The early Neoproterozoic Chandindu Formation of the Fifteenmile Group in the Ogilvie Mountains

Marcus Kunzmann[1], Galen P. Halverson, Malcolm Hodgskiss, Pierre D. Sansjofre, Dirk Schumann
Department of Earth & Planetary Sciences/GEOTOP, McGill University, Montreal, Quebec, Canada

Francis A. Macdonald
Department of Earth & Planetary Sciences, Harvard University, Cambridge, MA, USA

Robert H. Rainbird
Geological Survey of Canada, Ottawa, Ontario, Canada

Kunzmann, M., Halverson, G.P, Macdonald, F.A., Hodgskiss, M., Sansjofre, P.D., Schumann, D., and Rainbird, R.H, 2014. The early Neoproterozoic Chandindu Formation of the Fifteenmile Group in the Ogilvie Mountains. *In:* Yukon Exploration and Geology 2013, K.E. MacFarlane, M.G. Nordling, and P.J. Sack (eds.), Yukon Geological Survey, p. 93-107.

ABSTRACT

Studies of biogeochemical and evolutionary change in the Neoproterozoic require a detailed understanding of stratigraphic successions and their intrabasinal correlation to integrate those records into regional and global frameworks. The early Neoproterozoic Fifteenmile Group in the Ogilvie Mountains has previously been shown to archive important information on the evolution of the biosphere, including ocean redox and early evolution of eukaryotes. Here, we formally define the Chandindu Formation, a 150 to 420-m-thick siltstone-dominated mixed carbonate-siliciclastic succession of the lower Fifteenmile Group in the Coal Creek and Hart River inliers. We present ten sections of the Chandindu Formation and propose a type section and formalization to promote the development of a consistent stratigraphic framework for Proterozoic successions in northwest Canada.

The Chandindu Formation begins with muddy tidal flat facies, which are succeeded by shale-siltstone-sandstone coarsening-upward cycles deposited in a predominantly subtidal environment. However, carbonate occurrences throughout the entire unit suggest localized carbonate buildups, likely nucleated on fault-bound paleohighs where siliciclastic background sedimentation was low. These paleohighs originated from rift-inherited complex basin topography and syn-depositional faulting during deposition of the upper Chandindu Formation.

[1] *marcus.kunzmann@mail.mcgill.ca*

INTRODUCTION

Proterozoic strata in northwest Canada are exposed in erosional windows through Phanerozoic cover (Fig. 1a); from west to east, these are the Tatonduk, Coal Creek, and Hart River inliers of the Ogilvie Mountains, the Wernecke inlier in the Wernecke Mountains, and the Mackenzie Mountains. Broad stratigraphic correlation between Neoproterozoic successions in the Mackenzie Mountains and elsewhere in the Amundsen Basin in Arctic Canada is relatively straightforward (*e.g.,* Rainbird *et al.*, 1996), although new radiometric ages and chemostratigraphy (Jones *et al.*, 2010; Macdonald *et al.*, 2010b) motivate refinement of this correlation. Although broad stratigraphic similarities between Proterozoic inliers in northwest Canada were noticed decades ago (*e.g.*, Gabrielse, 1972; Eisbacher, 1978a; Young *et al.*, 1979), refined correlations on the formation scale have remained elusive. The difficulty in correlating between the inliers is due to many factors, including a paucity of radiometric dates, incomplete stratigraphic records, complex tectonostratigraphic evolution, and significant lateral facies changes, even within inliers (Macdonald *et al.*, 2012). Nonetheless, a detailed understanding of regional correlations based on mapping, stratigraphic analysis including the definition and introduction of new formations, geochronology, and geochemistry, is necessary both to reconstruct the tectonic setting and basin evolution, and also to calibrate records of biogeochemical change and biological evolution obtained from these strata.

The early Neoproterozoic Fifteenmile Group in Yukon was deposited during a time span characterized by globally increasing eukaryotic diversity (*e.g.,* Schopf *et al.*, 1973; Porter and Knoll, 2000; Butterfield, 2004; Knoll *et al.*, 2006) possibly facilitated by a non-sulphidic deep ocean (Canfield *et al.*, 2008; Johnston *et al.*, 2010; Sperling *et al.*, 2013). Recent studies of the Fifteenmile Group identified scale microfossils (Macdonald *et al.*, 2010a; Cohen *et al.*, 2011; Cohen and Knoll, 2012) of which some show the "earliest compelling evidence for biologically controlled eukaryotic biomineralization" (Cohen *et al.*, 2011, p. 541). A recent study of the Fifteenmile Group by Sperling *et al.* (2013) concluded that mostly ferruginous deep waters were overlain by oxygenated shelf waters and that the oxygen level in the surface mixed layer should have been high enough to support early metazoa.

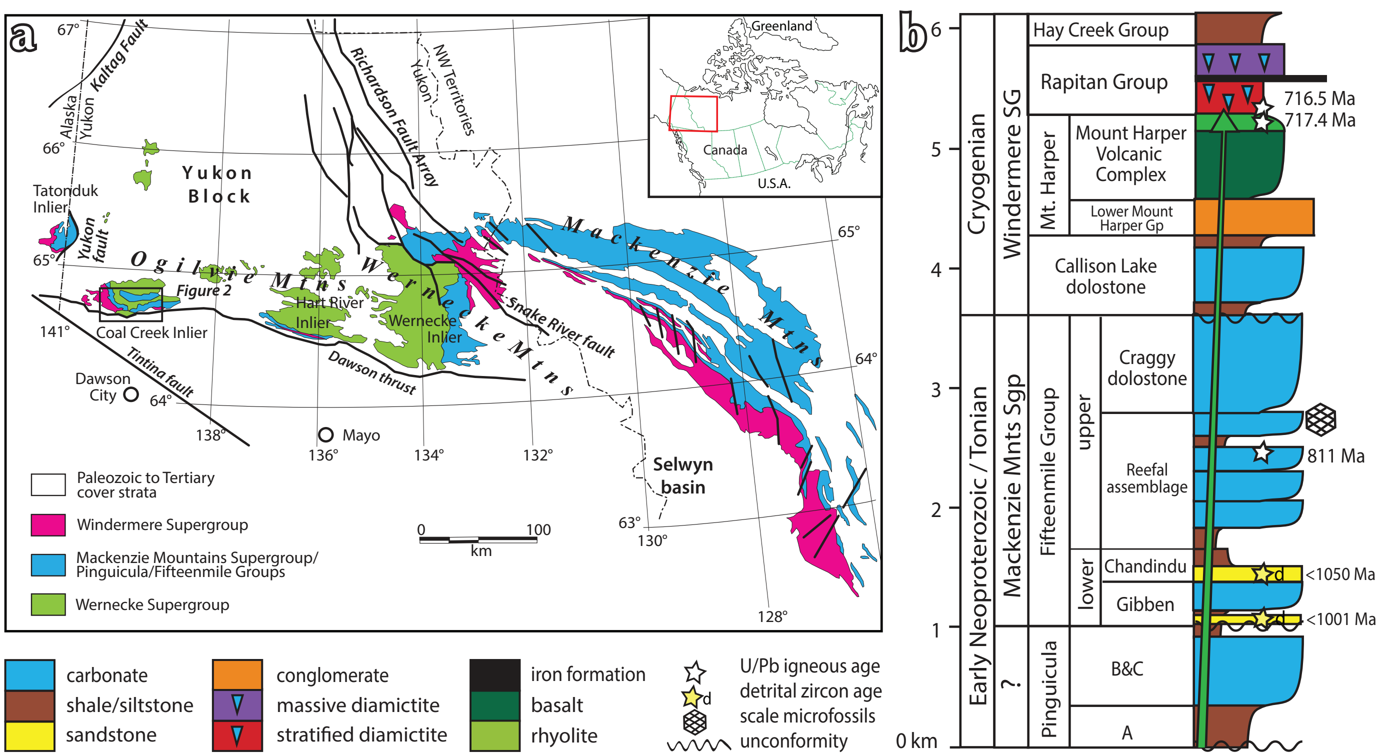

Figure 1*. Simplified geology and stratigraphy of the study area: (a) distribution of Proterozoic strata in inliers in Yukon and the Northwest Territories. Black box of the Coal Creek inlier indicates the area shown in Figure 2. Modified from Macdonald et al. (2011); and (b) lithostratigraphy of Tonian and Cryogenian strata in the Ogilvie Mountains. Modified from Macdonald et al. (2012).*

In this paper, we describe the sedimentology and lateral variation of the Chandindu Formation of the lower Fifteenmile Group in the Coal Creek and Hart River inliers, and also describe a proposed type section in detail. These data provide constraints on the depositional environment and basin topography, which in turn have implications for basin evolution, regional correlations, and biogeochemical data obtained from this succession.

