Early Neoproterozoic scale microfossils in the Lower Tindir Group of Alaska and the Yukon Territory

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ABSTRACT

The Tindir Group is a <4-km-thick Neoproterozoic succession exposed in the Tatonduk inlier of east-central Alaska and the western Yukon Territory. The Tindir Group is informally divided into the Lower Tindir Group, which consists of <2 km of mixed carbonate and clastic rocks, and the overlying Upper Tindir Group, which contains two Cryogenian glacial deposits and an additional Ediacaran succession of mixed carbonate and clastic strata. Unique mineralized scale microfossils have been recovered from sections previously correlated with the Upper Tindir Group, and interpreted variously as Cryogenian to early Cambrian in age. Our remapping of the area indicates that these sections are stratigraphically below an early Cryogenian glacial diamictite, unit 2 of the Upper Tindir Group, and are actually part of the Lower Tindir Group. Carbon and strontium isotope correlations further suggest that the fossiliferous Lower Tindir Group is correlative with early Neoproterozoic strata of the northwestern Canadian Cordillera. This new age model is consistent with the accompanying microfossil assemblage and indicates that the diverse microfossils in the Lower Tindir Group can be added to the early Neoproterozoic record of eukaryotic evolution.

INTRODUCTION

Neoproterozoic strata host evidence of a major eukaryotic radiation (Knoll et al., 2006) occurring alongside multiple low-latitude glaciations (Evans, 2000; Harland, 1964), and the reorganization of geochemical cycles (Halverson et al., 2005; Logan et al., 1995). Understanding the feedbacks and relationships between early eukaryotic radiation and environmental perturbations is limited by both relative and absolute age uncertainties in the Neoproterozoic fossil and biogeochemical records.

Unique mineralized scale microfossils (e.g., *Characodictyon* sp; Fig. 1) have been described in early diagenetic chert from within the Tindir Group (Allison, 1981; Allison and Hilgert, 1986). The assemblage includes multiple morphologies, mainly ovate forms 5–80 µm in maximum dimension (Allison and Hilgert, 1986). The most parsimonious interpretation of these fossils is that they were scales distributed on the surface of a larger cell, similar to those formed by modern haptophytes, although a satisfactory functional and taxonomic interpretation remains a work in progress.

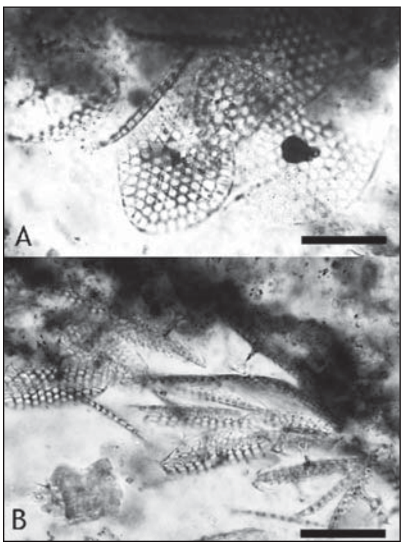

Figure 1. A, B: Clusters of *Characodictyon* sp. Scale bar 15 µm for A, 20 µm for B; each image is focal plane merger of three separate photomicrographs created using Helicon Focus software (http://www.heliconsoft.com/index.php?heliconfocus). Collected from meter 312.8, section T714.

The scale microfossils were originally reported as early Cambrian in age (Allison, 1981); however, citing relatively heavy $\delta^{13}C$ and low $^{87}Sr/^{86}Sr$ values, Kaufman et al. (1992) suggested that the fossil-bearing portion of the Upper Tindir Group was deposited during the Cryogenian and is correlative with the Twitya Group in the Mackenzie Mountains. Since then, the age assignment of these microfossils has remained ambiguous; consequently, these unique forms have not been fully integrated into the framework of early eukaryotic diversification.

