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Upper Windermere Supergroup and the transition from rifting to continent-margin sedimentation, Nadaleen River area, northern Canadian Cordillera

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ABSTRACT

Neoproterozoic–Cambrian rocks of the Windermere Supergroup and overlying units record the breakup of Rodinia and formation of the northwestern Laurentian ancestral continental margin. Understanding the nature and timing of this transition has been hampered by difficulty correlating poorly dated sedimentary successions from contrasting depositional settings across Mesozoic structures. Here we present new litho- and chemo-stratigraphic data from a Cryogenian–lower Cambrian succession in east-central Yukon (Canada), establish correlations between proximal and distal parts of the upper Windermere Supergroup and related strata in the northern Canadian Cordillera, and consider implications for the formation of the northwestern Laurentian margin. The newly defined Nadaleen Formation hosts the first appearance of Ediacaran macrofossils, while the overlying Gametrail Formation features a large negative carbon isotope anomaly with $\delta^{13}C_{carb}$ values as low as –13‰ that correlates with the globally developed Shuram-Wonoka anomaly. We also define the Rackla Group, which includes the youngest (Ediacaran) portions of the Windermere Supergroup in the northern Cordillera. The top of the Windermere Supergroup is marked by an unconformity above the Risky Formation that passes into a correlative conformity in the Nadaleen River area. This surface has been interpreted to mark the top of the rift-related succession, but we draw attention to evidence for tectonic instability through the early-middle Cambrian and argue that the transition from rifting to post-rift thermal subsidence is marked by a widespread unconformity that underlies upper Cambrian carbonate rocks. This is younger than the interpreted age of the rift to post-rift transition elsewhere along the ancestral western Laurentian continental margin.

INTRODUCTION

Neoproterozoic to lower Cambrian rocks of the North American Cordillera (Fig. 1) record protracted rifting that led to breakup of the supercontinent Rodinia and formation of the early Paleozoic western Laurentian (Cordilleran) passive margin (Levy and Christie-Blick, 1991; Ross, 1991; Cecile et al., 1997; Lund, 2008; Yonkee et al., 2014). As well as being of regional tectonic importance, global significance attends these strata as they contain some of the best-preserved physical and geochemical manifestations of major environmental and ecological changes that characterize the Neoproterozoic–early Cambrian, including periods of widespread glaciation, the evolution of Ediacaran megafauna and metazoans, and secular changes in the composition of seawater (e.g., Narbonne and Hofmann, 1987; Narbonne and Aitken, 1995; Halverson et al., 2005; Macdonald et al., 2010, 2013; Sperling et al., 2016; Miller et al., 2017).

The Neoproterozoic–Terreneuvian Windermere Supergroup (Young et al., 1979) and correlative rocks are exposed intermittently throughout the western North American Cordillera from near the Alaska-Yukon border to northern Mexico (Ross, 1991; Lund, 2008; Yonkee et al., 2014; Fig. 1). Some of the most comprehensively studied exposures are located in the northern Canadian Cordillera within the Mackenzie, Ogilvie, and Wernecke mountains of Yukon and Northwest Territories (Figs. 1 and 2; Eisbacher, 1981; Aitken, 1989; Dalrymple and Narbonne, 1996; Pyle et al., 2004; MacNaughton et al., 2000; Halverson et al., 2005; Macdonald et al., 2013; Strauss et al., 2015). These rocks record mostly slope and platformal sedimentation, while little is known of their relationship to broadly age-equivalent rocks that formed in paleogeographically distal settings to their southwest.

More distal parts of the Windermere Supergroup of the northern Canadian Cordillera are represented by the Hyland and Ingenika groups (Mansy and Gabrielse, 1978; Gordey and Anderson, 1993). The Hyland Group crops out extensively in an arcuate region in eastern Yukon, on the east side of the Tintina fault, a Cenozoic structure with ~430 km of dextral offset (Gabrielse, 1985; Gabrielse et al., 2006), while the Ingenika Group is largely confined to the western side of the Tintina fault (Fig. 1). The Hyland and Ingenika groups were defined independently of units in the Mackenzie and Wernecke mountains, and stratigraphic relationships between these broadly age-equivalent successions remain unresolved. This is mostly due to a lack of tight age control on both successions and the fact that rocks assigned to the Hyland Group are almost exclusively in fault contact with slope and platformal rocks to the northeast. These ambiguous correlations have limited our understanding of the sedimentation and rifting history of the northern Laurentian margin.

Views differ on the tectonic setting of the Windermere Supergroup of the northern Canadian Cordillera, the relationship between proximal and distal strata, and the timing of transition from rifting to post-rift sedimentation (e.g., Ross, 1991; Dalrymple and Narbonne, 1996; Fritz, 1997; Colpron et al., 2002; Post and Long, 2008; Turner et al., 2011; Yonkee et al., 2014; Strauss et al., 2015). Contrasting interpretations concerning the age of the rift to post-rift transition contributes to uncertainty in the degree to which the Cordilleran margin

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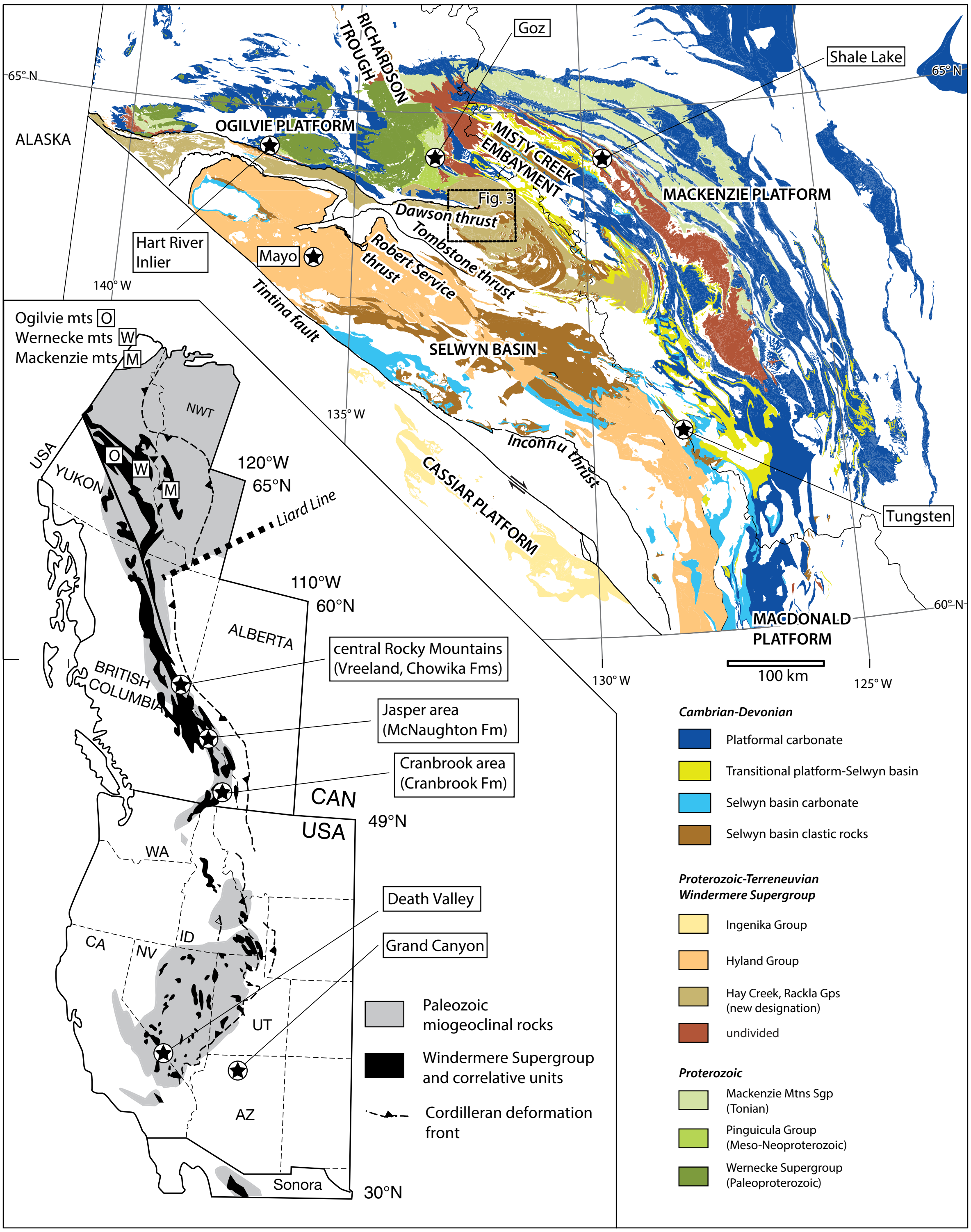

Figure 1. Lower left: Distribution of (1) Windermere Supergroup and correlative units, and (2) Paleozoic rocks of the Laurentian continental margin in western North America. Each is exposed throughout the North American Cordillera from Alaska to Mexico. The study area is located in east-central Yukon, Canada. After Lund et al. (2010). Top right: Simplified geological map of the northern Canadian Cordillera, after Colpron et al. (2016) and Okulitch and Irwin (2014). Neoproterozoic–Paleozoic rocks discussed in the paper are located in the arcuate Selwyn-Mackenzie fold-thrust belt, which overprinted an embayment in the early Paleozoic continental margin (Selwyn basin). The fold-thrust belt is truncated by the Tintina fault, a major dextral structure with ~430 km of Cenozoic dextral offset. Major Mesozoic structures in the core of the fold belt are shown; the study area lies around the eastern tip zone of the Dawson thrust. The outline of Figure 3 is marked with a dashed line. Stars on both maps mark the locations of important sites/areas discussed in the text. Fm—Formation; Gps—groups; Sgp—Supergroup.

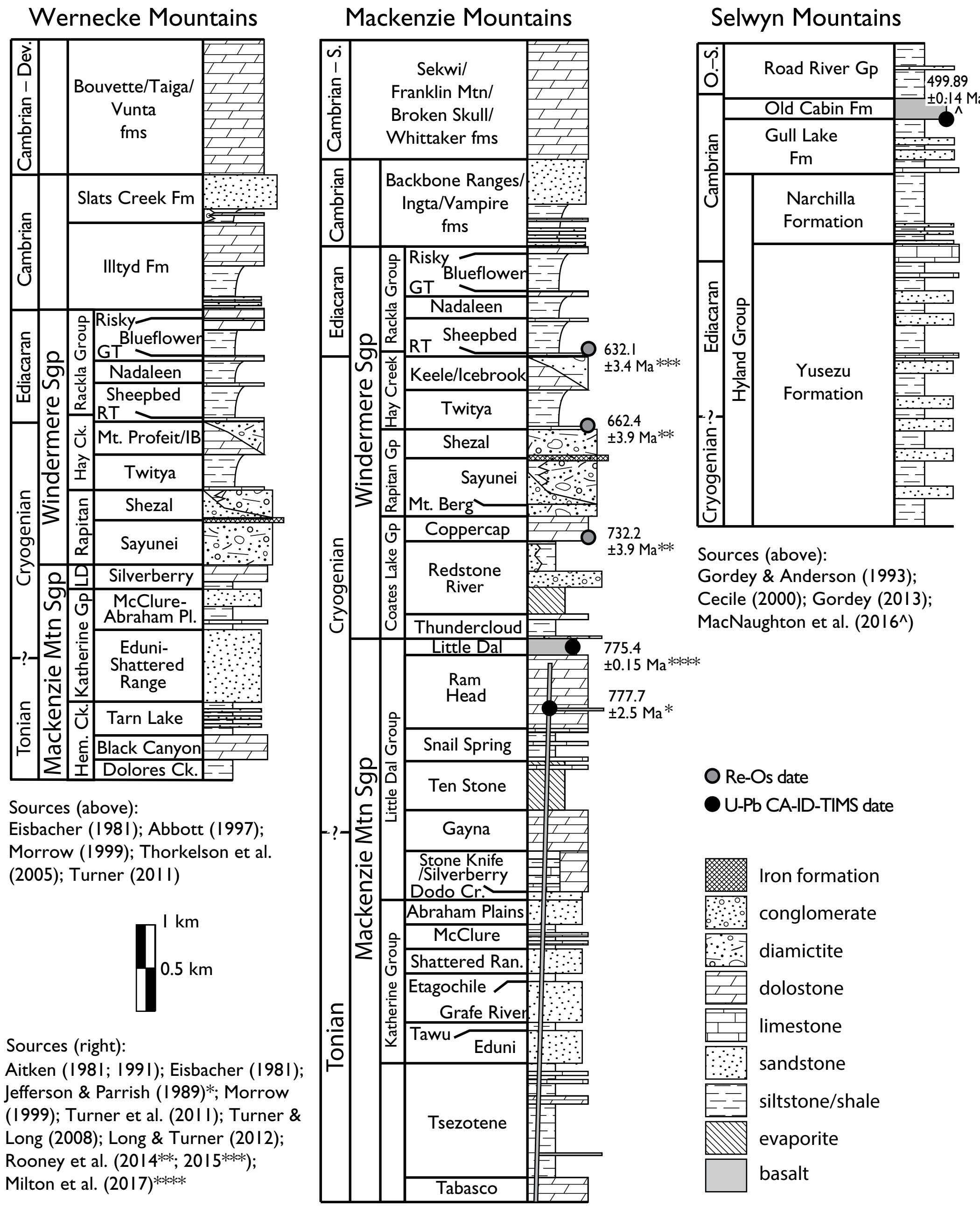

Figure 2. Neoproterozoic stratigraphic architecture of the northern Canadian Cordillera. Three representative sections are shown from the Mackenzie Mountains (vicinity of Mackenzie platform; Fig. 1), Wernecke Mountains (vicinity of Goz Creek; Fig. 1), and the Selwyn Mountains (vicinity of Selwyn basin; Fig. 1). Modified after Strauss et al. (2015). Fm—Formation; Mtn—Mountain; Gp—Group; Sgp—Supergroup; Ck.—Creek; Pl.—plains; Dev.—Devonian; O.—Ordovician; S.—Silurian; GT—Gametrail Formation; RT—Ravensthroat formation; CA-ID-TIMS—chemical abrasion–isotope dilution–thermal ionization mass spectrometry.

experienced diachronous rifting, the relationship of rifting to magmatism, and how the rift mechanisms of the ancient western Laurentian margin compare with other ancient and modern examples. In this paper, we describe the Neoproterozoic–Cambrian stratigraphy around the upper reaches of the Nadaleen and Stewart river drainages in central Yukon (Fig. 3). This region is characterized by exceptional exposure of strata ranging in age from late Cryogenian to Paleozoic, including structurally intact successions that span the entire Ediacaran Period. We document the litho- and chemo-stratigraphy of these strata for the first time, introduce a new Ediacaran formation (Nadaleen Formation), and define a new group (Rackla Group) that encompasses uppermost formations of the Windermere Supergroup. We also establish regional and global correlations and discuss the implications of these data for the evolution of the northern Laurentian Cordilleran margin, in particular the age of the transition from rifting to continent-margin sedimentation. We suggest that this transition is likely to have taken place during the latter part of the Cambrian in the northern Cordillera, later than has been previously suggested (e.g., Aitken, 1993; Yonkee et al., 2014; Beranek, 2017).

NEOPROTEROZOIC–LOWER PALEOZOIC STRATIGRAPHY AND TECTONIC DEVELOPMENT OF THE NORTHWESTERN LAURENTIAN MARGIN

The northern Canadian Cordillera hosts extensive exposures of Proterozoic sedimentary strata, including the Mesoproterozoic Wernecke Supergroup, the Tonian Mackenzie Mountains Supergroup and related units, and the Cryogenian–Terreneuvian Windermere Supergroup (Figs. 1 and 2). Major unconformities bound each of these successions (Young et al., 1979).

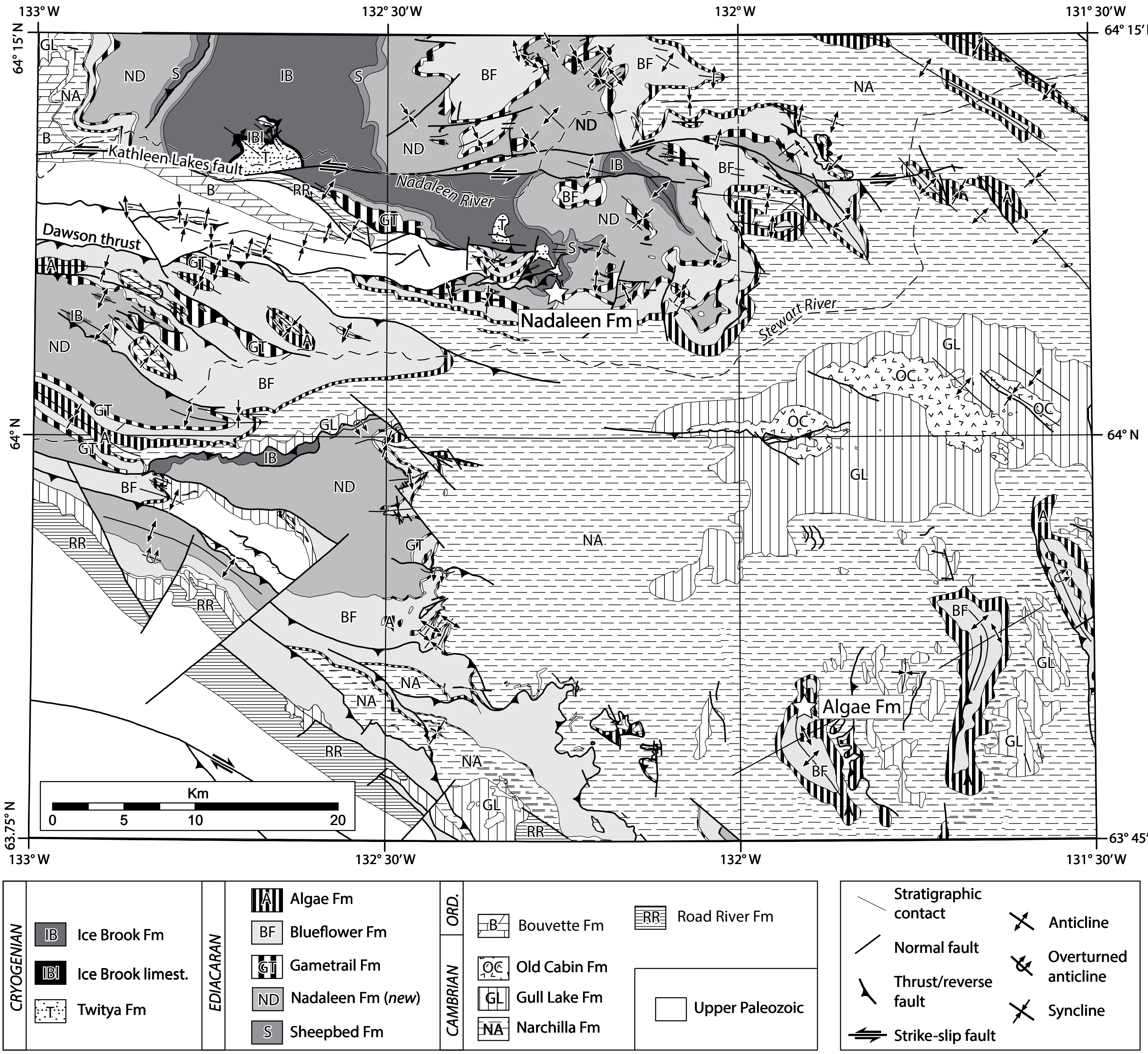

Figure 3. Simplified geological map of the study area in the northern Canadian Cordillera. The location of the Nadaleen Formation type section is marked by a white star and Nadaleen Fm label, as is the Algae Formation type section (Algae Fm; Cecile, 2000). After Colpron et al. (2013) and Moynihan (2016). Fm—Formation; limest.—limestone; ORD.—Ordovician.