FIFTEENMILE GROUP

The Fifteenmile Group (Fig. 1b; Thompson *et al*., 1987; Roots and Thompson, 1992; Thompson *et al*., 1994) in the Ogilvie Mountains is part of the early Neoproterozoic "Succession B" of northwestern Laurentia which also comprises the Mackenzie Mountains Supergroup in the Wernecke and Mackenzie mountains, and the Shaler Supergroup on Victoria Island (Young *et al*., 1979; Eisbacher, 1981; Rainbird *et al*., 1996; Long *et al*., 2008). In the central Ogilvie Mountains, the Fifteenmile Group originally included all strata that unconformably rest on the late Paleoproterozoic Wernecke Supergroup (Delaney, 1981; Thorkelson, 2000; Thorkelson *et al*., 2005) and unconformably underlie the mid-Neoproterozoic Callison Lake dolostone (Abbott, 1997; Macdonald and Roots, 2010) and Mount Harper Group (Mustard and Roots, 1997; Macdonald *et al*., 2011; Cox *et al*., 2013) of the Windermere Supergroup. Following initial subdivision of the Fifteenmile Group into five lower (PR1-PR5) and three upper (PF1-PF3) map units (Thompson *et al*., 1994), Abbott (1993) introduced a fourth upper map unit (PF4) and extended the nomenclature to the Hart River inlier. Subsequently, Abbott (1997) renamed PF4 the "Callison Lake dolostone" and interpreted the entire succession between Wernecke Supergroup and Callison Lake dolostone to represent the Pinguicula Group in the Ogilvie Mountains. The Pinguicula Group is a mixed siliciclastic-carbonate unit and was originally defined in the Wernecke Mountains (Eisbacher, 1978b; 1981), where it was subdivided into five units (A-E). Young *et al*. (1979) subsequently correlated it with the Mackenzie Mountains and Shaler supergroups. Later, Thorkelson *et al*., (2005) proposed that only the upper units correlate with the Mackenzie Mountains Supergroup. Following re-mapping, Macdonald *et al*. (2011) assigned the lower four map units (PR1-PR4) to the Pinguicula Group and the upper map units (PF1-PF3) to the Fifteenmile Group. Correlation of PR1 and PR2 with the Pinguicula Group was also suggested by Medig *et al*. (2010) based on stratigraphic similarities and contact relationships with the underlying Wernecke Supergroup. Medig *et al*. (2013) subsequently suggested that the base of the purported Pinguicula Group in the Coal Creek inlier (PR1, or PA in our mapping) is in fact an older unit. This raises the possibility that the Pinguicula Group does not occur in the Coal Creek inlier.

Recently, new radiometric ages coupled with chemostratigraphy motivated revised regional correlations of the Fifteenmile Group in the central Ogilvie Mountains with strata in other inliers in Yukon, the Mackenzie Mountains, and on Victoria Island (Macdonald *et al*., 2010a,b; Macdonald and Roots (2010); Halverson *et al*., 2012; Macdonald *et al*., 2012). The first direct age constraint on the Fifteenmile Group came from a tuff in the upper half of the succession (Fig. 1b) that yielded a U-Pb zircon age of 811.51 ± 0.25 Ma (Macdonald *et al*., 2010b). A 717.43 ± 0.14 Ma U-Pb zircon age from a rhyolite in the Mount Harper Volcanic Complex, upper Mount Harper Group, places a minimum age on the Fifteenmile Group. Subsequently, Macdonald and Roots (2010) correlated the Fifteenmile Group in the Coal Creek inlier with the Lower Tindir Group of the Tatonduk inlier and refined correlations with strata in the Hart River inlier. As a consequence, Macdonald *et al*. (2011) recommended abandonment of the term Tindir Group to simplify stratigraphic nomenclature across the inliers. Furthermore, they subdivided the Fifteenmile Group into a "Lower Assemblage" composed of mixed clastic rocks and dolostone, conformably followed by the "Craggy Dolostone" (Macdonald *et al*., 2011). Most recently, Halverson *et al*. (2012) subdivided the Lower Assemblage into the "Gibben", "Chandindu", and "Reefal Assemblage" formations. They proposed correlation of a basal sandstone in the Gibben formation with map unit PPD1 in the Hart River inlier (Abbott, 1997), correlation of the remaining Gibben formation with PPD2, and correlation of the Chandindu formation with PPD3.

The basal sandstone unit in the Gibben formation unconformably overlies the Pinguicula Group (as mapped), and grades upward into shallow marine ooid and coated-grain packstone and grainstone, with microbial laminite and evidence of subaerial exposure increasing up section (Halverson *et al*., 2012; Macdonald *et al*., 2012). In the Hart River inlier, the Gibben formation, as currently defined, includes a basal interval of fine-grained siliciclastic rocks, which is succeeded by a shoaling upward carbonate sequence that is virtually identical to that described in the Coal Creek inlier. Due to syn-depositional extensional tectonics and deposition in fault-bound grabens, the thickness can vary from less than 20 m to 600 m (Halverson *et al*., 2012; Macdonald *et al*., 2012).

The Gibben formation is overlain by a prominent interval of mud-cracked, maroon shale and siltstone which grade into grey shale, and siltstone and sandstone with rare stromatolite bioherms and olistoliths. This mainly clastic unit comprises the up to 400-m-thick Chandindu Formation, as informally proposed by Halverson *et al*. (2012). The top of the Chandindu Formation is a prominent flooding interval.

The overlying 500 to 1700-m-thick Reefal Assemblage is mostly composed of thick, grey, stromatolitic boundstone, grainstone, ribbonite, and rhythmite interbedded with prominent black shale intervals representing maximum flooding surfaces (Halverson *et al*., 2012; Macdonald *et al*., 2012). The formation is marked by significant lateral facies changes controlled by early Fifteenmile Group syn-depositional, down-to-the-northwest, normal faulting that generated significant basin relief. Lateral facies variation is interpreted to represent NW-prograding reef systems that grade laterally into siliciclastic basinal deposits representing grabens or half-grabens (Halverson *et al*., 2012; Macdonald *et al*., 2012).

The following >500-m-thick Craggy Dolostone is mostly composed of light grey, strongly silicified and recrystallized, ridge-forming dolostone, consisting mostly of microbial laminite, ooid and coated-grain pack and grainstone, tabular clast conglomerate, and gravity flow breccia. Macdonald *et al*. (2012) concluded that the Craggy Dolostone represents the establishment of a broad stable carbonate platform and infilling of Reefal Assemblage sub-basins. However, more recent observations show significant lateral facies changes and large volumes of gravity flow breccia that imply more complex seafloor topography and may indicate continued extensional tectonism. The top of the Craggy Dolostone is truncated by the sub-Callison Lake Dolostone unconformity.

CHANDINDU FORMATION (NEW)

The proposed type section of the Chandindu Formation is M103, about 15 km northeast of Mount Harper (Fig. 2). A northeast-trending ridge provides continuous exposure of the unit, which is typically recessive weathering and slightly more vegetated than the grey-weathering rubble-covered slopes of the over and underlying units (Fig. 3). Here the Chandindu Formation is 249 m thick (Fig. 4), with clear lower and upper boundaries. The base of the section (N64°45′15.4′′, W139°32′21.9′′) is located on a north-facing slope and repeated by a fault. This fault causes a repetition of about 20 m of the uppermost underlying Gibben formation and the base of the Chandindu Formation (Fig. 5a).

The top of the underlying Gibben formation is composed of medium-grey and medium-bedded microbial laminite and minor grainstone indicating deposition in a peritidal environment. Secondary black chert bands, up to 5 cm thick, cut carbonate bedding in places. A sharp contact with a prominent mud-cracked (Fig. 5b), reddish siltstone with grey-brown shale interbeds marks the base of the Chandindu Formation. This distinct and laterally continuous mud-cracked interval makes identifying the base of the Chandindu Formation straightforward. In this section, the mud-cracked interval consists of 17 m of alternating fine-grained, grey-green (black-weathering), mostly thickly laminated to very thinly bedded, well-sorted sandstone with common mud cracks and grey-green siltstone. The mud-cracked interval is succeeded by 232 m of moderately well defined coarsening-upward cycles with no mud cracks. These cycles typically consist of dark grey to black, thinly laminated silty shale and shale between a few decimeters and a few meters thick at the base; a middle interval of tens of metres of grey-green, thickly laminated siltstone; and fine-grained, well sorted, very thinly bedded, grey sandstone ranging in thickness from 1 decimeter to 1-2 m at the top (Fig. 5c). Coarsening-upward cycles are typical for the Chandindu Formation and are observed in every section (Fig. 8). Sandstone beds commonly contain hummocky cross-stratification (*e.g.*, in section MY1301, Fig. 8), and locally other indications of a storm-dominated environment (Fig. 5d). Three beds of ribbonite-facies carbonate (facies types were described by Macdonald and Roots, (2010) and Macdonald *et al*., (2012)) also occur throughout this interval. A prominent feature of the uppermost Chandindu Formation in this section is the occurrence of olistoliths: a 2 m-thick block of stromatolite and a 6 m-thick block of grainstone and stromatolite. Following Halverson *et al*. (2012), we place the top of the Chandindu Formation at the base of the uppermost maximum flooding surface (that is an abrupt shift to finer grained rocks, typically black shale) which separates the siliciclastic-dominated Chandindu Formation from the overlying carbonate-dominated informal Reefal Assemblage. However, we note that in more siliciclastic-dominated sections, this boundary can be somewhat difficult to identify.