STRATIGRAPHY

The Tindir Group is exposed in the Tatonduk inlier, a wedge of the relatively unmetamorphosed Laurentian margin, which straddles the Alaska-Yukon border (Fig. DR1 in the GSA Data Repository[1]). Herein we follow Payne and Allison's (1981) original, and commonly used (e.g., Young, 1982; Rainbird et al., 1996), separation of the Lower and Upper Tindir Groups, which is a useful distinction for regional correlation schemes as it roughly corresponds to the boundary between the Mackenzie Mountains and Windermere Supergroups of the Canadian Cordillera.

Lower Tindir Group

The Lower Tindir Group is as much as 2 km thick, although the base of the lowest unit is nowhere exposed. The informal "lower shale" unit begins with gray to black mudstone overlain by light gray quartzite that contains discontinuous stromatolite bioherms. The lower shale unit is unconformably overlain by the lower dolostone unit (Van Kooten et al., 1997), which consists of <350 m of carbonate dominated by branching to massive domal stromatolites. The informal "upper shale" unit consists of <500 m of fissile black shale with interbedded quartzite and carbonate. The uppermost unit of the Lower Tindir Group is the "upper dolostone," which is a yellow-weathering dolomite with common intraclast breccias, black chert nodules, shale interbeds, and molar tooth structures (Young, 1982). All units in the Lower Tinder Group are intruded by NNW-trending mafic dikes (Fig. 2).

Upper Tindir Group

Young (1982) separated the Upper Tindir Group into five informal units; we retain these unit distinctions, but we further subdivide unit 3 into units 3a and 3b, and unit 4 into units 4a and 4b (Fig. 3; Fig. DR2). The mafic volcanic rocks of unit 1 are as much as 200 m thick and consist chiefly of amygdaloidal pillow basalt and cherty hyaloclastic breccia, with minor tuff, shale, and conglomerate. Unit 2 is a stratified diamictite with a fine-laminated purple and red mudstone to siltstone matrix. Iron formation is also present near the top of the unit (Fig. DR3a). Clast size varies from

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[1]GSA Data Repository item 2010028, Figures DR1-DR4 and Table DR1, is available online at www.geosociety.org/pubs/ft2010.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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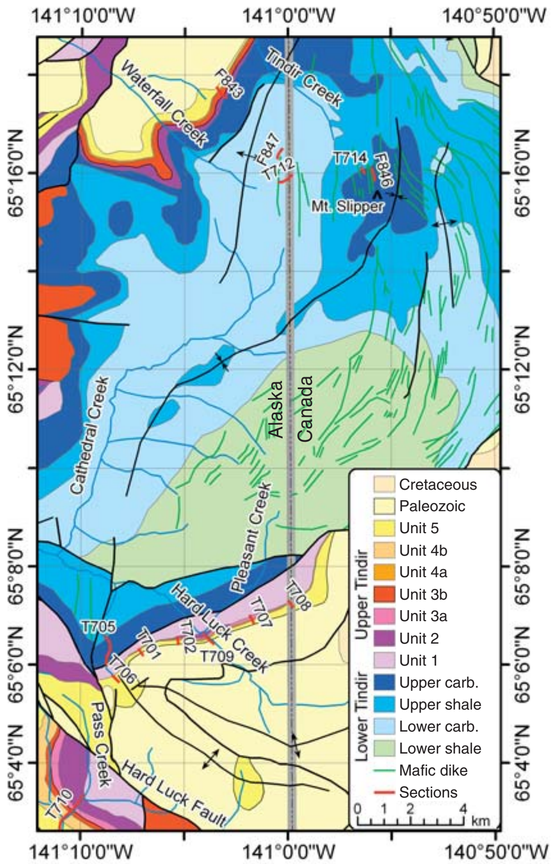

Figure 2. Geological map of Tatonduk inlier. Geology by F.A. Macdonald with modifications to Van Kooten et al. (1997).

