular nodules up to 10 cm in diameter. North of Dismal Lakes, we measured and sampled in detail for carbonate geochemistry the upper 50 m of the Kendall River Formation (DL-2 in Figure 2). This section consists of variably stromatolitic and intraclastic dolostones and at least one partly silicified oolite bed.

The Sulky Formation comprises a lower unit of dark grey cherty dolostone with stromatolites, oolite and intraclast breccia, and minor black shale partings (member s1; Ross and Kerans 1989). We measured a section north of Dismal Lakes (DL-2 in Figure 2) and observed laminated dolostone with soft-sediment deformation, synsedimentary microfaults, overlain by a thin recessive interval of interlayered dolomudstone and grey-black shale. Overlying this unit are stromatolitic dolostone and breccia west of the Coppermine River, and stromatolitic dolostone with conical and domal stromatolites up to 40 m high east of the Coppermine River (member s2; section DL-3; Figure 3E; Kerans and Donaldson 1989; Kah et al. 2006). Overlying this unit are cherty dolostone with oolite and conical to branched conical stromatolite biostromes west of the Coppermine River, and dololutite with pisolites, teepee structures and silicified evaporites east of the Coppermine River (member s3; Ross and Kerans 1989). Our section north of Dismal Lakes (DL-2 in Figure 2) contains a resistant dolomudstone interval with ubiquitous dewatering structures, and an interval of cross-bedded dolostone overlain by stromatolites.

The Greenhorn Lakes Formation east of the Leith Line (Kerans 1982; Ross and Kerans 1989) contains a lower unit of dolostone with cryptalgal laminites and teepee structures, isolated domal stromatolites (Figure 3F), black to green dolomitic shale, and oolitic stromatolitic and intraclastic dolostone. North of Dismal Lakes (DL-2 in Figure 2) the lower contact of the Greenhorn Lakes Formation is marked by a 1-m-thick layer of white chert with dolomudstone nodules. West of the Leith Line this lower unit contains dolostone, cryptalgal laminites, intraclastic breccia and teepee structures interbedded with stromatolite biostromes (member g1). The Upper Greenhorn Lakes Formation east of the Leith Line includes dolomitic sandstone and red dolomitic shale with mudcracks, overlain by cherty dolostone with stromatolites, intraclastic breccia and oolites. A dolostone megabreccia is found in the September Lakes area that is interpreted as a paleokarst deposit (Kerans and Donaldson 1988). West of the Leith Line, the upper Greenhorn Lakes Formation comprises grey-pink, thick-bedded stromatolitic dolostone bioherms and biostromes intercalated with tan-red shales and an upper part consisting of oolitic and intraclastic grainstone (member g2).

Coppermine River Group

The Coppermine River Group (Baragar and Donaldson 1973) includes Mesoproterozoic continental flood basalts of the Copper Creek Formation overlain by clastic "red-beds" and interbedded basaltic lava flows of the Husky Creek Formation. An angular unconformity separates the Coppermine River Group and overlying Rae Group. The thickest preserved section of the Coppermine River Group lies in the Coppermine River valley.

Copper Creek Formation

The Copper Creek Formation is a ~3000 m thick sequence (Coppermine River Valley) of continental flood basalts associated with the ca. 1.27 Ga Mackenzie igneous events (Baragar et al. 1996; LeCheminant and Heaman 1989). The lava flows are generally well exposed and form distinctive plateau basalt topography with cliff-forming flow interiors and recessive weathering flow tops (Figure 4b). In order to unravel the magmatic and stratigraphic evolution of the Coppermine River Group, we have analyzed whole rock samples of lava flows for a full suite of major and trace elements (T. Skulski unpublished). These include 104 samples of mafic volcanic rocks from sections collected in 2017 (sections T1, T2, and T3 in Figure 2) and 226 whole rock samples originally collected and reported by Baragar (1969; sections 1-5 in Figure 2) and Dostal et al. (1983; section 6 in Figure 2). This internally consistent dataset of 330 whole rock analyses (same analytical methods, laboratory and timeframe) are supplemented with data for 26 samples from Day et al. (2013; section D in Figure 2). The geochemical data from sections spanning 130 km along strike, along with field and petrographic descriptions provide the basis for subdivision of the Copper Creek Formation into three new stratigraphic members summarized below.

September Creek member

The September Creek member comprises the lowest stratigraphic member of the

Copper Creek Formation. The lowest basalt flow in the September Creek member lies conformably on carbonates of the upper Greenhorn Lakes Formation (Figure 4A). Geochemical analyses (this study) reveal that high (Th/Nb)n values (>2) characterize the lower (~1000 m) of the Copper Creek Formation across the map area, and the transition to lower values in overlying lavas is abrupt. The youngest basalt flow with (Th/Nb)n >2 defines the top of the September Creek member. The September Creek member is characterized by mottled greenish and reddish (fresh) basalt flows with less abundant olivine-phyric picrite, orthopyroxene-phyric high MgO basalt, and glassy high Cr andesite (Baragar et al. 1996; Day et al. 2013; this study). Pillow basalts are rare and occur within lowermost flows east of the Coppermine River and north of the western extremity of Dismal Lakes (Figure 2; Baragar 1969). Basaltic flows, of which there are approximately 50, are typically 20-30 m thick, to a maximum thickness of 110 m. The groundmass of the flows have a granular texture with common intersertal patches of devitrified glass (Baragar 1969). Granophyric patches occur in the groundmass of the lowermost basalts. Partly resorbed quartz-rich xenoliths characterize the high Cr andesite in the upper part of the member identified by Day et al. (2013). Uppermost flows contain microscopic native copper in amygdules.

Stratigraphic, petrographic and geochemical study of lavas from the September Creek member of the Copper Creek Formation, reveal that these magmas have assimilated continental crust (Dostal et al. 1983; Baragar et al. 1996; Griselin et al. 1997; Day et al. 2013). Evidence for contamination includes, partly resorbed quartz-rich xenoliths, felsic granophyric patches in the lower basalt flows, and a geochemical crustal contamination signature including both high K/Ti values (Baragar et al. 1996) and primitive mantle normalized Th/Nb (Figure 6 in Griselin et al. 1997), and negative epsilon Nd values (Griselin et al. 1997; Day et al. 2013).