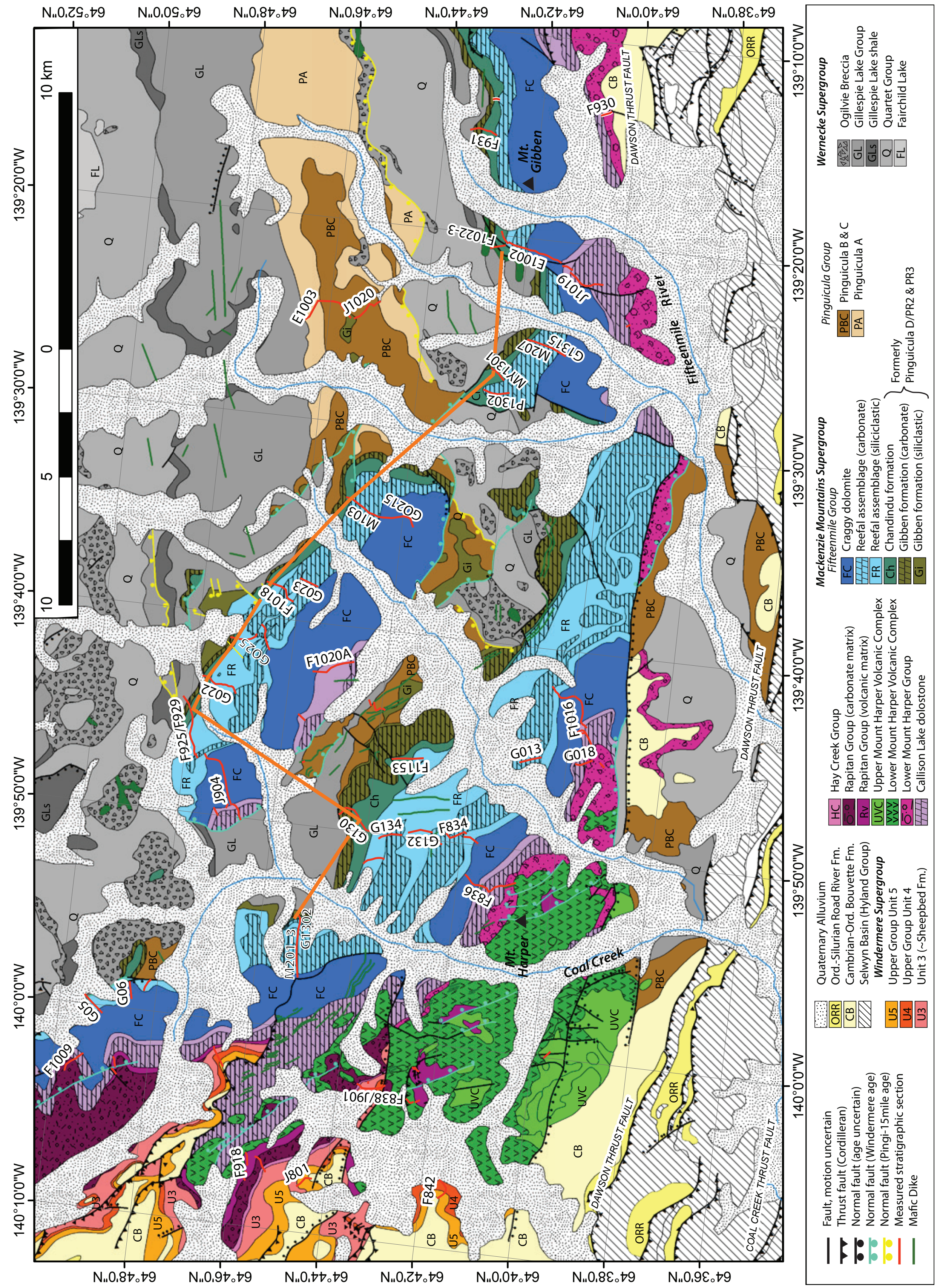

Figure 2*. Geological map of the Coal Creek inlier in the central Ogilvie Mountains. Orange line indicates the location of the Chandindu Formation transect shown in Figure 8.*

Figure 3. *View northwestward of Fifteenmile Group including the well exposed type section of the Chandindu Formation. Field of view is about 3 km.*

PETROGRAPHY OF SILICICLASTIC ROCKS

To characterize the siliciclastic Chandindu Formation, we applied optical microscopy and scanning electron microscopy (SEM) on specimens of sandstone, siltstone, and shale collected from type section M103. Here, we describe one example from each type (Fig. 4). Petrographic thin sections were investigated with a Hitachi S-3000N Variable Pressure-SEM (VP-SEM) equipped with an Oxford INCA microanalytical system (energy dispersive X-ray spectrometry (EDS) detector). The samples were studied in backscattered electron (BSE) SEM mode at an acceleration voltage of 15 kV, an emission current of 64 µA, and a vacuum pressure of 20 Pa. Selected areas were analyzed with the SEM-EDS microanalytical system for approximately 15 to 20 minutes to obtain element distribution maps. Descriptions of the carbonate facies types can be found elsewhere (e.g., Macdonald *et al*., 2012).

Sandstone (M103.1.0): This sample comes from a 3.1 m-thick sandstone interval at the base of M103 (Fig. 4). The black-weathering, fine-grained sandstone is reddish-grey on fresh surfaces and breaks into laminae 0.5-1.0 cm thick. Siltstone interbeds, shale partings, mm-scale mud drapes, and mud cracks occur. In thin section, the rock is composed of about 90% quartz and 10% sericite. The mineralogically mature rock is very well sorted with up to 160 µm-large monocrystalline quartz crystals that show slight undulose extinction. Roundness and sphericity of quartz grains are difficult to evaluate due to compaction (Fig. 6a), which causes straight crystal boundaries and the undulose extinction. However, quartz grains seem to have a high sphericity. Porosity is estimated to be less than 1%. The sericite occurs in mud drapes up to 2 cm long and 2 mm thick and indicates alteration of primary phyllosilicates. Precise identification of minerals would require Transmission Electron Microscopy (TEM) and X-ray powder diffraction (XRD). The mud drapes show an internal parallel and continuous lamination caused by a material difference (Fig. 6a) and also include up to 100 µm-large, anhedral, round to elliptical opaque phases (Fig. 6a). Scanning electron microscopy shows that these phases are often composed of a concentric core of organic matter and an iron oxyhydroxide rim (Fig. 6b-d). The rim also contains small quartz and phyllosilicate crystals, which are likely inclusions that could suggest a secondary origin of the iron oxyhydroxide. These inclusions are also visible on element distribution maps (Fig. 6e-h). Alternatively, the iron oxyhydroxide could have precipitated early and quickly in association with the inclusions. These structures could be fragments of microbial mats preserved by the iron oxyhydroxide rim or even represent microfossils, but additional SEM and TEM studies are necessary to distinguish between these possibilities.

Siltstone (M103.143.2): This sample comes from the top of a 21.1-m-thick siltstone interval (Fig. 4). The grey to dark grey, partly rusty-weathering siltstone breaks into laminae ~ 0.5 cm thick. The sample was taken at the contact with overlying fine-grained sandstone (Fig. 7a,b). The rock is composed of about 50% quartz and 50% small phyllosilicate crystals, likely sericite resulting from alteration and low-grade metamorphism of clay minerals and mica. Individual quartz grains show undulose extinction and are up to 30 µm in diameter (Fig. 7c). The phyllosilicate crystals are <10 µm across (Fig. 7c,d). Organic matter mostly occurs as <50 µm-large irregular accumulations and is always mixed with quartz crystals (Fig. 7c,e). In contrast to organic matter occurrences in

