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ARTICLE

Late Neoproterozoic – early Paleozoic basin evolution in the Coal Creek inlier of Yukon, Canada: implications for the tectonic evolution of northwestern Laurentia

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Abstract: The age and nature of the Neoproterozoic – early Paleozoic rift–drift transition has been interpreted differently along the length of the North American Cordillera. The Ediacaran "upper" group (herein elevated to the Rackla Group) of the Coal Creek inlier, Yukon, Canada, represents a key succession to reconstruct the sedimentation history of northwestern Laurentia across the Precambrian–Cambrian boundary and elucidate the timing of active tectonism during the protracted breakup of the supercontinent Rodinia. These previously undifferentiated late Neoproterozoic – early Paleozoic map units in the Coal Creek inlier are herein formally defined as the Lone, Cliff Creek, Mount Ina, Last Chance, Shade, and Shell Creek formations. New sedimentological and stratigraphic data from these units is used to reconstruct the depositional setting. In the Last Chance Formation, chemostratigraphic observations indicate a ca. 5‰ $\delta^{13}C_{carb}$ gradient coincident with the globally recognized ca. 574–567 Ma Shuram carbon isotope excursion. Map and stratigraphic relationships in the overlying Shell Creek Formation provide evidence for latest Ediacaran – middle Cambrian tilting and rift-related sedimentation. This provides evidence for active extension through the Cambrian Miaolingian Series in northwestern Canada, supporting arguments for a multiphase and protracted breakup of Rodinia.

Key words: Rodinia, Yukon, Shuram carbon isotope excursion, Rackla Group, Coal Creek inlier.

Résumé : Les interprétations diffèrent quant à l'âge et la nature de la transition de rifting à dérive, du Néoprotérozoïque au Paléozoïque précoce, le long de la cordillère nord-américaine. Le groupe d'Ediacara « supérieur » (élevé dans le présent article au Groupe de Rackla) de l'enclave de Coal Creek (Yukon, Canada) représente une succession clé pour reconstituer l'histoire sédimentaire du nord-ouest de la Laurentie de part et d'autre de la limite Précambrien–Cambrien et élucider la chronologie de l'activité tectonique durant la longue dislocation du supercontinent Rodinia. Ces unités cartographiques d'âge néoprotérozoïque tardif à paléozoïque précoce dans l'enclave de Coal Creek, qui n'étaient pas différenciées auparavant, sont formellement définies comme étant les Formations de Lone, de Cliff Creek, de Mount Ina, de Last Chance, de Shade et de Shell Creek. De nouvelles données sédimentologiques et stratigraphiques sur ces unités sont utilisées pour reconstituer le contexte sédimentaire. Dans la Formation de Last Chance, des observations chimiostratigraphiques indiquent un gradient du $\delta^{13}C_{carb}$ d'environ 5 ‰ coïncidant avec l'excursion des isotopes de carbone de Shuram vers 574–567 Ma, reconnue à l'échelle planétaire. Les relations cartographiques et stratigraphiques dans la Formation de Shell Creek sus-jacente fournissent des preuves d'un basculement et d'une sédimentation reliée au rifting de la fin de l'Ediacara au Cambrien moyen. Cela indiquerait une extension active pendant la série miaolingienne du Cambrien dans le nord-ouest du Canada, ce qui argue en faveur d'une dislocation de Rodinia en plusieurs phases et de longue durée. [Traduit par la Rédaction]

Mots-clés : Rodinia, Yukon, excursion des isotopes de carbone de Shuram, Groupe de Rackla, enclave de Coal Creek.

Introduction

Neoproterozoic and lower Paleozoic strata of the western United States and Canada generally record a transition from continental rifting to passive margin sedimentation during the breakup of the supercontinent Rodinia (e.g., Stewart 1972; Levy and Christie-Blick 1991; Lund 2008); however, views differ on the timing and number of rift episodes (e.g., Fritz et al. 1991; Ross 1991; Dalrymple and Narbonne 1996; Colpron et al. 2002; Post and Long 2008; Turner et al. 2011; Macdonald et al. 2012; Yonkee et al. 2014; Strauss et al. 2015; Beranek 2017; Campbell et al. 2019; Moynihan et al. 2019). Previous work suggested this transition was recorded in strata from the Cryogenian–Ediacaran Windermere Supergroup of northwestern Canada (e.g., Ross 1991; Narbonne and Aitken 1995; Ross et al. 1995), with evidence for multiphase rifting (Ross 1991; Colpron et al. 2002) and oblique extension (Eisbacher 1981; Strauss et al. 2015) prior to continental separation. In addition, more recent studies have drawn attention to evidence for intermittent extension, syntectonic sedimentation, and associated volcanism during the