gravel to boulders, the majority of which are dolomite from the Lower Tindir Group, but minor siltstone, quartzite, and basalt clasts are also present. The thickness of unit 2 varies along Hard Luck Creek from <50 m near the Yukon border to >700 m ~20 km downstream (Young, 1982). Unit 3 of Young (1982) has been divided into unit 3a, which is composed of >100 m of planar laminated siltstone and sandstone with minor dolomite marl, and unit 3b, which is a massive diamictite. Unit 3b is <250 m thick and contains faceted and striated clasts (Allison et al., 1981). Along Pass Creek (section T710), it is 50 m thick with boulders of dolomite, and cobbles of iron formation, siltstone, conglomerate, and volcanics in a pink marl matrix. On the east side of the Hard Luck fault, unit 3b is either absent, or represented by a dolomite-clast, dolomite-matrix breccia with minor basalt clasts and an erosional disconformity at the base. Unit 4a disconformably overlies, with a knife-sharp contact, all of the underlying units of the Upper Tindir Group. Unit 4a is <5 m thick and is composed of a white to buff colored dolomite, commonly with isopachous, bed-parallel cements that are contorted and buckled to form pseudo-tepee structures (Young, 1982). It is succeeded by <50 m of planar-laminated siltstone, sandstone, and dolomitic marl that is referred to herein as unit 4b. Unit 5, the uppermost unit of the Upper Tindir Group, is composed largely of black shales with minor allodapic limestone. Unit 5 also displays a major stratigraphic expansion across the Hard Luck fault ranging from 40 to 75 m thick northeast of the structure to ~700 m thick along the Tatonduk River. In contrast to the Lower Tindir Group, none of the Upper Tindir Group exposures above unit 1 contains mafic intrusions.

Fossiliferous Section at Mount Slipper

At Mount Slipper, ~670 m of mixed carbonate and shale are exposed on the east flank of an anticline, above a valley that drains to Tindir Creek. In the core of the anticline on the west side of the valley, the lower carbonate unit of the Lower Tindir Group structurally underlies the Mount