Stony Creek member

Tholeiitic basalts in the Copper Creek Formation that overly the September Creek member, show an initial up-section increase in TiO2 and iron abundances with increasing differentiation (e.g. decreasing MgO), followed by a decrease in TiO2 and concomitant increase in MgO up-section in the upper Copper Creek Formation (c.f. Figure 4 in Griselin et al. 1997). Peak TiO2 abundances of ~4% occur approximately 1000 m above the top of the September Creek member and are the basis for marking the upper part of the Stony Creek member. The Stony Creek member comprises closely stacked, reddish-grey to grey (fresh), thin basalt flows between 10-20 m thick, with one flow up to 80 m in thickness. The flows are very fine-grained to aphanitic, with rare phenocrysts of plagioclase. Microphenocrysts of plagioclase, clinopyroxene and iron and titanium oxides are common and coexist within an intergranular groundmass. Flow interiors may contain zoned amygdules and thin veins characterized by outer rims of quartz or chlorite with cores of calcite. Native copper commonly occurs associated with quartz.

Mackenzie dykes cut the September Creek member (Figure 1) but rarely extend into the higher reaches of the Copper Creek Formation. Baragar et al. (1996) interpret the Mackenzie dykes to be feeder dykes to lavas in the upper two-thirds of the Copper Creek Formation that make up the Stony Creek and Burnt Creek members of this study.

Burnt Creek member

Tholeiitic basalts overlying the Stony Creek member comprise greenish flows that are generally 15-20 m thick, and locally up to 118 m in thickness. Rare, thin red sandstone beds occur between basalt flows (sections 3 and 2 in Figure 2; Baragar 1969). The basalts are typically fine-grained to aphanitic, and less commonly, contain small plagioclase phenocrysts (2-3 mm). Microphenocrysts of plagioclase, clinopyroxene and iron-titanium oxides are common and are hosted in a granular groundmass of plagioclase, clinopyroxene, K-feldspar, and Fe-Ti oxides. Native copper is common and occurs near the outer margin of amygdules (interior and flow-top), and at the quartz-calcite (core) transition in zoned amygdules and thin veins. Less commonly, microscopic native copper occurs as skeletal crystals in the groundmass of basalts.

Husky Creek Formation

The Husky Creek Formation is the upper unit of the Coppermine River Group (Barager and Donaldson 1973; Figure 2) and comprises an estimated 1900 m of red-stained, lithic sandstone, with interbedded basalt flows capped by a grey-green sandstone (Figure 2). The basalt flows are coeval with sedimentation to a degree as previously observed by Barager and Donaldson (1973) and Campbell (1983). A well-defined, depositional contact occurs between the Husky Creek Formation and the underlying Copper Creek Formation. The contact displays an undulatory attitude at the outcrop scale, with swales 30-50 cm in relief and spaced 5-10 m from each other. In the Husky Creek Formation, most lithic fragments derive from basalt, and as such the chemically immature sandstone is prone to fast weathering. Exposures of the Husky Creek Formation are limited to sections along the Coppermine River, tributaries of the Coppermine, and areas where basaltic flows have protected the sandstone from erosion (Barager and Donaldson 1973, Campbell 1983). The formation records alternation between fine- and medium-grained sandstones. Red, mud-rich siltstone and conglomerate units are locally present and occur in close proximity to basaltic flow tops. Intraformational mud clasts abound throughout the entire formation. Concentrations of heavy mineral (mainly iron and titanium oxides with accessory zircon) bands are common, defined by dark laminae. Basaltic flows within the Husky Creek formation are highly vesiculated close to contacts with the sedimentary strata and are often pillowed. The flow tops of these flows are intermixed with mud near their upper contact as well. The conglomerate units are oligomictic with subangular, 1-40 cm clasts composed of either mudstone or basalt. Typically, a thin layer of massive mudstone separates conglomerate units from the underlying basaltic flow tops. Bedsets are 0.5- 9.0 m thick, and laterally continuous for at least 100 m (based on the widest exposures available). Medium-grained sandstones exhibit trough-cross stratification, forming sets between 0.5-3.0 m thick. Exceptionally, up to 6 m thick planar-cross sets with tangential base are found, enclosing <10 cm thick pin-stripe laminated foresets and adhesion structures at the top. Elsewhere, ripple-cross lamination, with sets between 0.10 – 9.0 m thick are also common throughout the formation. In addition, plane-parallel stratified sandstone, 5-130 cm thick, is present in bedsets separating cross-bedding (Figure 4F) and attains a maximum thickness of 20 cm thick. Small-scale, 5-15 cm intervals of undulatory bedding and sigmoidal cross-bedding are locally observed. Soft-sediment deformation structures, exemplified by fluid escape conduits and convolute bedding are present throughout the formation. 3D ripples, overlying the fine-grained units, are predominantly asymmetrical. Locally mixed and symmetrical ripples are observed.

Fine-grained units commonly contain a greater proportion of intraclasts compared to medium-grained sandstones. They generally occur in thin, 5-10 cm beds, rarely up to 70 cm thick. Plane-parallel bedding is dominant and no grading was observed. Trough-cross bedding, ripple-cross lamination, and wave ripples are observed locally throughout fine-grained units. Blocky weathering is pervasive and is distinguished from the widespread desiccation cracking (Figure 4E) on the basis of a lack of a finer-grained infill. In the lower Husky Creek Formation, possible pseudomorphs of evaporite minerals are present in a massive siltstone. Nodules are also present along distinct horizons.

The Husky Creek Formation records a prevalent fluvial environment, an inference justified by the ubiquitous occurrence of unidirectional flow-regime structures and red staining associated with sub-aerial weathering. The occurrence of aeolian reworking (possibly atop floodplains along-side paleo-channels) is not excluded, based on the occurrence of isolated, pin-stripe laminated sets. Evidence for sub-aerial exposure is provided by desiccation cracks and adhesion warts.

