Chapter 35

The Tatonduk inlier, Alaska–Yukon border

FRANCIS A. MACDONALD* & PHOEBE A. COHEN

Department of Earth and Planetary Sciences, Harvard University, Cambridge, MA 02138, USA

**Corresponding author (e-mail: fmacdon@fas.harvard.edu)*

Abstract: Glaciogenic deposits of the Rapitan and Hay Creek Groups are exposed in the Tatonduk inlier of east-central Alaska and the western Yukon. The Rapitan Group ranges in thickness from *c.* 50 to 700 m with Fe-formation common in the upper 10 m. In the most distal settings, the Rapitan Group is separated from the diamictite of the Hay Creek Group by over 100 m of sandstone and siltstone; however, the Hay Creek Group contains large erosive surfaces and cannibalizing breccia, and rarely preserves strata between the two glaciogenic deposits. The diamictite of the Hay Creek Group is capped by a white- to buff-coloured dolostone with pseudo-teepee structures, bed-parallel, isopachous sheet-crack cements, and a depleted C-isotope signature. Late Neoproterozoic glacial deposits in the Tatonduk inlier were formerly assigned to the Tindir Group. To simplify the nomenclature in the northwestern Canadian Cordillera, the Tindir Group was abandoned and replaced with nomenclature consistent with that of the Windermere Supergroup in the Mackenzie Mountains. The mixed lithology and anchizone-grade metamorphism distinguish the Rapitan and Hay Creek Groups in the Tatonduk inlier as attractive future targets for integrated micropalaeontology, geochemistry, palaeomagnetism and geochronology.

Cairnes (1914) referred to Precambrian stratigraphy exposed along the international border between the United States and Canada as the Tindir Group. Mertie (1930, 1933) later described the stratigraphy (and natural history of the region) in remarkable detail and divided the Tindir Group into seven units. Brabb & Churkin (1969) produced an excellent map of the geology on the Alaskan side of the border, while the Tindir Group was mapped on the Yukon side of the border by Norris (1982); however, exact correlations of specific units of the Tindir Group across the border remained ambiguous until more recent mapping and compilation (Dover 1992; Van Kooten *et al.* 1997) and integrated litho- and chemostratigraphy (Macdonald *et al.* 2010*a*, *b*, 2011; Macdonald & Roots 2010). To improve the consistency of geological maps of the Yukon and promote the synthesis of geological data, Macdonald *et al.* (2011) reassigned the Lower Tindir Group to the Pinguicula and Fifteenmile Groups of the Mackenzie Mountains Supergroup and the Upper Tindir Group to the Rapitan, Hay Creek and 'upper' groups of the Windermere Supergroup (Figs 35.1 & 2).

The Upper and Lower Tindir Groups were first distinguished by Payne & Allison (1981), despite the fact that no unconformable contacts have been observed between the two (Young 1982). The Lower Tinder Group consists primarily of dolomite and shale that are commonly cut with north-trending mafic dykes (Van Kooten *et al.* 1997). Unlike the Lower Tindir Group, the units of the Upper Tindir Group are not cut by mafic dykes (Van Kooten *et al.* 1997). Young (1982) separated the Upper Tindir Group into five units in ascending stratigraphic order from unit 1 to unit 5: unit 1 consists primarily of mafic volcanic rocks; unit 2, purple mudstones and diamictite, including Fe-formation; unit 3, an additional massive diamictite; unit 4, platfomal dolomites and green to light grey shales; unit 5, grey to black shales and limestones. In the updated stratigraphic framework (Macdonald *et al.* 2011), unit 1 is renamed the Pleasant Creek volcanic rocks, unit 2 is the Rapitan Group, unit 3 and the 'teepee' dolomite at the base of unit 4 constitute the Hay Creek Group, and the rest of unit 4 and unit 5 are assigned to the 'upper' group. The informal upper group is a provisional name that encompasses the Sheepbed, Gametrail, Blueflower and Risky formations in the Mackenzie Mountains (e.g. Aitken 1989; Dalrymple & Narbonne 1996; MacNaughton *et al.* 2000, 2008) and equivalent strata in the Ogilvie Mountains (Macdonald *et al.* 2011).

Exposures of the Windermere Supergroup in the Tatonduk inlier are typically limited to the walls of creek beds. Allison *et al.* (1981) followed Mertie (1933) in designating the exposures along the Tatonduk River as the type locality of the diamictite-bearing units. This choice is due in part to the relative ease of access, but is problematic because of structural complications and the presence of a major disconformity under the diamictite in the Hay Creek Group. Owing to lack of exposure, the critical features of both diamictites are not present at one single locality. Along Pass Creek (Fig. 35.3), Fe-formation of the Rapitan Group and portions of both diamictites are exposed, but the overlying teepee dolomite is not present. Along Hard Luck Creek (Fig. 35.3), the contact between the Fe-formation and underlying diamictite can be observed, and the teepee dolomite is present, although the diamictite of the Hay Creek Group is not exposed. This lack of exposure coupled with the presence of multiple disconformities creates a significant challenge (and many uncertainties) in regional stratigraphic correlations.

Structural framework

Neoproterozoic diamictites of the Windermere Supergroup are exposed through an erosional window, referred to as the Tatonduk inlier, which extends across the Canadian border into Alaska (Fig. 35.2). Present exposures are the product of a mid-Cretaceous to Palaeogene foreland fold-and-thrust belt (Norris 1972) associated with the underplating of the Yakutat Block (Fuis *et al.* 2008). The Tatonduk inlier protrudes from the elbow of the Ogilvie deflection, where the orientation of folds and thrusts transition from north-vergent to west-vergent due to Cenozoic activity on the Kaltag fault and associated dextral transpressional structures (Norris 1972). Anchizone-grade metamorphism is suggested by the presence of economic oil deposits in the overlying Phanerozoic strata sourced in part from Palaeozoic shales (Van Kooten *et al.* 1997).

Late Neoproterozoic strata in the Tatonduk inlier are a northwestern continuation of the Windermere Supergroup in the Mackenzie (Aitken 1989), Wernecke (Pyle *et al.* 2004) and Ogilvie Mountains (Mustard & Roots 1997), for which deposition commenced with rifting of the northwestern margin of Laurentia (Stewart 1975). Neoproterozoic strata in the Tatonduk inlier have also been correlated with the Katakturuk Dolomite in the northeastern Brooks Range of Arctic Alaska (Rainbird *et al.* 1996); however, the Katakturuk Dolomite was likely deposited

From: Arnaud, E., Halverson, G. P. & Shields-Zhou, G. (eds) *The Geological Record of Neoproterozoic Glaciations*. Geological Society, London, Memoirs, **36**, 389–396. 0435-4052/11/$15.00 © The Geological Society of London 2011. DOI: 10.1144/M36.35