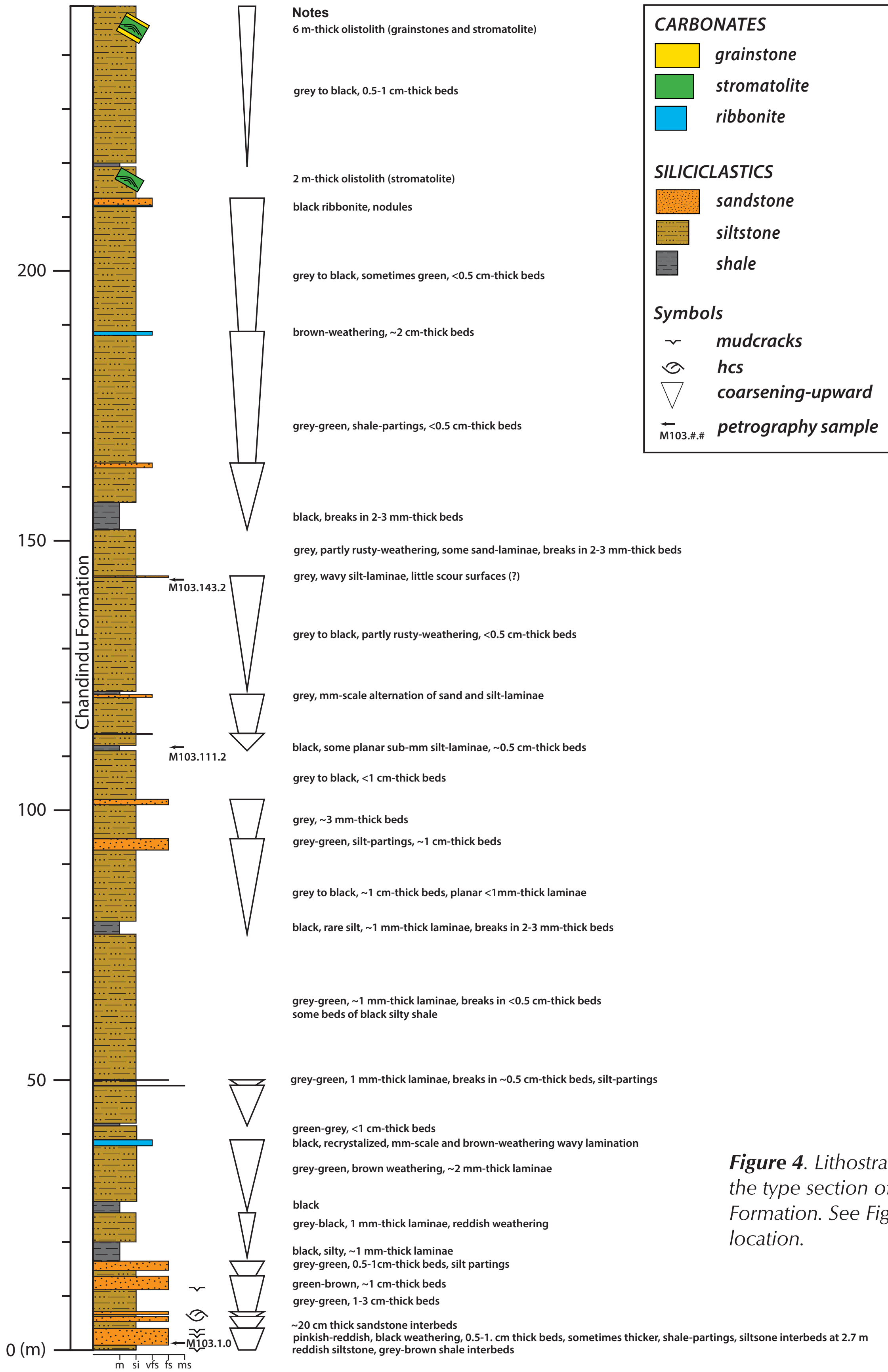

***Figure 4**. Lithostratigraphy of M103, the type section of the Chandindu Formation. See Figures 2 and 3 for location.*

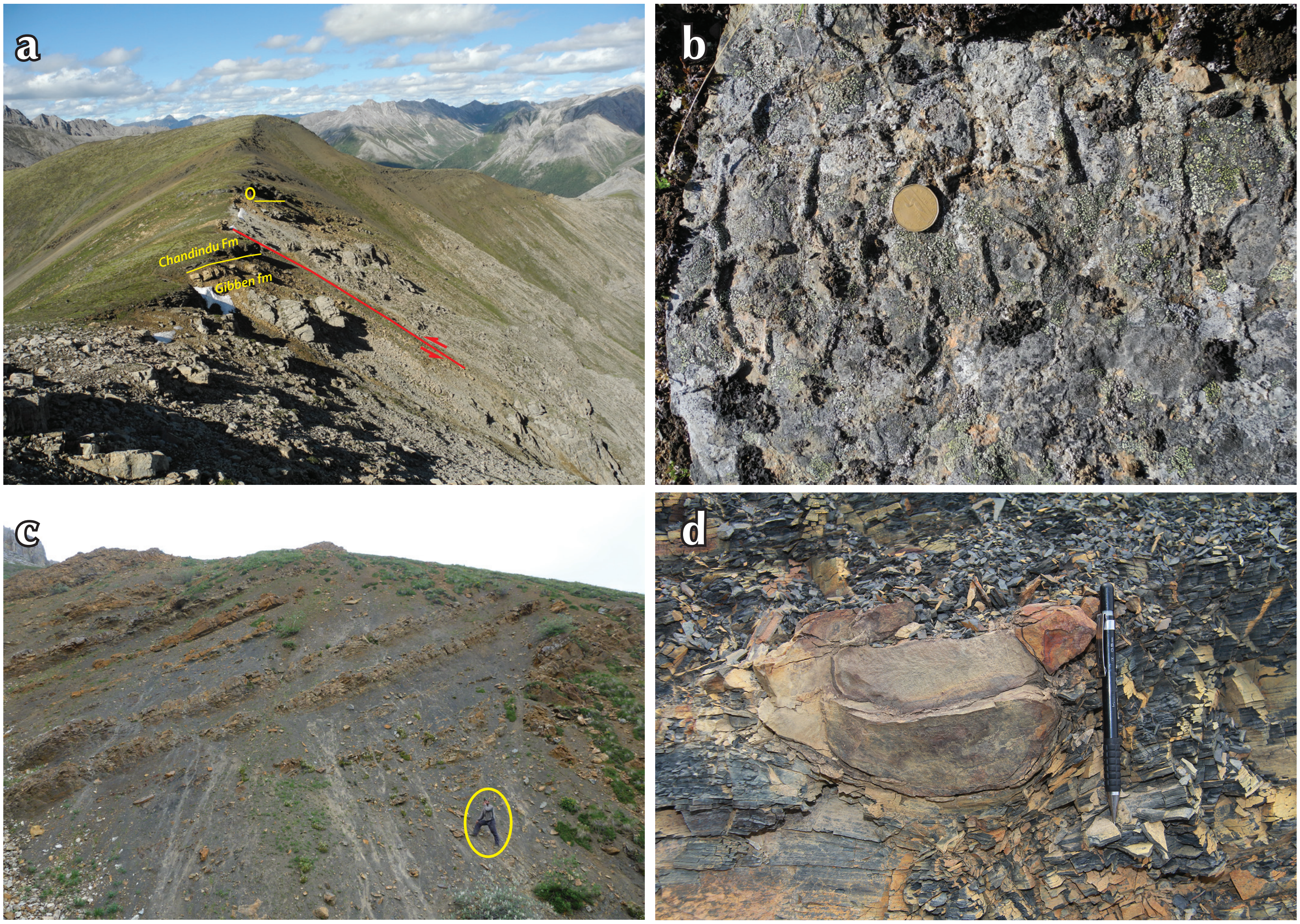

Figure 5. *Outcrop photos of the Chandindu Formation. (a) Base of the Chandindu Formation in section M103 (yellow line) looking westward. The Gibben-Chandindu contact is repeated by a fault. Person (yellow ellipse) for scale. (b) Mud cracks of the basal Chandindu Formation in section M103. Coin for scale is 2.65 cm across. (c) Shale-siltstone-sandstone cycles in section MY1301 between 190 and 260 m above base. Person (yellow ellipse) for scale. (d) Cross section of sand-filled gutter cast in the lower Chandindu Formation in section MY1301. Pencil length is 15 cm.*

mud drapes of the sandstone sample M103.1.0, organic matter in siltstone does not occur as round structures and is not rimmed by iron oxyhydroxide (Fig. 7c,e). Organic matter accumulations in overlying fine-grained sandstone are also irregular but larger (<80 µm) and more common (Fig. 7b).

Shale (M103.111.2): The shale sample described here comes from a 1-m-thick interval in the middle of the Chandindu Formation (Fig. 4). The rock is dark-grey and contains some sub-millimeter-thick silt laminae. SEM study reveals that the rock consists of about 20% quartz and 80% phyllosilicates (Fig. 7f-h). The quartz crystals are less than 15 µm in diameter. Phyllosilicate crystals are less than 10 µm across (Fig. 7f). Element mapping helped to identify calcium-phosphorous-bearing minerals, likely apatite (Fig. 7g,h).