Throughout the section, the paleoflow patterns have a high dispersion with a general indicated transport mainly to the south, similar to findings by Campbell (1983). However, a shift is apparent from the southwest- to a southeast-ward paleoflow direction moving up-section. Two areas showing a northern flow direction are associated with polymodal and highly dispersed paleocurrent readings.

Pre-Rae Group History of Deformation, Uplift and Basin Subsidence

Deposition of the Hornby Bay, Dismal Lakes and Coppermine River groups was followed by a number of pulses of deformation and uplift. Unravelling this structural history provides an important context for understanding the late Paleo-Mesoproterozoic basin evolution and metallogeny of this area. U-Pb ages constrain Hornby Bay Group deposition between 1663 +/- 8 Ma, the age of the Narakay Volcanic Complex (Bowring and Ross 1982), and >1592 +/- 3 Ma, the age of the undeformed Western Channel Diabase that intrudes the Hornby Bay Group up to lower East River Formation (Hamilton and Buchan 2010). Shallow marine sediments in the Narakay Volcanic Complex are interpreted to be time equivalent with the Lady Nye, East River and Kaertok formations (Figure 2) in the upper Hornby Bay Group (Ross 1983). The East River Formation contains detrital zircons as young as 1620 Ma (Rainbird et al. 2009) bracketing upper Hornby Bay Group sedimentation at <1620>1592 Ma. Northeast-trending folds of the Hornby Bay Group are believed to predate 1592 Ma intrusion of the Western Channel Diabase, and likely formed at ca. 1.6 Ga during the Forward orogeny (Cook and MacLean 1995). Deposition of the Kaertok and East River formations was influenced by uplift on faults that developed during the early stages of the Forward orogeny (Hahn et al. 2013; Cook and Maclean 1995).

The Dismal Lakes Group rests unconformably on the Hornby Bay Group (Figure 2) east of the Teshierpi Fault (Kerans 1983; Hahn et al. 2013) and is conformably overlain by the Coppermine River Group. Black shales in the basal LeRoux Formation contain diagenetic pyrite which has yielded a Re-Os model age of 1438 +/- 8 Ma (Geospec Consultants Ltd. in Bent 2009). Thus lower Dismal Lakes Group sedimentation is constrained to be <1600> ca.1438 Ma. The September Creek member of the Coppermine River Group is comagmatic with the Muskox Intrusion (c.f. Day et al. 2013) which has been dated at ca. 1269 Ma (U-Pb baddeleyite; French et al. 2002; Mackie et al. 2009). Thus the upper Dismal Lakes Formation (G2 member of the Greenhorn Lakes Formation; Figure 2) was deposited before 1269 Ma. Kerans (1983) proposed that syndepositional uplift and normal faulting in the Greenhorn Lakes Formation (local karstic disconformity separating G1 and G2 members) was the result of uplift associated with early Mackenzie magmatism.

Northeast- to northwest-striking normal faults cut the upper Dismal Lakes Group and overlying September Creek member, in the vicinity of the Coppermine River and September Mountains (Figure 2). Mackenzie dykes dated at 1267 +/- 2 Ma (LeCheminant and Heaman 1989) locally intrude along these faults, indicating that the normal faults are early syn-magmatic at 1269-1267 Ma. These normal faults, along with the Muskox Intrusion and the concentration of Mackenzie dykes east of the Coppermine River valley, indicate that this area was the locus of local extension and later intrusion of feeder dykes to basalts of the Stony Creek and Burnt Creek

members (c.f. Baragar et al. 1996; Day et al. 2013).
Lithic wacke in the upper Husky Creek Formation has a detrital zircon maximum depositional age of 1232 +/- 15 Ma (Rayner and Rainbird 2013). Interbedded basaltic flows extend into the upper reaches of the Husky Creek Formation (Figure 2). Day et al. (2013) noted that the volcanic member of the Husky Creek Formation, in contrast to flows in the underlying Burnt Creek member, comprise high MgO basalts derived from a more depleted mantle source. This change in mantle source appears to have occurred at some point during the ca. 35 m.y. that separate these two sequences.

The south-facing basalt sequence north of the Strike Lake Fault (Figure 2) has chemical affinities with the upper Burnt Creek member as originally pointed out by Hildebrand and Baragar (1990) and lies in the hanging wall of a south-vergent thrust fault. Movement on this thrust fault is <1232 Ma and older than the unconformably overlying Escape Rapids Formation (Rae Group; below) which is constrained to be <1151 +/-13 Ma (detrital zircon; Rayner and Rainbird 2013) and >892 +/- 13 Ma (Re-Os age of Boot Inlet Formation, Reynolds Point Group; van Acken et al. 2013). The northwest-striking, Long Lake fault (LLF in Figure 2) thrusts Stony Creek basalts over the September Creek flows (c.f. Hildebrand and Baragar 1990). The thrust faults appear to be syn- to late with respect to folding including a footwall syncline south of the Strike Lake fault, and a hanging-wall syncline north of the Long Lake thrust (Hildebrand and Baragar 1990).

A number of northeasterly- and north-striking normal faults cut the map area and include the Herb Dixon, Teshierpi, and Canoe Lake faults (HDF, TF and CLF in Figure 2). The Herb Dixon fault cuts the Long Lake thrust fault and establishes the relative age of these structures. The Teshierpi fault may have been active during deposition of the Hornby Bay Group (Hahn et al. 2013), and subsequently reactivated following deposition of the Coppermine River Group. Most of the larger copper showings are spatially associated with this structure (Kindle 1973; see below). We have adopted the interpretation of Hoffman (1980) and Kerans (1983) in including the west-side down, northeast-striking normal fault as an extension of the north-striking Canoe Lake fault that cuts the western side of the Muskox Intrusion (Figure 2).

The youngest phase of deformation to affect pre-Rae Group strata are broad, open north-striking folds best exemplified by the gently dipping (horizontal to 10° dip), north-plunging syncline with 160 km wavelength. The small, north-striking syncline south of the Melville Creek sill (MLS in Figure 2) is included in this deformation phase.