The two older supergroups are interpreted to have formed in intracratonic extensional basins (Turner et al., 2011), whereas deposition of the Windermere Supergroup overlapped with a protracted episode of rifting that led to the eventual formation of the paleo-Pacific margin on the western side of Laurentia (see review in Strauss et al., 2015).

There is broad consensus that the western Laurentian continental margin formed after a protracted history involving two main periods of extension (Bond et al., 1985; Levy and Christie-Blick, 1991; Ross, 1991; Colpron et al., 2002; Yonkee et al., 2014; Strauss et al., 2015; Beranek, 2017). The first of these rift episodes is recorded by basal units of the Windermere Supergroup, which were deposited in localized fault-controlled basins, possibly in a strike-slip setting, from ca. 775–660 Ma (Eisbacher, 1981; Aitken, 1991a; Turner et al., 2011; Strauss et al., 2015; Milton et al., 2017; Macdonald et al., 2017). Many of these units were deposited under the influence of the Sturtian global glaciation and were commonly accompanied by mafic magmatism (Devlin et al., 1988; Hein et al., 1994; Warren, 1997; Lund et al., 2010; Smith et al., 2011; Macdonald et al., 2010, 2017; Yonkee et al., 2014; Eyster et al., 2017). Views differ as to whether this early Windermere Supergroup rifting was accompanied by continental breakup (Ross, 1991; Narbonne and Aitken, 1995; Dalrymple and Narbonne, 1996; Colpron et al., 2002) or merely a prelude to the younger successful episode of rifting (e.g., Devlin and Bond, 1988; Yonkee et al., 2014; Strauss et al., 2015). Regardless, the Paleozoic western Laurentian margin formed as a result of rifting that took place during the Ediacaran–Cambrian (Bond et al., 1985; Devlin and Bond, 1988; Levy and Christie-Blick, 1991; Cecile et al., 1997; Colpron et al., 2002; Lund, 2008; Karlstrom et al., 2018), which ultimately led to the development of a continental margin >5000 km in length that persisted for over 150 m.y.

The lower Paleozoic passive margin succession of the northern Canadian Cordillera is generally characterized by extensive platformal carbonate to the north and east of coeval shale-dominated basinal strata (Cecile et al., 1997; Fig. 1). In detail, the northwestern Laurentian margin comprised a series of sub-basins and high-standing regions that were reactivated sporadically throughout the early Paleozoic (Cecile, 1982, 2000; Cecile et al., 1997; Morrow, 1999). In Yukon, a large southwest-facing embayment in the margin, referred to as Selwyn basin (Gordey and Anderson, 1993), was bounded on the east by the Mackenzie platform (Gordey and Anderson, 1993) and on the north by the Ogilvie platform (Fig. 1; Morrow, 1999 and references therein). The Ogilvie platform was in turn separated from the Mackenzie platform by the Richardson trough. Alkalic mafic volcanic rocks are locally intercalated with basinal and proximal platformal strata at several stratigraphic levels and have been interpreted to indicate intermittent or episodic extension in Selwyn basin and the adjacent carbonate platform during the early Paleozoic (Gordey and Anderson, 1993; Goodfellow et al., 1995; Pigage et al., 2015). Prominent examples include the Menzie Creek volcanics of the Anvil district (central Yukon; Pigage, 2004), the Dempster volcanics of northwest Selwyn basin (Abbott, 1997), and the Old Cabin Formation (Cecile, 2000) in the Nadaleen River area. The northern margin of Selwyn basin is marked by the Dawson thrust, which is approximately coincident with an antecedent, basin-bounding structure (ancestral Dawson fault of Abbott, 1997) that marked the platform-basin boundary for much of the lower Paleozoic. The area to the north of the Dawson thrust forms part of the Yukon block, or Yukon stable block, which is a triangular-shaped region in northern Yukon that has remained persistently high standing, and is interpreted to be isostatically distinct (Abbott, 1997). This fault-controlled northern margin contrasts with the eastern boundary of Selwyn basin, which migrated over a region ~50 km wide in response to changes in accommodation and sedimentation (Gordey and Anderson, 1993).

The broad miogeoclinal region of the northern Canadian Cordillera contrasts with a narrower preserved zone in the southern Canadian Cordillera (Cecile et al., 1997). The boundary between these regions corresponds with the Liard Line, a northeast-trending basement structure that crosses the Cordillera in southern Yukon/northeast British Columbia (Fig. 1). The narrow basinal region in northwestern British Columbia, equivalent to Selwyn basin in Yukon, is referred to as the Kechika trough, which evolved from the Kechka graben system (Post and Long, 2008). Cecile et al. (1997) interpreted the Liard Line as an ancient transfer zone, across which there was a change in the symmetry of the fault system that accommodated formation of the ancient northwestern Laurentian margin (see also Lister et al., 1986; Lund, 2008). A narrow belt of Paleozoic platformal rocks, referred to as Cassiar platform lies to the southwest of Selwyn basin, mostly to the southwest of the Tintina fault (Fig. 1). This platformal belt has been transported north of the Liard Line as a result of ~490 km of Cenozoic northward transport along the Tintina fault and possibly also by older Cretaceous displacement (Gabrielse et al., 2006).

Proximal Successions of the Windermere Supergroup—Mackenzie, Wernecke, and Ogilvie Mountains

The Windermere Supergroup crops out extensively in the Mackenzie, Ogilvie, and Wernecke mountains of Yukon and Northwest Territories, where it unconformably overlies platformal rocks of the Mackenzie Mountains Supergroup in fault-controlled rift basins (Eisbacher, 1981; Turner et al., 2011; Strauss et al., 2015; Figs. 1 and 2). Basal units include the Coates Lake Group in the Mackenzie and Wernecke mountains (Fig. 2) and the Mount Harper Group in the Ogilvie Mountains (Macdonald et al., 2012; Strauss et al., 2015). The Coates Lake and Mount Harper groups host rift-generated mafic and felsic volcanic rocks that were extruded at ca. 775 and 717–718 Ma, respectively (Macdonald et al., 2010, 2017; Milton et al., 2017), and they are overlain by rocks of the Rapitan Group (Fig. 2), which includes glaciomarine deposits of the ca. 717–660 Ma Sturtian glaciation (Rooney et al., 2015). Outcrops of the Rapitan Group extend beyond the limits of basal Windermere strata but remain restricted to small fault-bounded extensional or transtensional subbasins. In contrast, the upper part of the Windermere Supergroup comprises laterally extensive units that overstep older parts of the Windermere Supergroup (Aitken, 1991a).

The upper part of the proximal Windermere Supergroup in the northern Canadian Cordillera comprises several km of marine siliciclastic and carbonate strata, namely the Hay Creek Group and the unnamed "upper" group (Fig. 2; Yeo, 1978; Aitken, 1989, 1991a; Narbonne and Aitken, 1995 Turner et al., 2011; Macdonald et al., 2013). The Cryogenian Hay Creek Group includes the Twitya, Keele, and Ice Brook formations (Fig. 2), the Mount Profeit dolostone and the informal "Tepee dolostone" or Ravensthroat formation (Gabrielse et al., 1973; Eisbacher, 1978, 1981; Yeo, 1978; Aitken, 1991a; James et al., 2001; Turner et al., 2011). The Twitya Formation is dominated by deep-marine mudstone, sandstone, and minor conglomerate, with a discontinuous limestone unit at its base (Eisbacher, 1978). In paleogeographically proximal settings, the Twitya Formation is gradationally overlain by limestone, dolostone, and siliciclastic strata of the Keele Formation and broadly equivalent Mount Profeit dolostone (Day et al., 2004; Macdonald et al., 2017), each of which passes basinward into marine and glaciomarine rocks of the Ice Brook Formation (Aitken, 1991a). In distal settings, the Ice Brook Formation, which records the globally recognized ca. 640(?)–635 Ma Marinoan glaciation (Stelfox member of Aitken, 1991b), sits directly on the Twitya Formation (Fig. 2; Aitken, 1991a,b; James et al., 2001; Day et al. 2004; Halverson et al., 2005; Rooney et al., 2015). The Keele Formation and parts of the Ice Brook Formation are overlain by the Ravensthroat formation (Eisbacher 1981, Aitken, 1991a; James et al., 2001), which forms a "cap carbonate" to the Marinoan glacial succession and is correlated with similar units whose bases mark the start of the Ediacaran Period worldwide (Knoll et al., 2006). The cap dolostone is overlain in proximal locations by gray limestone and calcareous siltstone (Hayhook Formation of James et al. 2001) that commonly preserve pseudomorphs after aragonite fans. These mostly Cryogenian units are sharply overlain by the informal Ediacaran "upper group", which consists of the siliciclastic-dominated Sheepbed Formation (Gabrielse et al, 1973), the carbonate-dominated Gametrail Formation, the siliciclastic-dominated "June beds" (Macdonald et al., 2013) and Blueflower Formation, and the carbonate-dominated Risky Formation (Fig. 2; Aitken, 1989; Turner et al., 2011). As outlined below, we replace the informal "upper group" with the Rackla Group, which is formally defined herein (Table 1).

The proximal deposits of the Windermere Supergroup in the Mackenzie and Wernecke mountains are unconformably overlain by a siliciclastic-dominated Cambrian succession that includes the Backbone Ranges, Vampire, and Ingta formations (Fig. 2; Fritz, 1997; Mac-

TABLE 1. FORMALIZATION OF THE RACKLA GROUP

Name:	Rackla Group
Name derivation:	Type area and namesake (Rackla River) located in the southern Wernecke Mountains, Yukon Territory, Canada; NTS 106C.
Category and Rank:	Lithostratigraphic Group
Type area:	Situated broadly between Stewart River and Bonnet Plume River, southeastern Wernecke Mountains, Yukon Territory, Canada.
Distribution:	The Rackla Group is extensively exposed in the western Mackenzie Mountains, Wernecke Mountains, and in parts of the Ogilvie Mountains, Yukon and Northwest Territories.
Unit description:	Formerly referred to as the informal "upper" group (Turner et al., 2011) in the Mackenzie Mountains, Northwest Territories, Canada. Contains six formations: (1) Sheepbed Formation (Gabrielse et al., 1973); (2) Nadaleen Formation (this paper); (3) Gametrail Formation (Aitken, 1989); (4) Blueflower Formation (Aitken, 1989); (5) Risky Formation (Aitken, 1989); (6) Algae Formation (Cecile, 2000).
Dimensions:	~1900 m thick in type area (this paper)
Geologic age:	Ediacaran (ca. 635–541 Ma): Aitken (1989); Narbonne and Aitken (1995); Macdonald et al. (2013); Rooney et al. (2015).

Naughton et al., 2000; Turner et al., 2011); these units are in turn overlain by various carbonate-dominated lower Paleozoic strata. The unconformity at the top of the Windermere Supergroup cuts into deeper levels toward the north-northeast in the Mackenzie, Wernecke, and Ogilvie mountains, with increasing amounts of the Ediacaran succession preserved toward the south-southwest (Aitken, 1991a; Narbonne and Aitken, 1995; Macdonald et al., 2013).

Correlation of Ediacaran–early Cambrian proximal strata in different parts of Northwest Territories and Yukon has proven difficult and controversial, owing to the lithological similarity of the units, their variable thicknesses, the general absence of fossils, a fragmental stratigraphic record due to the effects of several Ediacaran–Cambrian unconformities, and Mesozoic deformation (MacNaughton et al., 2000; Pyle et al., 2004; Macdonald et al., 2013). Recent studies have employed carbon and oxygen chemostratigraphic analyses to assist in correlation (e.g., Halverson et al., 2005; Macdonald et al., 2013), but most stratigraphic, sedimentological, and paleontological work has been restricted to well-known sections (e.g., Sekwi Brook of the Mackenzie Mountains) and localities of small geographic extent. Outside of the study area, there has been little recent geological mapping to assist understanding of regional stratigraphic relationships.

Distal Successions of the Windermere Supergroup—The Hyland and Ingenika Groups

The Hyland Group (Figs. 1 and 2) comprises a thick succession of mostly siliciclastic Neoproterozoic–Cambrian rocks in eastern Yukon and northernmost British Columbia. It is generally separated from the rest of the Windermere Supergroup by major Mesozoic–Cenozoic faults or large areas of younger cover, such that no direct evidence of their stratigraphic relations has previously been reported. Prior to its definition (Gordey and Anderson, 1993), these rocks were informally referred to as the "Grit Unit" (Gabrielse et al., 1973) of uncertain Proterozoic age. The oldest and thickest unit is the Yusezyu Formation, which is dominated by granule-pebble conglomerate "grit" and sandstone horizons interbedded with shale and other variably calcareous sedimentary rocks. Gordey and Anderson (1993) estimated a minimum thickness of ~3 km for the Yusezyu Formation, whose base is nowhere exposed. A regionally widespread carbonate unit marks the top of the Yusezyu Formation; this carbonate is thin (~1–15 m thick) in the type area of the Hyland Group, but it is up to 250 m thick elsewhere in central Yukon (Gordey, 2013). The youngest part of the Hyland Group, the Narchilla Formation, conformably overlies the Yusezyu Formation and is dominated by fine-grained siliciclastic rocks, including characteristic varicolored shale, slate, and phyllite (typically maroon and green). The Hyland Group is overlain by mostly fine-grained siliciclastic and volcanic rocks of the Paleozoic Selwyn basin, including the Cambrian Gull Lake and Old Cabin formations and the Ordovician–Silurian Road River Group (Gordey and Anderson, 1993). The only widespread carbonate unit in Selwyn basin is the upper Cambrian–Lower Ordovician Rabbitkettle Formation (Gabrielse et al., 1973), which overlies a significant regional unconformity, as discussed in a later section.

Rocks that are broadly age-equivalent to the Hyland Group on the southwestern side of the Tintina fault (Fig. 1) belong to the Ingenika Group (Mansy and Gabrielse, 1978). The most distinctive part of the Ingenika Group is the Espee Formation, a thick upper Ediacaran limestone unit that overlies mostly siliciclastic rocks of the Swanell and Tsaydiz formations, and is succeeded by maroon and green shale, sandstone, and limestone of the Stelkuz Formation (Mansy and Gabrielse, 1978). The Ingenika Group most likely represented the southern continuation of the Hyland Group prior to dextral displacement along the Tintina fault (Gabrielse et al., 2006). Although the Hyland and Ingenika groups are lithologically similar, they underlie regions with contrasting Paleozoic histories—the Hyland Group underlies basinal siliciclastic rocks (Gordey and Anderson, 1993) and the Ingenika Group is succeeded by carbonate strata of the Cassiar platform (Gabrielse, 1963). The Hyland and Ingenika groups are commonly deformed and metamorphosed, and these successions have consequently undergone less sedimentological and paleontological study than their counterparts in the Mackenzie, Wernecke, and Ogilvie mountains.

UPPER NADALEEN RIVER STUDY AREA

The study area is located ~185 km east-northeast of Mayo in east-central Yukon, northwestern Canada (Figs. 1 and 3). It includes the eastern tip zone of the Dawson thrust (Fig. 3), a north-vergent fault with a strike length of >250 km that marks the northern boundary of the arcuate Selwyn fold belt (Gordey and Anderson, 1993), and approximates the boundary of the Selwyn basin during the Paleozoic (Abbott, 1997). Rocks exposed in the fold-thrust belt range in age from late Proterozoic–Early Cretaceous and were deformed during Cordilleran (Jurassic–Cenozoic) deformation (Gordey and Anderson, 1993). The oldest rocks in the Nadaleen River area, which are Cryogenian in age, are exposed in a composite domal structure (Fig. 3). The composite dome is offset by the sinistral Kathleen Lakes fault, which dies out in the northeast corner of the study area (Fig. 3).