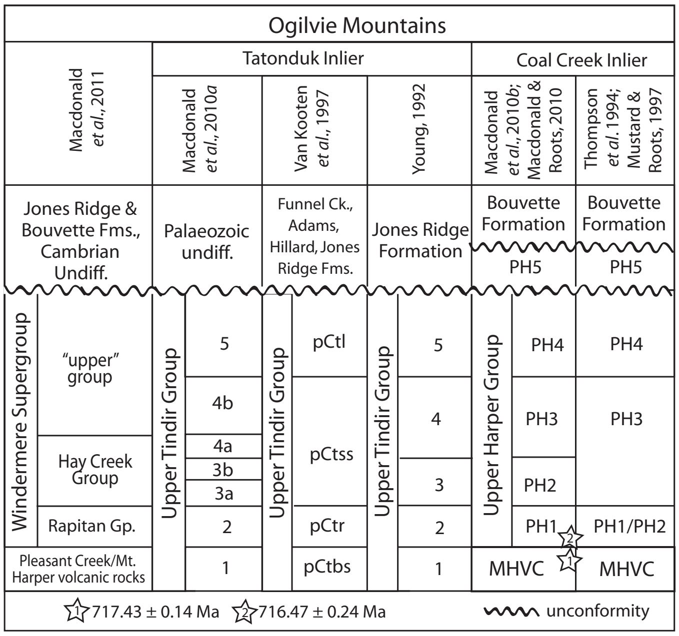

Fig. 35.1. Nomenclature chart depicting names used by different authors to describe Neoproterozoic stratigraphy in the Tatonduk and Coal Creek inliers. Dates are U–Pb CA-IDTIMS zircon ages (Macdonald *et al.* 2010*b*).

on a separate margin, as it is doubtful that the pre-Mississippian Arctic Alaska-Chukotka Plate was part of Laurentia (McClelland, 1997; Blodgett *et al.* 2002; Dumoulin *et al.* 2002).

Although unconformities have not been observed in the Windermere Supergroup of the Tatonduk inlier, multiple disconformities are present in the Hay Creek Group marked by erosional surfaces and breccias. The Hard Luck Creek Fault (HLF) marks an abrupt expansion of the stratigraphy, and can be extended to the SE into the Ogilvie Mountains where it has been named the Mt. Harper Fault, and roughly marks a former rift shoulder of the Laurentian margin (Mustard & Roots 1997). The HLF and other Precambrian faults in the region were inverted during mid-Cretaceous to Palaeogene shortening (Brabb & Churkin 1969; Van Kooten *et al.* 1997).

Stratigraphy

The stratigraphy of the diamictite-bearing units in the Tatonduk inlier was reviewed by Allison *et al.* (1981) and described in detail by Young (1982). Additional measured sections are presented in Macdonald *et al.* (2010*a*, supplementary material, 2010*b*, supplementary material, 2011). Diamictite of the Rapitan Group is underlain by the Pleasant Creek volcanic rocks, which are up to 200 m thick and consist chiefly of amygdaloidal pillow basalt and cherty hyaloclastic breccia, with minor tuff, shale and conglomerate. The Rapitan Group is composed primarily of fine-laminated purple and red mudstone and siltstone that are sprinkled with dolomite and basaltic lonestones. The upper *c.* 15 m of the Rapitan Group commonly hosts a massive diamictite and Fe-formation. The Rapitan Group is overlain by the Hay Creek Group, which is composed of up to 150 m of planar laminated siltstone and sandstone with minor dolomite marl, massive diamictite, and dolomite breccia capped by a white to buff-coloured dolostone with bed-parallel cements. The uppermost dolostone of the Hay Creek Group is less than 5 m thick and rests disconformably on all of the underlying units of the Windermere Supergroup and the Pleasant Creek volcanic rocks (Fig. 35.4). The upper group is composed largely of black shale with minor allodapic carbonate.

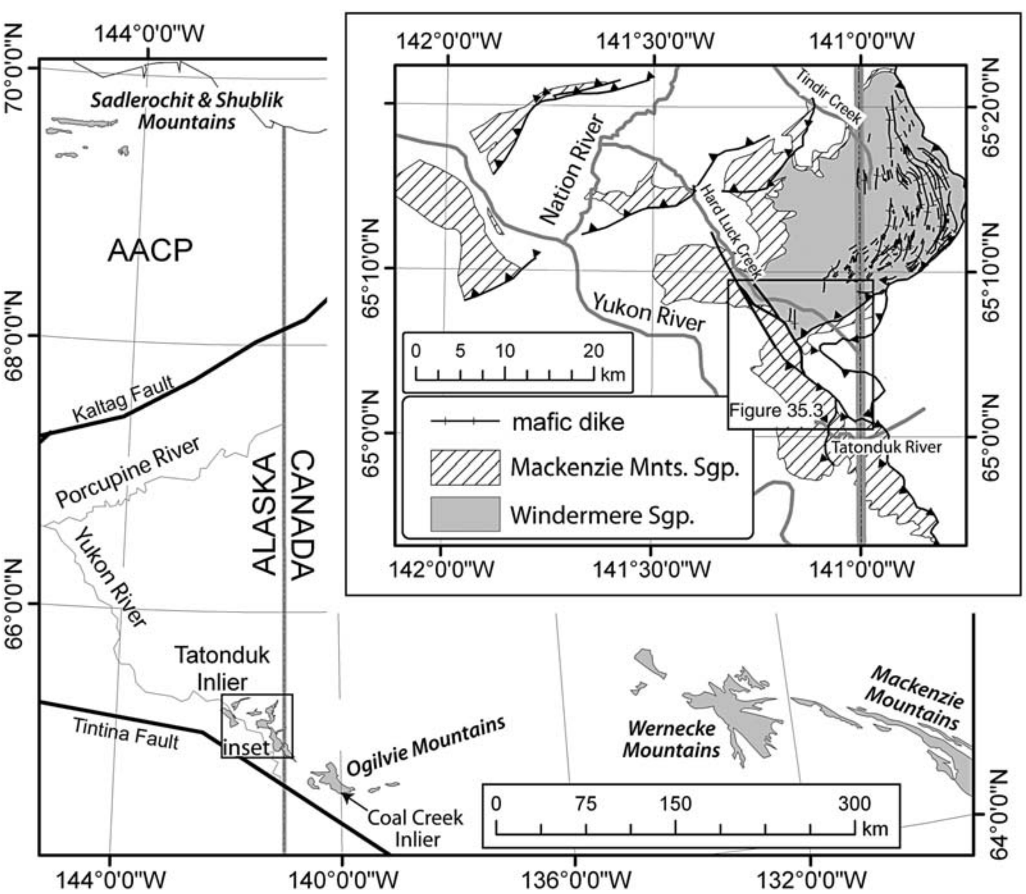

Fig. 35.2. Location map of the NW Cordillera with Cryogenian and Ediacaran strata in grey. AACP, Arctic Alaska-Chukotka Plate. Inset shows the distribution of the Mackenzie Mountains and Windermere Supergroups in the Tatonduk Inlier. Teeth on thrust faults.