Rae Group: Escape Rapids Formation

The Escape Rapids Formation, the basal unit of the Rae Group, is part of the Shaler Supergroup (Rainbird et al., 1994). It is exposed throughout the Amundsen Basin but the Coppermine River valley is the only region where the base of the formation and its contact with underlying rocks is exposed. The contact is well exposed along the Coppermine River, where it forms a low-angle (<10°) unconformity with the underlying Husky Creek Formation (Figure 5A). Here, the contact is marked by a thin pebble lag that separates parallel-laminated red siltstones from cross-laminated to small-scale crossbedded pinkish-green sandstones of the overlying Escape Rapids Formation (Figure 5B). The contact is blurred by diagenetic hematite alteration, presumably derived from the underlying red-beds, that has bled upward into the Escape Rapids Formation. The sandstone passes upward into parallel-laminated, grey siltstones with organic-rich interlayers that were sampled for micropaleontological study (Loron et al. 2018). These strata, in turn, pass upward into several meters of fine-grained, rusty weathering, green sandstone with well-developed hummocky crossbedding (see Dumas and Arnott 2006; Figure 5C). A stratigraphic section was not measured at this locality, but the lower section was observed and roughly logged at a former exploration camp site (Hope Lake, HL Figure 2; 67°25'51"N; 116°23'52"W; Kindle 1973), where drill core from a 2015 exploration program by Kaizen Discovery Ltd. intersected approximately 250m of the lower (Hihotok) member. In the core (CP15-DDH-007), which was collared about 20km west of the outcrop locality described above, the basal sandstone rests on a basaltic lava flow (top of Husky Ck. Formation) with a well-developed oxidized regolith overlying hematite-altered and calcite-veined basalt. The basal sandstone in the core is about 20m thick and grades upward into wavy-lenticular to parallel-laminated black siltstone and white to green, fine-grained sandstone. Desiccation cracks and graded bedding were noted in this interval. After another 15m-thick section of sandstone with faint hummocky cross-stratification, the wavy-lenticular facies reappears and is repeated several times between intervals of similar sandstone over the next ~100m of section (Figure 5D). A continuation of the Hihotok member is exposed in an outcrop section, ~100m thick, intruded by a 30-40m thick, Franklin gabbro sill on the west side of the Coppermine River, below Escape Rapids (ER in Figure 2). The base of this section (67°37'20"N; 115°28'55"W) is marked by a unit of wavy-bedded, fine-medium grained, tan quartz arenite interbedded with wavy-lenticular bedded green siltstone-fine sandstone. At the top of the sandstone, there is a possible transgressive lag followed by thin-laminated green mudstone-siltstone. The remainder of the section comprises interbedded parallel-laminated siltstone and wavy-lenticular bedded siltstone and sandstone punctuated by several <20-cm-thick interbeds of white, cross-bedded, medium to coarse-grained sandstone and one, rounded-cobble, intraformational conglomerate. Above 45m of this section, the lithology changes to variegated (red-green), mainly thin, parallel-laminated siltstone with very thin sandy laminae and lenses. Sand content varies up section but green color eventually gives way to red.

Crosscutting relationships suggest that green coloration is secondary. The top of the section contains several, 30-50 cm thick, horizons of light-green, fine-medium-grained sandstone with long-wavelength, low-amplitude ripples. These observations suggest that the Hihotok member was deposited in a mainly shallow marine setting affected by storms and tidal currents. Deposition of thin, parallel-laminated siltstone-mudstone occurred in the offshore zone, below the storm-wave base. The overlying Nipartoktuak member is exposed at the very top of this section (Figure 2), where it comprises mainly red, parallel-laminated siltstone. It was not studied in detail but it is well exposed in a cliff-face outcrop further downstream on the west side of the Coppermine River. The Nipartoktuak member is approximately 150-200 m thick and composed almost entirely of red, parallel-laminated, siltstone with rare interbeds of ripple cross-laminated fine-grained sandstone (Figure 5E). It is notable for containing very small (2 to 5mm diameter) clusters of a tabular, radiating white mineral resembling gypsum. The base of the conformably overlying Bloody Fall member (Figure 5F) is exposed on the east side of the river where it resembles shallow marine strata from the base of the Hihotok member. The Bloody Fall member is otherwise not well exposed and outcrops of it located further downstream on the Coppermine River were not studied at this time. Escape Rapids Formation member boundaries correspond to the map unit 19, 20 and 21 boundaries along the Coppermine River as shown on GSC Map 1337A (Baragar and Donaldson 1973; Rainbird et al. 1994).

Economic Geology

The Coppermine River area has a long history of mineral exploration for copper, nickel, platinum group elements (PGE) and uranium. Key mineral showings and styles of mineralization are briefly summarized here.

Uranium mineralization is found in ca. 1.85 Ga basement rocks of Wopmay orogen and in the overlying Hornby Bay Basin. Volcanic rocks of the Akaitcho Group host hematite-carbonate fractures containing uraninite at the Gnaw-Bikini showing southwest of the Muskox Intrusion (Rice and Kyser 2010). Granites of the Great Bear batholith host quartz veins with uraninite mineralization at the Bog showing (Rice and Kyser 2010). In the Mountain Lake deposit, in the overlying Hornby Bay Basin, uranium mineralization occurs at and above the disconformity between the Lady Nye Formation (Hornby Bay Group) and LeRoux Formation (Dismal Lakes Group; Figure 4D). Regional hydrothermal fluid flow and diagenesis were important in localizing uranium mineralization. Rice and Kyser (2010) describe a mineral paragenesis for sandstones of the Lady Nye and LeRoux formations that involved early hematite cement followed by quartz overgrowths, compaction (stylolite formation), kaolinite altered to muscovite and apatite cement. Hydrothermal minerals include pyrite, arsenopyrite, barite and uranium and copper-uranium arsenates such as trögerite and metazeunerite. Davis et al. (2008) dated (U-Pb) diagenetic xenotime associated with apatite in the Lady Nye Formation and obtained an age of 1284 +/-11 Ma. This age overlaps with the imprecise upper intercept age of 1221 +/-83 Ma for uraninite at the Gnaw-Bikini showing (Rice and Kyser, 2010). The 1284 Ma xenotime age is within error of the age of the MacKenzie igneous event at 1270-1267 Ma (LeCheminant and Heaman 1989) which may have acted as an important driver for basin-scale fluid flow associated with uranium mineralization (Davis et al. 2008).