LATERAL VARIABILITY OF THE CHANDINDU FORMATION

Ten sections of the Chandindu Formation were logged in the central and eastern Ogilvie Mountains (Fig. 8). Nine were logged in the Coal Creek inlier, about 80 km north of Dawson City, and one section was logged in the Hart River inlier, about 120 km north of Mayo. In the western part of the Coal Creek inlier, near Mount Harper, the Chandindu Formation thickness is between 150 and 250 m. Further to the east, at Fifteenmile River and Mount Gibben, the thickness increases to 400-420 m (Fig. 8). In the Hart River inlier, the top of the Chandindu Formation is commonly truncated on a low-angle unconformity beneath the Callison Lake dolostone (Abbott, 1997; Macdonald *et al.*, 2011); however, in our measured section, it is

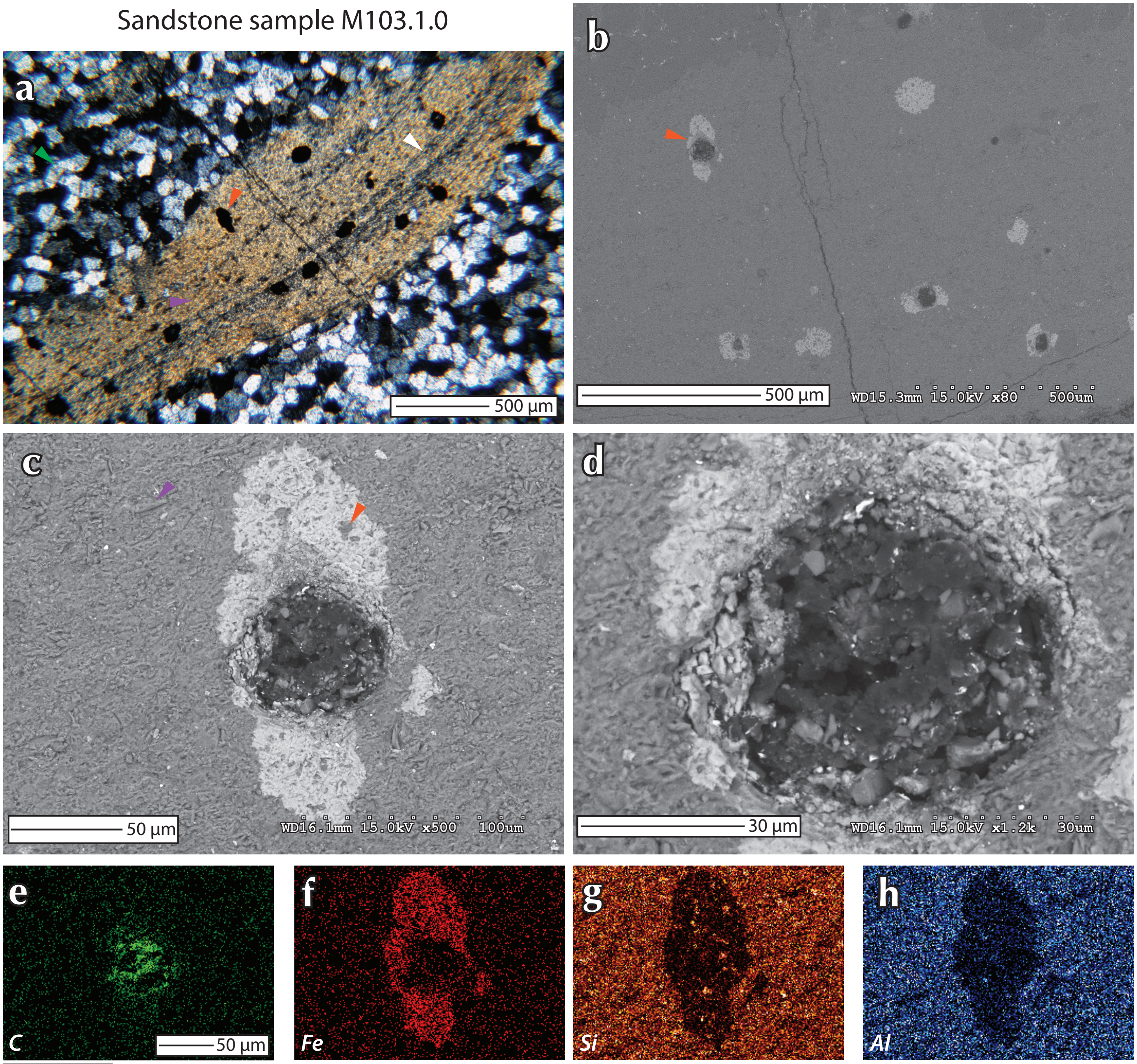

***Figure 6**. Thin section and SEM-BSE images of the sandstone sample M103.1.0. (a) Sericitized mud drape (purple arrow, brown interval) floats in well-sorted quartz arenite (green arrow). The mud drape shows an internal parallel lamination (white arrow) and about 100 μm-large opaque phases (orange arrow). Cross-polarized light. (b) SEM imaging reveals that many opaque phases consist of a core of organic matter. The object shown in (c) is indicated by the orange arrow. (c) Higher magnification shows that <5 μm-large quartz crystals occur as inclusion in the rim (orange arrow). Note small crystal size (<10 μm, purple arrow) of sericite. (d) Close-up of organic matter in (c) that forms the core. (e to h) Element distribution maps of the area shown in (c) clearly distinguishes the carbon-rich core, iron-rich rim and aluminium and silica-rich phyllosilicates (sericite) of the surrounding material. Scale shown in (e) also applies to maps (f, g, and h) of other elements.*