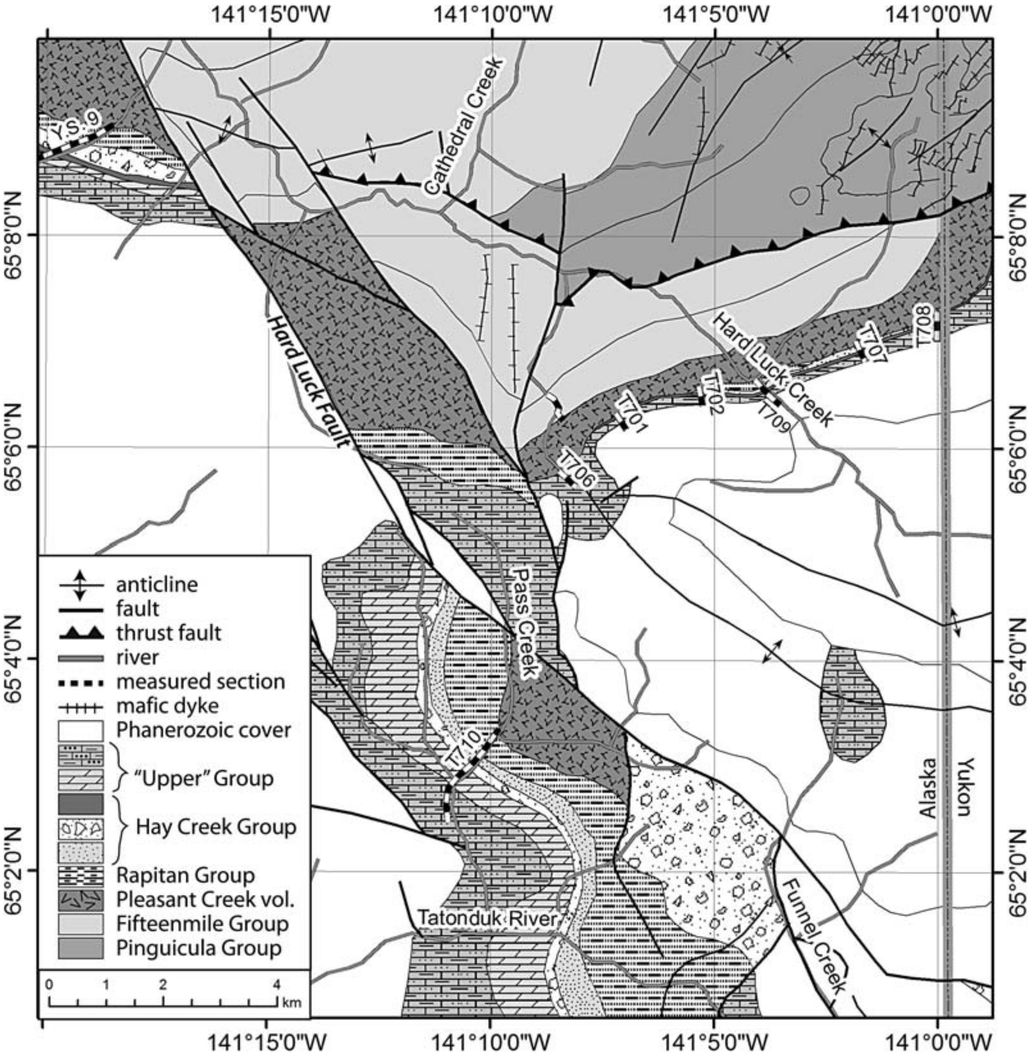

Fig. 35.3. Geological map of exposures along the Tatonduk River and Hard Luck Creek.

Glaciogenic deposits and associated strata

Rapitan Group

The Rapitan Group (formerly Upper Tindir unit 2) is exposed near the international border along Pleasant Creek and in outcrops close to the Tatonduk River (Macdonald *et al.* 2010*b*). These strata are chiefly composed of fine-laminated purple and red mudstone and siltstone speckled with dolomite gravel lonestones. Scattered throughout the siltstone are thin diamictite beds (<1 m) dominated by clasts of dolomite, clastic grit and volcanic cobbles. The Rapitan Group also contains faceted clasts, boulders with striations, slumped beds, flame structures, groove casts and flute structures (Young 1982). The upper *c.* 15 m of the Rapitan Group (Fig. 35.5a; section T709) hosts multiple *c.* 10-cm-thick beds of Fe-formation, which are interbedded with a laminated diamictite with bed-penetrating, outsized clasts. The majority of clasts in the Rapitan Group consist of dolomite derived from the underlying Fifteenmile Group. Where the upper contact of the Fifteenmile Group is exposed, it is overlain by a well-sorted, imbricated carbonate matrix conglomerate with abundant dolostone clasts of variable size, interpreted as a debris flow, which is followed by the parallel-bedded siltstone and sandstone of the Hay Creek Group. The thickness of the Rapitan Group varies greatly from <50 m near Pleasant Creek to >700 m *c.* 20 km to the NW (Young 1982). Palaeocurrent measurements in the interbedded siltstone suggest a west-facing margin (present coordinates) (Young 1982).

Calcareous concretions and jasper lenses are present in the Fe-formation, while foreign clasts are rare. Chemical analyses of the Fe-formation yield FeO concentrations up to 50%, high SiO_2/Al_2O_3, and depletions in most other elements, suggesting low clastic deposition and a chemical silica contribution (Young 1982).

Hay Creek Group (formerly units 3a, 3b and 4a of the Upper Tindir Group)

In the most western sections along Pass Creek (T710), the Rapitan Group is overlain by *c.* 140 m of planar bedded, siltstone, sandstone and marl. These beds lack any evidence of tidal influence, lack lonestones, are commonly stacked in fining-upward Bouma sequences, and as such, are interpreted as deep-water turbidites. The turbidite beds are succeeded by an additional diamictite unit, but the contact between the two is not exposed. In section T710 the diamictite of the Hay Creek Group is 22 m thick and consists of 10 m of massive diamictite, 10 m of laminated centimetre-beds of siltstone and an additional 2 m of stratified diamictite (Fig. 35.5b). The massive diamictite is clast-dominated with boulders of dolomite, and cobbles of Fe-formation, siltstone, conglomerate and basalt in a marly pink matrix. The bedded diamictite has the same clast composition as the rock below it, but clasts are slightly smaller with no boulders, and a matrix of purple silt. Approximately 20 km to the NW of Pass Creek (section Y.S. 9), still west of the HLF, the diamictite of the Hay Creek Group is poorly