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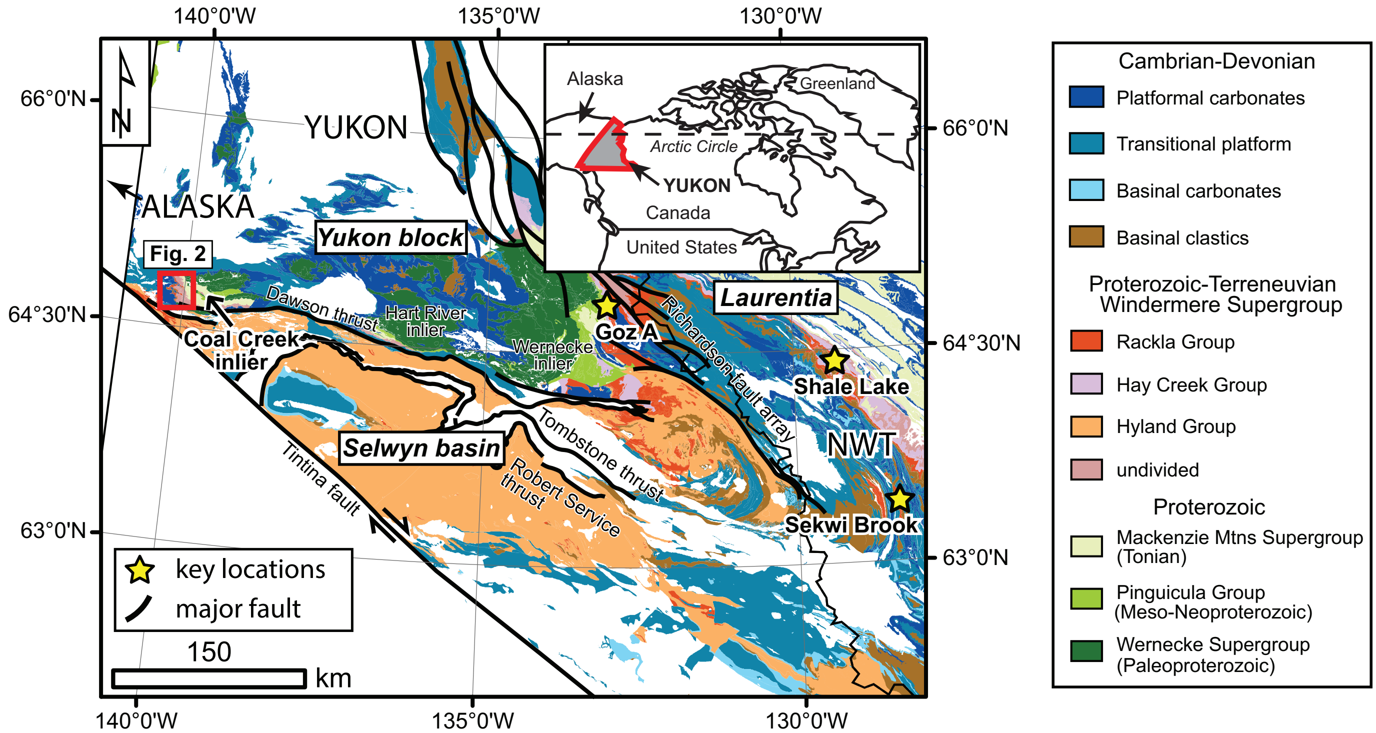
Fig. 1. Simplified geological map of Proterozoic–Paleozoic strata in northwestern Canada with major structural and paleogeographic elements labeled accordingly. The study location is outlined with a red box. Map created using ESRI ArcGIS version 10.7.1 and assembled from Colpron et al. (2016). [Color online.]



early Paleozoic, with continental margin re-establishment well after deposition of the Windermere Supergroup during the middle to late Cambrian (e.g., Beranek 2017; Link et al. 2017; Campbell et al. 2019; Moynihan et al. 2019).

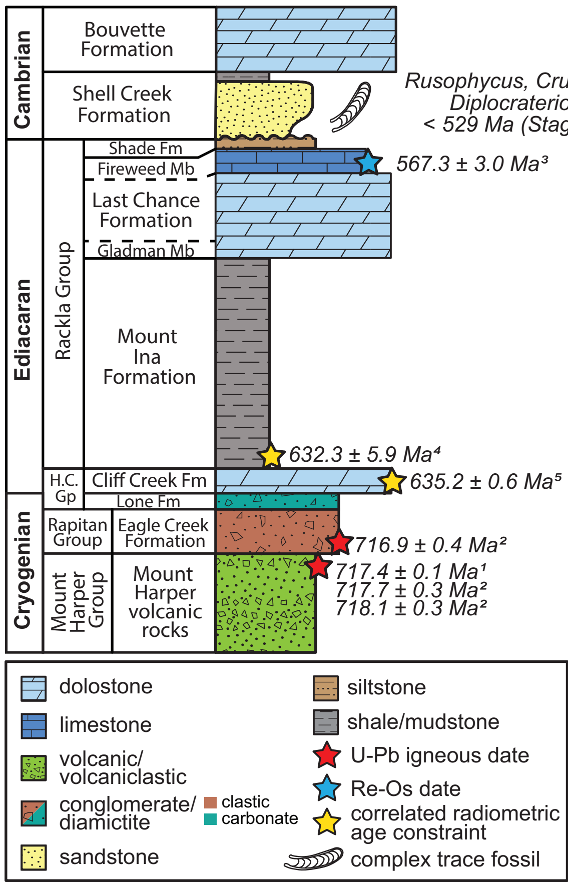
The Coal Creek inlier of the Ogilvie Mountains, Yukon, Canada, is positioned along the southwestern edge of the Yukon Stable Block (herein referred to as "Yukon block"), a paleogeographic high that accommodated early Paleozoic platformal carbonate deposition along the northwestern edge of the Laurentian craton (Fig. 1; Jeletzky 1962; Abbott 1997; Morrow 1999). Previous studies have correlated Neoproterozoic strata of the Coal Creek inlier with other regions in the northern Canadian Cordillera, where exceptionally preserved strata have been recognized as key locations for studying this interval of Earth history (Macdonald et al. 2012, 2013, 2018; Strauss et al. 2015); however, upper Neoproterozoic and lower Paleozoic units in the Coal Creek inlier have remained undifferentiated. To further investigate the evolution of the northwestern Laurentian margin, in particular the apparent multiphase rift history associated with the breakup of Rodinia, the previously undifferentiated Cryogenian–Ediacaran units of the Hay Creek and "upper" groups of the Coal Creek inlier (Macdonald et al. 2013, 2018) were re-examined. These had previously been referred to informally as the upper Mount Harper Group by Mustard (1988) and Mustard and Roots (1997). In this paper, the "upper" group is incorporated into the recently formalized Rackla Group of Moynihan et al. (2019). The previously informal Neoproterozoic–Cambrian map units are herein formally defined as the Lone, Cliff Creek, Mount Ina, Last Chance, Shade, and Shell Creek formations (Fig. 2, Tables 1–6). From a compiled data set of sedimentological observations, stratigraphic sections, and geochemical measurements, these strata provide evidence for protracted latest Ediacaran – early Cambrian rift-related tilting and middle Cambrian syn-rift sedimentation along the western margin of Laurentia.