Most of the strata in the northern part of the map area (Fig. 3) were assigned by Blusson (1974) to the Proterozoic "Grit Unit" of Gabrielse et al. (1973) and later to the Hyland Group (Gordey and Makepeace, 2001). Rocks in the southern part of the area were also assigned to the Hyland Group by Roots et al. (1995) and Cecile (2000), who defined the calcareous Algae Formation in the map area (Fig. 3). Rather than being typical of the apparently monotonous and undivided Yusezyu Formation, all units in the area have direct lithostratigraphic correlatives in the Hay Creek or—newly defined—Rackla groups of the Mackenzie, Wernecke, and Ogilvie mountains. Colpron et al. (2013) used local names for the units but tentatively correlated these strata with the upper part of the Winder-

TABLE 2. FORMALIZATION OF THE NADALEEN FORMATION

Name:	Nadaleen Formation
Name derivation:	Type area located near the upper reaches of the Nadaleen River; Stewart River drainage, NTS 106/C1, Yukon, Canada.
Category and rank:	Lithostratigraphic Formation
Distribution:	Exposed in the western Mackenzie Mountains and Wernecke Mountains, Yukon and Northwest Territories.
Type area:	Headwaters of the Nadaleen River, Yukon Territory, Canada.
Unit type section:	Section N1 (Fig. 6; this paper). Located on ~N-S–trending ridgeline directly north of Mount Stenbraten. Lower boundary: covered contact above Sheepbed Formation (N64° 5′ 36″, W132° 15′ 36″); the contact is sharp where it is exposed. Upper boundary: gradational transition into Gametrail Formation (N64° 5′ 21″, W132° 15′ 11″).
Unit description:	Divided into five informal members: (1) **Lower carbonate member:** 60 m of grey carbonate-clast rudstone and grainstone interbedded with coarse-grained siliciclastic strata. Clasts in the rudstone intervals range from pebble to boulder in size and include pale grey limestone and yellow-orange dolostone within a sandy calcareous matrix. Rudstones are interbedded with calcareous sandstone, grainstone, and granule-pebble conglomerate. This cliff-forming marker horizon is overlain by the Heterolithic member. (2) **Heterolithic member:** a heterogeneous mix of sandstone, calcareous sandstone, shale, limestone, and variably calcareous conglomerate. Some sandstone layers include reworked ooids and matrix-supported conglomerate, including clasts of oolitic limestone. Sandstone and granule-pebble conglomerate beds are thick, commonly massive or normal-graded, and locally preserve evidence for soft-sediment deformation. Limestone and shale are thin- to medium-bedded and exhibit partial Bouma sequences as well as rare circular impressions of the Ediacaran macrofossil *Aspidella*. The top of the Heterolithic member is marked by a thick olistostrome interval that comprises sparsely distributed m-scale clasts of tubestone stromatolites, limestone-bearing boulder conglomerate, and other lithologies in a dark mudstone matrix. (3) **Upper carbonate member:** a monotonous succession of mostly thin- to medium-bedded limestone and shale, arranged in partial to complete Bouma sequences. Limestone is dark grey to black on fresh surfaces and is locally fetid. The top of the unit is marked by >30 m of channelized carbonate pebble to boulder rudstone and is overlain by the Black Shale member. (4) **Black shale member:** divided into a lower part dominated by black shale and an upper part with abundant turbiditic quartz arenite to sublitharenite. (5) **Green siliciclastic member:** dominated by rhythmically-bedded mudstone, siltstone, and sandstone. These strata are typically normal-graded and arranged in partial Bouma sequences. They are green with a rusty orange weathering color, but are also commonly grey and locally maroon.
Dimensions:	767.7 m thick at type section (Fig. 6, this paper).
Geologic age:	Ediacaran (<635 Ma, >541 Ma; this paper).
Regional correlations:	Informal June beds of Macdonald et al. (2013; i.e., rocks previously assigned to middle and upper Sheepbed Formation, e.g., MacNaughton et al., 2000); Framstead Formation of Misinchinka Group, northern Rocky Mountains (McMechan, 2015).

mere Supergroup. Moynihan (2014) correlated the Algae Formation of Cecile (2000) with the Risky Formation, assigned rocks below it to the Gametrail and Blueflower formations of the upper group, and introduced the informal Nadaleen Formation to describe the "June beds" of Macdonald et al. (2013). The Nadaleen Formation is formalized here (Table 2), and we replace the informal "upper group" with the formal Rackla Group (Table 1) because the map area contains some of the most complete sections yet described from the youngest parts of the Windermere Supergroup. Cambrian rocks in the Nadaleen River area include mostly fine-grained siliciclastic rocks of the Narchilla and Gull Lake formations and overlying mafic volcanic rocks of the Old Cabin Formation (Cecile, 2000). North of the Dawson thrust (Ogilvie platform) the Gull Lake Formation is overlain by Cambrian–Devonian carbonate strata of the Bouvette Formation (Colpron et al., 2013) while to its south, this time period is represented by basinal shales of the Road River Group (Gordey and Anderson, 1993).

METHODS

The 1:50,000-scale geological mapping of Colpron et al. (2013) and Moynihan (2014, 2016) was supplemented with more detailed mapping in select locations and the measurement of stratigraphic sections at cm- to m-scale with a Jacob Staff and measuring stick. We present 775 new carbonate carbon ($\delta^{13}C_{carb}$) and oxygen ($\delta^{18}O_{carb}$) isotopic measurements from ten new stratigraphic sections of the Rackla Group (all data are presented in Table DR1[1]). Hand samples were collected at 0.25–2 m resolution through measured sections for carbonate carbon and oxygen isotope chemostratigraphy. $\delta^{13}C_{carb}$ and $\delta^{18}O_{carb}$ isotopic results are reported in per mil notation of $^{13}C/^{12}C$ and $^{18}O/^{16}O$, respectively, relative to the standard Vienna Pee Dee belemnite (VPDB). Carbonate samples were cut perpendicular to bedding and carefully drilled (~2–10 mg of powder) to avoid secondary veins, cements, and siliciclastic components. Additional analyses were carried out on samples with multiple carbonate components to test for systematic differences (e.g., clasts vs. lime mudstone). All of the $\delta^{13}C_{carb}$ and $\delta^{18}O_{carb}$ isotopic data were acquired simultaneously on a VG Optima dual inlet isotope ratio mass spectrometer coupled with a VG Isocarb preparation device (Micromass, Milford, Massachusetts, USA) in the Laboratory for Geochemical Oceanography at Harvard University, Cambridge, Massachusetts. Approximately 1 mg of sample powder was reacted in a common, purified phosphoric acid (H_3PO_4) bath at 90 °C. The evolved CO_2 was collected cryogenically and analyzed using an in-house reference gas. Measured data were calibrated to VPDB using an internal Cararra marble standard (CM2). Total analytical errors (1σ) are better than ± 0.1‰ for both $\delta^{13}C_{carb}$ and $\delta^{18}O_{carb}$ based on repeat analysis of standards and samples. Increasing the reaction time to eleven minutes for dolomite samples minimized "memory effects" resulting from the common acid-bath system, with the total memory effect estimated at <0.1‰ based on reproducibility of standards run directly after samples.

[1]GSA Data Repository item 2019014, Table DR1, is available at http://www.geosociety.org/datarepository/2019 or by request to editing@geosociety.org.

NEOPROTEROZOIC–TERRENEUVIAN STRATA OF THE NADALEEN RIVER AREA

Cryogenian

Hay Creek Group

Twitya Formation.

Lithostratigraphy. The oldest rocks exposed in the Nadaleen River area comprise brownish gray to green shale with intervals of fine- to very coarse-grained quartz and lithic arenite and granule-pebble conglomerate from what is tentatively assigned to the Twitya Formation (Figs. 4A and 5; Gabrielse et al., 1973). The sandstone and conglomerate beds are commonly massive, medium- to very thick-bedded with sharp to irregular bases and contain discrete layers with shale intraclasts. Normal grading is common throughout these coarser-grained strata, and locally they display complete Bouma (ABCDE) sequences (Bouma, 1962); some finer-grained siltstone and sandstone beds also exhibit evidence of soft-sediment deformation in the form of flame structures and convolute lamination (e.g., Maltman, 1984; Owen et al., 2011). The base of the Twitya Formation in the Nadaleen River area is nowhere exposed, and the top of the Twitya is locally marked by a thick-bedded quartz pebble conglomerate unit that displays amalgamated AB and AC Bouma sequences. The contact with the overlying Ice Brook Formation appears to be conformable.

Depositional environment and age. The Twitya Formation in the Nadaleen River area was most likely deposited below wave base in a slope to basin floor setting through a combination of hemipelagic sedimentation and sediment-gravity flows. The massive and graded beds of the Twitya Formation indicate deposition from the base of concentrated density flows (*sensu* Mulder and Alexander, 2001) or high-density turbidity currents (*sensu* Lowe, 1982) associated with gradual to rapid aggradation (e.g., Arnott and Hand, 1989). Mudstone intraclasts may have been transported along density boundaries between concentrated and dilute parts of these flows (Postma et al., 1988), and localized soft-sediment deformation most likely resulted from a combination of liquification, reverse density gradation, and/or slumping (Allen, 1977; Mills, 1983; Owen, 1996). Our lack of a detailed regional sedimentological analysis of this unit precludes a precise paleoenvironmental interpretation within the deep-water depositional system, although the presence of abundant soft-sediment deformation and coarse-grained turbidites most likely implies a position within a basin-floor fan or lobe complex (e.g., Prélat et al., 2010). Rooney et al. (2015) reported a Re-Os date of 662.4 ± 4.3 Ma from calcareous black shale at the base of the Twitya Formation in the Shale Lake area of the Mackenzie Mountains, Northwest Territories.

Figure 4 (*on following page*). Selected photographs from the Nadaleen River area, Yukon, Canada. (A) Upper part of the Twitya Formation and lower portion of the Ice Brook Formation, including the yellow-weathering limestone unit near its base. The location of section K1 (Fig. 5) is indicated. Elevation difference between slopes in the bottom left corner and the peak is ~200 m. (B) Yellow-orange-weathering polymict conglomerate layer in the Ice Brook Formation. Clasts include quartz arenite, pale gray limestone, dolostone, and gray siltstone in a sand-rich, calcareous matrix. Hammer for scale is 40 cm long. (C) Green lithic wacke with irregularly shaped and deformed clasts of mudstone and siltstone; Ice Brook Formation. White quartz grains form prominent white specks in the wacke. Hammer for scale is 40 cm long. (D) Large clasts of carbonate and quartz arenite rafts in the Ice Brook Formation, immediately north of the Nadaleen Formation type section (Fig. 1). Bright yellow dolostone of the Ravensthroat formation is visible in the left foreground. The elevation difference between the carbonate clasts and the top of the peak is ~200 m. (E) Isolated clast that disrupts laminations in mudstone-siltstone near the top of the Ice Brook Formation. This part of the formation is assigned to the Stelfox member. Canadian 10-cent coin for scale is 1.8 cm in diameter. (F) Planar laminated, yellow-orange-weathering dolostone of the Ravensthroat formation. Coin for scale is 1.8 cm in diameter. (G) Type section of the Nadaleen Formation (Fig. 6), viewed toward the west. The visible relief of the mountain shown in D is ~400 m, visible on the extreme right hand side. Fm—Formation; mbr—member; carb.—carbonate.

Ice Brook Formation

Lithostratigraphy. The Twitya Formation is overlain by mostly dark green to gray mudstone and siltstone, which grades into a package of thinly bedded silty to sandy limestone with green-gray mudstone partings (Figs. 4A and 5). The limestone weathers buff-pale yellow and is medium gray on fresh surfaces. Planar and ripple cross-lamination is ubiquitous in the limestone, and limestone-shale packages commonly display Bouma BCDE sequences (Bouma, 1962). The carbonate-bearing succession is also marked by local discontinuous matrix-supported rudstone intervals dominated by shale and limestone intraclasts. Calcareous strata of the Ice Brook Formation transition gradationally into several hundred meters of well-bedded dark green mudstone, siltstone, and sandstone that weather creamy brown, brown, and bright orange. The orange weathering color is intensely developed adjacent to splays of the Kathleen Lakes fault (Fig. 4A) and contrasts with duller weathering colors of the underlying Twitya Formation. This well-bedded turbiditic succession is generally thin-bedded and locally displays normal grading, as well as planar- and ripple cross-lamination. There are also intervals (10–20 m thick) of medium- to thick-bedded, medium- to coarse-grained gray quartz arenite and minor orange-weathering calcareous sandstone dominated by Bouma AB and ABC subdivisions (Bouma, 1962). Tens of cm thick clast-supported polymict conglomerate layers also form a minor portion of this succession (Fig. 4B) and include clasts of quartz arenite, pale limestone or dolostone, and dark brown siltstone in a sandy, slightly calcareous orange-weathering matrix.

In places, the upper part of the Ice Brook Formation consists of structureless green lithic wacke with subangular to rounded clasts (commonly vein quartz) of widely varying size (mostly sand to pebble) in a green, creamy brown, or orange weathering matrix. This wacke unit hosts highly deformed and disaggregated intraclasts of mudstone and siltstone (Fig. 4C), carbonate olistoliths up to tens of meters in maximum dimension, and large boulders or rafts of discontinuous, isoclinally folded sandstone blocks up to 100s of meters long (Fig. 4D). Granule-pebble sized clasts in the wacke include siltstone, sandstone, carbonate, individual plagioclase, muscovite and K-feldspar crystals, polycrystalline quartz with sutured boundaries, and mafic volcanic clasts. Some carbonate olistoliths contain abundant columnar stromatolites, including *Boxonia* and *Jacutophyton* forms. Locally, the uppermost few meters of the Ice Brook Formation includes a thin and laterally discontinuous interval of orange-weathering, mostly matrix-supported polymictic diamictite and mudstone and siltstone that locally contain sparsely distributed lonestones (Fig. 4E).

Aitken (1991a) recognized three informal members in the type area of the Ice Brook Formation of the Mackenzie Mountains, Northwest Territories. The limit of the Keele Formation and its transition into the Ice Brook Formation coincides with a "breakaway scarp," which transitions laterally into an olistostrome (lowermost Durkan member of the Ice Brook Formation) derived from the lower part of the Keele Formation. This is overlain by the Delthore member, which comprises mudstone, siltstone, and sandstone with minor diamictite and sparse lonestones; the Delthore member also commonly preserves evidence for soft-sediment deformation. The uppermost member, the glaciomarine Stelfox member, is dominated by orange weathering diamictite and conglomerate that is globally correlated with the Marinoan snowball Earth glaciation (Aitken, 1991a,b; Hoffman et al., 1998; James et al., 2001; Rooney et al., 2015). We assign the mostly well-bedded portion of the Ice Brook Formation in the Nadaleen River area to the Delthore member of Aitken (1991a). The overlying Stelfox member of the Ice Brook Formation may be represented by the discontinuous olistolith-bearing interval and the thin intervals of orange-weathering diamictite at the top of the formation. The Durkan member is most likely absent from the Nadaleen River area, which can make separation of the Twitya and Ice Brook formations difficult (Aitken, 1991a); therefore,

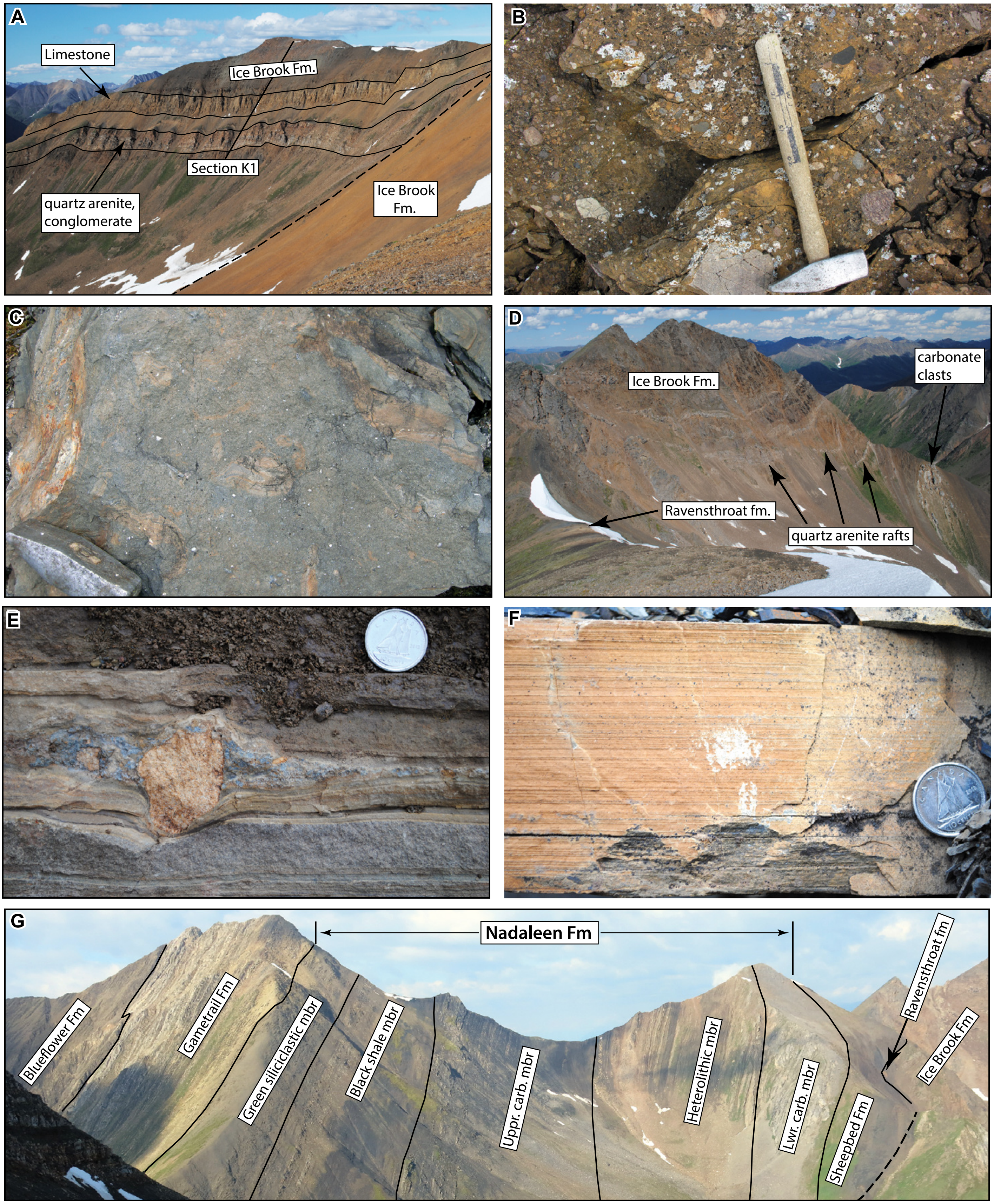
A
Limestone
Ice Brook Fm.
Section K1
quartz arenite, conglomerate
Ice Brook Fm.
B
C
D
Ice Brook Fm.
carbonate clasts
Ravensthroat fm.
quartz arenite rafts
E
F
G
Nadaleen Fm
Blueflower Fm
Gametrail Fm
Green siliciclastic mbr
Black shale mbr
Uppr. carb. mbr
Heterolithic mbr
Lwr. carb. mbr
Sheepbed Fm
Ravensthroat fm
Ice Brook Fm

Figure 4.

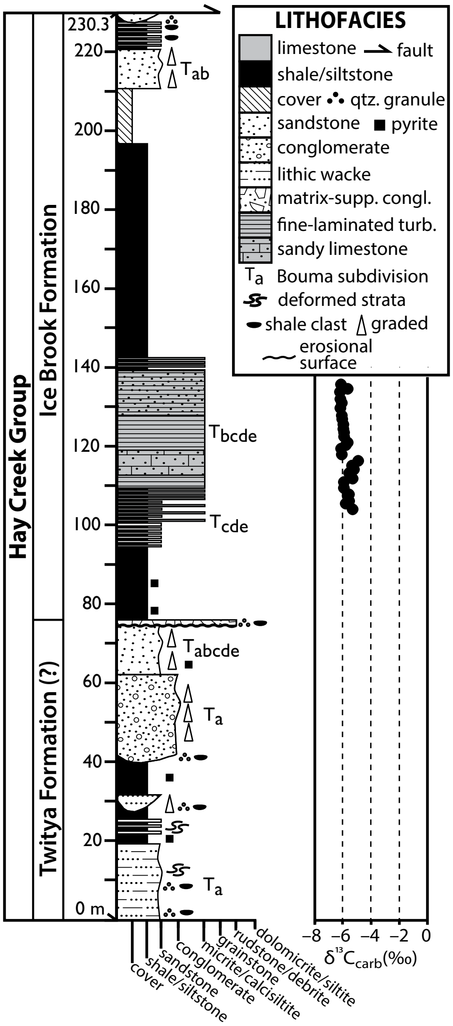

Figure 5. Measured stratigraphic section though the lower part of the Ice Brook Formation. Location of the section is shown in Figure 4A. qtz—quartz; supp.—supported; congl.—conglomerate; turb.—turbidite.

the placement of the Twitya-Ice Brook contact in the study area is informed by observations made at Shale Lake in the Mackenzie Mountains (location B of Aitken, 1991a) where the Keele Formation and its contact with the Durkan member of the Ice Brook Formation coincides with a change in weathering color from dull brown/green (Twitya Formation; below) to orange (Ice Brook Formation; above).