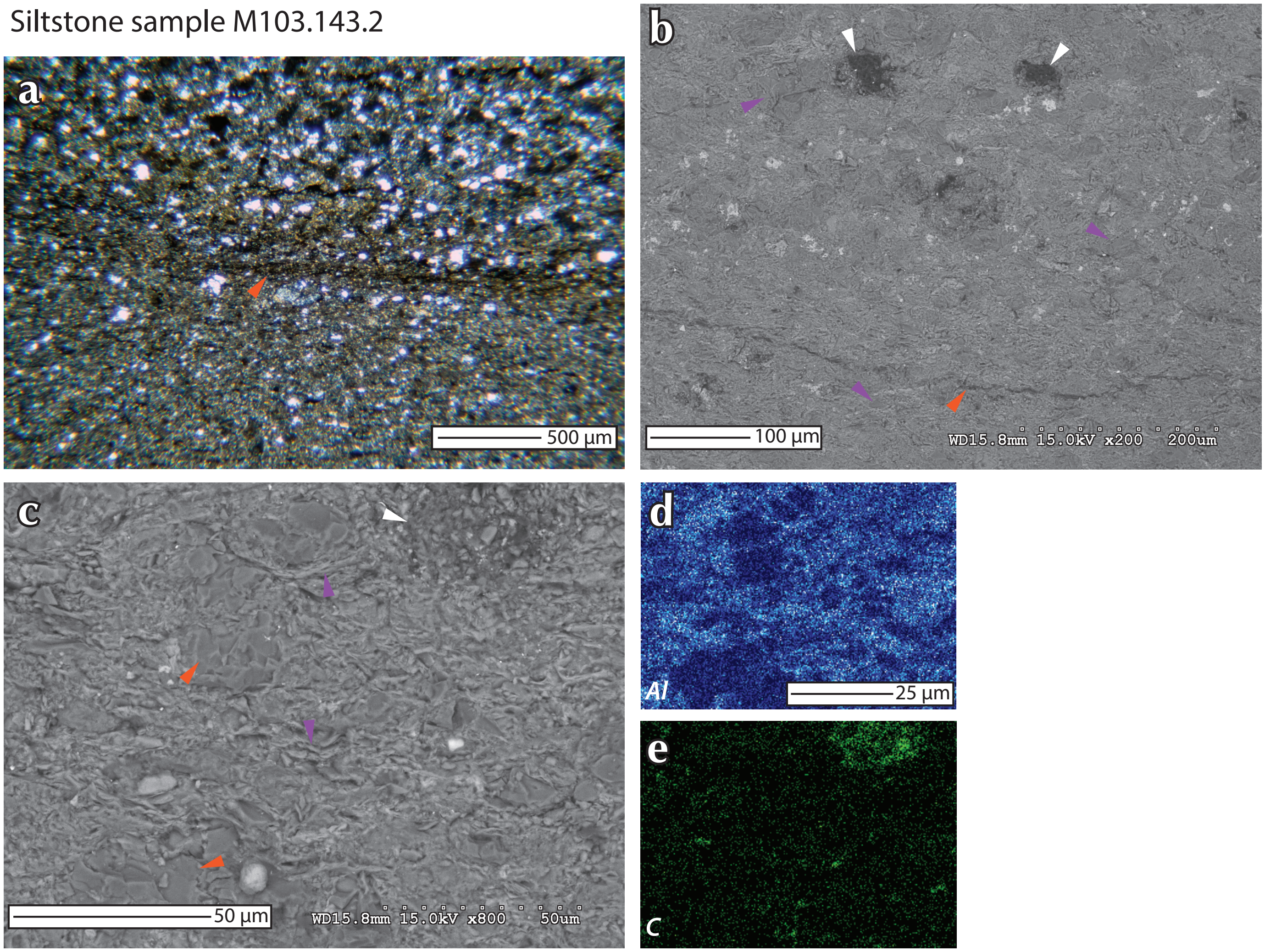

***Figure 7**. Thin section and SEM-BSE images of the siltstone sample M103.143.2 (a-e; this page) and shale sample M103.111.2 (f-h; next page). (a) Thin section photograph of the contact (orange arrow) between siltstone (below) and fine-grained sandstone (above). (b) SEM backscatter image of the siltstone-sandstone contact (orange arrow). Note significant larger size of quartz crystals (purple arrows) above the contact and larger accumulations of organic matter (white arrows, black clots). (c) Higher magnification of the siltstone part shows up to 30 µm-large quartz crystals (orange arrows), less than 10 µm-large phyllosilicates (purple arrows), and an irregular accumulation of organic matter (white arrow). (d) Aluminium distribution map shows dominance of phyllosilicates and occurrence of larger quartz crystals (lack of aluminium, dark areas). (e) Carbon distribution map helps to identify the concentration of organic matter in the upper right corner of photo. See (d) for scale.*

truncated by an unconformity at the base of the early Paleozoic Bouvette Formation, resulting in a partial thickness of the Chandindu Formation of < 200 m.

The dominant lithology in the Chandindu Formation is siltstone with minor shale and sandstone typically arranged in coarsening-upward cycles (for example in the type section M103 or in MY1301 about 190-260 m above base, Figs. 4 and 5c). However, carbonate rocks representing diverse depositional environments occur in every section.

DISCUSSION

The Chandindu Formation is conformably bound by the older Gibben formation and the younger Reefal Assemblage (Fig. 1b). The sharp base of the Chandindu Formation reflects an abrupt change of the depositional environment from a shallow marine carbonate environment dominated by microbial laminite formed on tidal flats and high-energy grainstone bars, to a muddy tidal flat where fine-grained siliciclastic sediments were deposited. The contact with the overlying Reefal

Shale sample M103.111.2

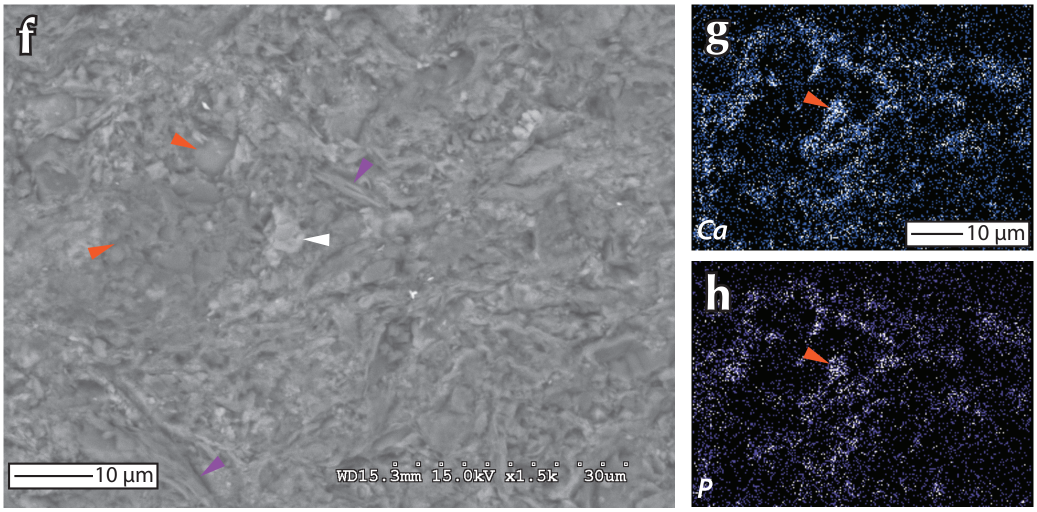

Figure 7 con'd. *(f) SEM-BSE image of shale sample M103.111.2. Note occurrence of quartz crystals (orange arrows), phyllosilicates (purple arrows), and apatite (white arrow). (g and h) Distribution maps of calcium and phosphorous show correlation in some areas (for example orange arrow) indicating occurrence of apatite. Scale in (g) also applies to (h).*

Assemblage is marked by a prominent maximum flooding surface indicated by the occurrence of black shale. This flooding interval is usually overlain by the first reef deposits of the Reefal Assemblage. An exception is the section reported by Macdonald and Roots (2010) north of Mount Harper where deposition of black shale continued to dominate until deposition of the upper Reefal Assemblage.

The laterally extensive mud-cracked siliciclastic interval at the base of the Chandindu Formation (Fig. 8) suggests deposition on a large, partly exposed, muddy tidal flat. Base level rise up-section is indicated by the transition of this mud-cracked interval to coarsening-upward cycles of shale, siltstone, and sandstone, sporadically capped by carbonate, commonly stromatolitic (Halverson *et al*., 2012). The coarsening-upward cycles indicate progradation and shallowing of the depositional environment. The occurrence of stromatolites at the top of some cycles points towards decreasing siliciclastic sedimentation rates and presages the eventual proliferation of stromatolite reef facies in the overlying Reefal Assemblage. Hummocky cross-stratification in sandstone of coarsening upward-cycles is evidence of common storm events and suggest deposition between storm and fair weather wave base (*e.g.*, Dott and Bourgeois, 1982; Duke, 1985; Leckie and Krystinic, 1989; Dumas and Arnott, 2006). Mild lateral thickness and facies variations, in particular in the lower part of the formation (Fig. 8), may indicate less extensional tectonic activity compared to the underlying Gibben formation. However, map relationships (Fig. 2) and the occurrence of large olistoliths in the upper part of the formation (for example in the type section, Fig. 4, see also Macdonald *et al*., 2012) indicate syn-depositional faulting. Significant basin relief is also likely the reason why lithostratigraphic correlation of coarsening-upward cycles in the Chandindu Formation is not readily apparent. However, at least one flooding event (indicated by shale intervals) in the middle part of the unit is present in every section west of Mount Gibben.

One of the most striking features of the Chandindu Formation is the occurrence of different carbonate facies types throughout the formation in every section. The carbonate facies range from supratidal intraclast breccia to deep marine debris flow deposits and rhythmite (Fig. 8), and often forms laterally discontinuous mounds. Carbonate deposition was therefore not restricted to one depositional environment and the carbonate factory was never completely overwhelmed by the abundant siliciclastic input. What controlled carbonate versus siliciclastic deposition? A possible explanation is that a laterally extensive carbonate depositional environment, parallel to the shoreline, was interrupted by terrigenous input from a delta. Lateral migration of distributary channels could have controlled the spatial distribution of siliciclastic versus carbonate deposition. Another possible explanation is that rift-inherited complex basin topography, further enhanced by syn-depositional faulting, controlled the sedimentation regime. Carbonate deposition established in areas of low siliciclastic background sedimentation, for example, on paleohighs on fault-bound rift blocks. Here, stromatolite bioherms and grainstone bars (the two most common carbonate facies types in the Chandindu Formation) preferentially developed (Fig. 8), providing a source for olistoliths in the Chandindu Formation (*e.g.*, M103; Figs. 4 and 8).