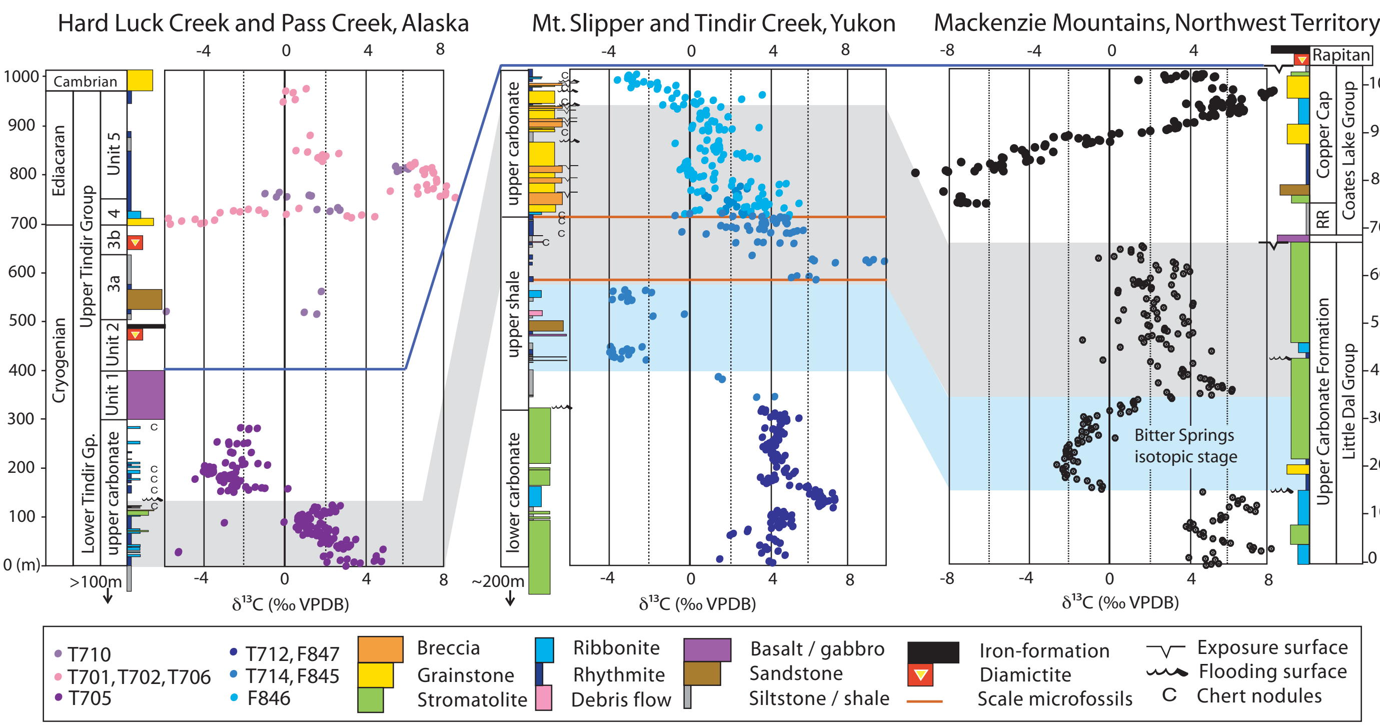

Figure 3. Chemostratigraphy and lithostratigraphy of Tindir Group exposed between Pass Creek and Hard Luck Creek in Alaska, Mount Slipper section in Yukon Territory, and Upper Carbonate Formation of Little Dal Group and Coates Late Group from Halverson et al. (2007). Thickness of Upper Tindir Group units 1–3b is based on section T710 along Pass Creek, and thicknesses of units 4a, 4b, and 5 are from sections T701, T702, and T706. Other sections are stretched to fit these sections. See Figure DR2 (see footnote 1) for chemostratigraphy and lithostratigraphy of individual sections of Upper Tindir Group. Locations of sections are in Figure 2. VPDB—Vienna Peedee belemnite.

Slipper section, (Figs. 2 and 3, sections T712, F847). Above tens of meters of nonexposure, the Mount Slipper section begins with ~143 m of fissile black shale containing minor thin (~10 cm thick) yellow dolostone interbeds and mafic sills. These are overlain by ~21 m of fine- to medium-grained sandstone with mud chips. The succeeding ~48 m consists predominantly of fissile black shale with dolomite olistostromes. This second shale interval is overlain by ~173 m of dark gray limestone rhythmite with interbedded shale and tabular clast debris flows. The mineralized microfossils are in early diagenetic black chert nodules (Fig. DR3d) from ~3 m of section near the top of this unit (Fig. 3). These facies are interpreted as subtidal in a shallowing-upward sequence. The rhythmite is overlain by ~144 m of buff to light gray weathering dolo-grainstone with common microbialaminite and intraclast breccia, a flooding surface with ~22 m of green shale, and an additional ~121 m of dolostone that forms the ridge of Mount Slipper. The entire section is intruded by numerous NNW-trending mafic dikes (Fig. 2; Fig. DR3c).

The lower black shale and limestone rhythmite have previously been mapped as unit 5 of the Upper Tindir Group, and the upper dolostone with green shale as the Cambrian Jones Ridge Formation (Allison, 1981; Norris, 1978; Young, 1982). Following the stratigraphy exposed at Mount Slipper westward, across the international border, we found that equivalent strata are underlain by the lower carbonate unit of the Lower Tindir Group, albeit with the upper shale unit truncated along a faulted contact, and overlain by units 2, 3b, and 4a of the Upper Tindir Group (Fig. 2, section F843). We thus reassigned the stratigraphy exposed at Mount Slipper to the upper shale and upper carbonate units of the Lower Tindir Group. The disagreement with the unit assignment at Mount Slipper stems from the fact that the mixed shale-limestone to dolomite transition at the top of unit 5 of the Upper Tindir Group is lithologically very similar to that at top of the upper shale unit of the Lower Tindir Group. This is compounded by structural complications and imperfect exposures. Thus, we further employed chemostratigraphic methods to test our proposed correlation.