Depositional setting and age. The Ice Brook Formation of the Nadaleen River area was most likely deposited below wave base in a slope to basin floor setting through a combination of hemipelagic sedimentation and sediment-gravity flows. Massive and graded beds of the Delthore member indicate deposition from the base of concentrated density flows (sensu Mulder and Alexander, 2001) or high-density turbidity currents (sensu Lowe, 1982). Mudstone/limestone intraclasts may have been transported down-slope along density boundaries between concentrated and dilute parts of these flows (Postma et al., 1988), although the poorly sorted and matrix-supported nature of many of the deposits indicate that many of these flows may have been poorly stratified and transitional between cohesive and non-cohesive flows (e.g., Talling, 2013). Localized soft-sediment deformation, including the deformation of interbedded mudstone-siltstone-sandstone rafts, most likely resulted from a combination of liquification, reverse density gradation, and/or slumping (e.g., Owen et al., 2011). The deformed clasts indicate that they were consolidated but not lithified at the time of transport, which may be representative of en masse freezing during transport (Mulder and Alexander, 2001; Talling et al., 2012).

The size of the larger olistoliths in the Ice Brook Formation and their occurrence in a thick package of incoherent wacke suggests that this horizon may represent a significant mass-transport complex derived from a subaqueous slump (e.g., Martinsen and Posamentier, 2006, and references therein). Its composition and weathering color is the same as that of coherent parts of the Ice Brook Formation, and almost all the clasts are compatible with internal derivation indicating disaggregation of semi-coherent sediment from more proximal settings. Exceptions are provided by olistoliths of stromatolitic dolostone that we interpret as being derived from the underlying Tonian Little Dal Group (Aitken, 1981; Turner and Long, 2012) due to their unique lithology and stromatolite morphologies. These potential slump deposits and their associated olistoliths may reflect influences from syn-sedimentary tectonism or slope instability arising from regional regression. We interpret the lonestones and thin wedges of discontinuous diamictite in the uppermost Ice Brook Formation as evidence for a glacial influence on sedimentation during the ca. 640(?)–635 Ma Marinoan glaciation (e.g., Aitken, 1991a; Rooney et al., 2015; Prave et al., 2016).

Ediacaran–Terreneuvian

Ravensthroat Formation.

Lithostratigraphy. Well-bedded and chaotic strata of the Ice Brook Formation in the Nadaleen River area are overlain by a distinctive yellow-, tan-, or orange-weathering and medium gray dolostone (Fig. 4F) that we assign to the informal Ravensthroat formation (originally referred to as the "Tepee dolostone" of Aitken, 1991a; James et al., 2001; Turner et al., 2011). This discontinuous unit is ~1–2 m thick and forms characteristic bright yellow talus aprons throughout the Nadaleen River area. The Ravensthroat formation comprises very thinly laminated dolosiltite to dolograinstone with minor low-angle cross-lamination (Fig. 4F). Locally, these laminated dolostones overlie or interfinger with very poorly sorted polymictic diamictite of the Stelfox member of the Ice Brook Formation with lithologically varying clasts (up to boulder size) set within a yellow-weathering dolomitic matrix.

Depositional setting and age. These strata most likely record hemipelagic carbonate sedimentation in a slope or outer-shelf setting, although the presence of minor low-angle cross-lamination supports traction sedimentation potentially associated with contour or distal turbidity currents. The presence of diamictite in the basal Ravensthroat formation is interpreted to record rapid post-glacial cap carbonate sedimentation during deglaciation (e.g., Creveling and Mitrovica, 2014; Hoffman et al., 2017; Myrow et al., 2018). As highlighted previously, the Ravensthroat formation has been correlated globally with ca. 635 Ma basal Ediacaran cap dolostones that overlie Marinoan glacial deposits (Hoffman et al., 1998; James et al., 2001; Turner et al., 2011; Macdonald et al., 2013; Rooney et al., 2015).

Rackla Group (Formerly Part of the Unnamed "Upper Group")

Sheepbed Formation.

Lithostratigraphy. The Ravensthroat formation is sharply overlain by over 100 m of black to dark gray shale, siltstone, and minor sandstone of the Sheepbed Formation (Gabrielse et al., 1973; Fig. 4G). This unit forms distinctive smooth, chocolate-brown colored talus slopes in the Nadaleen River area. In the central part of this region, Sheepbed mudstone and siltstone are succeeded by medium- to thick-bedded sandstone and subordinate thin- to medium-bedded argillaceous limestone. In the NW part of the study area, the upper part of the Sheepbed Formation includes thin-bedded gray to black carbonaceous limestone interbedded with dark gray to black siltstone. This upper Sheepbed carbonate unit is thin-bedded and planar- or cross-laminated with partially developed CDE Bouma sequences (Bouma, 1962). Several coarsening-upwards packages are present in the Sheepbed limestone, and some thicker limestone beds (1–2 m thick) exhibit convolute lamination (Maltman, 1984) and discontinuous matrix-supported rudstone horizons.

Depositional setting and age. The Sheepbed Formation of the Nadaleen area records a combination of hemipelagic and sediment-gravity sedimentation in the form of fine-grained turbidites, finely laminated shale and mudstone, and local convolute lamination (e.g., Bouma, 1962; Owen et al., 2011). It is interpreted to have been deposited in a siliciclastic-dominated basin floor or lower slope setting, consistent with the slope setting demonstrated by Dalrymple and Narbonne (1996) in the more proximal Mackenzie Mountains. Rooney et al. (2015) obtained a Re-Os date of 632.3 ± 5.9 Ma from the base of the Sheepbed Formation in the Shale Lake area of the Mackenzie Mountains, Northwest Territories (Fig. 1). In the same area, Macdonald et al. (2013) identified a shallow-water carbonate unit at the top of the Sheepbed Formation (informal Sheepbed carbonate), which may represent a proximal equivalent of the upper limestone unit in the Nadaleen River area. The lack of age constraints from upper Sheepbed strata precludes a precise age range for this Ediacaran unit.

Nadaleen Formation (new).

Lithostratigraphy. Whereas the Sheepbed Formation is generally dominated by fine-grained mudstone and siltstone, the overlying Nadaleen Formation, formalized herein (Table 1; Figs. 4 and 6), comprises a heterogeneous mixed siliciclastic and carbonate succession with abundant sandstone, conglomerate, and coarse-grained rudstone or matrix-supported conglomerate. Five informal members are recognized in this contribution. The base of the Nadaleen Formation (lower carbonate member) comprises 60 m of cliff-forming, gray carbonate-clast rudstone and grainstone interbedded with coarse-grained siliciclastic strata (Fig. 7A). Clasts in the rudstone intervals range from pebble to boulder in size and include pale gray limestone and yellow-orange dolostone within a sandy calcareous matrix. These rudstones are interbedded with calcareous sandstone, grainstone, and granule-pebble conglomerate. This unit is overlain by a heterogeneous mix of sandstone, calcareous sandstone, shale, limestone, and variably calcareous conglomerate of the informal heterolithic member. Some sandstone layers include reworked ooids, and the matrix-supported conglomerate contains clasts of oolitic limestone. Sandstone and granule-pebble conglomerate beds are thick, commonly massive or normal graded, and locally preserve evidence for soft-sediment deformation (Maltman, 1984). Limestone and shale are thin- to medium-bedded and exhibit partial Bouma sequences (Bouma, 1962). Scour surfaces, sole marks, flutes, and mudstone intraclasts are also common at the base of these turbidite horizons. The limestone turbidites also host rare circular impressions of the Ediacaran macrofossil *Aspidella* (Fig. 7B), whose stratigraphic distribution and taxonomy will be presented elsewhere. The top of the heterolithic member is marked by a thick dark gray to brown olistostrome and

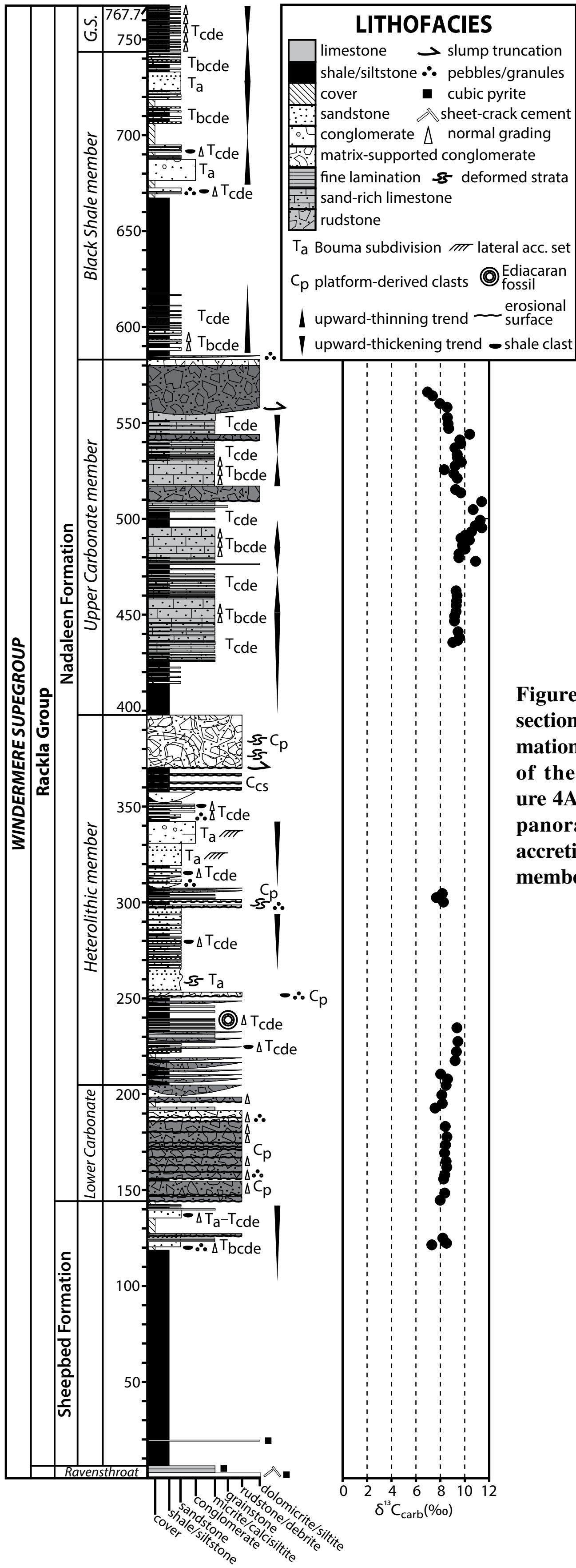

Figure 6. Measured stratigraphic section through the Nadaleen Formation at its type section. Location of the section is shown in Figure 4A. See Figure 4G for a photo panorama of this section. acc.—accretion; G.S.—green siliciclastic member.

matrix-supported rudstone interval that comprises sparsely distributed m-scale clasts of shallow- and deep-water origins. For example, some of the clasts are similar to shallow-water facies of the Ravensthroat formation (e.g., tubestone stromatolite), while others include limestone-bearing rudstone and chaotically deformed turbiditic sandstone and mudstone.

The upper carbonate member of the Nadaleen Formation (Fig. 4G) comprises a monotonous succession of mostly thin- to medium-bedded limestone and shale arranged in partial to complete Bouma sequences (Bouma, 1962). The limestone is dark gray to black on fresh surfaces and is locally fetid. Some rudstone beds are also present within the carbonate member and the top of the unit is marked by >30 m of carbonate pebble to boulder rudstone. This rudstone marker bed is overlain by the black shale member, which comprises a lower part dominated by black shale and an upper part with abundant turbiditic sandstone consisting of quartz arenite to sublitharenite. This is succeeded by rhythmically bedded mudstone, siltstone, and sandstone of the green siliciclastic member (Figs. 4G and 6). These strata are typically green with a rusty orange weathering color but are also commonly gray and locally maroon. This uppermost unit is dominated by normal-graded partial Bouma sequences (Bouma, 1962), and its thickness is highly variable; it is ~20 m thick at the type section but an order of magnitude thicker elsewhere in the Nadaleen River area.

Depositional setting and age. The Nadaleen Formation exhibits characteristic features of slope to basin floor sedimentation through a combination of suspension deposition and submarine sediment gravity flows. Siliciclastic, carbonate, and mixed siliciclastic-carbonate strata exhibit both rhythmic layering, which is attributed to hemipelagic sedimentation, and full to partial Bouma sequences as a result of turbidity currents (Bouma, 1962). Scour surfaces, sole marks, flutes, and mudstone intraclasts are all hallmarks of deposition from concentrated density flows (*sensu* Mulder and Alexander, 2001) or high-density turbidity currents (*sensu* Lowe, 1982). The medium- to very thick-bedded and crudely stratified matrix-supported conglomerate and rudstone layers are interpreted as debris flow or slump deposits derived from shelf-and/or slope systems as indicated by the clast lithologies (e.g., Moscardelli and Wood, 2008). Evidence for soft-sedimentation deformation throughout the Nadaleen Formation, including discontinuous folds, flame structures, and slump folds (Mills, 1983; Owen, 1996), provides supportive evidence for a slope depositional setting.

There are no direct geochronological constraints on the age of the Nadaleen Formation, but the presence of the Ediacaran macrofossil *Aspidella* in its lower part in the Nadaleen River area (lower part of the heterolithic member; Fig. 7B) suggests that it was mostly deposited after ca. 580 Ma, the approximate time at which Ediacaran fauna first appear in the fossil record (Narbonne et al., 2012). In the Sekwi Brook area of the Mackenzie Mountains, these strata also host the radiating attachment disk *Hiemalora* and two genera of rangeomorph fronds (Narbonne, 1994; Narbonne et al., 2014), which provide a tentative correlation with the Avalon assemblage of Ediacaran megafossils elsewhere dated to ca. 580–560 Ma. The Nadaleen Formation is overlain by the Gametrail Formation, which contains the >551 Ma Shuram-Wonoka carbon isotope excursion (see below).

Figure 7 (*on following page*). Selected photographs from the Nadaleen River area, Yukon, Canada. (A) Carbonate-clast conglomerate in basal member of the Nadaleen Formation. Clasts are gray limestone and pale buff to orange dolostone. Hammer for scale is 40 cm long. (B) Circular impression of the Ediacaran fossil *Aspidella*. Coin for scale is 2.6 cm in diameter. (C) Measured stratigraphic section through the Gametrail Formation, with upper part of the Nadaleen Formation also visible. Maroon shale layers are prominent in the lower part of the section. Thickness of the section is ~200 m. (D) Dolostone-block rudstone at the top of the Gametrail Formation, overlying ribbon-bedded limestone (gray) and dolostone (yellowish). Geologist for scale. (E) Bright yellow weathering Gametrail Formation, overlain by the lower and middle parts of the Blueflower Formation. The lower member is composed of thinly interbedded carbonate and shale, and is overlain by green mudstone, siltstone, and sandstone. Relief from base of slope to top of the peak is ~300 m. (F) Resistant ribs of thick-bedded sandstone in the upper member of the Blueflower Formation (mixed facies). Geologist for scale. (G) Thin- to medium-bedded gray limestone of the Algae Formation. The upper part of the outcrop is dolomitized. Hammer for scale is 40 cm long. (H) Erosional contact between the Algae Formation and overlying Narchilla Formation. The Narchilla Formation was deposited on an irregular surface, which is marked by a bright red *terra rosa* horizon. The elevation difference between the peak in the center of the photograph and the base of the talus slope to the left is ~300 m. Fm—Formation; mbr—member.

Gametrail Formation.

Lithostratigraphy. The cliff-forming Gametrail Formation (Aitken, 1989; Figs. 4G, 7C, and 8) gradationally overlies the Nadaleen Formation and is the most distinctive unit in the Nadaleen River Ediacaran succession. The formation is distinguished by its buff-, yellow-, and yellow-orange weathering carbonate cliffs and talus, and locally by several maroon shale intervals. The dominant rock types of the Gametrail Formation are buff-, yellow-, and orange-weathering silty and sandy dolostone, gray limestone, calcareous sandstone, and carbonate rudstone. The top of the Gametrail Formation is marked by a multimeter-thick dolorudstone interval (Fig. 7D) in many places within the map area, but everywhere it coincides with a change from bright weathering colors into duller tones of the overlying Blueflower Formation. Maroon shale intervals (Fig. 7C), locally up to 5 m thick, are thinly laminated and locally interbedded with thin-bedded gray limestone in the basal 20 m of the Gametrail Formation. Silty to sandy dolostone, limestone, and calcareous shale/siltstone strata are commonly thin- to medium-bedded and display normal grading, planar lamination, ripple cross-lamination, irregular load structures, and prominent flute casts. Stylonodular diagenetic textures are also locally developed in the Gametrail carbonate strata (e.g., Husson et al., 2015). Locally, there is convolute lamination beneath carbonate rudstone intervals, and there are also intervals of low-angle cross-bedding that resemble hummocky or swaley cross-stratification (HCS/SCS). Rudstones of the Gametrail Formation are dominated by carbonate intraclasts with occasional siliciclastic pebbles to boulders, all of which are set in a buff-gray dolomudstone matrix.

Depositional environment and age. Similar to other units within the Nadaleen area, the Gametrail Formation is mostly representative of slope sedimentation, as indicated by the presence of hemipelagic deposits, sediment-gravity flow indicators, and abundant evidence for soft-sediment deformation (e.g., Bouma, 1962; Mulder and Alexander, 2001; Owen et al., 2011); however, evidence for shoaling into storm wave base in an outer ramp or shelf setting may be indicated by the development of localized HCS/SCS and lightly disrupted flat-pebble conglomerate layers within the Gametrail Formation (Fig. 8). There are no direct age constraints on the Gametrail Formation, but as discussed below, these strata host a large negative carbon isotope excursion that has been correlated globally with the poorly constrained ca. 579–551 Ma Shuram-Wonoka anomaly (Macdonald et al., 2013).


A
B
C
Section G2
Black shale mbr
Green clastic mbr
Gametrail Fm
D
E
Bluefl. Fm, middle mbr
Bluefl. Fm, lower mbr
Gametrail Fm
Nadaleen Fm
F
G
H
Narchilla Fm
Algae Fm

Figure 7.