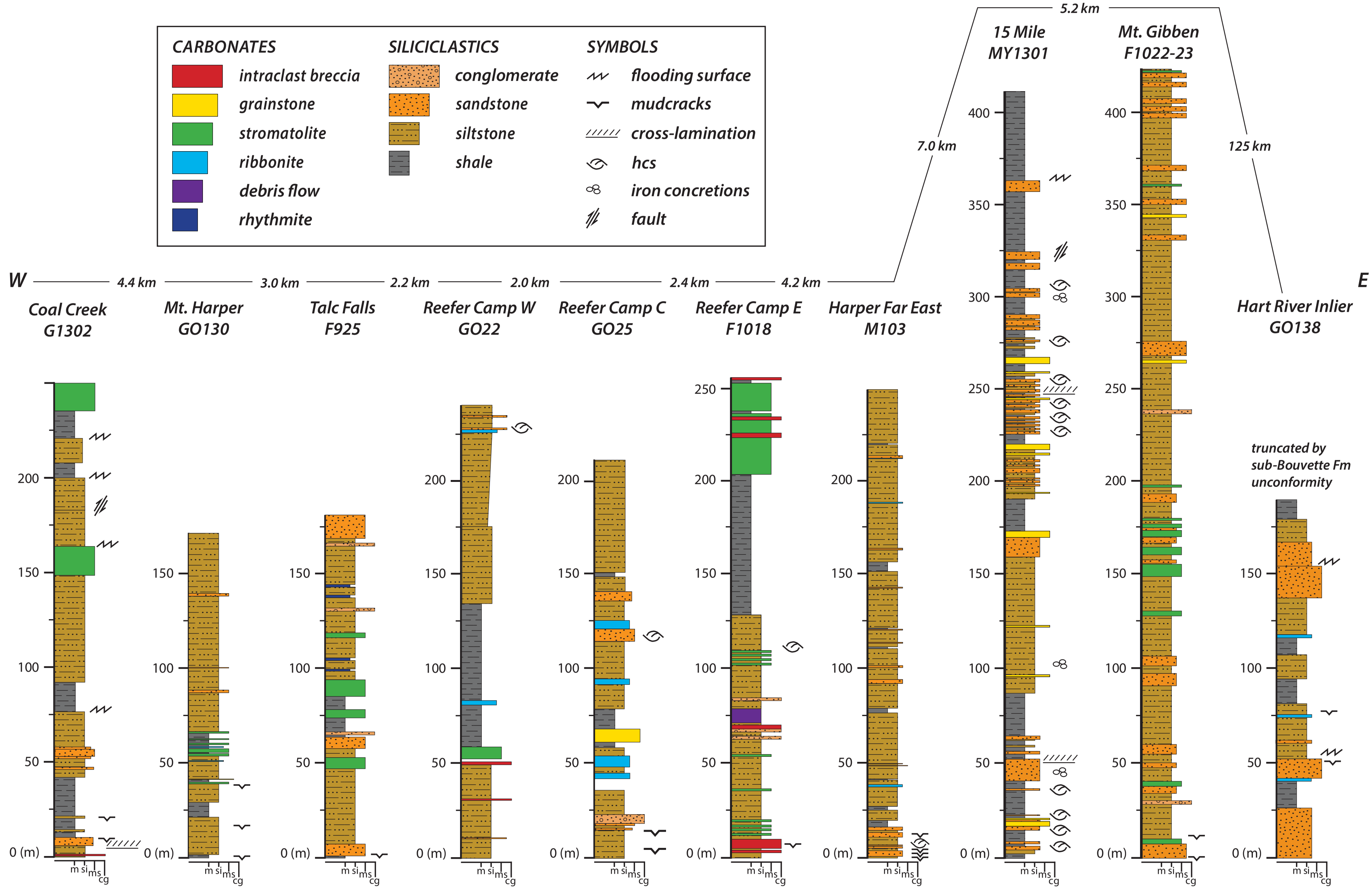

Figure 8*. West-east transect of the Chandindu Formation across the Coal Creek inlier (see Figure 2 for location of sections) plus additional section from the Hart River Inlier. Note dominance of siltstone and occurrence of carbonate (ranging from tidal flat to sub-storm wave base deposits) in every section.*

The Chandindu Formation in the Hart River inlier contains a significantly higher ratio of sandstone to siltstone, which is consistent with the occurrence of a deltaic system to the east (in present coordinates) and at least partial correlation of the Chandindu Formation with the Katherine Group. In the Wernecke and Mackenzie mountains, the Katherine Group is a thick succession of fluvial-deltaic quartz arenite and marine siltstone and sandstone (Eisbacher, 1978b, 1981; Thorkelson, 2000; Thorkelson *et al*., 2005; Turner, 2011; Long and Turner, 2012) that likely represents the proximal facies of a delta. Rainbird *et al*., (1997) previously postulated that the Katherine delta was fed by continent-scale, northwesterly migrating river systems that originated from the Grenvillian orogeny based on the predominance of *ca.* 1 Ga detrital zircons in the Katherine sands. The high degree of maturity of the sandstones in the Chandindu Formation (see petrographic description) is consistent with an interpretation of distal equivalent of parts of the Katherine Group, although documentation of Grenvillian-aged tectonothermal activity in the northern Cordillera (Thorkelson *et al*., 2005; Milidragovic *et al*., 2011) allows that the *ca.* 1 Ga zircons may have been more locally sourced. Correlation of the lower Fifteenmile Group in the Coal Creek and Hart River inliers with parts of the Katherine and Hematite Creek groups in the Wernecke Mountains (Turner, 2011; Macdonald *et al*., 2012) is still poorly understood and needs to be tested in future studies.

CONCLUSION

We describe the type section of the early Neoproterozoic Chandindu Formation. This overall deepening-upward unit represents diverse depositional regimes ranging from supra and intertidal to subtidal environments dominated by siliciclastic sedimentation. Deposition of carbonate most likely occurred on rift-related paleohighs where the site of deposition was protected from siliciclastic input. Parts of the fluvial-deltaic Katherine Group further to the east (present coordinates) are a possible source of the terrigenous material.

ACKNOWLEDGMENTS

We are grateful for financial support from the Yukon Geological Survey, NSERC, American Chemical Society Petroleum Research Fund, and the Polar Continental Shelf Program. MK acknowledges support by a GEOTOP scholarship and a J.B. Lynch Fellowship. Justin Strauss, Emily Smith, Eric Bellefroid, Thomas Maguire, Lyle Nelson, and Danielle Thomson helped in the field. Hojatollah Vali is thanked for access to the Facility for Electron Microscopy Research (FEMR) at McGill and Tanja Bosak for discussions. We sincerely thank Charlie Roots and his family for their hospitality and help with logistics. Charlie Roots is also thanked for a constructive and detailed review that improved the paper. We acknowledge logistical support by Don Francis. Finally, we thank Fireweed Helicopters for safe transportation.

REFERENCES

Abbott, J.G., 1993. Revised stratigraphy and new exploration targets in the Hart River region (NTS 116A/10, 116A/11), southeastern Ogilvie Mountains. *In:* Yukon Exploration and Geology 1992, Exploration and Geological Services Division, Yukon, Indian and Northern Affairs, Canada, p. 13-23.

Abbott, J.G., 1997. Geology of the Upper Hart River area, eastern Ogilvie Mountains, Yukon Territory (116A/10, 116A/11). Exploration and Geological Services Division, Yukon Region, Bulletin 9, 76 p.

Butterfield, N.J., 2004. A vaucheriacean algae from the middle Neoproterozoic of Spitsbergen: implications for the evolution of Proterozoic eukaryotes and the Cambrian explosion. Paleobiology, vol. 30 (2), p. 231-252.

Canfield, D.E., Poulton, S.W., Knoll, A.H., Narbonne, G.M., Ross, G., Goldberg, T., and Strauss, H., 2008. Ferruginous conditions dominated later Neoproterozoic deep-water chemistry. Science, vol. 321, p. 949-952.

Cohen, P.A. and Knoll, A.H., 2012. Scale microfossils from the mid-Neoproterozoic Fifteenmile Group, Yukon Territory. Journal of Paleontology, vol. 86 (5), p. 775-800.

Cohen, P.A., Schopf, J.W., Butterfield, N.J., Kudryavtsev, A.B., and Macdonald, F.A., 2011. Phosphate biomineralization in mid-Neoproterozoic protists. Geology, vol. 39 (6), p. 539-542.

Cox, G.M., Roots, C.F., Halverson, G.P., Minarik, W.G., Macdonald, F.A., and Hubert Théou, L., 2013. Mount Harper Volcanic Complex, Ogilvie Mountains: A far-flung occurrence of the Franklin Igneous Event? *In:* Yukon Exploration and Geology 2012, K.E. MacFarlane, M.G. Nordling, and P.J. Sack (eds.), Yukon Geological Survey, p. 19-36.

Delaney, D.G., 1981. The mid-Proterozoic Wernecke Supergroup, Wernecke Mountains, Yukon Territory. *In:* Proterozoic Basins of Canada, F.H.A. Campbell (ed.), Geological Survey of Canada, Paper 81-10, p. 1-24.

Dott, R.J. and Bourgeois, J., 1982. Hummocky stratification: Significance of its variable bedding sequences. Geological Society of America Bulletin, vol. 93, p. 663-680.

Duke, W.L., 1985. Hummocky cross-stratification, tropical hurricanes, and intense winter storms. Sedimentology, vol. 32, p. 167-194.

Dumas, S. and Arnott, R.W.C., 2006. Origin of hummocky and swaley cross-stratification – The controlling influence of unidirectional current and aggradation rate. Geology, vol. 34 (12), p. 1073-1076.

Eisbacher, G.H., 1978a. Redefinition and subdivision of the Rapitan Group, Mackenzie Mountains. Geological Survey of Canada, Paper 77-35, 21 p.

Eisbacher, G.H., 1978b. Two major Proterozoic unconformities, northern Cordillera. Geological Survey of Canada, Current Research Paper 78-1A, p. 53-58.

Eisbacher, G.H., 1981. Sedimentary tectonics and glacial record in the Windermere Supergroup, Mackenzie Mountains, northwestern Canada. Geological Survey of Canada, Paper 80-27, 40 p.