Geologic setting of the Coal Creek inlier

The Coal Creek inlier is the westernmost of three domal Cordilleran structural culminations that are located along the southern boundary of the Yukon block (Fig. 1). The Yukon block is a triangular-shaped region in northern Yukon that formed a relatively high-standing block (Ogilvie platform) throughout much of the early Paleozoic (Jeletzky 1962; Morrow 1999). Extensive deposition of platformal carbonate in this region contrasts with deeper marine siliciclastic-dominated sedimentation in the Selwyn basin to the south (Gordey and Anderson 1993; Cecile 2000). The Yukon block is surrounded on three sides by Mesozoic–Cenozoic fold-thrust/strike-slip deformation zones, whereas its interior region is largely unaffected by Cordilleran deformation (Fig. 1; Colpron et al. 2016). It is distinguished geophysically by (1) a high velocity region interpreted as a cold thermal anomaly within the upper mantle (Estève et al. 2020); (2) a regional magnetic anomaly produced by mafic lower crust (Pilkington and Saltus 2009); and (3) a long wavelength, high Bouguer gravity anomaly (Estève et al. 2020). The lithosphere of the Yukon block is approximately 100–200 km thick, which is 2–4 times the current thickness of the lithosphere in the Selwyn basin region (Gaudreau et al. 2019). Collectively, the geological and geophysical evidence support interpretation of the Yukon block as a buried cratonic promontory that is composed of cold, thick, and mechanically robust lithosphere (Abbott 1997; Nelson et al. 2013; Schaeffer and Lebedev 2014; Estève et al. 2020).

The southern boundary of the Yukon block is generally marked by the trace of the Dawson thrust, a Mesozoic north-vergent fault that accounts for limited structural overlap (Fig. 1; Abbott 1997). The Dawson thrust approximately coincides with the position of an antecedent, basin-bounding structure that controlled the margin of the Selwyn basin, a large southwest-facing embayment that served as a depocenter from the Neoproterozoic – late Paleozoic (Gordey and Anderson 1993; Abbott 1997). The boundary between

Fig. 2. Generalized stratigraphic column of Cryogenian–Cambrian strata in the Coal Creek inlier of west-central Yukon ([1]Macdonald et al. 2018, [2]Macdonald et al. 2010, [3]Rooney et al. 2020, [4]Rooney et al. 2015, [5]Condon et al. 2005). [Color online.]



the Yukon block and Selwyn basin is broadly collinear with a belt of middle Cambrian alkaline mafic volcanic rocks (Goodfellow et al. 1995; Cecile 2000; MacNaughton et al. 2016; Mamrol et al. 2016) and ultramafic rocks of unknown age (Colpron 2012). Lower Paleozoic volcanic rocks are sporadically distributed in the Selwyn basin and adjacent carbonate platforms and have been interpreted as products of local extension following continental breakup (Cecile 1984; Goodfellow et al. 1995; Campbell et al. 2019).

The Coal Creek inlier hosts exposures of the ca. 1.7–1.2 Ga Wernecke Supergroup, the ca. 1.2–0.78 Ga Mackenzie Mountains Supergroup, and the ca. 0.78–0.54 Ga Windermere Supergroup (Fig. 1; Young et al. 1979). Evidence for Neoproterozoic extension and rift-related sedimentation in the Coal Creek inlier is manifest in the ca. 755–660 Ma Mount Harper and Rapitan groups of the Windermere Supergroup (Mustard 1991; Mustard and Roots 1997; Macdonald et al. 2012, 2018; Strauss et al. 2015). The Mount Harper Group contains bimodal volcanic rocks that have been dated to ca. 719–717 Ma (Macdonald et al. 2010, 2018), which are overlain by ca. 717–660 Ma Sturtian glacial deposits of the Rapitan Group (Macdonald et al. 2010, 2018; Rooney et al. 2015). Paleomagnetic data from the Mount Harper volcanic rocks suggest the Yukon block may have been rotated counterclockwise relative to autochthonous Laurentia in the Cryogenian–Ediacaran (Eyster et al. 2017). Ediacaran rocks in the Coal Creek inlier have previously been assigned informal designations, including map units PH3, PH4, and PH5, of the upper Mount Harper Group or the undifferentiated Hay Creek and "upper" groups (Mustard et al. 1988; Thompson et al. 1994; Mustard and Roots 1997; Macdonald et al. 2010, 2011, 2013; Strauss et al. 2014). These Ediacaran map units are unconformably overlain by unnamed Cambrian siliciclastic rocks (formerly map unit PH5), which are in turn disconformably succeeded by carbonate strata of the Bouvette Formation (Strauss et al. 2014). The Bouvette Formation in the Coal Creek inlier marks the beginning of widespread platformal carbonate sedimentation that comprises the Cambrian–Devonian Ogilvie platform (Morrow 1999).