Drill hole samples were collected from the Mountain Lake deposit and from the LeRoux Formation as well as veins in the Copper Creek Formation, with the aim to characterize the fluids associated with basin-scale fluid flow by means of fluid inclusion mineralogy, microthermometry and geochemistry. These studies will allow a comparison with diagenetic and hydrothermal fluids associated with uranium mineralization in the Mesoproterozoic Thelon and Athabasca basins.

The Muskox Intrusion has been explored for Ni and PGE mineralization, and mineralization has been located associated with sulphides along the margins of the intrusion (Barnes and Francis 1995). There is evidence for crustal contamination along the margins of the intrusion, and sulphur isotopes indicate that the source of sulphur was likely in the surrounding country rocks (Sasaki 1969).
Copper mineralization is widespread in the Copper Creek Formation and includes copper sulphides associated with shear zones, faults and veins, and native copper showings in amygdaloidal flow tops and veins (Kindle 1973). Isolated sulphide veins (Figure 4C), or veins associated with shear zones and faults comprise assemblages of quartz, +/- calcite, chalcocite, +/- bornite, +/- chalcopyrite, +/- malachite, +/- azurite. Amygdules and disseminated native copper mineralization (volcanic redbed copper) comprises quartz +/- calcite +/- native copper +/- chlorite, and less commonly chalcocite. Visible native copper showings in amygdules and flow tops typically occurs in Stony Creek and Burnt Creek basalt flows. The highest copper concentrations are in chalcocite-bearing deposits associated with the Teshierpi fault near Hope Lake (Figure 2; Kindle 1973). Sulphide mineralization associated with the Long Lake and Cliff Lake faults is locally hosted in the September Creek member.

Stratiform, disseminated copper sulphide mineralization (bornite, covellite and chalcopyrite) occurs at the contact between the Husky Creek Formation and the Escape Rapids Formation and is currently under exploration permits held by Kaizen Discoveries of Vancouver B.C. (S. Clay and B. Penner, personal communication, 2015 and 2016). Drill cores taken during the exploration activity are currently stored at Hope Lake. The mineralization is interpreted to be of red-bed or Kupferschiefer-type, where oxidizing fluids moving through the Husky Creek Formation interacted with S-rich, organic shales in the overlying Escape Rapids

Formation (e.g. Hitzman et al. 2010). The oxidizing fluids move along faults and permeable strata in Husky Creek Formation sandstones, scavenging copper from labile, volcanic-rich lithic arenite interbeds within the Husky Creek Formation. These sandstones are mainly derived from weathering of the underlying Copper Creek Formation flood basalts, long interpreted as a copper metallotect (Kindle 1973).

Summary

The Coppermine River transect study provides a stratigraphic context for ongoing investigations into sedimentological and geobiological investigations of the Dismal Lakes and Rae groups. Measured stratigraphic sections of the Kendall River, Sulky and Greenhorn Lakes formations in the Dease Lake and Dismal Lakes areas were sampled in detail (1-1.5m) for carbonate carbon and oxygen isotope geochemistry. Samples of black shale and chert were acquired from these units as well as from the Fort Confidence Formation for micropaleontological analysis. Stratigraphic sections were measured in the lower two members of the Rae Group, and shale samples from these were augmented with samples from drill core for micropaleontology (Loron et al. 2018) and Re-Os geochronology.

Whole rock major and trace element analyses of Coppermine River Group basalts have been completed on newly acquired samples from stratigraphic sections, augmented by re-analyses of samples collected originally by W.R.A. Baragar. These geochemical-stratigraphic data provide the basis for subdivision of the Copper Creek Formation into three new members. These new subdivisions reflect temporal changes in magmatic sources and processes and as such, have important impact on the exploration for Ni, Cu and PGE. The new higher resolution stratigraphy is used to identify faults that have affected the western parts of the map area (Fig. 2) and further understand the sequence of deformation episodes that have affected this area. Finally, the revised stratigraphy permits a direct evaluation of the extent of erosion along the angular unconformity separating the Coppermine and overlying Rae groups.

The Husky Creek Formation along the Coppermine River valley comprises mainly fluvial, sandstones, siltstones and interbedded basalt flows. Locally, eolian reworking may have occurred atop floodplains. The Husky Creek Formation was mainly derived locally, from the weathering and erosion of Copper Creek Formation basalts. A study of the U-Pb detrital zircon geochronology, is focused on further constraining the provenance of the sediments and provide better estimates on the maximum ages of sediment deposition.

The Coppermine River area has been explored for a wide range of mineral commodities. This study is focused on better understanding the basin-scale fluids responsible for U mineralization at the base of the Dismal Lakes Group using detailed petrography, geochemistry and fluid inclusion microthermometry. The origin of native copper mineralization in the overlying Copper Creek Formation is being investigated, and in particular with respect to the sources of native copper and implications on changes in sulphide saturation in Coppermine magmas with time. Hydrothermal remobilization of copper and precipitation of copper sulphides along faults, fractures and subaerial lava flow tops is being examined in light of new observations on faults in the western map area. The lower Rae Group has potential for sediment-hosted (red-bed type) copper mineralization and this is being evaluated through study of new stratigraphic sections and including observations from industry drill core.