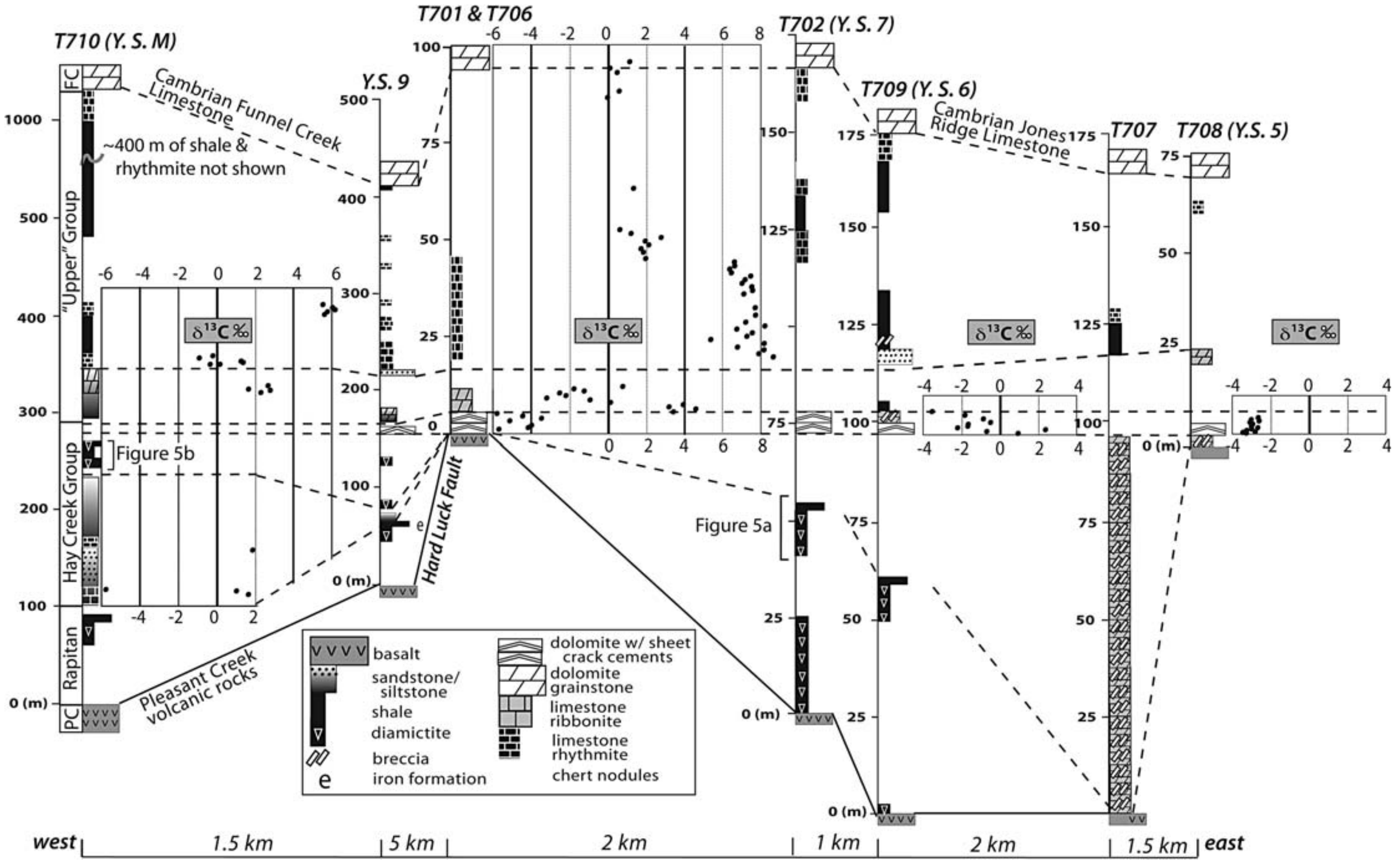

Fig. 35.4. Chemo- and lithostratigraphy of the ‘upper’ group in east-central Alaska. Y.S. indicates section from Young (1982). Sections have been projected along the Hard Luck Fault (i.e. to the NW) to an east–west line, with distances between sections estimated from the projection. Note the change in scale for two sections SW of the Hard Luck fault, which are approximately four times as thick as sections NE of the fault. See Figure 35.3 for section locations.

exposed, but lonestones *c.* 2 m in diameter are present, and the diamictite is capped by a buff-coloured dolostone (Young 1982).

Along the Tatonduk River, Young (1982) described a massive, over 250-m-thick, crudely stratified, purple diamictite interbedded with minor amounts of contorted purple mudstone and lenses of chert. We assign this diamictite to the Hay Creek Group. Clasts are up to 0.6 m across, and consist predominantly of dolomite from the Fifteenmile Group, with minor limestone, basalt and chert. Faceted and striated clasts have been described at this locality (Allison *et al.* 1981), but have not been observed elsewhere in the Tatonduk inlier. The diamictite of the Hay Creek Group is also very thick *c.* 20 km due north, NE of the HLF (Van Kooten *et al.* 1997), where it cuts down into the underlying stratigraphy.

Northeast of the HLF, the diamictite of the Hay Creek Group is either absent, or represented by a dolomite (matrix and clast) breccia. No foreign clasts have been identified with the exception of some clasts of the Pleasant Creek volcanic rocks near the base. This breccia cuts out the underlying units of the Windermere Group and rests on the Pleasant Creek volcanic rocks (Fig. 35.4).

The overlying dolomite, <5 m thick, rests disconformably on underlying units of the Hay Creek Group as well as the Pleasant Creek volcanic rocks and Rapitan Group strata. It is white to buff-coloured dolostone with bed-parallel cements (pseudo-teepee structures of Young 1982). These pseudo-teepees do not show a polygonal plan-form or a concentration of cements along the broken pieces, as is typical of teepees that are of a subaerial exposure origin (Kendall & Warren 1987). Instead, cements are isopachous and bed-parallel, and beds are contorted and irregularly buckled, suggesting intraformational detachment during deposition. Similar ‘sheet-crack’ cements are present in several basal Ediacaran cap carbonates globally (Hoffman & Macdonald 2010).

The ‘Upper’ Group

The Hay Creek Group is overlain by the ‘upper’ group (formerly units 4b and 5 of the Upper Tindir Group), which consists of as much as 50 m of planar laminated siltstone, sandstone and dolomitic marl, and an additional sequence of black shale interbedded with minor organic-rich limestone (Fig. 35.4; section T707). Like the underlying units, the ‘upper’ group displays a major stratigraphic expansion to the SW ranging from 40–75 m thick in the Yukon to *c.* 700 m thick along the Tatonduk River in Alaska (Macdonald *et al.* 2010*a*). Both Hay Creek and the ‘upper’ group strata are consistent with a SW-facing margin (present coordinates).

These ‘upper’ group units form the final clastic-carbonate cycle prior to deposition of the Cambrian sandstone (Backbone Ranges Formation) and the commencement of the miogeocline after break-up of Rodinia. This group completes Windermere Supergroup sedimentation and episodic extension.

Boundary relations with overlying and underlying non-glacial units

The basal contact of the Rapitan Group was not seen; however, volcanic fragments similar in composition to the underlying Pleasant Creek volcanic rocks are common in the lower half of the massive diamictite. The uppermost exposures of the Rapitan Group commonly consist of Fe-formation. At some localities the upper contact is exposed, and overlain by a well-sorted, dolomite