Stretching associated with formation of the western Laurentian continental margin led to widespread subsidence of the attenuated Selwyn basin region, but evidently did not affect lithosphere of the Yukon block (Cecile et al. 1997; Morrow 1999). Ediacaran and Cambrian units near the southern boundary of the Yukon block exhibit facies and thickness trends that generally indicate southward deepening from the Yukon block into the Selwyn basin region (e.g., Gordey and Anderson 1993; Moynihan et al. 2019), but it is not clear how or when the profound boundary that separates these regions was first established. The Coal Creek inlier sits directly adjacent to the Yukon block – Selwyn basin interface and is therefore a key location to evaluate the significance of this boundary and how it relates to the history of Neoproterozoic–Paleozoic rifting in northwestern Laurentia.

Methods

Geological mapping, measurement of stratigraphic sections, and geochemical sampling were undertaken in the Coal Creek inlier in 2017 and 2018. Two remote camps were situated within a well-exposed and laterally extensive panel of upper Ediacaran and lower Paleozoic strata northwest of Mount Harper (Fig. 3). This region marks the type region of the new units proposed herein (Tables 1–6). The camps were accessed via helicopter from Dawson City.

$\delta^{13}C_{carb}$ and $\delta^{18}O_{carb}$ chemostratigraphy

Carbonate rock samples were analyzed in the Stable Isotope Geochemistry Laboratory at Dartmouth College. Limestone and dolostone samples (ca. 0.1–0.5 kg) were collected approximately every metre throughout measured stratigraphic sections and targeted to avoid obvious fracturing or veining. The samples were then slabbed perpendicular to bedding using a lapidary saw and ca. 5–10 mg of powder was drilled from individual laminations using a drill press with a dental carbide drill bit. Carbonate powders were reacted with phosphoric acid (H_3PO_4) at 70 °C on a Gasbench II preparation device attached to a ThermoFinnigan DeltaPlus XL continuous flow isotope ratio mass spectrometer. The $\delta^{13}C_{carb}$ and $\delta^{18}O_{carb}$ measurements were performed simultaneously and isotopic data are reported in standard delta notation as the per mil difference from Vienna Pee Dee Belemnite. Precision and accuracy were monitored by running a total of 12 standards for every 76 samples using 11–3 sample-standard bracketing. Two international standards (NBS-18 and Elemental Microanalysis Carrara Marble) and one internal laboratory standard were employed. Samples were measured relative to an internal CO_2 gas standard and then converted to the Vienna Pee Dee Belemnite scale using the known composition of NBS-18 ($\delta^{13}C_{carb}$ = −5.01; $\delta^{18}O_{carb}$ = −23.20) and Elemental Microanalysis Carrara Marble ($\delta^{13}C_{carb}$ = 2.10; $\delta^{18}O_{carb}$ = −2.01). The measured precision was 0.15‰ (1σ) for $\delta^{13}C_{carb}$ and 0.2‰ (1σ) for $\delta^{18}O_{carb}$. All $\delta^{13}C_{carb}$ and $\delta^{18}O_{carb}$ data collected for this study are presented in Supplementary Material S1[1].

[1]Supplementary data are available with the article at https://doi.org/10.1139/cjes-2020-0132.

Table 1. Formal definition of the Lone Formation, Hay Creek Group.

Name	Lone Formation
Name derivation	Named after Lone Mountain within the southeastern Ogilvie Mountains, Yukon Territory, Canada; NTS 116B6
Category and rank	Lithostratigraphic Formation
Type area	Exposures within unnamed drainage networks of the westernmost headwaters of Coal Creek, northwest of Mount Harper, Coal Creek inlier, Yukon
Unit type section	Section J1713 (this study)
	Located in the headwaters of an unnamed tributary to the Monster River approximately 12 km north–northwest of Mount Harper, Yukon Territory, Canada
	Lower boundary: irregular to sharp contact with matrix-supported conglomerate of the Eagle Creek Formation (Macdonald et al. 2018; 64.7870, –140.0717)
	Upper boundary: a sharp-gradational contact with yellow/buff-weathering fine-grained dolograinstone and dolomudstone of the Cliff Creek Formation (this study)
Historical list of symbols	Previously referred to as map unit PH1/PH2 of the upper Mount Harper Group by Mustard et al. (1988), Thompson et al. (1994), and Mustard and Roots (1997); was subsequently referred to as the undifferentiated Hay Creek Group by Macdonald et al. (2010, 2011, 2013) and Strauss et al. (2014)
Unit description	A highly localized white- to grey-weathering matrix-supported carbonate rudstone or diamictite; the base begins with 5.4 m of medium- to thick-bedded white-weathering dark grey matrix-supported carbonate clast diamictite with subrounded to subangular clasts of oolitic dolograinstone, dolomudstone, stromatolitic doloboundstone, silicified carbonate, blue to black chert, and rare quartzite; this is followed by a thin $<$5 cm thick drape of grey-weathering pink dolomudstone with abundant cubic pyrite, which transitions up-section into 0.5 m of similar diamictite facies with abundant pyrite; this is followed by another 10 cm thick drape of blue-grey-weathering thin-bedded silty dolograinstone with ripple cross-lamination and abundant pyrite; the final 0.4 m is composed of pebble to cobble matrix-supported diamictite with abundant cubic pyrite, followed by a sharp contact with yellow/buff-weathering very-fine-grained dolograinstone of the overlying Cliff Creek Formation; in other locations of the Coal Creek inlier and Yukon block, the Lone Formation only consists of matrix-supported diamictite and does not feature a gradational contact with the overlying Cliff Creek Formation or its equivalents
Dimensions	6.4 m thick at type section
Geologic age	Neoproterozoic (Cryogenian). Overlies the Cryogenian Eagle Creek Formation (ca. 717–660 Ma, Macdonald et al. 2010, 2018)
Regional correlations	Stelfox Member of the Ice Brook Formation of the Hay Creek Group, Wernecke and Mackenzie mountains, Yukon and Northwest Territories, Canada (Eisbacher 1978, 1981, 1985; Aitken 1991*b*; Moynihan et al. 2019)

Table 2. Formal definition of the Cliff Creek Formation, Hay Creek Group.