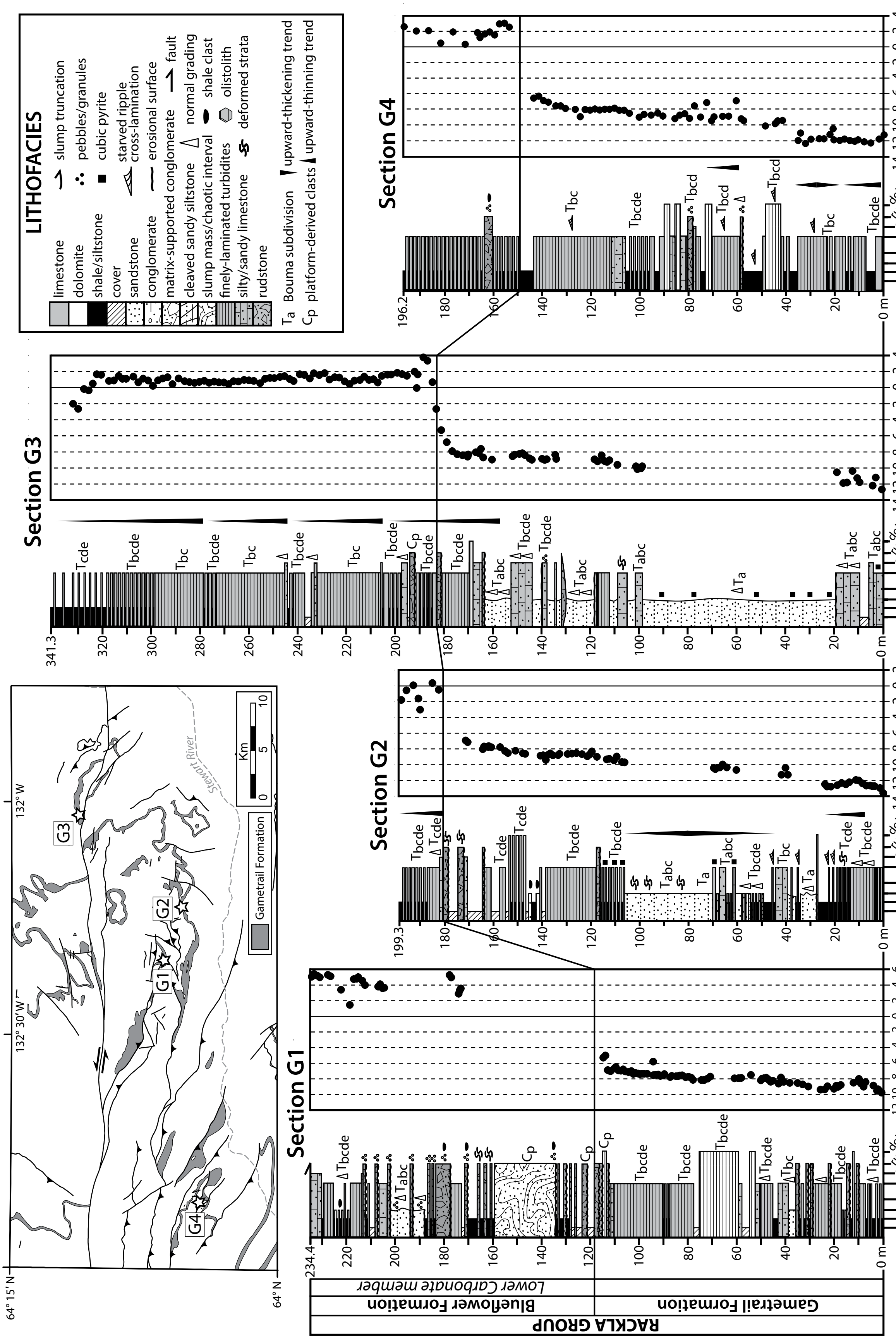

Figure 8. Measured stratigraphic sections and $\delta^{13}C_{carb}$ data from the Gametrail Formation from the Nadaleen River area, Yukon, Canada. Inset map shows the distribution of the formation and the location of measured sections.

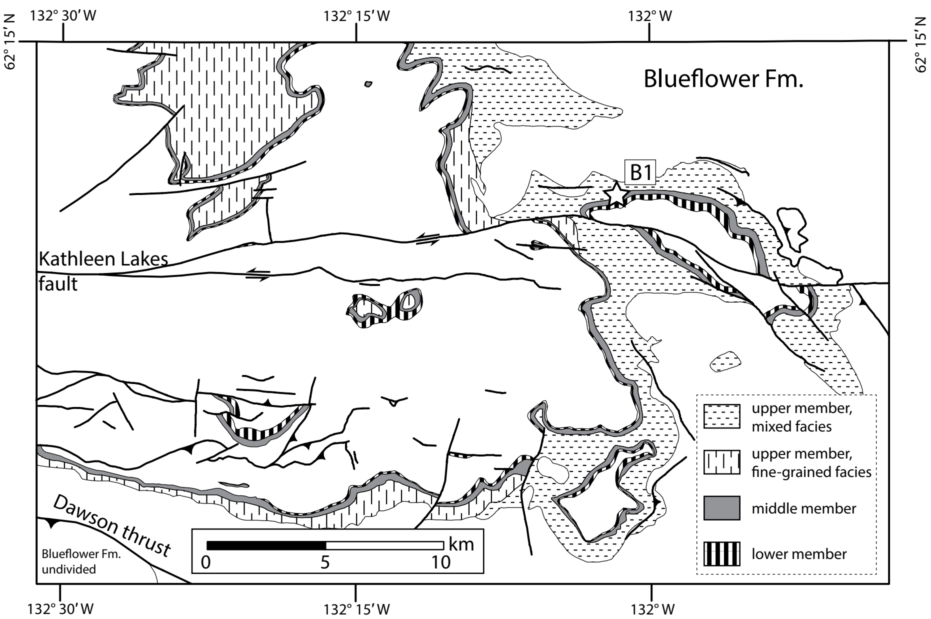

Figure 9. Distribution of the Blueflower Formation in the study area, Yukon, Canada. The two lower members are similar throughout the area, but there is east-to-west variation in the nature of rocks near the top of the formation. See text for discussion. The location of the measured section (Fig. 10) is indicated (B1). Fm.—Formation.

Blueflower Formation.

Lithostratigraphy. Moynihan (2014, 2016) previously recognized three informal members in the Blueflower Formation (Aitken, 1989) of the Nadaleen area. The lower two members are relatively homogeneous, whereas the upper member exhibits significant facies changes across the region (Fig. 9). The Blueflower Formation has not been subdivided south of the Dawson thrust (Fig. 9). The lower member of the Blueflower Formation (Figs. 7E and 10) comprises a ~150-m-thick mixed carbonate-siliciclastic succession, which is typically dominated by thin- to medium-bedded, buff to gray silty limestone and green mudstone; graded bedding is common in this unit, and these strata are rhythmically interbedded with partial Bouma sequences (Bouma, 1962). Locally, the limestone is graphitic, dusty gray on weathered surfaces and dark gray to black on fresh surfaces. Sandy limestone and rudstone also form parts of this lower succession, and are locally abundant (as in section G1, Fig. 9). In some places, these coarser grained rocks are accompanied by extensive soft-sediment deformation. Limestone turbidites of the lower member grade into ~150 m of rhythmically bedded mudstone, siltstone, and minor sandstone of the informal middle member (Fig. 7E). These finer-grained green to greenish gray strata are dominated by amalgamated Bouma BCDE sequences that locally display graded bedding and planar and ripple cross-lamination. The middle member also includes a prominent matrix-supported rudstone up to 10s of m thick, which is composed of orange-weathering carbonate boulders in a green mudstone-siltstone-sandstone matrix. Simple bed-parallel trace fossils (e.g., *Planolites*, *Helminthoidichnites*) have been identified in these middle member strata.

The upper member of the Blueflower Formation is heterogeneous in the Nadaleen River area. In the western part of the map area, it is dominantly fine-grained siliciclastic strata, whereas a mix of fine- and coarse-grained facies is common in the eastern region (Fig. 9). The fine-grained strata are dominated by brown-weathering, rhythmically bedded gray mudstone and siltstone, with intervals of gray thin-bedded silty limestone. Sandstone beds are also common but a minor constituent of the upper member in the western area. The mixed facies is generally coarser grained and contains abundant beds of medium to thick-bedded sandstone, separated by mudstone-siltstone intervals, and locally by matrix-supported rudstone

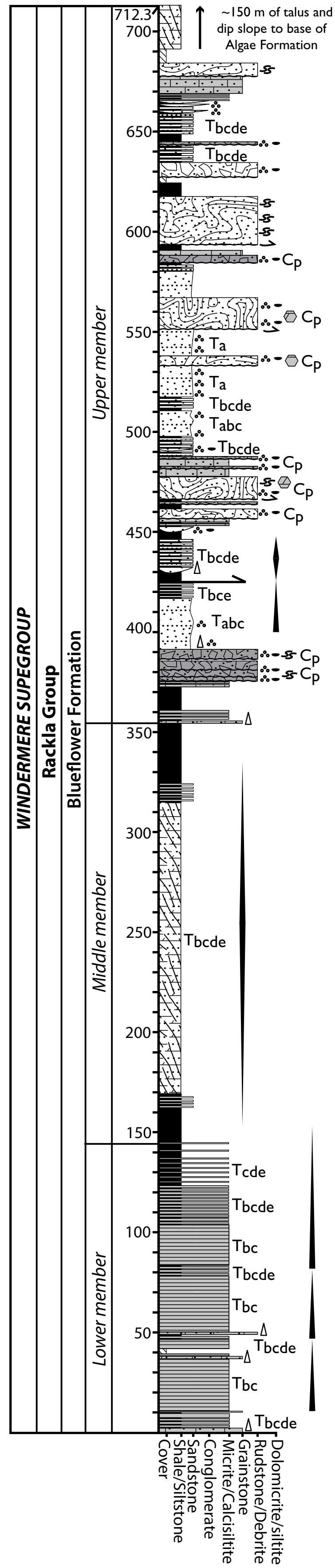

Figure 10. Measured stratigraphic section through the Blueflower Formation in the eastern part of the Nadaleen River area, Yukon, Canada. The location of the measured section is shown on Figure 9 (marked B1). See Figure 6 for legend. T_a—Bouma subdivision; C_p—platform-derived clasts.

and slump-folded intervals. Calcareous sandstone, calcareous granule-pebble conglomerate, and thin- to medium-bedded silty and sandy limestone are also constituent rock types of this coarser-grained facies (Figs. 7F and 10).

Depositional environment and age. Similar to previous studies by MacNaughton et al. (2000) and Macdonald et al. (2013), we interpret the Blueflower Formation to be mostly dominated by slope sedimentation. This is supported by the dominance of siliciclastic and mixed clastic-carbonate strata characterized by turbidites, slump folds and soft-sediment deformation, and debris flow horizons (e.g., Mulder and Alexander, 2001; Owen et al., 2011). The significance of large lateral sedimentological differences in the upper part of the Blueflower Formation is unclear—in the western part of the study area, these strata comprise fine-grained siliciclastic and lesser carbonate rocks, while eastern regions are dominated by very coarse-grained siliciclastic strata with abundant coarse-grained sandstone and conglomerate (Figs. 9 and 10). More sedimentological work needs to be completed between these two regions, but we tentatively interpret this lateral transition as representing the gradational boundary between an active channel and levee complex and the adjacent inactive slope region (e.g., Prélat et al., 2010 and references therein). There is no evidence in the Nadaleen River area for regional shoaling into wave base as is recorded in different locations of the Mackenzie Mountains (Aitken, 1989; MacNaughton et al., 2000; Macdonald et al., 2013; Sperling et al., 2016).

In the Sekwi Brook area of the Mackenzie Mountains, the Blueflower Formation contains trace fossils, a moderately diverse assemblage of Ediacaran body fossils, and a single occurrence of the putative dickinsonid *Windermeria*, which is consistent with correlation to the ca. 558–550 Ma White Sea assemblage and/or ca. 549–541 Ma Nama assemblage of Ediacaran megafossils worldwide (Narbonne, 1994; Narbonne and Aitken, 1995; MacNaughton et al., 2000; Narbonne et al., 2012; Macdonald et al., 2013). These broad age relationships are also consistent with the presence of trace fossils in the Blueflower Formation from the Nadaleen River area, although no Ediacaran body fossils have been identified in the study area at this time.

Algae Formation.

Lithostratigraphy. The Algae Formation (Cecile, 2000) is a gray cliff-forming carbonate unit that ranges in thickness from ~80 m in the southern part of the area to >200 m in the north (Fig. 11). The type section of the Algae Formation is in the Nadaleen River area, where it measures 266 m thick (Cecile, 2000; Fig. 3). The Algae is dominated by medium gray, thin- to medium-bedded silty limestone and minor mudstone, with subordinate lime grainstone, wackestone, and intraclast rudstone with local chert nodules (Figs. 7G and 7H). Complete to partial ooid fragments are a common constituent of the grainstone and wackestone strata. Limestone beds are commonly planar- and cross-laminated, and define partial (BCDE, CDE) Bouma sequences (Bouma, 1962), while low-angle bedforms HCS/SCS are only rarely present near the top of the unit. Limestone near the base of the Algae Formation is commonly dark and fetid, which emits a sulfurous smell upon hammering or walking over talus. Locally, limestone of the Algae Formation is replaced by fabric-destructive sucrosic dolostone, particularly in the upper part of the unit. Some planar-laminated calcareous sandstone is also present near the top of the formation, and locally the upper Algae Formation hosts trough cross-bedded quartz arenite in association with HCS-dominated strata (Fig. 11). In the northern part of the study area (Fig. 3), the top of the Algae Formation is heavily fractured in places and locally displays irregular, meter-scale erosional relief (Fig. 7H). In situ carbonate rock can commonly be traced upwards into a zone of disarticulated carbonate breccia and irregularly preserved bright red to maroon calcareous siltstone. Quartz sandstone-filled cavities are also locally developed within the uppermost Algae Formation and form distinct fill horizons between the brecciated carbonate blocks. The contact between the Algae Formation and the Narchilla Formation appears conformable further south in the map area (section A3; Fig. 11) and is interpreted to be conformable at the Algae Formation type section (Cecile, 2000).

Depositional setting and age. The Algae Formation most likely accumulated through a combination of hemipelagic carbonate sedimentation, sediment-gravity flows, and traction sedimentation as indicated by the sedimentary structures and depositional features (Mulder and Alexander, 2001). The presence of abundant turbidites, normal-graded beds, and grainstone composed of re-sedimented ooids indicates derivation of high-concentration sediment-gravity flows from a more proximal shallow-water environment. A distinct shoaling succession into a lower shoreface setting in the upper Algae Formation is indicated by the appearance of HCS/SCS and trough cross-stratified sandstone. In the northern part of the study area, subaerial emergence of the Algae Formation prior to deposition of the Narchilla Formation is indicated by the irregular erosional surface, the development of widespread breccia that we interpret as being related to subaerial exposure and paleokarst development, the development of *terra rosa* (Merino and Banerjee, 2008), and the reworking of Algae Formation clasts in the basal conglomerate of the Narchilla Formation. The Algae Formation is unfossiliferous, but its stratigraphic position beneath Cambrian (Terreneuvian) strata of the Narchilla Formation suggests a terminal Ediacaran age.

Post-Rackla Group strata

Narchilla Formation.

Lithostratigraphy. Two members are recognized in the Narchilla Formation (Gordey and Anderson, 1993; Cecile, 2000) throughout the Nadaleen River area. The basal Senoah member (Cecile, 2000), which weathers drab shades of brown, beige, and gray, is composed of up to 100 m of massive- to thick-bedded limestone-clast conglomerate, thin- to medium-bedded mudstone and limestone, thin-bedded calcareous sandstone, and medium- to thick-bedded sandstone and granule-pebble conglomerate. The characteristic rock type of the basal part of this member is a brown-weathering matrix-supported conglomerate or breccia that consists of clasts of gray limestone (similar to the underlying Algae Formation) in a poorly sorted sandy or granule-clast matrix. Where several layers of limestone conglomerate are present, there is generally an upward decrease in the clast:matrix ratio (Moynihan, 2014).

The overlying Arrowhead Lake member (Cecile, 2000), which is up to 600 m thick, is dominated by varicolored maroon, green, gray, and brown mudstone and siltstone, with subordinate sandstone and minor limestone. Thin-bedded mudstone and siltstone of the Arrowhead Lake member is locally graded and includes lenses of cross-bedded siltstone and fine-grained sandstone. Medium- to thick-bedded sandstone in this unit display upward transitions from planar- to ripple cross-lamination with occasional sole marks, which are interpreted as partial BC Bouma sequences (Bouma, 1962). Channelized sandstone-rich intervals up to 10 s of meters thick are present in the Arrowhead Lake member and a ~10–15-m-thick unit of sandstone with minor granule-pebble conglomerate forms a prominent marker horizon in the map area (Moynihan, 2014). Simple, bed-parallel *Planolites* and *Helminthoidichnites* trace fossil assemblages are commonly preserved in sandstone beds of the Arrowhead Lake member, and *Oldhamia* collections have been reported by Hofmann et al. (1994) and MacNaughton et al. (2016).