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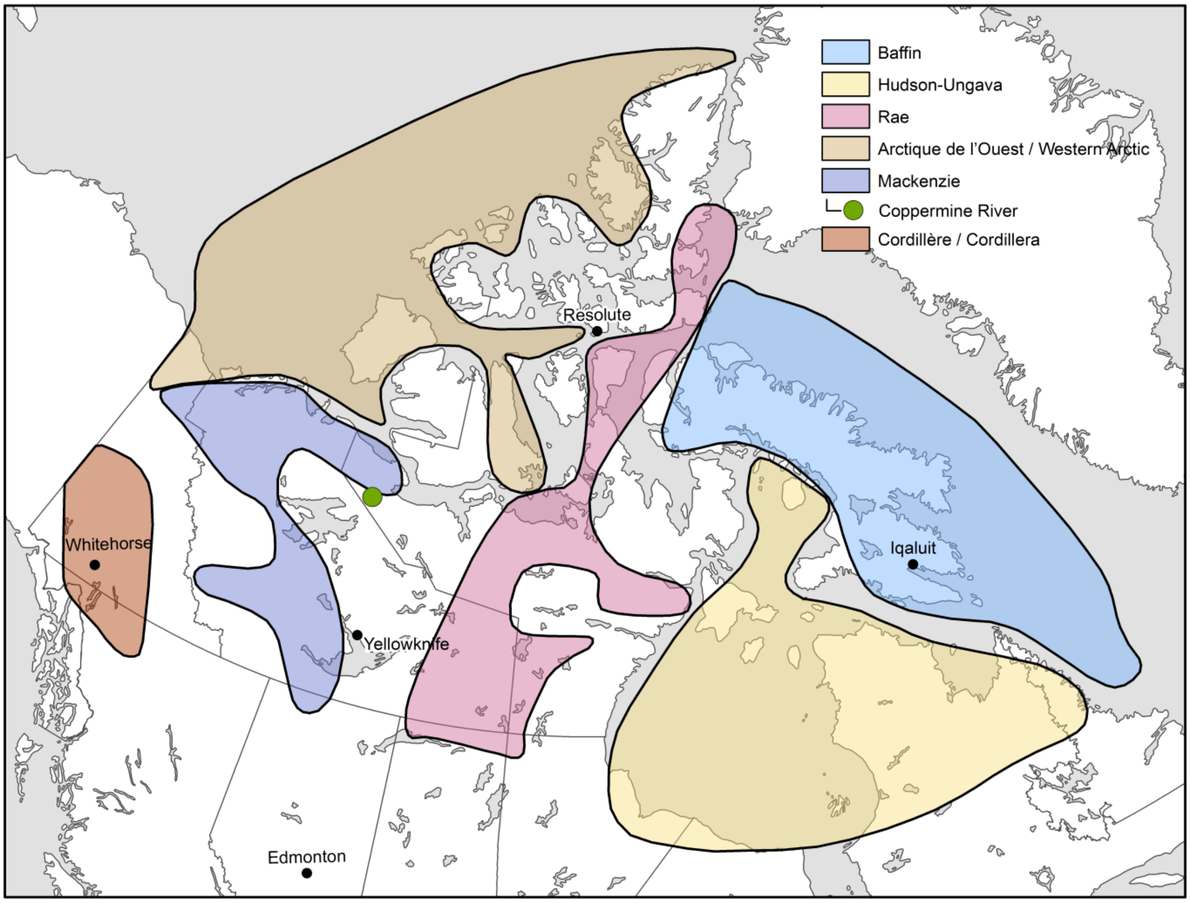


Figure 1. Location of the Mackenzie Project area in northwest Canada (purple polygon) and the Coppermine River Transect Activity field location, represented by the green dot. Colored areas are active GEM2 projects.