Name	Cliff Creek Formation
Name derivation	Named after Cliff Creek within the southwestern Ogilvie Mountains, Yukon Territory, Canada; NTS 116C09
Category and rank	Lithostratigraphic Formation
Type area	Exposures within unnamed drainage networks of the westernmost headwaters of Coal Creek, northwest of Mount Harper, Coal Creek inlier, Yukon
Unit type section	Section J1713 (this study)
	Located in the headwaters of an unnamed tributary to the Monster River approximately 12 km north–northwest of Mount Harper, Yukon Territory, Canada
	Lower boundary: gradational contact with matrix-supported diamictite of the Lone Formation (this study; 64.7870, −140.0717)
	Upper boundary: sharp contact with black- to dark-blue-weathering sulfidic shale of the Mount Ina Formation (this study)
Historical sist of symbols	Previously referred to as map unit PH1/PH2 of the upper Mount Harper Group by Mustard et al. (1988), Thompson et al. (1994), and Mustard and Roots (1997); was subsequently referred to as the undifferentiated Hay Creek Group by Macdonald et al. (2010, 2011, 2013) and Strauss et al. (2014)
Unit description	Predominantly thinly laminated very thin- to medium-bedded grey- to buff-yellow-weathering interbedded dolomudstone and dolograinstone; basal contact of this facies with underlying matrix-supported carbonate clast rudstone or diamictite of the Lone Formation is often sharp, but in the type section, the basal 1.1 m is interbedded with $<$0.45 m thick intervals of diamictite; the overlying 3.8 m consists of buff/light grey-weathering dolomudstone and dolograinstone with millimetre-scale laminations and distinctive bedding-parallel and cross-cutting calcite or silica void-filling “sheet crack” cements (Kennedy et al. 2001), with drusy, botryoidal, and isopachous textures; these cements are often associated with buckling, brecciation, and local up-warping of the thin- to medium-bedded dolostone; the upper 6.8 m of the Formation is marked by buff/grey-weathering very-fine- to fine-grained dolograinstone dominated by trochoidal cuspate bedforms (“giant wave ripples” of Allen and Hoffman 2005) with wavelengths of ca. 2–4 m, as well as amalgamated hummocky and swaley cross-stratification; upper contact with black- to blue-weathering sulfidic shale of the Mount Ina Formation is marked by 0.9 m of cover beneath shale talus, but regionally it is well exposed and sharp
Dimensions	7.3 m thick at type section
Geologic age	Neoproterozoic (Ediacaran). Overlies either the Cryogenian Lone Formation (this study) or the Cryogenian Eagle Creek Formation (ca. 717–660 Ma, Macdonald et al. 2010, 2018)
Regional correlations	Informal Ravensthroat formation (Tepee dolostone) of the Hay Creek Group, Wernecke and Mackenzie mountains, Yukon and Northwest Territories, Canada (James et al. 2001)

Table 3. Formal definition of the Mount Ina Formation, Rackla Group.

Name	Mount Ina Formation
Name derivation	Named after Mount Ina located in the southeastern Ogilvie Mountains, Yukon Territory, Canada; NTS 116B5
Category and rank	Lithostratigraphic Formation
Type area	Exposures within unnamed drainage networks of the westernmost headwaters of Coal Creek, northwest of Mount Harper, Coal Creek inlier, Yukon
Unit type section	Section F838 (Macdonald et al. 2011, 2013)
	Located along a prominent north–south-trending ridge and saddle approximately 5 km north of Mount Harper, Yukon Territory, Canada
	Lower boundary: directly overlies brecciated dolostone beds of the Cliff Creek Formation (this study; 64.726, −140.040)
	Upper boundary: poorly exposed contact with buff-weathering dolostone of the Last Chance Formation (this study; 64.720010, −140.041317)
Historical list of symbols	Previously referred to as map unit PH3 of the upper Mount Harper Group of Mustard et al. (1988), Thompson et al. (1994), and Mustard and Roots (1997); was subsequently classified as part of the "upper group" by (Macdonald et al. 2011, 2013) and labeled map unit nPu_1 in Strauss et al. (2014)
Unit description	Generally a thick succession of largely homogenous fissile dark grey to black shale with minor thin (<20 cm thick) interbeds of dark greyish green siltstone and grey- to tan-weathering finely laminated very-fine-grained dolograinstone; the latter is only locally present within the first ca. 10 m of the base of the Formation; the type section begins with 2.7 m of black shale that lies in contact with blue-grey thin-bedded slightly fetid limestone of the Cliff Creek Formation; there is 5 m of cover before a thin bed of fine-grained white dolograinstone that is then succeeded by 250 m of black shale or mudstone with dolostone interbeds at 180.2 and 187.8 m; the uppermost 56 m consists of black shale or mudstone subcrop and rubble exposure before an abrupt contact with tan-olive-weathering thin-bedded dolograinstone of the Last Chance Formation
Dimensions	319.8 m thick at type section
Geologic age	Neoproterozoic (Ediacaran); correlated with the Sheepbed Formation of the Mackenzie Mountains (Gabrielse et al. 1973); Re–Os radiometric age of 632.3 ± 5.9 Ma <2 m above the base of the Sheepbed Formation in the Mackenzie Mountains provides a robust lower age constraint (Rooney et al. 2015)
Regional correlations	Sheepbed Formation of the Rackla Group (Gabrielse et al. 1973; Moynihan et al. 2019), Wernecke and Mackenzie mountains, Yukon and Northwest Territories, Canada

Formal definition of new lithostratigraphic units

Formal descriptions of new lithostratigraphic units are provided in Tables 1–6, with additional information and interpretation detailed below.