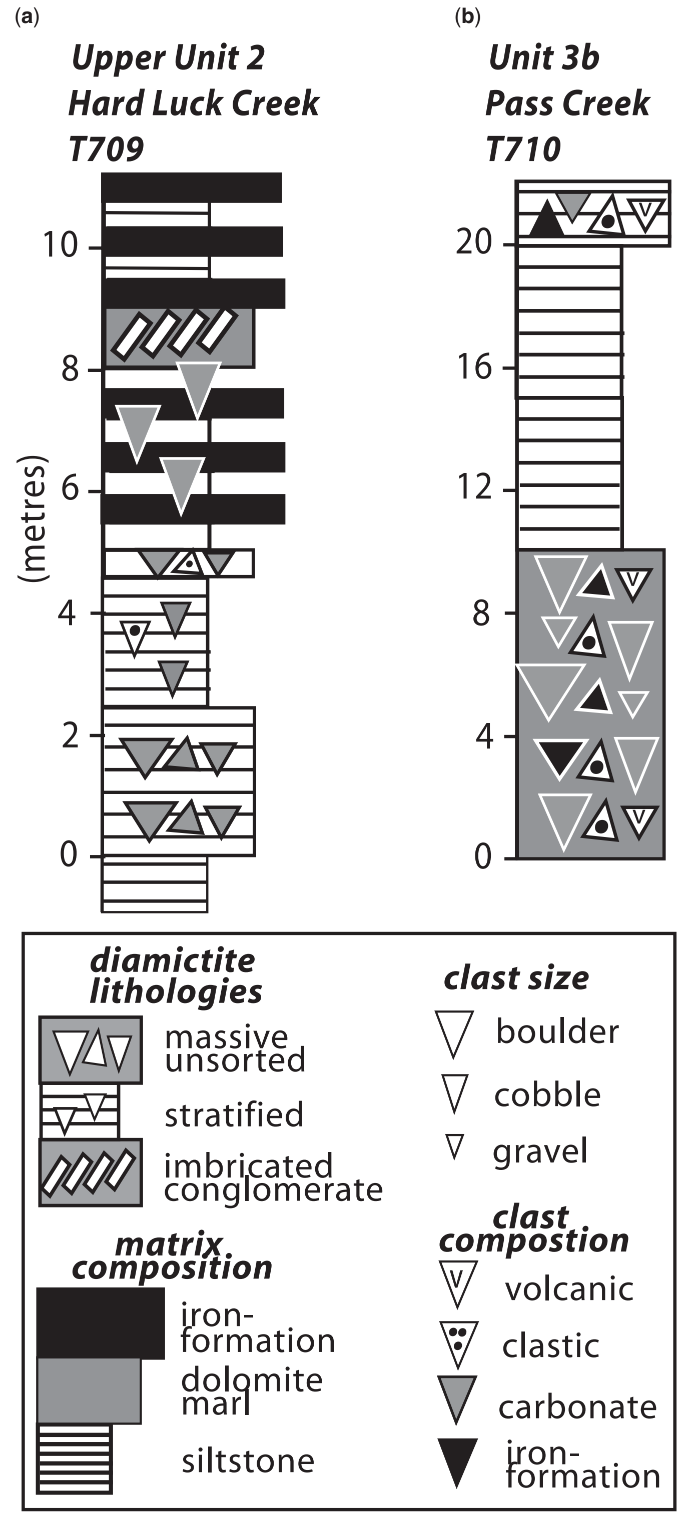

Fig. 35.5. (**a**) Stratigraphy of the Rapitan Group exposed along Hard Luck Creek, showing diamictite and its relationship to the Fe-formation. (**b**) Stratigraphy of the Hay Creek diamictite along Pass Creek, including diamictite and associated lithofacies. See Figure 35.3 for section locations.

clast, dolomite matrix diamictite, interpreted as a debris flow, which is followed by the parallel-bedded siltstone and sandstone with Bouma sequences of the Hay Creek Group.

Young (1982) interpreted the diamictite of the Hay Creek Group along the Tatonduk River as allochthonous in the sedimentary sense, having been derived from a more proximal setting to the east of the HLF in a massive slope failure, with an unconformable basal contact. Allison *et al.* (1981) interpreted this contact as an erosional disconformity. These interpretations are consistent with the erosional disconformity and breccia in the Hay Creek Group NE of the HLF where much of the underlying stratigraphy is missing. Although the top contact is not exposed SW of the HLF, to the NE the breccia is sharply overlain by the buff-coloured dolostone that defines the top of the Hay Creek Group.

Chemostratigraphy

Carbon-isotope values of the dolomite at the top of the Hay Creek Group are extremely depleted, although somewhat variable (Fig. 35.4; Macdonald *et al.* 2010*a*, supplementary data). Near the international border (section T708), values are consistently between −3‰ and −3.5‰, whereas near Hard Luck Creek (sections T701 and T709), values are more scattered, ranging from −6‰ to +2‰. In the 'upper' group, C-isotope values tend to be enriched (Fig. 35.4).

Carbon and Sr isotopes were reported from unit 5 of the Upper Tindir Group in Canada (Kaufman *et al.* 1992); however, these sections are actually correlative with the Fifteenmile Group (Macdonald *et al.* 2010*a*, *b*, 2011). The lowest Sr-isotope values from these sections are near 0.7064 (Macdonald *et al.* 2010*a*), a value that is typical for pre-Sturtian carbonate rocks (Halverson *et al.* 2007).

Palaeolatitude and palaeogeography

No palaeomagnetic studies have been reported from the Tatonduk inlier. Although the lithologies of Pleasant Creek volcanic rocks and the Rapitan Group (basalts and Fe-rich clastic sediments, respectively) are ideal targets, most palaeomagnetic studies in northern Alaska are compromised by a pervasive Late Cretaceous overprint (Plumley *et al.* 1989). However, palaeopoles on the Rapitan Group in the Mackenzie Mountains yield a palaeolatitude of $6 \pm 4^\circ$ (Park 1997). This pole is consistent with the grand mean pole on the contemporaneous Franklin LIP (Denyszyn *et al.* 2009), and demonstrates that Laurentia straddled the equator during deposition of the Rapitan Group (Macdonald *et al.* 2010*b*). Although Laurentia remained at low latitudes until 615 Ma according to the controversial Long Range Dyke pole (Murthy *et al.* 1992; Hodych *et al.* 2004), Laurentia appears to have migrated to high latitudes by 590 Ma (Murthy 1971). McCausland *et al.* (2007) provide an excellent review of the Ediacaran palaeomagnetic data from Laurentia.

Geochronological constraints

Radiometric data

The NNW-trending mafic dykes that intrude the Fifteenmile Group in the Tatonduk inlier have yielded a wide range of K–Ar biotite and whole-rock ages: 532 ± 11 Ma, 572 ± 16 Ma, 588 ± 14 Ma and 644 ± 18 Ma (Van Kooten *et al.* 1997). These dykes have not been observed to intrude any of the Windermere Supergroup units and are possibly feeder dykes for the Pleasant Creek volcanic rocks. Because alteration can lead to argon loss (Westcott 1966), these dates are minimum age constraints for the Fifteenmile Group.

Along strike to the east in the Coal Creek inlier (Fig. 35.3), Rapitan Group correlatives rest above the Mt. Harper volcanic complex (MHVC). Zircons extracted from rhyolite in member D of the MHVC were dated at 717.43 ± 0.14 Ma, and zircons from a tuff within the Rapitan Group correlatives were dated at 716.47 ± 0.24 Ma (U–Pb ID-TIMS; Macdonald *et al.* 2010*b*). In the Rapitan Group of the Mackenzie Mountains, a clast of leucogranite in the Rapitan Group has a U–Pb TIMS bulk zircon age of 755 ± 18 Ma (Ross & Villeneuve 1997).

Micropalaeontology

Fossils interpreted as microscopic flatworm impressions by Allison (1975), but possibly sponge spicules (Andy Knoll pers. comm.), have been described in the shale interbedded with basalt in the lower portion of the Windermere Supergroup. It is not clear if these samples were collected from the Pleasant Creek volcanic rocks, Rapitan Group or the Hay Creek Group, as they are reported in the 'basalt and red beds' unit of Brabb & Churkin (1969), which incorporates all three. Recent biomarker work suggests that the presence of sponge spicules in the Windermere Supergroup is not inconsistent with a Cryogenian age (Love *et al.* 2009). Microfossils have also previously been described in chert of Fifteenmile Group (in strata previously mis-mapped as unit 5 of the Upper Tindir Group; Macdonald *et al.* 2010*a*), including cyanobacterial coccoids, acritarchs such as *Trachyhystrichosphaera*, vase-shaped microfossils and unique, enigmatic siliceous scales (Allison 1980; Allison & Hilgert 1986; Allison & Awramik 1989). More recent studies have extracted these microfossils from the surrounding carbonate rock, and have demonstrated that they are composed of phosphate rather than silica, suggesting a green algae taxonomic affinity (Cohen *et al.* 2011). A pre-717 Ma for these fossils is supported by C- and Sr-isotope correlations (Macdonald *et al.* 2010*a*), the presence of dykes cutting the sections that are co-magmatic with the Pleasant Creek volcanic rocks, and geochronology of correlative rocks in the Coal Creek inlier (Macdonald *et al.* 2010*b*, 2011).