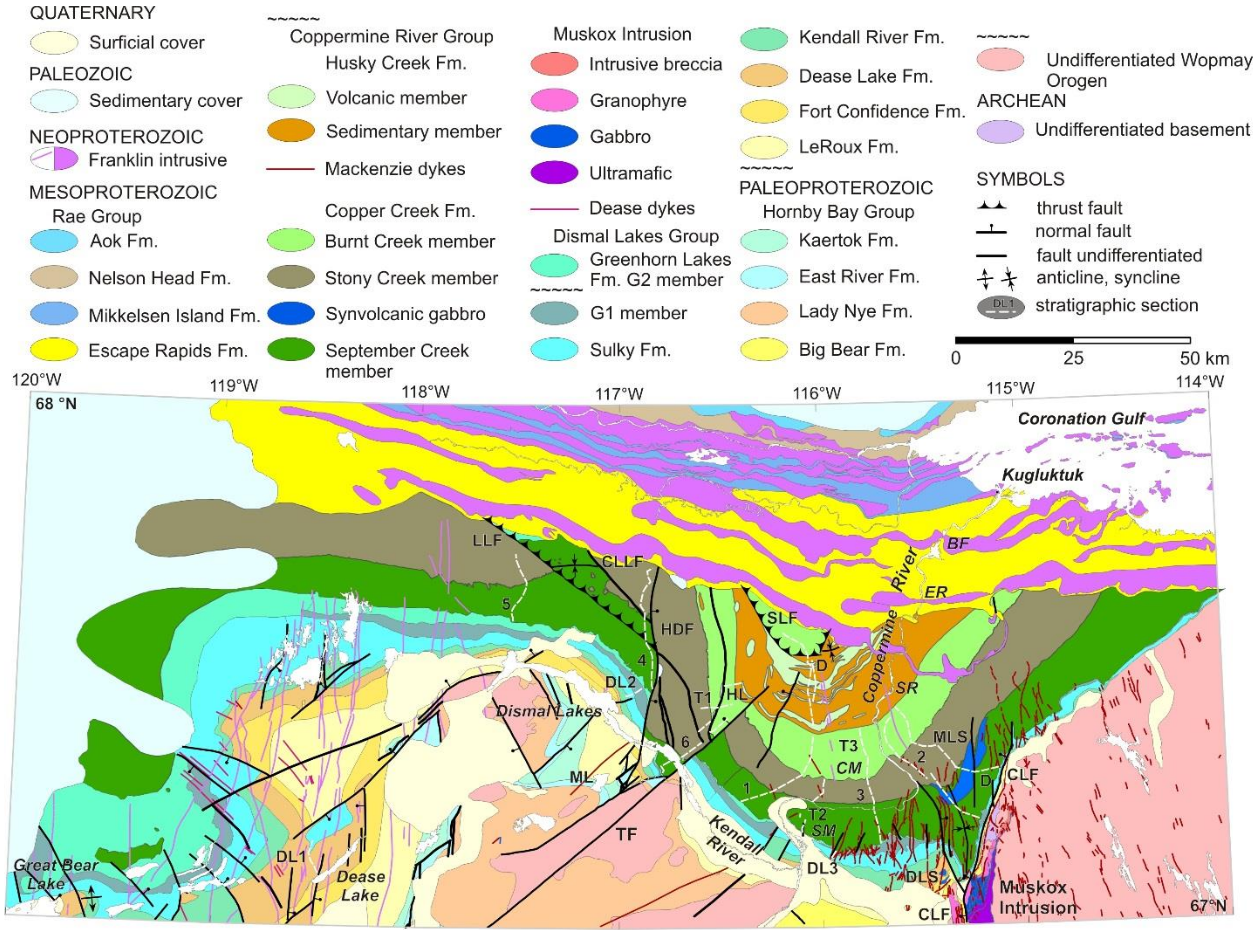


Figure 2. Simplified bedrock geology of the Dismal Lakes-lower Coppermine River area. Hornby Bay and Dismal Lakes Group geology adapted after Ross and Kerans (1989) and Hildebrand (2011). Geology of the Muskox Intrusion modified from Hulbert (2005). Geology of the Coppermine River Group modified from Baragar and Donaldson (1973), Hildebrand (2011), and this study. Geology of the Rae Group, Franklin Intrusive suite and Paleozoic cover modified from Hildebrand (2011). Place name abbreviations (in italics): Bloody Falls (BF), Coppermine Mountains (CM), Escape Rapids (ER), Hope Lake airstrip (HL), Mountain Lake (ML), Sandstone Rapids (SR) and September Mountains (SM). Geological features: Canoe Lake Fault (CLF; after Hoffman, 1980), Cliff Lake Fault (CLLF), Dismal Lake Sills (DLS), Herb Dixon Fault (HDF), Long Lake Fault (LLF), Melville Creek Sill (MLS; Baragar and Donaldson 1973; Gall 1997; this study), Strike Lake Fault (SLF; after Hildebrand and Baragar 1990) and Teshierpi Fault (TF). Stratigraphic sections include Dismal Lakes Group (DL-1, -2, -3; this study); Coppermine River

Group from Baragar (1969; 1-5), Dostal et al. (1983; 6), Day et al. (2013; D), and this study (T1, -2, -3).

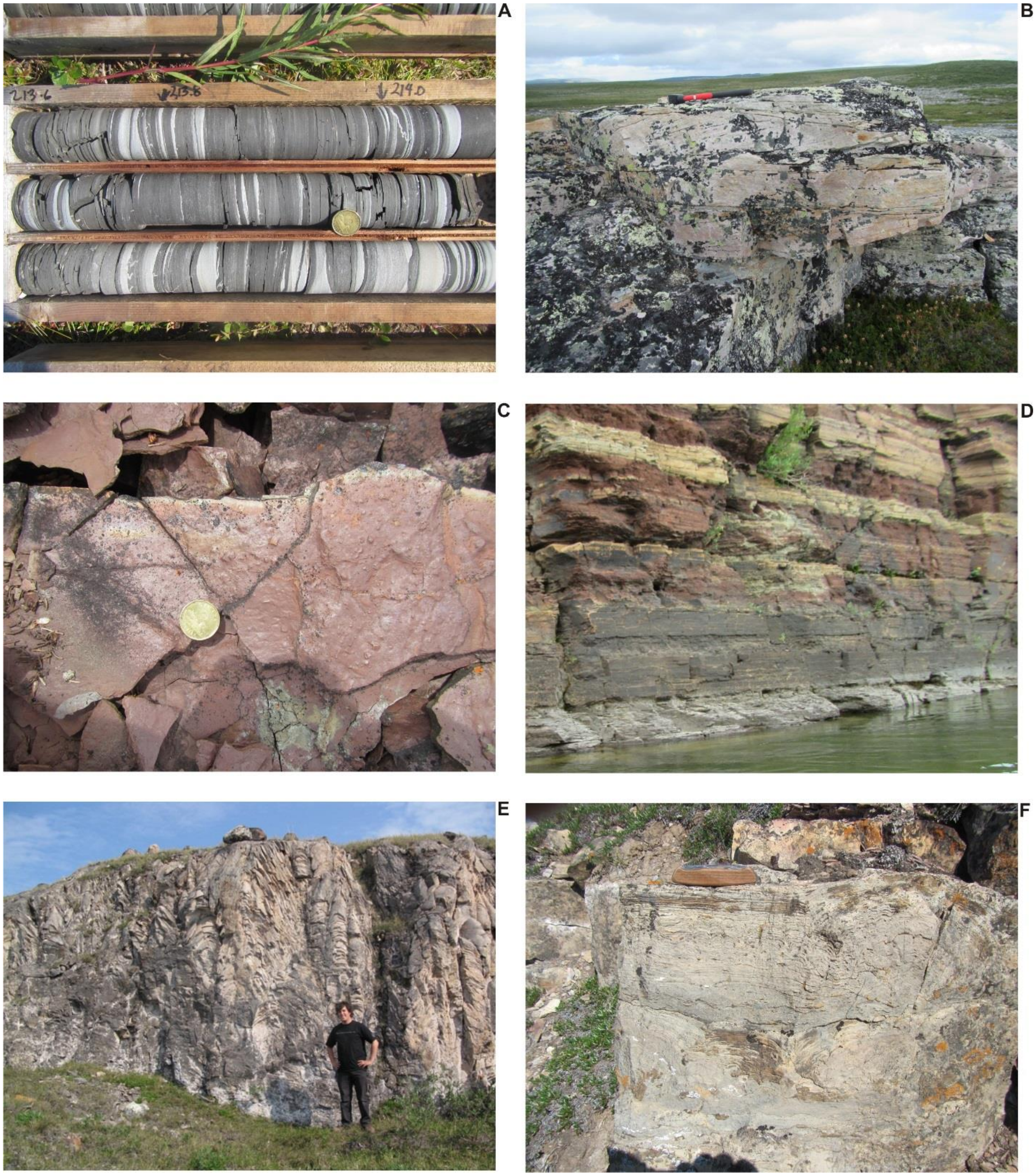
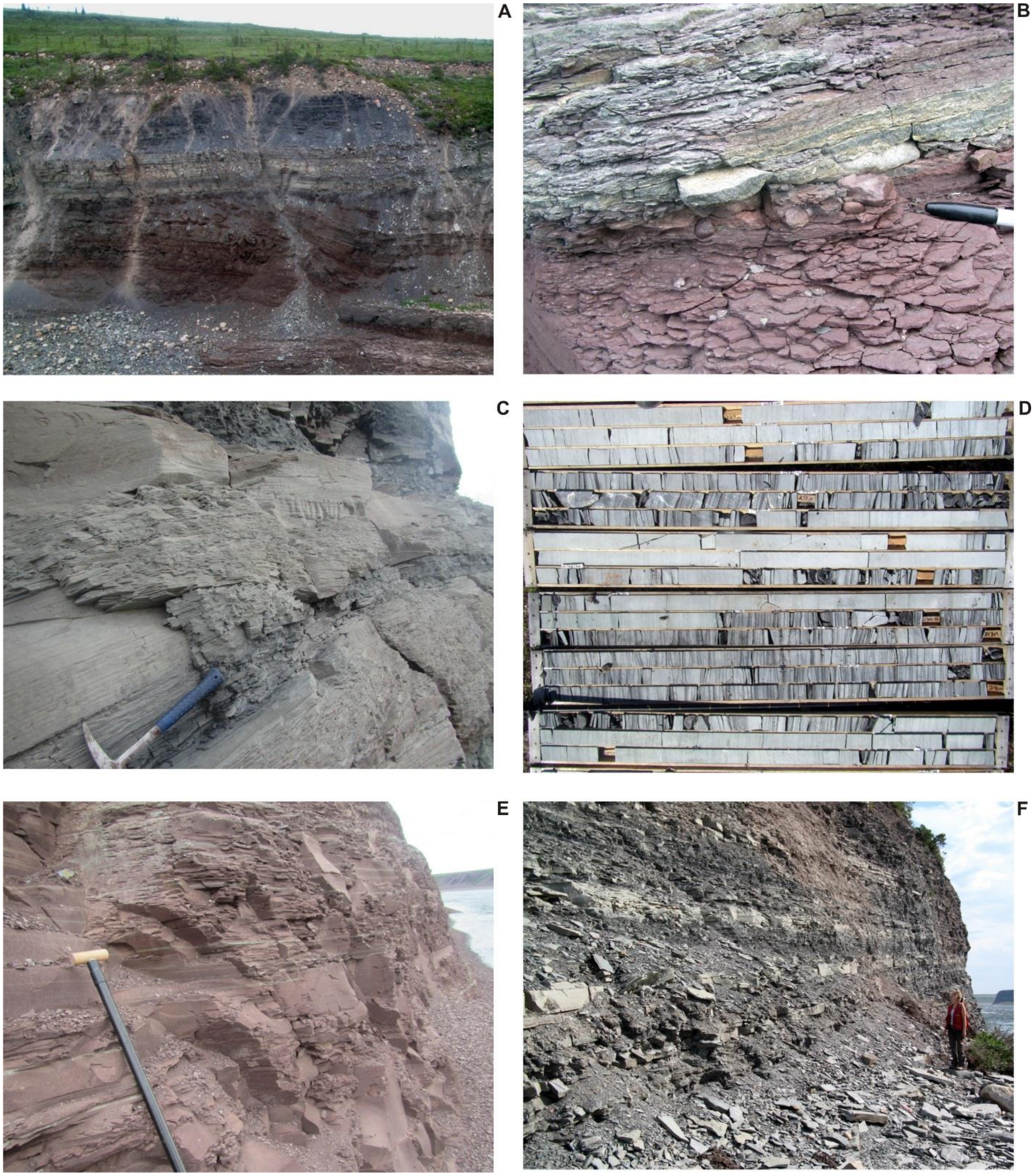