Lone Formation (new), Hay Creek Group (Cryogenian)

Lithostratigraphy

The oldest strata examined in this study consist of matrix-supported polymict rudstone or diamictite of the Lone Formation (Table 1). These strata were previously referred to as map units PH1/PH2 of the upper Mount Harper Group of Mustard (1988), Thompson et al. (1994), and Mustard and Roots (1997), or the undifferentiated Hay Creek Group by Macdonald et al. (2010, 2011, 2013) and Strauss et al. (2014). The maximum observed thickness of the Lone Formation is 6.4 m at the type section (Fig. 4); however, the Formation is highly localized in the study area and is thicker in other regions of the Yukon block. The Lone Formation is composed of white to grey matrix-supported carbonate clast rudstone or diamictite and contains subrounded to subangular clasts up to boulder size of oolitic dolograinstone, dolomudstone, stromatolitic doloboundstone, silicified carbonate, chert, and rare quartzite (Fig. 5A). These strata can be challenging to differentiate from the underlying Eagle Creek Formation (Macdonald et al. 2018), but generally there is a prominent change in clast composition and locally there is intervening non-conglomeratic strata. The contact between the Lone Formation and overlying fine-grained carbonate strata of the Cliff Creek Formation is gradational, with 0.4–0.5 m thick packages of diamictite interbedded with <5 cm thick beds of grey-weathering pink dolomudstone (Fig. 4).

Depositional setting and age

The structureless polymict diamictite of the Lone Formation resembles terminal Cryogenian glaciogenic deposits described elsewhere in northern Canada (e.g., Aitken 1991*a*; Macdonald et al. 2018), and the highly localized nature of this unit is consistent with thickness variations in the equivalent Stelfox Member of the Ice Brook Formation in the Mackenzie and Wernecke mountains (Aitken 1991*b*; Moynihan et al. 2019). Although the Lone Formation lacks definitive evidence for glacial sedimentation, we tentatively interpret it to represent a thin wedge of till deposited prior to and during cap dolostone sedimentation. This suggests the Lone Formation spans the terminal Cryogenian and basal Ediacaran periods (ca. 650–635 Ma).

Cliff Creek Formation (new), Hay Creek Group (Ediacaran)

Lithostratigraphy

The Cliff Creek Formation consists of grey- to buff-weathering, thinly laminated dolograinstone and dolomudstone (Table 2). These strata were previously referred to as map units PH1/PH2 of the upper Mount Harper Group of Mustard (1988), Thompson et al. (1994), and Mustard and Roots (1997), or the undifferentiated Hay Creek Group by Macdonald et al. (2010, 2011, 2013) and Strauss et al. (2014). The maximum observed thickness of the Cliff Creek Formation is 7.3 m at the type section (Fig. 4). Characteristic strata of the Cliff Creek Formation are typically composed of very-thin- to medium-bedded grey- to buff-yellow-weathering interbedded dolomudstone and dolograinstone (Fig. 4). These strata most commonly include millimetre-scale lamination and bedding-parallel to cross-cutting "sheet crack" cements that are composed of void-filling calcite and silica crystals with drusy, isopachous, and botryoidal textures (Fig. 5B). The sheet crack cements are locally associated with buckling, brecciation, and up-warping of the dolomudstone and dolograinstone beds, with local cross-cutting silica veins. In the type section, the sheet-crack-bearing interval is succeeded by medium-bedded and fine-grained dolograinstone strata with prominent cuspate to trochoidal bedforms with wavelengths of ca. 2–4 m, which are topped by amalgamated hummocky and swaley cross-stratification (HCS/SCS). These cuspate bedforms are rarely present elsewhere in the Coal Creek inlier. The upper contact of the Cliff Creek Formation is marked by a sharp transition into black to dark grey sulfidic shale of the Mount Ina Formation.

Table 4. Formal definition of the Last Chance Formation, Rackla Group.