Depositional setting and age. The Senoah member of the Narchilla Formation records renewed marine sedimentation above the Algae-Narchilla subaerial exposure surface. Sandstone, pebble clast-supported conglomerate, limestone,

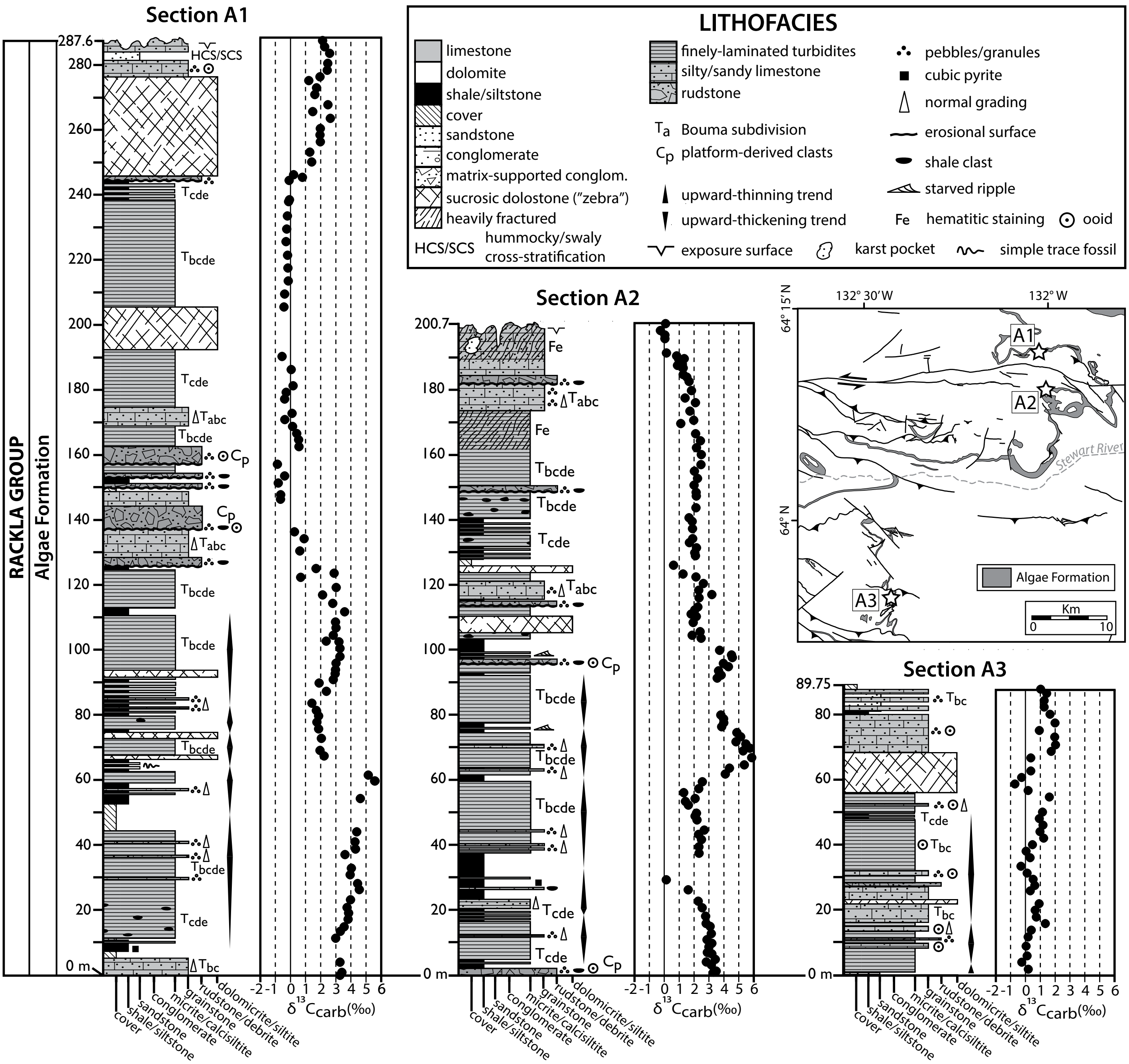

Figure 11. Measured stratigraphic sections and $\delta^{13}C_{carb}$ profiles through the Algae Formation in the Nadaleen River area, Yukon, Canada. Inset map shows the distribution of the formation and the location of measured sections.

and mudstone of the Senoah member are most likely products of this marine flooding event, and while some in situ regolith is preserved within the Algae Formation, most of the overlying conglomerate horizons are matrix-supported and interpreted to have been deposited as debris flows (Martinsen and Posamentier, 2006). The fine grain size and rhythmic nature of the layering, as well as the predominance of sedimentary structures such as graded bedding, sole marks, and partial to complete Bouma sequences suggests most of the Narchilla Formation was deposited below wave base by hemipelagic sedimentation and turbidity currents (Bouma, 1962; Lowe, 1982). This is broadly supported by the presence of *Oldhamia* trace fossil assemblages in the Narchilla Formation. While simple trace fossils exist at lower stratigraphic levels of the Rackla Group, the Arrowhead Lake member of the Narchilla Formation is the first unit in which trace fossils are conspicuous and abundant. Occurrences of *Oldhamia* most likely record deposition during Cambrian Stages 2–3 (Hofmann et al., 1994; MacNaughton et al., 2016). Fritz et al. (1983) previously placed the base of the Narchilla Formation in the uppermost Ediacaran based on other trace fossil assemblages.

Gull Lake Formation.

Lithostratigraphy. The Gull Lake Formation comprises a thin but distinctive basal member, overlain by a thick succession of mostly brown-weathering thin-bedded bioturbated mudstone and sandstone (Gordey and Anderson, 1993; Abbott, 1997; Cecile, 2000; Moynihan, 2014). The basal member is dominated by matrix-supported conglomerate comprising cobbles and boulders of limestone set in a calcareous sandy matrix. The limestone clasts are generally dominated by calcareous lime mudstone, but they are locally oolitic and in rare cases contain archaeocyathids (Gordey and Anderson, 1993; Moynihan, 2014). The heterogeneous basal member also includes white-weathering sandstone, non-calcareous pebble conglomerate, and discontinuous mafic volcanic rocks (Abbott, 1997; Cecile, 2000).

The upper member of the Gull Lake Formation is dominated by green to brown-weathering, rhythmically bedded mudstone and siltstone. Normal graded bedding is characteristic and individual beds are commonly heavily bioturbated. The uppermost parts of the formation also include intervals up to 10s of meters thick of interbedded mudstone and sandstone. Sandstone beds are 2–40 cm thick and commonly display flute and load casts on their bases. Other rocks types in the upper member include thin- to medium-bedded beige-tan-weathering silty limestone that display upward transitions from planar- to cross-lamination (Bouma BC) and limestone rudstone layers.

Depositional setting and age. The basal Gull Lake conglomerate is interpreted to have been deposited by sediment-gravity flows (Mulder and Alexander, 2001; Martinsen and Posamentier, 2006), at least some of which were derived from failure of shallow marine archaeocyathid-bearing reefs in the approximately age-equivalent Sekwi Formation (Dilliard et al., 2010). The remainder of the formation is interpreted to have been deposited below wave base by a combination of hemipelagic sedimentation and turbidity currents based on characteristics such as graded bedding, partial Bouma sequences and load casts on the base of sandstone beds (Bouma, 1962). Archaeocyathids in limestone clasts of the basal Gull Lake Formation indicate an age of Cambrian Global Series 2 or younger. Abbott (1997) reported *Bonnia-Olleneus* Zone trilobite fossils near the base of the formation in the Hart River area, ~220 km west of the study area. Similar trilobite faunas have also been recovered from the Gull Lake Formation in southeastern Yukon (Blusson, 1968). A younger limit on the age of the Gull Lake Formation in the Nadaleen River area is provided by the overlying ca. 499 Ma volcanic rocks of the Old Cabin Formation (MacNaughton et al., 2016), but where this formation is absent, it may include younger rocks.

Old Cabin Formation.

Lithostratigraphy. The Old Cabin Formation includes mafic volcaniclastic and fragmental volcanic rocks. The dominant rock types are basaltic conglomerate and breccia, including hyaloclastite, with lesser interbedded siltstone and sandstone. Basaltic clasts are clinopyroxene and locally phlogopite-phyric, are lapilli to boulder sized, and sit in a matrix of volcanic detritus. Sparry calcite commonly occupies the sites of former voids in breccias and the basalt is locally amygdaloidal. The rocks are generally green and weather brown, but are locally altered maroon, particularly adjacent to faults (Moynihan, 2014). The breccias and conglomerates are crudely stratified and contain sparsely distributed clasts and olistoliths of pale gray limestone. Siltstone and sandstone layers are most common in the lower part of the unit and are dominated by grains of plagioclase and pyroxene.

Depositional setting and age. Pillow basalts and hyaloclastite indicate formation of the Old Cabin Formation in a submarine environment (Cecile, 2000 and references therein). A volcaniclastic bed near the base of the Old Cabin Formation yielded a unimodal population of zircon grains with a U-Pb thermal ionization mass spectrometry date of 499.98 ± 0.14 Ma (MacNaughton et al., 2016).

CARBON AND OXYGEN ISOTOPE RESULTS

The stratigraphically lowest limestone unit (Ice Brook Formation limestone) yielded depleted $\delta^{13}C_{carb}$ values that range from –4.9 to –6.2‰ with $\delta^{18}O_{carb}$ values of ~–10‰ (Fig. 5; Table DR1, see footnote 1, Supplementary Data). Carbonate strata of the overlying Nadaleen Formation have highly enriched $\delta^{13}C_{carb}$ values, ranging from +5.0 to +11.3‰, with increased variability in the upper carbonate member (Fig. 6). $\delta^{18}O_{carb}$ data from the Nadaleen Formation range from –2.2 to –12.7‰, although most samples yield $\delta^{18}O_{carb}$ values of ~–9‰. The Gametrail Formation is characterized by consistent $\delta^{13}C_{carb}$ profiles from all of the measured stratigraphic sections, which display a pronounced nadir of ~–13‰, followed by a gradual increase up-section to around –8‰ and a rapid increase to positive values at/near the top of the formation (Fig. 8). $\delta^{18}O_{carb}$ data from the Gametrail Formation yield a small range of values from –8.8 to –12.4‰ (Supplementary Data, see footnote 1). $\delta^{13}C_{carb}$ values are enriched in the lower member of the Blueflower Formation, with values mostly in the +2.9 to +5.4‰ range and $\delta^{18}O_{carb}$ data ranging from –6.0 to –8.6‰. $\delta^{13}C_{carb}$ isotopic data from the Algae Formation are typically enriched, with most values in the range +0.1 to +5.9‰ (Fig. 11); however, all the measured sections yield variable negative-trending intervals down to approximately –0.8‰ (Fig. 11). $\delta^{18}O_{carb}$ data from the Algae Formation range from –1.1 to –12.1‰, although most $\delta^{18}O_{carb}$ values are –9‰ (Table DR1).

DISCUSSION

Stratigraphic Correlations

Interpretation of the stratigraphic architecture of the uppermost parts of the Windermere Supergroup in the proximal Mackenzie, Wernecke, and Ogilvie mountains has been hampered by differential erosion beneath the "sub-Cambrian" unconformity (Aitken, 1991a) and by juxtaposition of contrasting stratigraphic levels across different Cordilleran thrust panels. As many of the units in the Hay Creek and Rackla groups are lithologically similar, this erosion has complicated correlations within northwestern Canada and with other Cryogenian–Ediacaran successions along the length of the Cordillera. In contrast, there is stratigraphic continuity from the Cryogenian to the early Paleozoic in the Nadaleen River area, and units can be traced across and around the tip zone of the Dawson thrust (Fig. 1). In addition, the excellent exposure makes it an ideal location for formal definition of the Rackla Group (Table 2). Neoproterozoic rocks along strike to the west of the Nadaleen River area have not been mapped in sufficient detail to confidently assign to group level, but it is likely that the Rackla Group extends westward along the corridor between the Dawson and Robert Service faults and that the Yusezyu Formation is restricted to the hanging wall of the Robert Service thrust, as illustrated in Figure 1.

The Nadaleen River area includes distal expressions of latest Cryogenian sedimentation in the form of the Ice Brook Formation. Though clearly identifiable, the Ice Brook Formation in the Nadaleen River area exhibits contrasts with its type area in the Mackenzie Mountains. For example, the Durkan member olistostrome is absent and the Delthore member is an order of magnitude thicker than in its type area; however, the Delthore member is comparable to an equivalent unit in the adjacent Wernecke Mountains (Eisbacher 1981; Macdonald et al., 2017). Aitken (1991a) interpreted clasts in the Ice Brook Formation to have been derived locally from the Keele and Twitya formations in its type area. In contrast, the Ice Brook contains abundant detritus from older units in the Nadaleen River area. The presence of megaclasts derived from the Mackenzie Mountains Supergroup requires removal or non-deposition of the Rapitan Group and lower Hay Creek Group in the source region. The area surrounding the study area is covered by younger strata, but in the Goz River area, ~30 km to the north-northwest (Fig. 1), the Rapitan Group is absent and the lower Hay Creek Group lies directly on the Katherine Group (Eisbacher, 1981; Thorkelson et al., 2001; Macdonald et al., 2017); therefore much or all of the exhumation of these older units may have been complete before the Ice Brook Formation was deposited. Eisbacher (1981) and Macdonald et al. (2017) have suggested extensional tectonism accompanied deposition of the Keele and Ice Brook formations and facilitated exposure of the Mackenzie Mountains Supergroup. The mass transport deposits in the Ice Brook Formation could have formed in response to this period of faulting, but it is also plausible that these deposits may have formed as a response to global sea level fall associated with the onset of the Marinoan glaciation. The Ravensthroat formation, which records the end of the Marinoan glaciation and the beginning of the Ediacaran Period, is thin in the Nadaleen River area but it ultimately records similar lithofacies to those described elsewhere in the northern Cordillera (e.g., Eisbacher, 1981; Aitken, 1991a; Hoffman et al., 1998; James et al., 2001; Macdonald et al., 2013). Likely correlatives of the Ice Brook Formation in the Canadian Cordillera include the Toobally Formation in SE Yukon (Pigage and MacNaughton, 2004) and the Vreeland Formation in the central Rocky Mountains (McMechan, 2015; Fig. 12).

As highlighted above, the Rackla Group of the Nadaleen River area includes the Sheepbed, Nadaleen, Gametrail, Blueflower, Algae, and Risky formations. The Algae Formation is a deep-water equivalent of the Risky Formation; although they are stratigraphic equivalents, each is included in the Rackla Group because they were formally defined independently (Aitken, 1989; Cecile, 2000). Cecile (2000) assigned the Algae Formation to the Hyland Group, but its type section is in the Nadaleen River area and it forms an integral part of the succession described above. The newly defined Nadaleen Formation (Table 1) is equivalent to an interval of the Ediacaran succession that was previously included in the middle-upper Sheepbed Formation (Dalrymple and Narbonne, 1996) and later informally identified as the "June beds" by Macdonald et al. (2013). Macdonald and colleagues (2013) documented a submarine erosional contact between the "June beds" and underlying Sheepbed Formation and noted that previous reports of Ediacaran fauna in the Sheepbed Formation (Dalrymple and Narbonne, 1996) were from higher parts of the stratigraphic succession that are now correlative with the Nadaleen Formation. As noted by Macdonald et al. (2013), the ~55 m.y. difference between the bottom of the Sheepbed Formation and the lowest Ediacaran-bearing strata likely reflects slow sedimentation rates in the Sheepbed Formation, in combination with the removal of an undetermined amount of strata beneath the Nadaleen Formation basal erosional surface. In the Nadaleen River area, this erosional event is most likely recorded by the localized removal of carbonate-bearing strata in the uppermost Sheepbed Formation.

The Nadaleen Formation varies greatly in thickness from <50 m in some proximal locations to >600 m in the Nadaleen River type area (Macdonald et al., 2013; this paper). The base of the formation records an influx of coarse-grained carbonate sediment to the slope environment, presumably in response to a fall in relative sea level. $\delta^{13}C_{carb}$ measurements from these carbonate rudstones and grainstones are similar to those from limestone deposits of the informal Sheepbed carbonate (*sensu* Macdonald et al., 2013), but clasts identical to the Ravensthroat formation in this member suggest that deeper levels may also have been eroded in the source region.

Significant basinward changes are also evident in the Gametrail Formation, which thins from >300 m in the north of the study area to ~15 m in the south. A similar unit has not been identified in the Yusezyu Formation, which suggests that the Gametrail Formation pinches out to the southwest as part of the basinward facies transition between the Rackla and Hyland groups (Fig. 12). A possible correlative of the Gametrail Formation elsewhere in the Canadian Cordillera is the Chowika Formation of the central Rocky Mountains (Fig. 12; McMechan, 2015); it is in a similar stratigraphic position and shares many lithological characteristics.

The Nadaleen River area occupies an intermediate position between proximal successions of the Mackenzie/Ogilvie mountains and basinal strata of the Hyland group. Early workers suggested correlation between the Yusezyu Formation of the Hyland Group and the Rapitan Group (Blusson, 1974; Gabrielse et al., 1973), whereas Aitken (1991a) proposed an Ediacaran correlation. The only unambiguous correlation of the Hyland Group with the Rackla Group is of its upper limestone member with the Algae Formation. Strata below the limestone member are correlative with the Blueflower Formation (Fritz, 1997; this work), but it is likely that lower parts of the Yusezyu Formation include strata correlative with other Ediacaran (Rackla Group) and possibly Cryogenian (Hay Creek Group) units. The siliciclastic portion of the Yusezyu Formation is correlative with the Swanell and Tsaydiz formations of the Ingenika Group (Fig. 12).

The latest Ediacaran Algae Formation plays an important role in correlating Neoproterozoic strata proximal to the Laurentian craton with more distal parts of the Windermere Supergroup. The Algae Formation is a litho- and chemo-stratigraphic equivalent of the Risky Formation and occupies the same stratigraphic position as the limestone member at the top of the Yusezyu Formation (Gordey and Anderson, 1993; Cecile, 2000) and Espee Formation (Cassiar platform; Mansy and Gabrielse, 1978). These late Ediacaran carbonates form prominent marker units throughout the northern Canadian Cordillera (Fig. 12). A well-developed subaerial exposure and erosional surface marks the top of the Algae and Risky formations in the Mackenzie and Wernecke mountains (Aitken, 1989; Osborne et al., 1986; MacNaughton et al., 2000; Macdonald et al., 2013). This surface can be traced into the northern part of the Nadaleen River area, but there is no evidence for subaerial exposure at the Algae-Narchilla contact in the southern part of the study area (section A3 and the type section of Cecile, 2000); therefore it is likely the upper Risky-Algae erosional surface passes basinward into a correlative conformity. The base of the overlying Narchilla Formation is also considered conformable in the type area of the Hyland Group in southeastern Yukon (Gordey and Anderson, 1993).