Discussion

Depositional setting

The Windermere Supergroup contains two Cryogenian glaciogenic deposits (Rapitan Group and the diamictite of the Hay Creek Group) separated by *c.* 140 m of non-glacial strata (Fig. 35.4). A glaciomarine depositional setting for the Rapitan Group is suggested by the presence of faceted and striated clasts, bed-penetrating dropstones, and common outsized and exotic clasts, along with evidence for subaqueous slumping in the form of graded grain flows and debris flows. Young (1988) ascribed the Fe-formations of the Rapitan Group, and equivalent strata in the Tatonduk inlier, to rift-related hydrothermal activity. However, these Fe-formations are intimately associated with well-developed dropstones. Presuming these diamictites were deposited during the terminal ice retreat, and presuming an increased solubility of iron in the ocean due to low oxygen levels under long-lived sea ice (Martin 1965), Fe-formation can be attributed to an influx of oxygenated fresh water concentrated at the termini of ice streams (Kirschvink 1992).

The parallel bedded sandstones and siltstones in the lower portion of the Hay Creek Group are interpreted as turbidites as

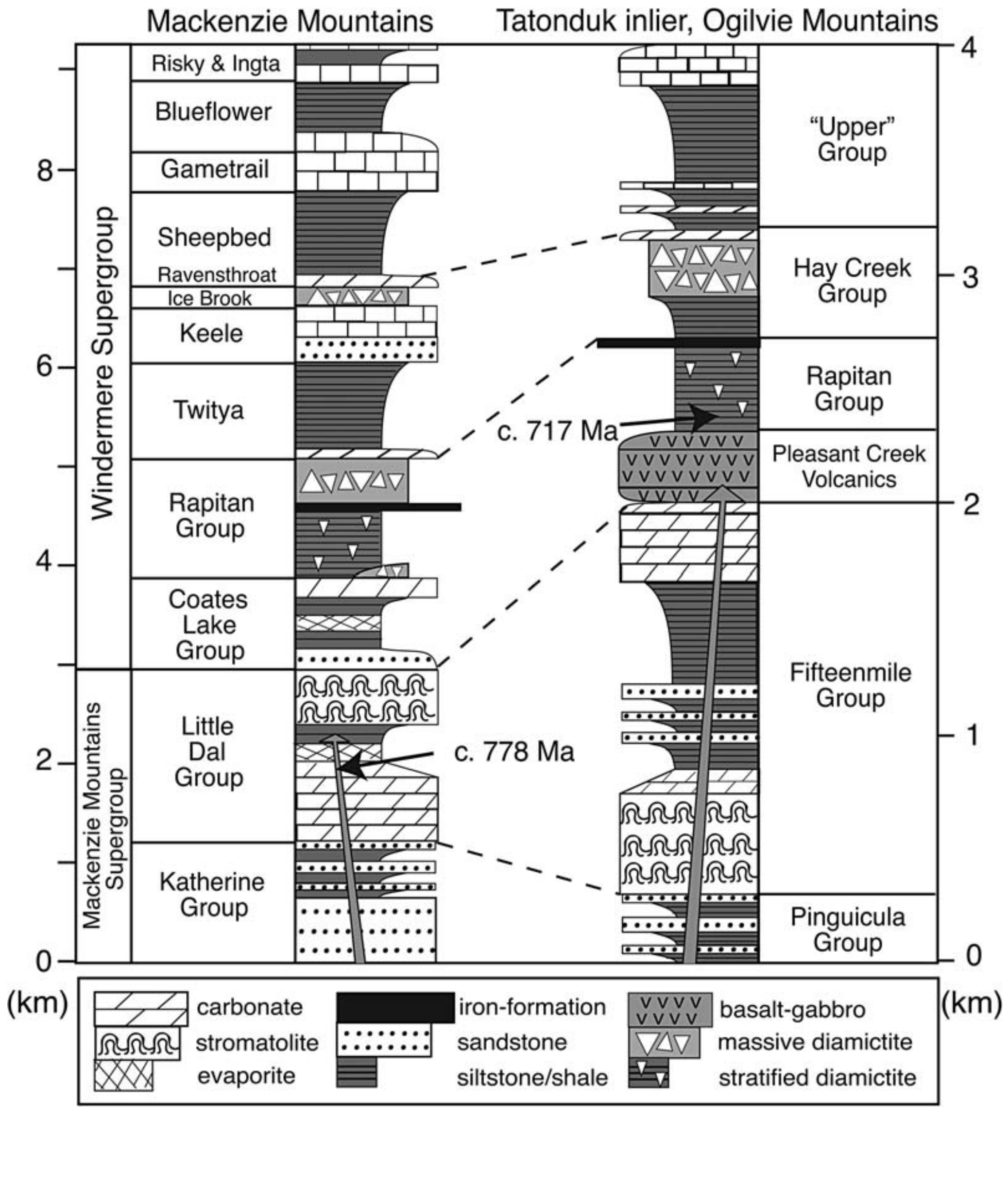

Fig. 35.6. Neoproterozoic stratigraphy in the Tatonduk inlier and correlations with the Windermere Supergroup exposed *c.* 500 km east in the Mackenzie Mountains of Canada. The schematic stratigraphy of the Windermere Supergroup is modified from Halverson *et al.* (2008). IRD mudstones are laminated fine-grained sediments with lonestones interpreted as ice rafted debris.

they lack any evidence of wave action or traction currents, and beds are stacked in fining-upward Bouma cycles. These green-grey turbidites are distinguished from the red and purple grain flows in the Rapitan Group by the lack of lonestones.

Young (1982) interpreted the diamictite of the Hay Creek Group SW of the HLF as the product of a massive slope failure, and identified an unconformity at the base. Nonetheless, there is evidence of a glaciomarine influence on deposition with the presence of striated clasts (Allison *et al.* 1981), and a well-bedded diamictite with dropstones near the top of Hay Creek Group along Pass Creek (Fig. 35.5b). A depositional setting along the upper slope, with diamictite being the product of syn-glacial slope failure, is consistent with the interpretation that the expansion of the stratigraphy of all of the Windermere Supergroup across the HLF roughly approximates the slope–shelf transition.

From outcrops along the Tatonduk River, Allison *et al.* (1981) cited deformation in Rapitan Group sediments near the overlying disconformity to suggest that the underlying stratigraphy was unconsolidated at the time of deposition of the upper diamictite. However, slumps and syn-sedimentary folds are common throughout the Rapitan Group (Young 1982), so this deformation in the Rapitan Group may be syn-sedimentary or the product of grounded ice during the Rapitan glaciation.