Figure 3. Field photographs Dismal Lakes Group: A. Interbedded shale and white sandstone-siltstone, LeRoux Formation, Hornby Bay resources, drill core from Mouse Lake camp; B. Cross-bedded quartzite, Fort Confidence Formation, Dismal Lakes north shore; C. Salt casts in red shales, Dease Lake Formation, north of Dease Lake (informal); D. Interbedded red shales and sandstones (yellow), cliff is approximately 5m high, Dease Lake Formation, Kendall River area; E.

Stromatolitic (conophyton) biostrome, Sulky Formation, September Mountains; F. Domal stromatolite, Greenhorn Lakes Formation, north of Dismal Lakes.

Figure 4 Field photographs of Coppermine River Group and associated mineralization: A. Conformable contact between buff-colored carbonates in the upper Greenhorn Lakes Formation, and the basal basalt lava flow, lower Copper Creek Formation, north of Dismal Lakes. B. Typical stair-step topography of continental tholeiitic basalts with cliff-forming flow interiors, and flat, red, recessive weathering flow tops, upper Copper Creek Formation, southeast of Hope

Lake; C. Malachite-chalcocite mineralization in quartz veins cutting upper Copper Creek Formation, west of Muskox Rapids, Coppermine River; D. Typical uranium mineralization (black zone in the upper left) at the Mountain Lake uranium deposit and related alteration (quartz dissolution + clays) hosted in the LeRoux Formation, Dismal Lakes Group; E. Desiccation-crack structures in the lower Husky Creek Formation within the fine-grained lithic sandstone, Coppermine River; F. Cross stratification in medium grained lithic sandstone, Husky Creek Formation, Coppermine River.



A) Figure 5. Field photographs Rae Group: A. Low-angle unconformity between Husky Creek Formation (red sandstone with large channel structure) and Escape Rapids Formation (tan-green sandstone overlain by dark shale), Coppermine River; B. Thin pebble lag developed at unconformity shown in A; C. Hummocky crossbedding in lower Hihotok member of the Escape Rapids Formation, Coppermine River; D. Alternating sandstone and wavy-lenticular bedded sandstone-siltstone in basal Hihotok member from CP15-DDH-007, Kaizen Discovery, Hope Lake); E. Parallel-laminated siltstone typical of the Nipartoktuak member of the Escape Rapids Formation; F. Base of Bloody Fall member on east side of Coppermine River.