CHEMOSTRATIGRAPHY

While mapping, we collected samples for $\delta^{13}C$, $\delta^{18}O$, $^{87}Sr/^{86}Sr$, and elemental analyses within measured stratigraphic sections (Figs. 3 and DR2). More than 650 samples were processed and analyzed using standard laboratory procedures (see Table DR1).

Strontium Isotopes

We report 19 new $^{87}Sr/^{86}Sr$ measurements from the Tindir Group, adding to the 2 measurements made by Kaufman et al. (1992). In Table 1, we list "very reliable" data based on Sr concentration (here >500 ppm), because most alteration pathways decrease Sr concentration, thus increasing the susceptibility to overprinting (Banner and Hanson, 1990). We also include "moderately reliable" data based on Sr concentration and relatively low $^{87}Sr/^{86}Sr$ (Fig. DR4). Diagenetic overprinting usually increases $^{87}Sr/^{86}Sr$ (Banner and Hanson, 1990), and consequently, low values (here <0.7068) are likely near primary values.

In the Lower Tindir Group on the Alaskan side of the border (section T705), moderately reliable $^{87}Sr/^{86}Sr$ data range from 0.70651 to 0.70679 (n = 2). In the Upper Tindir Group on the Alaskan side of the border (section T710), very reliable $^{87}Sr/^{86}Sr$ data range from 0.70737 to 0.70744 (n = 3). In the fossiliferous section at Mount Slipper, very reliable $^{87}Sr/^{86}Sr$ data range from 0.70658 to 0.70693 (n = 2) and moderately reliable data range from 0.70641 to 0.70652 (n = 4). These data are similar to those reported by Kaufman et al. (1992).

DISCUSSION

Regional and Global Correlations

The fossiliferous Mount Slipper section can be correlated with the fault-bounded exposures of the Lower Tindir Group in Alaska. This correlation is supported by map relationships and the presence of mafic dikes that regionally cut only the Lower Tindir Group. Moreover, $\delta^{13}C$ profiles and $^{87}Sr/^{86}Sr$ values through the Mount Slipper section are more similar to those of the Lower Tindir Group (Table 1); additional scatter in the $\delta^{13}C$ profile in the upper carbonate at Mount Slipper may be attributable to the presence of multiple exposure surfaces and interclast breccia (Fig. 3, section F846).

TABLE 1. LEAST ALTERED Sr ISOTOPE DATA FROM THE LOWER TINDIR GROUP, THE UPPER TINDIR GROUP, AND THE MOUNT SLIPPER SECTIONS

Section	Height (m)	Sr (ppm)	$^{87}Sr/^{86}Sr$
Lower Tindir Group, upper carbonate unit			
T705	6.1	418	0.706793
T705	13.0	256	0.706507
Upper Tindir Group, unit 5			
T710	401.0	1015	0.707369
T710	404.0	1164	0.707373
T710	406.0	631	0.707442
Mount Slipper Section			
T714	168.0	628	0.706934
T714	293.0	222	0.706519
T714	305.0	172	0.706472
T714	307.0	291	0.706412

Note: See Table DR1 (see footnote 1) for complete data. Stratigraphic datum is measured from lowest exposures at each section, and is depicted in Figure 3 and Figure DR2. Scale microfossils are present in section T714 at meters 256.0, 310.0, 312.8, and 313.2.

Fossiliferous cherts were collected in section T714 between meters 256.0 and 313.2 (measured from the lowest exposures in the valley). The 0.7064 value from meter 307.0 is in a continuous rhythmite sequence to meter 318.0 with no evidence of an erosional unconformity. Young (1982) documented a possible stratigraphic break in the Mount Slipper sections; however, this putative surface is at the limestone-dolostone transition, above the rhythmite, and thus has little effect on our reinterpretation of the age of the microfossils.