Regional correlations

Another line of evidence that the upper diamictite represents a second, later glacial event is that it is overlain with a buff-coloured dolostone. The latter is considered a basal Ediacaran cap carbonate as it contains bed-parallel, isopachous sheet-crack cements (Hoffman & Macdonald 2010) and a C-isotope profile similar to that of thin basal Ediacaran cap carbonates in China (Zhou & Xiao 2007), Australia (Kennedy 1996) and Namibia (Halverson *et al.* 2005).

Lithologically, the Rapitan Group in the Tatonduk inlier is very similar to the clast poor siltstone and Fe-formation of the Sayunei Formation in the Mackenzie Mountains (Young 1976; Yeo 1984). The diamictite of the Hay Creek Group can be correlated with the Ice Brook Formation (Fig. 35.6). This correlation is particularly attractive because the carbonate at the top of the Hay Creek Group shares sedimentological and isotopic characteristics with the Ravensthroat cap dolomite in the Mackenzie Mountains (Aitken 1991; James *et al.* 1999).

Regional correlations of Neoproterozoic strata in NW Canada are particularly important in light of the recent geochronological constraints provided by volcanic tuffs interbedded with the Fifteenmile and Rapitan Groups in the Ogilvie Mountains (Macdonald *et al.* 2010*b*). Coupled with the robust palaeomagnetic poles in NW Canada (Evans 2000; Denyszyn *et al.* 2009) and the rich micropalaeontological record in the Tatonduk inlier (Allison & Arwimik 1989; Macdonald *et al.* 2010*b*), the inliers of the Ogilvie Mountains hold great promise of a calibrated record of tectonics, climate, chemistry and life in Cryogenian oceans.

We are grateful to the Yukon Geological Survey, the Department of Earth and Planetary Sciences, Harvard University, P. Hoffman, A. Knoll and the NSF for support. We thank R. B. Blodgett and D. Jones for helpful discussions. We also thank the YUCH National Park office in Eagle for allowing access to the field area. This represents a contribution of the IUGS- and UNESCO-funded IGCP (International Geoscience Programme) project #512.

References

Aitken, J. D. 1989. Uppermost Proterozoic formations in central Mackenzie Mountains, Northwest Territories. *Geological Survey of Canada Bulletin*, **368**, 1–26.

Aitken, J. D. 1991. The Ice Brook Formation and Post-Rapitan, Late Proterozoic glaciation, Mackenzie Mountains, Northwest Territories. *Geological Survey of Canada Bulletin*, **404**, 1–43.

Allison, C. W. A. 1975. Primitive fossil flatworm from Alaska: new evidence bearing on ancestry of the Metazoa. *Geology*, **3**, 649–653.

Allison, C. W. A. 1980. Siliceous microfossils from the lower Cambrian of northwest Canada: possible source for biogenic chert. *Science*, **211**, 53–55.

Allison, C. W. A. & Hilgert, J. W. 1986. Scale micro-fossils from the Early Cambrian of northwest Canada. *Journal of Paleontology*, **60**, 973–1015.

Allison, C. W. A. & Awramik, S. M. 1989. Organic-walled microfossils from earliest Cambrian or latest Proterozoic Tindir Group rocks, northwest Canada. *Precambrian Research*, **43**, 253–294.

Allison, C. W. A., Young, G. M., Yeo, G. M. & Delaney, G. D. 1981. Glaciogenic rocks of the Upper Tindir Group, east-central Alaska. *In*: Hambrey, M. J. & Harland, W. B. (eds) *Earth's Pre-Pleistocene Glacial Record*. Cambridge University Press, Cambridge, 720–723.

Blodgett, R. B., Rohr, D. M. & Boucot, A. J. 2002. Paleozoic links among some Alaskan accreted terranes and Siberia based on megafossils. *In*: Miller, E. L., Grantz, A. & Klemperer, S. L. (eds) *Tectonic Evolution of the Bering Shelf–Chukchi Sea–Arctic Margin and Adjacent Landmasses*. Geological Society of America Special Paper 360, Boulder, Colorado, 273–290.

Brabb, E. E. & Churkin, M. J. 1969. *Geologic Map of the Charley River Quadrangle, East-Central Alaska*. U.S. Geological Survey Map **I-573**.

Cairnes, D. D. 1914. *The Yukon-Alaska International Boundary Between Porcupine and Yukon Rivers*. Geological Survey of Canada Memoir 67, Map **140-A**.

Cohen, P. A., Schopf, J. W., Butterfield, N. J., Kudryaytsev, A. & Macdonald, F. A. 2011. Phosphate biomineralization in mid-Neoproterozoic protists. *Geology*, **39**, 539–542.

Dalrymple, R. W. & Narbonne, G. M. 1996. Continental slope sedimentation in the Sheepbed Formation (Neoproterozoic, Windermere Supergroup), Mackenzie Mountains, N.W.T. *Canadian Journal of Earth Sciences*, **33**, 848–862.

Denyszyn, S. W., Halls, H. C., Davis, D. W. & Evans, D. A. D. 2009. Paleomagnetism and U–Pb geochronology of Franklin dykes in High Arctic Canada and Greenland: a revised age and paleomagnetic pole for constraining block rotations in the Nares Strait region. *Canadian Journal of Earth Sciences*, **46**, 689–705.

Dover, J. H. 1992. *Geologic map and fold and thrust belt interpretation of the south eastern part of the Charley River Quadrangle, East Central Alaska*. US Geological Survey Miscellaneous Investigations, Map **I-1942**, scale 1:100,000, 2 sheets.

Dumoulin, J. A., Harris, A. G., Gagiev, M., Bradley, D. C. & Repetski, J. E. 2002. Lithostratigraphic, conodont, and other faunal links between lower Paleozoic strata in northern and central Alaska and northeastern Russia. *In*: Miller, E. L., Grantz, A. & Klemperer, S. L. (eds) *Tectonic Evolution of the Bering Shelf–Chukchi Sea–Arctic Margin and Adjacent Landmasses*. Geological Survey of America Special Paper 360, Boulder, Colorado, 291–312.

Evans, D. A. D. 2000. Stratigraphic, geochronological and paleomagnetic constraints upon the Neoproterozoic climatic paradox. *American Journal of Science*, **300**, 347–433.

Fuis, G. S., Moore, T. E. *et al.* 2008. Trans-Alaska Crustal Transect and continental evolution involving subduction underplating and synchronous foreland thrusting. *Geology*, **36**, 267–270.

Halverson, G. P., Hoffman, P. F., Schrag, D. P., Maloof, A. C. & Rice, A. H. N. 2005. Toward a Neoproterozoic composite carbon-isotope record. *Geological Society of America Bulletin*, **117**, 1181–1207.

Halverson, G. P., Dudás, F. O., Maloof, A. C. & Bowring, S. A. 2007. Evolution of the $^{87}Sr/^{86}Sr$ composition of Neoproterozoic Seawater. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **256**, 103–129.

Hodych, J. P., Cox, R. A. & Kosler, J. 2004. An equatorial Laurentia at 550 Ma confirmed by Grenvillian inherited zircons dated by LAM ICP-MS in the Skinner Cove volcanics of western Newfoundland: implications for inertial interchange true polar wander. *Precambrian Research*, **129**, 93–113.

Hoffman, P. F. & Macdonald, F. A. 2010. Sheet-crack cements and early regression in Marinoan (635 Ma) cap dolostones: regional benchmarks of vanishing ice-sheets? *Earth and Planetary Science Letters*, **300**, 374–384.