The Narchilla Formation grades eastward into shallow water and terrestrial facies of the Vampire Formation (Fritz, 1982) and the upper part of the Backbone Ranges Formation (Fig. 12; Fritz et al., 1991; Gordey and Anderson, 1993; Cecile, 2000; see discussion in Turner et al., 2011). The Ingta Formation represents a tongue of Narchilla Formation within the upper Backbone Ranges Formation (MacNaughton et al., 2000), while a tongue of Vampire Formation overlies the Narchilla Formation in the Nahanni region of Yukon and Northwest Territories (Roots et al., 1966; Gabrielse et al., 1973; Gordey and Anderson, 1993). Pigage et al. (2015) found the Vampire and Narchilla formations largely indistinguishable from one another in the Coal River area of SE Yukon. The Narchilla Formation is also likely correlative with the Stelkuz Formation of the Ingenika Group (Fig. 12). The Ingta (MacNaughton and Narbonne, 1999), Vampire (Fritz et al., 1983), and Stelkuz formations (Fritz and Crimes, 1985) each contain the Ediacaran–Cambrian boundary. The Narchilla Formation is correlative with post-Windermere Supergroup strata in the Mackenzie and Wernecke Mountains (Ingta Formation, Vampire Formation, and part of the Backbone Ranges Formation). This

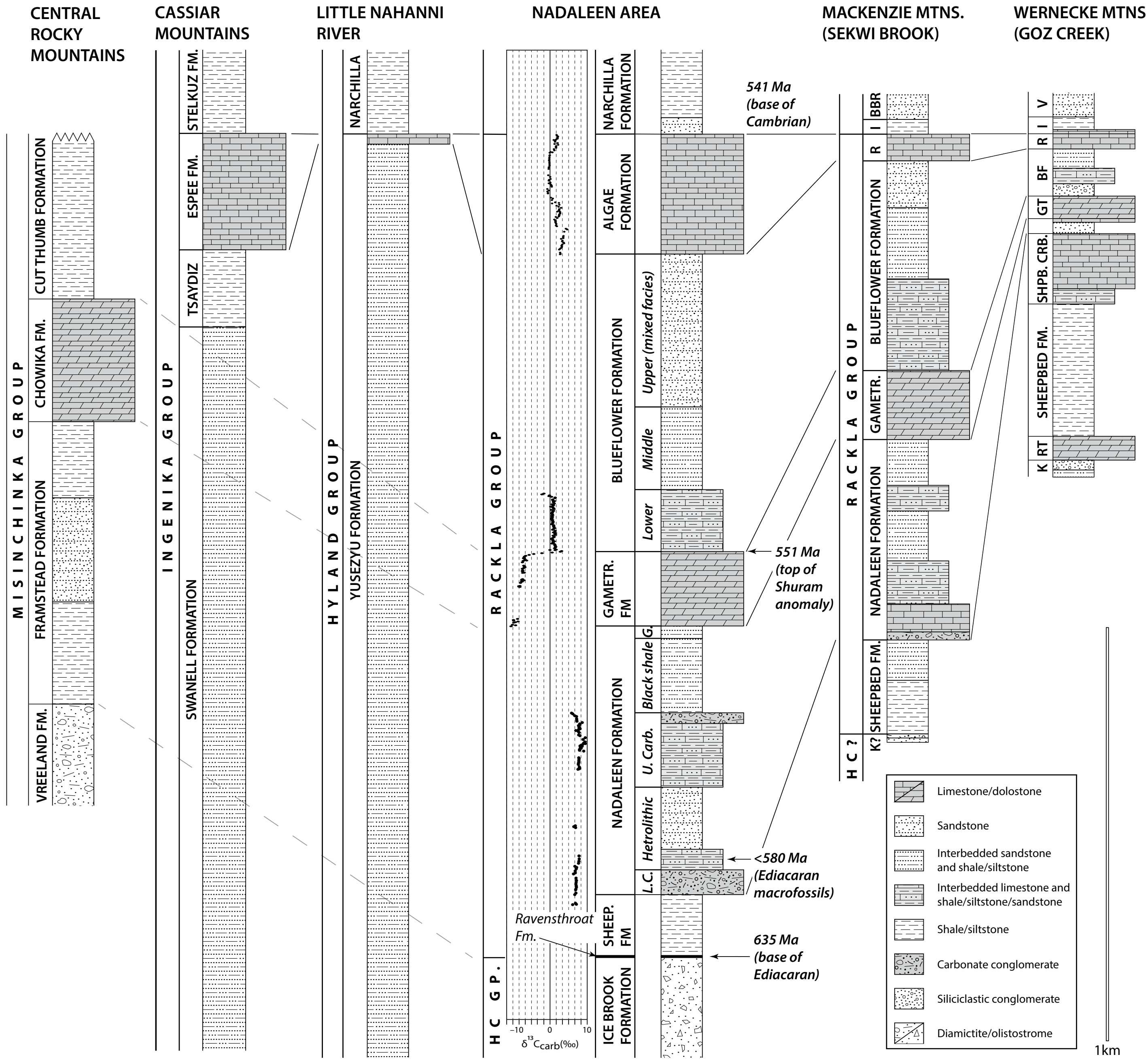

Figure 12. Stratigraphic correlations among the major units in the Windermere Supergroup of the northern Canadian Cordillera and central Rocky Mountains. Cassiar Mountains data from Mansy and Gabrielse (1978); Little Nahanni River data from Gordey and Anderson (1993); Central Rocky Mountains data from McMechan (2015); Mackenzie and Wernecke mountains data from Macdonald et al. (2013). FM.—Formation; MTNS—Mountains; GAMETR.—Gametrail; GT—Gametrail; HC GP.—Hay Creek Group; HC?—Hay Creek Group; K?—Keele Formation; SHEEP—Sheepbed; SHPB. CRB.—Sheepbed carbonate; L.C.—lower carbonate; U. Carb.—upper carbonate; G.—Gametrail Formation; R—Ravensthroat formation; I—Ingta Formation; BBR—Backbone Ranges Formation; RT—Ravensthroat formation; BF—Blueflower; V—Vampire Formation.

highlights inconsistency in how the top of the Windermere Supergroup is defined, as the Hyland Group, whose upper part is represented by the Narchilla Formation, has previously been included in the Windermere Supergroup (Gabrielse and Campbell, 1991).

The oldest metazoan-bearing unit in the Nadaleen River area is the Gull Lake Formation, which is partly correlative with the Hess Formation in the Misty Creek embayment (Cecile, 1982), and with the oldest parts of the Road River Group in Richardson trough (Fig. 13; Fritz, 1985, 1997). It is age-equivalent with all or part of the Sekwi Formation of the Mackenzie platform and the Illtyd Formation on the Yukon block (Fritz, 1997). MacNaughton et al. (2016) suggested that the base of the Gull Lake Formation may correlate with a prominent regressive

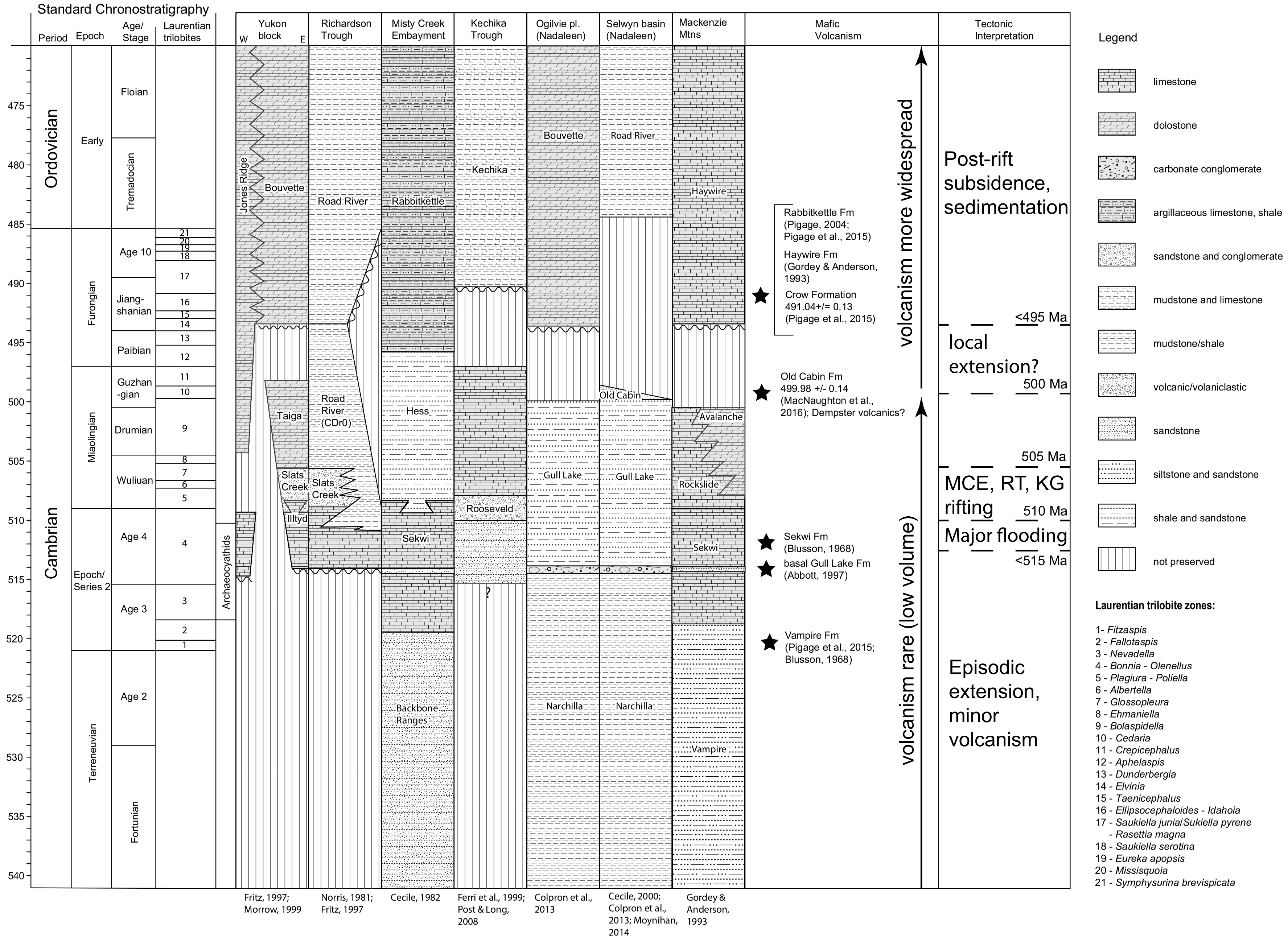

Figure 13. Summary chart of latest Ediacaran–Cambrian stratigraphy of the northern Canadian Cordillera and Kechika trough, along with the timing of regional magmatism, and an interpretation of its tectonic development. Sources are indicated at the base of each stratigraphic column. Fm—Formation; pl.—platform; carb. sed.—carbonate sedimentation; MCE—Misty Creek embayment, RT—Richardson Trough, KG—Kechika graben.

sandstone within the Sekwi Formation rather than its older (*Fallotaspis* and *Nevadella* Zone) parts. The correlative unit on Cassiar platform is the archaeocyathid-bearing Rosella Formation of the Atan Group (Fig. 12; Fritz, 1980). The top of the *Nevadella* Zone is located just 1.5–1.6 m above the base of the Rosella Formation, most of which belongs to the *Bonnia-Ollenelus* Zone (Fritz, 1980; Fig. 14). The Old Cabin Formation is likely correlative with the Dempster volcanics of northwestern Selwyn basin (Abbott, 1997); although it is lithologically similar to a variety of other alkaline lower Paleozoic volcanic sequences in the northern Cordillera (Goodfellow et al., 1995), volcanic rocks of this age are not otherwise widely distributed.

Carbon Isotope Chemostratigraphy

As is typical of most Neoproterozoic carbonate successions worldwide, there is pronounced variation in $\delta^{13}C_{carb}$ data from the Cryogenian Hay Creek and Ediacaran Rackla groups of the Nadaleen River area. We use the carbon isotopic data solely for chemostratigraphic purposes to inform our regional lithostratigraphic correlations and do not discuss the origin and processes surrounding this variation. The carbon isotopic data presented herein are consistent with previously reported $\delta^{13}C_{carb}$ data from the Hay Creek and Rackla groups in the Mackenzie and Wernecke mountains (e.g., Narbonne et al., 1994; Kaufman et al., 1997; Halverson et al., 2005; Macdonald et al., 2013, 2017). Most of the succession is enriched in $\delta^{13}C_{carb}$, with two notable exceptions: limestone of the Ice Brook Formation is systematically depleted down to ~–5‰ (Figs. 5 and 12), and the Gametrail Formation yields a prominent negative $\delta^{13}C_{carb}$ excursion down to –13‰ (Figs. 6, 8, and 12). The depleted $\delta^{13}C_{carb}$ data from the Ice Brook Formation (Fig. 5) are consistent with recently reported data from the Ice Brook Formation and Mount Profeit dolostone in the Goz Creek region of the Wernecke Mountains, which were tentatively correlated with the pre-Marinoan Trezona negative carbon isotope excursion (Macdonald et al., 2017).

Macdonald et al. (2013) previously reported negative $\delta^{13}C_{carb}$ values in the lower part of the Gametrail Formation of the Wernecke Mountains and correlated this excursion with the globally recognized Shuram-Wonoka anomaly (see recent reviews in Grotzinger et al., 2011 and Husson et al., 2015). The data presented herein strengthen this correlation, as the Nadaleen River area data set is remarkably consistent with $\delta^{13}C_{carb}$ profiles from other Ediacaran successions that host the Shuram-Wonoka anomaly. In particular, $\delta^{13}C_{carb}$ values in the lower Gametrail Formation are as low as those measured elsewhere globally (–13‰), and the $\delta^{13}C_{carb}$ profiles exhibit the same asymmetry with a mostly truncated base, gradual increase up-section and an abrupt increase near the Gametrail-Blueflower formational boundary (Figs. 8 and 12). This excursion is systematically developed in all our measured sections (Fig. 8) and is unrelated to later Carlin-type gold mineralising fluids, which locally reset $\delta^{13}C_{carb}$ systematics in thin carbonate units (Tucker, 2015). Geochronological constraints from other localities suggest that the Shuram-Wonoka anomaly occurred between ca. 580 and 551 Ma (Condon et al., 2005; Le Guerroué et al., 2006); although recent reports questioning the stratigraphic position of the ca. 551 Ma tuff in the Duoshantuo Formation of South China makes this upper age constraint slightly ambiguous (Zhou et al., 2017). The cause of the Shuram-Wonoka has been widely speculated upon but remains uncertain (e.g., Husson et al., 2015).

Carbonate carbon isotopic data from the Nadaleen and Blueflower formations are similar to $\delta^{13}C_{carb}$ data presented in Macdonald et al. (2013) from the Sekwi Brook region of the Mackenzie Mountains, confirming our lithostratigraphic correlations between the two disparate regions and providing a solid chemostratigraphic framework with which future lithostratigraphic correlations can be tested. Finally, we present the first high-resolution carbon isotopic data from the Algae Formation, which locally resembles low resolution $\delta^{13}C_{carb}$ data from the Risky Formation of the Mackenzie Mountains (Narbonne et al., 1994; Kaufman et al., 1997), including a decrease in $\delta^{13}C_{carb}$ values approaching the Algae-Narchilla or Risky-Ingta contacts (Fig. 11). This decrease has been interpreted as part of a negative carbon isotope anomaly coincident with the Ediacaran–Cambrian boundary (Narbonne et al., 1994), although its association with widespread dolomitization and a subaerial exposure surface makes its origins ambiguous.

Ediacaran–Cambrian Evolution of the Northern Cordilleran Margin and the Age of the Rift-Drift Transition

Although parts of the Hay Creek Group, Rackla Group, and overlying units have features suggestive of syn-sedimentary tectonism (e.g., Eisbacher, 1981; Aitken, 1989; Gordey and Anderson, 1993; Dilliard et al., 2010; Macdonald et al., 2017), the stratigraphic units are generally continuous over large regions and direct evidence for extension in the late Ediacaran–early Cambrian is not as emphatic as that recorded in the basal Windermere Supergroup. Levy and Christie-Blick (1991) noted a similar dearth of evidence for upper crustal extension in equivalent rocks of the southern Cordillera (USA) and attributed the relatively subtle record of Ediacaran–Cambrian extension to (1) heterogeneous distribution of stretching in the lithosphere (depth-dependent stretching, e.g. Huismans and Beaumont, 2014), and/or (2) a position continent-ward of the hinge zone between stretched and unstretched lithosphere. Geographic and temporal variation in the locus of extension is compatible with asymmetric rift models proposed by Cecile et al. (1997), Lund (2008), Lund et al. (2010), and Beranek (2017).

Bond and various colleagues (Bond and Kominz, 1984; Bond et al., 1985; Devlin and Bond, 1988) and Levy and Christie-Blick (1991) suggested the transition from rift to post-rift subsidence took place around the start of the Cambrian along the Cordilleran margin of western Laurentia. This suggestion is in broad agreement with other workers who interpreted the "sub-Cambrian" unconformity of the Mackenzie Mountains as the base of the post-rift continental margin sequence (e.g., Aitken, 1993; Yonkee et al., 2014; Beranek, 2017); however, revisions to the geological timescale necessitates modification of estimates based on subsidence analysis (Dickinson, 2004), and there is ample evidence for later extension in the northern Canadian Cordillera (e.g., Blusson, 1968; Fritz, 1997; Morrow, 1999; Post and Long, 2008; Dilliard et al., 2010).

The Nadaleen River area contains a near continuous record of the Ediacaran–Cambrian interval during which regional rifting led to eventual continental separation and widespread passive margin sedimentation. Here we review geological constraints on the timing of the rift to post-rift transition throughout the northern Canadian Cordillera. In particular, we discuss evidence for major tectonic reorganizations indicated by changes in the nature and distribution of sedimentation patterns, stratigraphic architecture, and the locus of regional erosion.