Gabrielse, H., 1972. Younger Precambrian of the Canadian Cordillera. American Journal of Science, vol. 272, p. 521- 536.

Halverson, G.P., Macdonald, F.A., Strauss, J.V., Smith, E. F., Cox, G.M, and Hubert-Théou, L., 2012. Updated definition and correlation of the lower Fifteenmile Group in the central and eastern Ogilvie Mountains. *In:* Yukon Exploration and Geology 2011, K.E. MacFarlane and P.J. Sack (eds.), Yukon Geological Survey, p. 75-90.

Johnston, D. T., Poulton, S.W., Dehler, C., Porter, S., Husson, J., Canfield, D.E., and Knoll, A.H., 2010. An emerging picture of Neoproterozoic ocean chemistry: Insights from the Chuar Group, Grand Canyon, USA. Earth and Planetary Science Letters, vol. 290, p. 64-73.

Jones, D.S., Maloof, A.C., Hurtgen, M.T., Rainbird, R.H., and Schrag, D.P., 2010. Regional and global chemostratigraphic correlation of the early Neoproterozoic Shaler Supergroup, Victoria Island, Northwestern Canada. Precambrian Research, vol. 181, p. 43-63.

Knoll, A.H., Javaux, E.J., Hewitt, D., and Cohen, P.A., 2006. Eukaryotic organisms in Proterozoic oceans. Philosophical Transactions of the Royal Society of Biological Sciences, vol. 361, p. 1023-1038.

Leckie, D.A. and Krystinic, L.F., 1989. Is there evidence for geostrophic current preserved in the sedimentary record of inner to middle-shelf deposits? Journal of Sedimentary Petrology, vol. 59, p. 862-870.

Long, D.G.F., Rainbird, R.H., Turner, E.C., and MacNaughton, R.B., 2008. Early Neoproterozoic strata (Sequence B) of mainland northern Canada and Victoria and Banks islands: a contribution to the Geological Atlas of the Northern Canadian Mainland Sedimentary Basin. Geological Survey of Canada, Open File 5700, p. 1-24.

Long, D.G.F. and Turner, E.C., 2012. Formal definition of the Neoproterozoic Mackenzie Mountains Supergroup (Northwest Territories), and formal stratigraphic nomenclature for terrigenous clastic units of the Katherine Group. Geological Survey of Canada, Open File 7113, 40 p.

Macdonald, F.A. and Roots, C.F., 2010. Upper Fifteenmile Group in the Ogilvie Mountains and correlations of early Neoproterozoic strata in the northern Cordillera. *In:* Yukon Exploration and Geology 2009, K.E. MacFarlane, L.H. Weston, and Blackburn L.R. (eds.), Yukon Geological Survey, p. 237-252.

Macdonald, F.A., Cohen, P.A., Dudás, F.Ö., and Schrag, D.P., 2010a. Early Neoproterozoic scale microfossils in the Lower Tindir Group of Alaska and the Yukon Territory. Geology, vol. 38 (2), p. 143-146.

Macdonald, F.A., Schmitz, M.D., Crowley, J.L., Roots, C.F., Jones, D.S., Maloof, A.C., Strauss, J.V., Cohen, P.A., Johnston, D.T., and Schrag, D.P., 2010b. Calibrating the Cryogenian. Science, vol. 327, p. 1241-1243.

Macdonald, F.A., Smith, E.F., Strauss, J.V., Cox, G.M., Halverson, G.P., and Roots, C.F., 2011. Neoproterozoic and early Paleozoic correlations in the western Ogilvie Mountains, Yukon. *In:* Yukon Exploration and Geology 2010, K.E. MacFarlane, L.H. Weston, and Relf, C. (eds.), Yukon Geological Survey, p. 161-182.

Macdonald, F.A., Halverson, G.P., Strauss, J.V., Smith, E.F., Cox, G.M., Sperling, E.A., and Roots, C.F., 2012. Early Neoproterozoic Basin Formation in Yukon, Canada: Implications for the make-up and break-up of Rodinia. Geoscience Canada, vol. 39, p. 77-99.

Medig, K.P.R., Thorkelson, D.J., Davis, W.J., Rainbird, R.H., Gibson, H.D., Turner, E.C., and Marshall, D.D., 2013. Evidence of the Laurentia-Australia connection? Detrital zircons from the Mesoproterozoic strata in Yukon, Canada. GAC-MAC 2013, Winnipeg, Program with abstracts, vol. 36, p. 143.

Medig, K.P.R., Thorkelson, D.J., and Dunlop, R.L., 2010. The Proterozoic Pinguicula Group: Stratigraphy, contact relationships and possible correlations. *In:* Yukon Exploration and Geology 2009, K.E. MacFarlane, L.H. Weston, and Blackburn, L.R. (eds.), Yukon Geological Survey, p. 265-278.

Milidragovic, D., Thorkelson, D.J., Davis, W.J., Marshall, D.D., and Gibson, H.D., 2011. Evidence for late Mesoproterozoic tectonism in northern Yukon and the identification of a Grenville-age tectonothermal belt in western Laurentia. Terra Nova, vol. 23, p. 307-313.

Mustard, P.S. and Roots, C.F., 1997. Rift-related volcanism, sedimentation, and tectonic setting of the Mount Harper Group, Ogilvie Mountains, Yukon Territory. Geological Survey of Canada Bulletin, vol. 492, 92 p.

Porter, S.M. and Knoll, A.H., 2000. Testate amoebae in the Neoproterozoic Era: evidence from vase-shaped microfossils in the Chuar Group, Grand Canyon. Paleobiology, vol. 26, p. 360-385.

Rainbird, R.H., Jefferson, C.W., and Young, G.M., 1996. The early Neoproterozoic sedimentary Succession B of northwestern Laurentia: Correlations and paleogeographic significance. Geological Society of America Bulletin, vol. 105, p. 454-470.

Rainbird, R.H., McNicoll, V.J., Thériault, R.J., Heaman, L.M., Abott, J.G., Long, D.G.F., and Thorkleson, D.J., 1997. Pan-continental River System Draining Grenville Orogen Recorded by U-Pb and Sm-Nd Geochronology of Neoproterozoic Quartzarenites and Mudrocks, Northwestern Canada. The Journal of Geology, vol. 105, p. 1-17.

Roots, C.F. and Thompson, R.I., 1992. Long-lived basement weak zones and their role in extensional magmatism in the Ogilvie Mountains, Yukon Territory. *In:* Basement Tectonics 8: Characterization and Comparison of Ancient and Mesozoic Continental Margins – Proceedings of the 8th International Conference on Basement Tectonics (Butte, Montana, 1988), M.J. Bartholomew, D.W. Hyndman, D.W. Mogk and R. Mason (eds.), Kluwer Academic Publishers, Dordrecht, The Netherlands, p. 359-372.

Schopf, W.J., Ford, T.D., and Breed, W.J., 1973. Microorganisms from the Late Precambrian of the Grand Canyon, Arizona. Science, vol. 179, p. 1319-1321.

Sperling, E.A., Halverson, G.P., Knoll, A.H., Macdonald, F.A., and Johnston, D.T., 2013. A basin redox transect at the dawn of animal life. Earth and Planetary Science Letters, vol. 371-372, p. 143-155.

Thompson, R.I., Mercier, E., and Roots, C.F., 1987. Extension and its influence on Canadian Cordilleran passive-margin evolution. *In:* Continental Extensional Tectonics, M.P. Coward, J.F. Dewey and P.L. Hancock (eds.), Geological Society of London Special Publication, vol. 28, p. 409-417.

Thompson, R.I., Roots, C.F., and Mustard, P.S., 1994. Dawson map area. Geological Survey of Canada, Open File 2849, scale 1: 50 000.

Thorkelson, D.J., 2000. Geology and mineral occurrences of the Slats Creek, Fairchild Lake and "Dolores Creek" areas. Wernecke Mountains (106D/16, 106C/13, 106C/14), Yukon Territory. Exploration and Geological Services Division, Yukon Region, Bulletin, vol. 10, 73 p.

Thorkelson, D.J., Abbott, J.G., Mortensen, J.K., Creaser, R.A., Villeneuve, M.E., McNicoll, V.J., and Layer, P.W., 2005. Early and Middle Proterozoic evolution of Yukon, Canada. Canadian Journal of Earth Sciences, vol. 42, p. 1045-1071.

Turner, E.C., 2011. Stratigraphy of the Mackenzie Mountains supergroup in the Wernecke Mountains, Yukon. *In:* Yukon Exploration and Geology 2011, K.E. MacFarlane, L.H. Weston, and C. Relf (eds.), Yukon Geological Survey, p. 207-231.

Young, G.M., Jefferson, C.W., Delaney, D.G., and Yeo, G.M., 1979. Middle and upper Proterozoic evolution of the northern Canadian Cordillera and Shield. Geology, vol. 7, p. 125-128.