James, N. P., Narbonne, G. M. & Kyser, K. T. 1999. *Neoproterozoic Cap Carbonate Facies; Mackenzie Mountains, NW Canada; Abiotic Precipitation and Global Glacial Meltdown*. Geological Society of America Abstracts with Programs, **31**, 487.

Kaufman, A. J., Knoll, A. H. & Awramik, S. M. 1992. Biostratigraphic and chemostratigraphic correlation of Neoproterozoic sedimentary successions: Upper Tindir Group, northwestern Canada, as a test case. *Geology*, **20**, 181–185.

Kendall, C. G. S. C. & Warren, J. 1987. A review of the origin and setting of teepees and their associated fabrics. *Sedimentology*, **34**, 1007–1027.

Kennedy, M. J. 1996. Stratigraphy, sedimentology and isotope geochemistry of Australian Neoproterozoic postglacial cap dolostones: deglaciation, $d^{13}C$ excursions and carbonate precipitation. *Journal of Sedimentary Research*, **66**, 1050–1064.

Kirschvink, J. L. 1992. Late Proterozoic low-latitude global glaciation: the snowball earth. *In*: Schopf, J. W. & Klein, C. (eds) *The Proterozoic Biosphere*. Cambridge University Press, Cambridge, 51–52.

Love, G. D., Fike, D. A. *et al.* 2009. Fossil steroids record the appearance of *Demospongiae* during the Cryogenian period. *Nature*, **457**, 718–722.

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

Macdonald, F. A., Cohen, P. A., Dudás, F. O. & Schrag, D. P. 2010*a*. Early Neoproterozoic scale microfossils in the Lower Tindir Group of Alaska and the Yukon Territory. *Geology*, **38**, 143–146.

Macdonald, F. A., Schmitz, M. D. *et al.* 2010*b*. Calibrating the Cryogenian. *Science*, **327**, 1241–1243.

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

MacNaughton, R. B., Narbonne, G. M. & Dalrymple, R. W. 2000. Neoproterozoic slope deposits, Mackenzie Mountains, northwestern Canada: implications for passive-margin development and Ediacaran faunal ecology. *Canadian Journal of Earth Sciences*, **37**, 997–1020.

MacNaughton, R. B., Roots, C. F. & Martel, E. 2008. Neoproterozoic–(?)Cambrian lithostratigraphy, northeast Sekwi Mountain map area, Mackenzie Mountains, Northwest Territories: new data from measured sections. *Geological Society of Canada, Current Research 2008*, **16**, 1–17.

Martin, H. 1965. Beobachtungen zum Problem der jung-präkambrischen Glazialen Ablagerungen in Südwestafrika. (Observations concerning the problem of the late Precambrian glacial deposits in South West Africa.) *Geologische Rundschau*, **54**, 115–127.

McCausland, P. J. A., Van der Voo, R. & Hall, C. M. 2007. Circum-Iapetus paleogeography of the Precambrian–Cambrian transition with a new paleomagnetic constraint from Laurentia. *Precambrian Research*, **156**, 125–152.

McClelland, W. C. 1997. Detrital zircon studies of the Proterozoic Neruokpuk Formation, Sadlerochit and Franklin Mountains, northern Alaska. *Geological Society of America Abstracts with Programs*, **25**, 28.

Meertie, J. B. 1930. Geology of the Eagle-Circle district, Alaska. *US Geological Survey Bulletin*, **816**, 121–122.

Meertie, J. B. 1933. The Tatonduk-Nation district, Alaska. *US Geological Survey Bulletin*, **836-E**, 345–454.

Murthy, G. S. 1971. The paleomagnetism of diabase dykes from the Grenville Province. *Canadian Journal of Earth Sciences*, **8**, 802–812.

Murthy, G. S., Gower, C. F., Tubrett, M. & Patzold, R. 1992. Paleomagnetism of Eocambrian Long Range dykes and Double Mer Mormation from Labrador, Canada. *Canadian Journal of Earth Sciences*, **29**, 1224–1234.

Mustard, P. S. & 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*, **492**.

Norris, D. K. 1972. En echelon folding in the northern Coldillera of Canada. *Bulletin of Canadian Petroleum Geology*, **20**, 634–642.

Norris, D. K. 1982. Geology, Ogilvie River, Yukon Territory, Geological Survey of Canada, Map 1526A, 1:250,000 scale.

Park, J. K. 1997. Paleomagnetic evidence for low-latitude glaciation during deposition of the Neoproterozoic Rapitan Group, Mackenzie Mountains, N.W.T., Canada. *Canadian Journal of Earth Sciences*, **34**, 34–49.

Payne, M. W. & Allison, C. W. A. 1981. Paleozoic continental-margin sedimentation in east-central Alaska. *Geology*, **9**, 274–279.

Plumley, P. W., Vance, M. S. & Milazzo, G. 1989. Structural and paleomagnetic evidence for Tertiary bending of the Eastern Brooks Range Flexure, Alaska. *In*: Hillhouse, J. W. (ed.) *Deep Structure and Past Kinematics of Accreted Terranes, Geophysical Monograph 50.* American Geophysical Union, Washington, DC, 127–150.

Pyle, L. J., Narbonne, G. M., James, N. P., Dalrymple, R. W. & Kaufman, A. J. 2004. Integrated Ediacaran chronostratigraphy, Wernecke Mountains, northwestern Canada. *Precambrian Research*, **132**, 1–27.

Rainbird, R. H., Jefferson, C. W. & Young, G. M. 1996. The early Neoproterozoic sedimentary Succession B of Northwestern Laurentia: correlations and paleogeographic significance. *Geological Society of America Bulletin*, **108**, 454–470.

Ross, G. M. & Villeneuve, M. E. 1997. U–Pb geochronology of stranger stones in Neoproterozoic diamictites, Canadian Cordillera: implications for provenance and ages of deposition. *Radiogenic age and isotopic studies, Report 10, Geological Survey of Canada, Current Research* **1997-F**, 141–155.

Stewart, J. H. 1975. Initial deposits in the Cordilleran geosyncline: evidence of a late Precambrian (<850 m.y.) continental seperation. *Geological Society of America Bulletin*, **83**, 1345–1360.

Van Kooten, G. K., Watts, A. B. *et al.* 1997. Alaska Division of Geological and Geophysical Surveys, Report of Investigations 96-6A, 3 sheets, scale 1:125,000, Fairbanks.

Westcott, M. R. 1966. Loss of argon from biotite in a thermal metamorphism. *Nature*, **210**, 83–84.

Yeo, G. M. 1984. *The Rapitan group: relevance to the global association of Late Proterozoic glaciation and iron-formation*. PhD thesis, University of Western Ontario, London, Ontario.

Young, G. M. 1976. Iron-formation and glaciogenic rocks of the Rapitan Group, Northwest Territories, Canada. *Precambrian Research*, **3**, 137–158.

Young, G. M. 1982. The late Proterozoic Tindir Group, east-central Alaska; evolution of a continental margin. *Geological Society of America Bulletin*, **93**, 759–783.

Young, G. M. 1988. Proterozoic plate tectonics, glaciation and iron-formations. *Sedimentary Geology*, **58**, 127–144.

Zhou, C. & Xiao, S. 2007. Ediacaran $\delta^{13}C$ chemostatigraphy of South China. *Chemical Geology*, **237**, 107–126.