Name	Last Chance Formation
Name derivation	Named after Last Chance Creek in the western Ogilvie Mountains, Yukon Territory, Canada; NTS 116C15
Category and rank	Lithostratigraphic Formation
Type area	Exposures within unnamed drainage networks of the westernmost headwaters of Coal Creek, northwest of Mount Harper, Coal Creek inlier, Yukon
Unit type section	Section JB1704/J1711 (this study)
	Located along the northern flank of a prominent north–south-trending ridge approximately 5 km north of Mount Harper, Yukon Territory, Canada
	Lower boundary: first exposure of grey-colored dolostone above subcropping black shale and mudstone of the Mount Ina Formation (this study; 64.72006, −140.04134)
	Upper boundary: sharp contact with brown to yellow-weathering thin- to medium-bedded blue-grey very-fine- to fine-grained quartz arenite with ripple cross-lamination and minor dolomitic siltstone of the Shade Formation (this study; 64.71945, −140.04172)
Historical list of symbols	Previously referred to as map unit PH4 of the upper Mount Harper Group of Mustard et al. (1988), Thompson et al. (1994), and Mustard and Roots (1997); was subsequently classified as part of the "upper group" by (Macdonald et al. 2011, 2013) and labeled map unit nPu_2 in Strauss et al. (2014)
Unit description	Predominantly a distinctive unit of orange- to tan-weathering dolograinstone interbedded with maroon- to green-weathering calcareous siltstone and rare intraclast rudstone, but contains two informal members (Gladman and Fireweed members) with different lithofacies and variable exposures throughout the Coal Creek inlier (see below); basal contact between recessive black shale and mudstone of Mount Ina Formation and silicified and brecciated dolostone of the informal Gladman member is sharp to irregular;
	Gladman member: localized highly silicified and brecciated orange- to white-weathering dolostone; at the type section of the Last Chance Formation, this member is not exposed, but ca. 0.36 km to the southeast there are isolated outcrops of pink- to grey-weathering thin-bedded and brecciated dolostone ca. 9 m above recessive black shale of the uppermost Mount Ina Formation; the exposure consists of ca. 2 m of pink- to grey-weathering thin-bedded coarsely recrystallized dolostone before 2.5 m of cover; the upper 3 m is pink-weathering, massive, and coarsely recrystallized dolostone before 15 m of cover preceding exposure of orange-weathering dolograinstone of the type Last Chance Formation; elsewhere, strata of the Gladman member are composed of 19.5 m of orange-weathering massive and thick-bedded dolomudstone, intraclast rudstone, and breccia with pervasive silicification of dolostone facies and distinctive bedding parallel and cross-cutting quartz veins; there are also "tepee" structures that consist of thin, silicified beds that are fractured and upwarped and are sometimes overlain by thinly laminated dolograinstone with wave ripple cross-lamination; the upper contact is marked by a highly irregular erosional surface at the top of the heavily brecciated and silicified dolostone that variably incises into the upper brecciated rudstone and is draped by tan-orange dolomudstone with reworked clasts from the underlying strata;
	Exposures above the discontinuous Gladman member consist of dark grey siltstone interbedded with 5–10 cm thick orange- tan-weathering silty dolograinstone with abundant ripple cross-lamination; the silty dolograinstone becomes dominantly carbonate and thick bedded at 9.3 m with 3–10 cm thick interbeds of grey siltstone; this interval has abundant hummocky and swaley cross-stratification that continues for much of the section; at 35.3 m, interbeds of maroon calcareous siltstone appear with the thin- to medium-bedded orange- to tan-weathering dolograinstone and continues for 6.8 m; this is overlain 14.8 m of light-grey-weathering fine dolograinstone with abundant hummocky and swaley cross-stratification and minor ripple cross-lamination before a 6 cm thick bed of maroon and grey laterally linked hemispheroidal stromatolitic doloboundstone (ca. 2–5 cm in diameter) at 56.9 m; the following 12.2 m consists of tan-grey ripple cross-laminated dolograinstone with 9–15 cm thick interbeds of intraclast rudstone containing gravel- to cobble-sized tabular clasts within a silty matrix at 58.6 and 61.6 m; the upper 4.7 m of the section consist of covered intervals (69.7–72.2 and 72.4–74.0 m) with intervening outcrops of grey thin- to medium-bedded fine dolograinstone interbedded with tan silty dolograinstone; there is 24.2 m of cover before a contact at 98.6 m with the Fireweed Member;
	Fireweed member: generally a light to dark grey finely laminated concretionary carbonate unit; at the type section, the lower contact with the Last Chance Formation is covered for 24.2 m with two patches of subcrop from 90.3–91.2 and 94.6–95.1 m, which consist of interbedded brownish black calcareous shale and nodular fetid lime mudstone; these strata are overlain by 17.7 m of interbedded calcareous black to grey mudstone with dark grey thin- to medium-bedded very finely laminated concretionary lime mudstone; carbonate concentric concretions are lozenge- to oblate-shaped, ca. 2–15 cm tall, and ca. 5–95 cm wide; the upper 1.2 m consists of a similar facies that is partially dolomitized before transitioning at 117.9 m into 3.4 m of brown- to yellow-weathering thin- to medium-bedded blue-grey very-fine- to fine-grained quartz arenite with ripple cross-lamination and minor dolomitic siltstone of the Shade Formation
Dimensions	117.9 m thick at type section
Geologic age	Neoproterozoic (Ediacaran); contains a Re–Os radiometric age of 567.3 Ma ± 3.0 16.3 m above the base of the Fireweed member at the type section (Rooney et al. 2020); correlated with the Gametrail Formation, which has a Re–Os radiometric age constraint in the Wernecke Mountains of <574 Ma (Rooney et al. 2020)
Regional correlations	Nadaleen and Gametrail formations, Rackla Group (Aitken 1989, Moynihan et al. 2019) of the Mackenzie and Wernecke Mountains, Northwest and Yukon Territories, Canada

Depositional setting and age

The Cliff Creek Formation has previously been correlated with globally distributed ca. 635 Ma cap carbonates of the Cryogenian Marinoan glaciation based on its sedimentological and geochemical characteristics (Macdonald et al. 2010, 2011, 2018; Ahm et al. 2019). Cliff Creek strata probably record hemipelagic carbonate sedimentation in an outer-shelf to slope depositional setting during post-glacial marine transgression (e.g., James et al. 2001; Hoffman 2011).

Table 5. Formal definition of the Shade Formation, Rackla Group.