The $\delta^{13}C$ profile from the fossiliferous section at Mount Slipper can be correlated with that of the Upper Carbonate Formation of the Little Dal Group (Fig. 3). These correlations are supported by the least-altered (lowest) $^{87}Sr/^{86}Sr$ values of ~0.7064 from the Lower Tindir Group that are similar to those in the Little Dal and Coates Lake Groups (Halverson et al., 2007), and the upper portion of the pre–718 Ma Shaler Supergroup (Asmerom et al., 1991). These $^{87}Sr/^{86}Sr$ values are also less radiogenic than any values from Ediacaran carbonates reported to date (Halverson et al., 2007).

The chemostratigraphic position of the microfossils is below that of the Little Dal basalt in the Mackenzie Mountains, which has been correlated with the 777 +2.5/–1.8 Ma Tzetzone sills (Jefferson and Parrish, 1989). A more robust minimum age constraint on the scale microfossils is provided by unit 2 of the Upper Tindir Group, which is above equivalent strata on the west limb of the anticline that straddles the international border near Tindir Creek (Fig. 2). Lithologically, unit 2 is extremely similar to the clast-poor diamictite and iron formation of the Sayunei Formation in the Rapitan Group (Young, 1982). A maximum age of the Rapitan Group is provided by a 755 ± 18 Ma U-Pb zircon age from a leucogranite dropstone near the base of the Sayunei Formation (Ross and Villeneuve, 1997). Sensitive high-resolution ion microprobe (SHRIMP) ages have been reported from within and above diamictites of the Pocatello Formation (Fanning and Link, 2004), previously correlated with the Rapitan Group, but these ages have recently come into question, both on the grounds of the quality of the analyses and the geological context, as the contacts between the Bannock Volcanics and glacial deposits at Oxford Mountain are tectonic and repeated analyses have given very different results (Fanning and Link, 2008).

Higher in the succession, the upper diamictite of the Upper Tindir Group, unit 3b, can be tied to the 635 Ma end-Cryogenian glaciation (Hoffmann et al., 2004). This correlation is particularly attractive because unit 3b is overlain with the buff colored unit 4a cap dolomite, which contains sheet-crack cements and a negative carbon isotope anomaly, and is evocative of the basal Ediacaran Ravensthroat cap dolomite in the Mackenzie Mountains (Aitken, 1991; James et al., 2001).

Paleobiological Implications

Microfossils, including cyanobacterial coccoids, acritarchs such as *Trachyhystrichosphaera* and *Cymatiosphaeroides*, putative vase-shaped microfossils, and the enigmatic mineralized scale microfossils (Allison and Awramik, 1989; Allison and Hilgert, 1986), have previously been described in cherts from the Mount Slipper section. Allison and Awramik (1989) suggested that these fossils were early Cambrian or latest Ediacaran in age, yet this interpretation is inconsistent with the organic-walled assemblage, a combination of forms that has only been observed in pre-Ediacaran strata (Knoll et al., 2006).

Plausible taxonomic affinities for the enigmatic mineralized microfossils include modern scale-forming groups such as chrysophytes, haptophytes, and members of the heliozoa. While taxonomic interpretation of the Lower Tindir Group microfossils is ongoing, none of these candidate groups currently have unambiguous pre-Mesozoic fossil records (Graham and Wilcox, 2000), indicating that one of these clades likely has a much deeper fossil history than previously acknowledged. Regardless of specific taxonomic affinity, our reassignment of the rock unit containing the mineralized microfossils to the early Neoproterozoic Lower Tindir Group is consistent with current information about the timing of early eukaryotic diversification. Multiple early Neoproterozoic successions, including the Lower Tindir Group, contain diverse protistan and algal fossils indicating that major branches of the eukaryotic tree had diverged by the time of the early Cryogenian glaciations (Javaux et al., 2003; Porter, 2004).

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