The "Sub-Cambrian" Unconformity

As stated previously, Ediacaran strata in the Mackenzie Mountains generally display unconformable relationships with Cambrian rocks; this is exemplified by the westward appearance of progressively younger Ediacaran units beneath Cambrian rocks of the Backbone Ranges Formation (Aitken, 1989). This "sub-Cambrian" unconformity (e.g., Aitken, 1991a) is an amalgamation of multiple late Ediacaran–early Cambrian erosional sequence boundaries, whose combined effects are significant in proximal locations (MacNaughton et al. 2000). The most significant surface, which is coincident with a basinward shift in facies, occurs high in the Blueflower Formation (MacNaughton et al., 2000), and the high concentration of composite

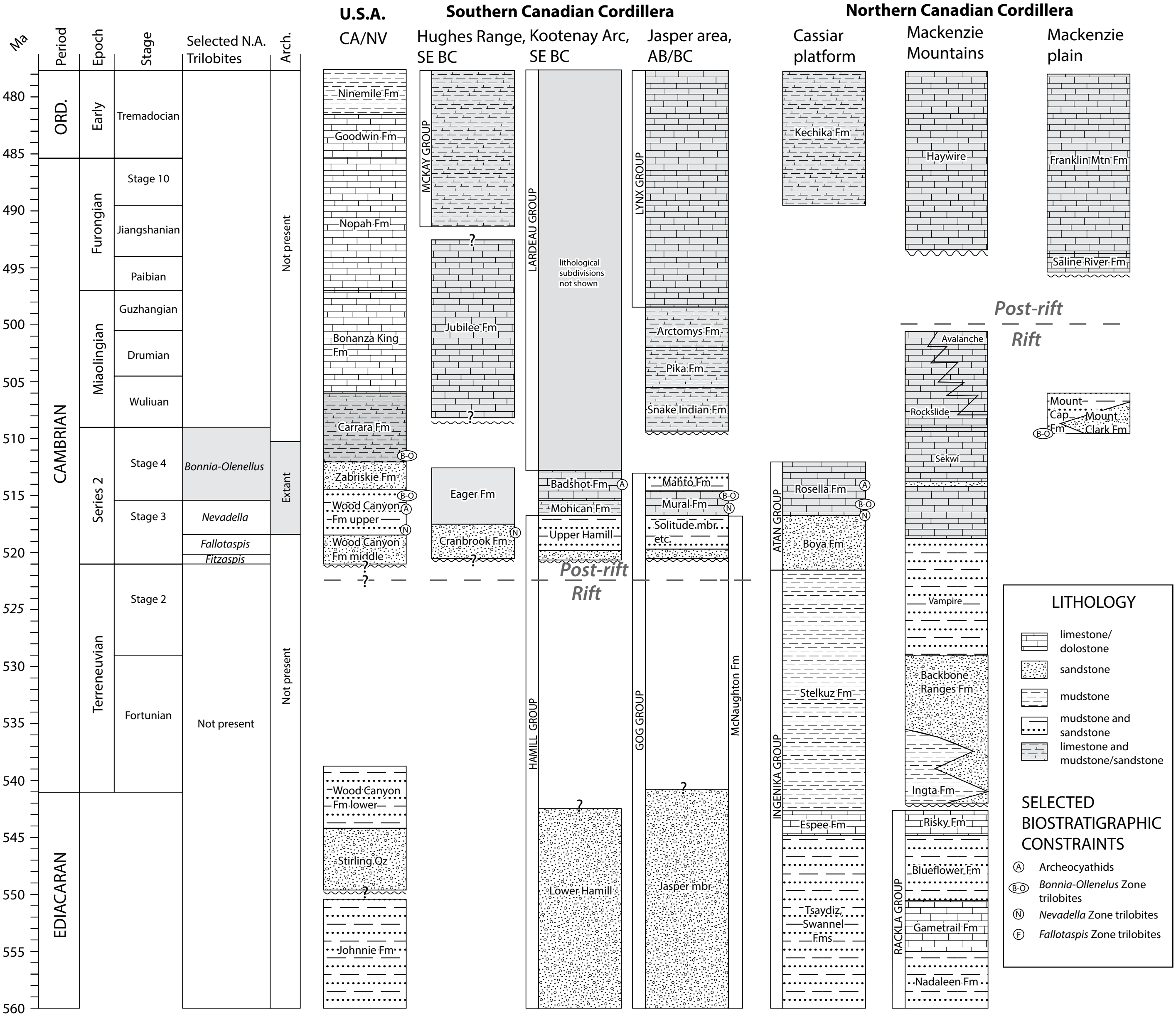

Figure 14. Age ranges of selected upper Proterozoic–lower Ordovician units of the western North American Cordillera. The interpreted ages of rift to post-rift transitions are marked with dashed lines. The section from the southern Cordillera (USA) includes a dashed line showing the interpreted position of the rift to post-rift transition in California/Nevada (CA/NV) (e.g., Levy and Christie Blick, 1991). The locations of many boundaries are approximate as a result of sparse fossil/geochronological data. The stratigraphic position of selected early Cambrian fossils are shown. The timescale is after Cohen et al. (2013) and was produced using TSCreator version 6.3 (2017) (http://www.tscreator.org). Stratigraphic data for California/Nevada from Stewart, 1970 and Poole et al., 1992; for southern Canadian Cordillera from Fyles and Hewlett, 1959; Warren, 1997; Lickorish and Simony, 1995; Leech, 1954; Hein et al., 1994; Slind et al., 1994; for northern Cordillera from Fritz, 1997; Morrow, 1999; Cecile, 2000; Turner et al., 2011; Herbers et al., 2016; this work. Fm—Formation; mbr—member; Mtn—Mountain; ORD.—Ordovician; Qz—quartz; Arch.—Archaeocyathids; SE BC—Southeastern British Columbia; AB/BC—Alberta/British Columbia.

sequence boundaries in the uppermost Blueflower and Risky formations was previously interpreted by MacNaughton et al. (2000) to reflect regional thermal uplift. The subaerial exposure surface between the Algae/Risky and Ingta/Narchilla formations [referred to by Aitken and Narbonne (1995) as the "sub-Cambrian" unconformity] passes laterally into conformable strata in the Nadaleen River area and does not coincide with a significant shift in facies. While the "sub-Cambrian" unconformity is aerially extensive and responsible for removal of significant amounts of strata, the interpretation that it marks the base of the continental margin sequence following continental breakup (Aitken, 1993; Yonkee et al., 2014; Beranek, 2017) warrants scrutiny because syn-sedimentary tectonism is recorded in overlying units (e.g., Blusson, 1967;

Fritz, 1997; Morrow, 1999; Dilliard et al., 2010) and some of these younger Cambrian strata appear to record more significant changes in the tectono-sedimentary evolution of the margin (see below). Rather than marking a rift-drift transition, the unconformity may instead record regional uplift during a period of extension prior to final development of the continental margin.

The Sub-Bonnia-Olleneus Zone Unconformity

The "sub-Cambrian" unconformity is overlain by a complete Terreneuvian succession in the Mackenzie Mountains, but late Neoproterozoic to earliest Cambrian strata are absent in the Ogilvie platform and Richardson trough where early Paleozoic rocks unconformably overlie a variety of early Neoproterozoic and Mesoproterozoic sedimentary units (Fig. 13; Fritz, 1997). Rocks above the unconformity belong to the *Bonnia-Ollenelus* Zone (Cambrian Global Series 2); this includes the carbonate-dominated Illtyd Formation of the Yukon block and Richardson trough and the Mount Clark Formation of the Mackenzie Plain (Aitken, 1991a; Fritz, 1997; Herbers et al. 2016; Fig. 14). The Mount Clark Formation mostly overlies Proterozoic rocks of the Mackenzie Mountains and Shaler supergroups, but onlaps crystalline basement around Great Slave Lake (Aitken, 1993; Fritz, 1997). Rocks above this unconformity thus record a large northeastward overlap of the previous basin margin and expansion of Cambrian sedimentation within northwestern Laurentia.

This major transgression coincides with deposition of the main part of the Gull Lake Formation in the Nadaleen River area, and the *Bonnia-Ollenelus* Zone portion of the Sekwi Formation, which overlies a prominent sequence boundary and regressive sandstone deposit (Dilliard et al., 2010; MacNaughton et al., 2016). Therefore, the sub-*Bonnia-Ollenelus* Zone unconformity and overlying strata record a significant change in the depositional history of the northern Cordilleran margin, with widespread erosion followed by large-magnitude overstepping of the previous basin margin; however, this regional transgression was followed by further substantial rifting during the middle Cambrian (Global Series 2–3), which led to the establishment of the deep-water Misty Creek embayment (Cecile, 1982), Richardson trough (Fritz, 1997; Morrow, 1999), and Kechika graben system (Post and Long, 2008).

Cambrian Series 2–3 Rifting and the Sub-Jiangshanian Unconformity

The Richardson trough (Fig. 1) began to subside during the deposition of the Illtyd Formation (*Bonnia-Ollenelus* Zone), whose middle and upper parts record negative movement of the trough relative to the Yukon block (Fritz, 1997). Further subsidence and block faulting accompanied deposition of coarse clastic rocks of the Wuliuan Slats Creek Formation (Fritz, 1997; Fig. 13). Initial subsidence in the Misty Creek embayment (Fig. 1) also took place during the *Bonnia-Ollenelus* Zone (Cecile, 1982). The Richardson trough and Misty Creek embayment formed a significant rift corridor that accommodated separation of the Yukon block relative to Laurentia during Cambrian Stages 4–5 (Fig. 13; Cecile, 1982; Fritz, 1997), although there is some evidence for earlier (Neoproterozoic) transtension in the same region (Eisbacher, 1981; Eyster et al., 2017; Macdonald et al., 2017).

The syn-rift Mount Roosevelt Formation of the Kechika trough, northern British Columbia, was mostly deposited during the *Plagiura-Poliella* Zone, but deposition may have begun during the *Bonnia-Ollenelus* Zone (Fig. 13; Post and Long, 2008). The end of Stage 4–Wuliuan rifting was followed by a return to carbonate sedimentation in the Kechika region (Post and Long, 2008), and there was contemporaneous carbonate sedimentation on the Mackenzie and Ogilvie platforms (Gordey and Anderson, 1993; Fritz, 1997; Morrow, 1999). Carbonate units in the Mackenzie Mountains (Rockslide and Avalanche formations) exhibit a NW-SE–trending facies boundary during the Wuliuan-Drumian, which is interpreted to indicate the orientation of a shelf edge (Gordey and Anderson, 1993). This facies boundary is orthogonal to earlier and later facies belts, and is further evidence for middle Cambrian tectonism (Gordey and Anderson, 1993).

Across much of the Ogilvie platform, lower Cambrian deposits are thin to absent and unconformably overlain by widespread upper Cambrian strata of the Jones Ridge and Bouvette formations (Fig. 13). This flooding surface is also prominent in the subsurface of northern Yukon, where it cuts the sub-Illtyd unconformity (Morrow, 1999). The lower Bouvette Formation is correlative with the carbonate-dominated Rabbitkettle Formation (Gabrielse et al., 1973), which also overlies a widely developed unconformity in parts of Selwyn basin (Fig. 13; Gordey and Anderson, 1993). This sub-Jiangshanian unconformity (formerly referred to as the sub-Franconian unconformity, e.g., Aitken, 1993) is also developed across much of the Mackenzie platform, where it underlies upper Cambrian rocks of the Franklin Mountain and Broken Skull formations (Gordey and Anderson, 1993; Gordey and Roots, 2011). An unconformity is similarly developed under the upper Cambrian Otter Creek and Crow formations of southeastern Yukon (Pigage et al., 2015). The sub-Jiangshanian unconformity is commonly angular (e.g. Gabrielse et al., 1973), which has been attributed to tilting caused by Stage 4-Wuliuan faulting (Gordey and Anderson, 1993; Fritz, 1997).

In summary, the regionally extensive sub-Jiangshanian unconformity separates fragmented early-middle Cambrian successions that were influenced by episodic tectonism from a relatively thick and complete package of upper Cambrian–Devonian carbonate strata that formed under stable paleogeographic conditions. The paleogeographic domains of the northern Cordillera (basins and high blocks) that were established during Cambrian Stage 4–Wuliuan rifting represent first-order features of the margin that persisted through much of the lower Paleozoic (Cecile et al., 1997; Morrow, 1999), and in some cases underwent further episodic extensional deformation (Cecile, 1982; Cecile et al., 1997). We therefore interpret the sub-Jiangshanian unconformity as the base of the "passive" continental margin sequence in the northern Canadian Cordillera.

Relationship of the Rift to Post-Rift Transition to Seafloor Spreading and Volcanism

Cecile et al. (1997) noted similarities between the history of the Cordilleran margin and the Atlantic margin of eastern North America, and Beranek (2017) explicitly used the Newfoundland-Iberia rift system as an analogue for the Cordilleran margin. Magma-poor rifting of the Newfoundland-Iberia margin was achieved in stages, by breakup of continental crust and exhumation of mantle to the ocean floor, followed by complete lithospheric breakup (Péron-Pinvidic et al., 2007; Soares et al., 2012). Interpretations differ as to the age of the oldest oceanic crust (Péron-Pinvidic et al., 2010; Soares et al., 2012 and references therein), but seafloor may have been generated prior to formation of the principle (Aptian-Albian) surface that separates syn-rift from post-rift rocks (lithospheric breakup surface of Soares et al., 2012). By analogy with the Atlantic margin, we interpret the transition from Stage 4-Wuliuan rifting to widespread post-Jiangshanian sedimentation to reflect the onset of typical seafloor spreading in the northern Canadian Cordillera; it may not, however, record the earliest generation of oceanic crust in the region. There was little magmatism during Atlantic rifting, but a significant amount of alkaline basalt was intruded on the distal Newfoundland side of the margin ~7–15 m.y. after final breakup (Péron-Pinvidic et al., 2010).

In common with the North Atlantic and other magma-poor rifted margins (Franke, 2013), the northern Canadian Cordilleran margin experienced some post-rift alkaline mafic magmatism. Volcanism was not restricted to distal regions of the margin, as host rocks include shallow marine/terrestrial rocks of the Bouvette, Haywire, and Crow formations (Green, 1972; Gordey and Anderson, 1993; Pigage et al., 2015), as well as deep-water strata in the Selwyn basin (Goodfellow et al., 1995; Cecile, 2000; Pigage, 2004). The Old Cabin Formation and correlative Dempster volcanics (Abbott, 1997) are not the oldest alkalic volcanic rocks preserved in the northern Canadian Cordillera (Blusson, 1968; Cecile, 2000; Pigage et al., 2015), but they represent the first extensive and geographically widespread accumulations. They lie beneath the sub-Jiangshanian unconformity, but post-date Stage 4-Wuliuan rifting by several million years. Further study is needed to determine whether this volcanism was accompanied by a final pulse of extension immediately prior to stabilization of the margin, or took place during post-rift thermal subsidence.

Comparison with the Rift-Drift Transition Elsewhere on the Laurentian Margin

In the southern and central Canadian Cordillera, Neoproterozoic rocks of the Windermere Supergroup are conformably to unconformably overlain by the Ediacaran–lower Cambrian Gog and Hamill groups (Fritz et al., 1991; Hein et al., 1994). An unconformity within the Hamill Group separates syn-rift deposits from regionally extensive, post-rift orthoquartzite of the upper Hamill Group (Warren, 1997) and correlative units such as the Cranbrook Formation (Schofield, 1922) and Quartzite Range Formation (Walker, 1934). Strata beneath the unconformity include 569.6 ± 5.3 Ma trachyandesite in the lower part of the Hamill Group (Colpron et al., 2002). The unconformity, which passes westward into a conformable surface, is interpreted to mark the transition from rift-related extension to post-rift subsidence (Devlin and Bond, 1988; Warren, 1997). The orthoquartzite represents the base of the Paleozoic passive margin succession and is overlain by archaeocyathid-bearing limestone of the Badshot, Donald, and Mural formations. *Nevadella* Zone trilobites have been identified near the top of the Cranbrook Formation (Leech, 1954). An analogous unconformity within the Gog Group was recognized by Lickorish and Simony (1995), who documented truncation of the lower Gog Group and Windermere Supergroup under the Solitude member of the MacNaughton Formation. The syn-rift to post-rift transition has not been documented in the Cassiar platform, but the base of the Atan Group (Boya Formation), appears to be approximately the same age as the post-rift sandstones of the southern Canadian Cordillera (Fig. 14) and may record a similar transition. The presence of *Nevadella* Zone trilobites in the first post-rift rocks of the southern Canadian Cordillera suggests that the syn to post-rift transition took place over 15 m.y. earlier than in the northern Canadian Cordillera (Fig. 14). Some caution may be warranted, however, as overlying rocks of the Lardeau Group record younger phases of extension and magmatism (Fyles and Hewlett, 1959; Logan and Colpron, 2006), and a dearth of geochronological and biostratigraphic data from the Lardeau Group means that the significance of this extension and magmatism for the development of the margin is uncertain.

The boundary between syn-rift and post-rift deposits of the southern Cordilleran Laurentian margin (USA) has been interpreted to coincide with a transition from coarse-grained lower Cambrian feldspathic deposits to widespread quartz arenite and carbonate sedimentation in the late early and middle Cambrian (Levy and Christie-Blick, 1991; Yonkee et al., 2014 and references therein). This boundary is marked by the middle member of the Wood Canyon Formation in the Death Valley region of California and Nevada, which is overlain by the fossiliferous upper member that yields *Nevadella* to *Bonnia-Ollenelus* Zone trilobites (Stewart, 1970; Diehl, 1976, 1979; Christie-Blick and Levy, 1989; Levy and Christie-Blick, 1991; Fig. 14). The interpreted age of the rift to post-rift transition for the western Laurentian margin in the southern (USA) Cordillera (Nevadella zone or earlier) is therefore indistinguishable from that in the southern Canadian Cordillera, and likewise significantly older than that inferred for the Northern Canadian Cordillera. Nevertheless, evidence from the Grand Canyon region (Karlstrom et al., 2018), suggests there was also some further tectonic activity through Cambrian Stages 2–4 in that area.

The apparent difference in the age of the rift to post-rift transition in the northern Canadian Cordillera compared with elsewhere suggests there was diachronous development of the ancestral western Laurentian margin, with latest continental separation along its northernmost segment. This variation is compatible with structural segmentation of the Laurentian margin. Transverse structures account for along-strike variation in deformation, subsidence and sedimentation (Cecile et al., 1997; Lund, 2008), and could separate regions with different rift histories. However, rocks of the Kechika trough, which record Cambrian Stage 4-Wuliuan rifting, are located south of the Liard Line, and are interpreted to have formed in the same "upper plate" segment of the margin as rocks of the southern Canadian Cordillera (Cecile et al., 1997).

Inferring ancient plate tectonic evolution from the stratigraphic record is inherently challenging, particularly in polyphase rift environments where there is significant temporal and spatial variation in the locus of extensional deformation and resultant sedimentation (Peron-Pinvidic et al., 2007; Soares et al., 2012). In particular, youngest rift events can be restricted to distal portions of rifted margins (e.g. Huismans and Beaumont, 2008) where they may no longer be preserved.

Data from throughout the Cordilleran margin are broadly consistent with formation of the "passive" Laurentian margin between Cambrian Stage 3 and the Jiangshanian, and while it appears that final continental separation was youngest in the northern Canadian Cordillera, future research may uncover further complexity.

CONCLUSIONS

Neoproterozoic rocks of the Nadaleen River region of east-central Yukon belong to the uppermost parts of the Windermere Supergroup and share a common stratigraphic architecture with age-equivalent strata of the Mackenzie, Ogilvie, and Wernecke mountains. The Hyland Group, with which they were previously correlated, is restricted to more distal settings to the southwest. Excellent exposure and structural continuity provide some of the best stratigraphic sections of latest Cryogenian to early Cambrian strata in the northern Canadian Cordillera. These strata record continental slope sedimentation during major environmental and regional tectonic changes. Cryogenian strata record slope failure in response to tectonic activity and fluctuations in sea level, while the first appearance of Ediacaran macrofauna occurs in the newly defined Nadaleen Formation. The global Shuram-Wonoka negative $\delta^{13}C_{carb}$ excursion is recorded in the overlying Gametrail Formation, which yields $\delta^{13}C_{carb}$ values as low as –13‰. The upper part of the Windermere Supergroup is formalized as the Rackla Group, the youngest part of which, represented by the Algae and Risky formations, is overlain by a prominent exposure surface that passes into a correlative conformity within the study area. This surface, which marks the top of the Windermere Supergroup, has been interpreted to record the transition from rifting to post-rift subsidence in the northern Cordillera. Instead, we draw attention to evidence for tectonism in the fragmented early to middle Cambrian stratigraphic record and suggest the passive continental margin formed later in the Cambrian. Post-rift subsidence is recorded by widespread late Cambrian carbonate strata (Bouvette, Rabbitkettle, Franklin Mountain, and Broken Skull formations), which overlie a geographically widespread sub-Jiangshanian unconformity. The interpreted age of the rift to post-rift transition is younger than equivalent estimates from elsewhere in the North American Cordillera.

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