Name	Shade Formation
Name derivation	Named after Shade Creek, located in the western Ogilvie Mountains adjacent to the Alaskan border, Yukon Territory, Canada; NTS 116C15
Category and rank	Lithostratigraphic Formation
Type area	Exposures within unnamed drainage networks of the westernmost headwaters of Coal Creek, northwest of Mount Harper, Coal Creek inlier, Yukon
Unit type section	Section J1708 (this study)
	Located along the northern flank of a prominent north–south-trending ridge ca. 5 km north of Mount Harper, Yukon Territory, Canada
	Lower boundary: sharp contact with peach-colored dolostone of the Last Chance Formation (this study; 64.79142001, −140.144478)
	Upper boundary: sharp and locally erosional contact with massive clast-supported conglomerate of the Shell Creek Formation (this study; 64.782488, −140.11849)
Historical list of symbols	Previously referred to as the uppermost part of unit PH4 of the upper Mount Harper Group of Mustard et al. (1988), Thompson et al. (1994), and Mustard and Roots (1997); was subsequently classified as part of the "upper group" by (Macdonald et al. 2011, 2013) and labeled map unit nPu_3 in Strauss et al. (2014)
Unit description	Generally a brown- to yellow-weathering thin- to medium-bedded blue-grey very-fine- to fine-grained sandstone succession with ripple cross-lamination and minor dolomitic siltstone; at the type section, the lower contact with the Last Chance Formation is sharp and begins with shale overlying peach-weathering massive dolostone; this is succeeded by 90.9 m of semi-continuous exposure of brown- to yellow-weathering, dark grey – green very-fine-grained quartz arenite to sublitharenite interbedded with brownish grey siltstone and minor shale; sandstone horizons are occasionally dolomite-cemented and contain normal grading, ripple cross-lamination, occasional flute casts, and distinct Bouma Tcde subdivisions; at 90.9 m, there is 7.3 m of cover succeeded by 4.8 m of brown-green micaceous very-fine- to medium-grained lithic arenite interbedded with <2 cm thick siltstone interbeds that is mostly planar-laminated; at 103 m, the upper contact is marked by metre-scale erosional relief beneath massive conglomerate of the Shell Creek Formation
Dimensions	103 m thick at type section
Geologic age	Neoproterozoic (Ediacaran); overlies the Fireweed member of the Last Chance Formation, which contains a Re–Os radiometric age of 567.3 Ma ± 3.0 (Rooney et al. 2020)
Regional correlations	Blueflower Formation, Rackla Group (Aitken 1989, Moynihan et al. 2019), Wernecke and Mackenzie mountains, Yukon and Northwest Territories.

The finely laminated dolograinstone was probably deposited beneath maximum storm wave base, with the appearance of cuspate bedforms and HCS/SCS towards the top of the unit indicating deposition above storm wave base by oscillatory and combined flow conditions (e.g., Duke 1985; Nøttvedt and Kreisa 1987; Lamb et al. 2012).

Mount Ina Formation (new), Rackla Group (Ediacaran)

Lithostratigraphy

The Cliff Creek Formation is abruptly overlain by the Mount Ina Formation (Table 3), which was formerly described as map unit PH3 of the upper Mount Harper Group of Mustard (1988), Thompson et al. (1994), and Mustard and Roots (1997) and part of the "upper group" by Macdonald et al. (2011, 2013). The Mount Ina Formation is commonly recessive in the study area and largely comprises homogenous black to dark grey shale and mudstone with minor thin interbeds of dark grey – green siltstone and grey- to tan-weathering finely laminated dolograinstone or dolomudstone. The base of the Mount Ina Formation in places begins with ca. 10 m of interbedded very-fine-grained dolograinstone and black shale/mudstone that transitions upsection into a maximum of ca. 320 m of predominantly black shale and mudstone (Supplementary Material S2[1]; Macdonald et al. 2013). The thin interbeds of grey–green finely laminated siltstone in this thick package of shale/mudstone are typically normally graded. In the central and northwestern most part of the study area, the Mount Ina Formation is unconformably overlain by siltstone, sandstone, and conglomerate of the Cambrian Shell Creek Formation, while in the southern and eastern parts of the map area, these strata are conformably overlain by silicified and brecciated dolostone of the Last Chance Formation (Figs. 6, 7).

Depositional setting and age

The Mount Ina Formation may reflect hemipelagic sedimentation with rare sediment-gravity flows in the form of the normal-graded carbonate and siltstone interbeds. The homogenous nature of this deposit and its general poor exposure in the Coal Creek inlier precludes a detailed reconstruction of its depositional environment, but its fine-grained nature suggests deposition on a siliciclastic-dominated basin floor or slope. This is similar to interpretations of the correlative Sheepbed Formation, described by Moynihan et al. (2019) and Dalrymple and Narbonne (1996) from the Wernecke and Mackenzie mountains, respectively. There are no absolute age constraints for the Mount Ina Formation in the Coal Creek inlier, but Rooney et al. (2015) obtained a Re–Os age of 632.3 ± 5.9 Ma from the correlative Sheepbed Formation in the Shale Lake area of the Mackenzie Mountains.

Last Chance Formation (new), Rackla Group (Edicaran)

Lithostratigraphy

Carbonate strata of the Last Chance Formation abruptly overlies black shale and mudstone of the Mount Ina Formation and underlies siliciclastic strata of the overlying Shade Formation (Table 4; Figs. 6E, 6F). These strata were formerly included with map unit PH4 of the upper Mount Harper Group of Mustard (1988), Thompson et al. (1994), and Mustard and Roots (1997) and part of the "upper group" by Macdonald et al. (2011, 2013). Here, the Last Chance Formation is defined as the diverse carbonate unit between the siliciclastic-dominated Mount Ina and Shade formations. The Formation is further divided into two informal members that are distinguished from characteristic strata of the Last Chance Formation by their distinct carbonate lithofacies.

Table 6. Formal definition of the Shell Creek Formation.

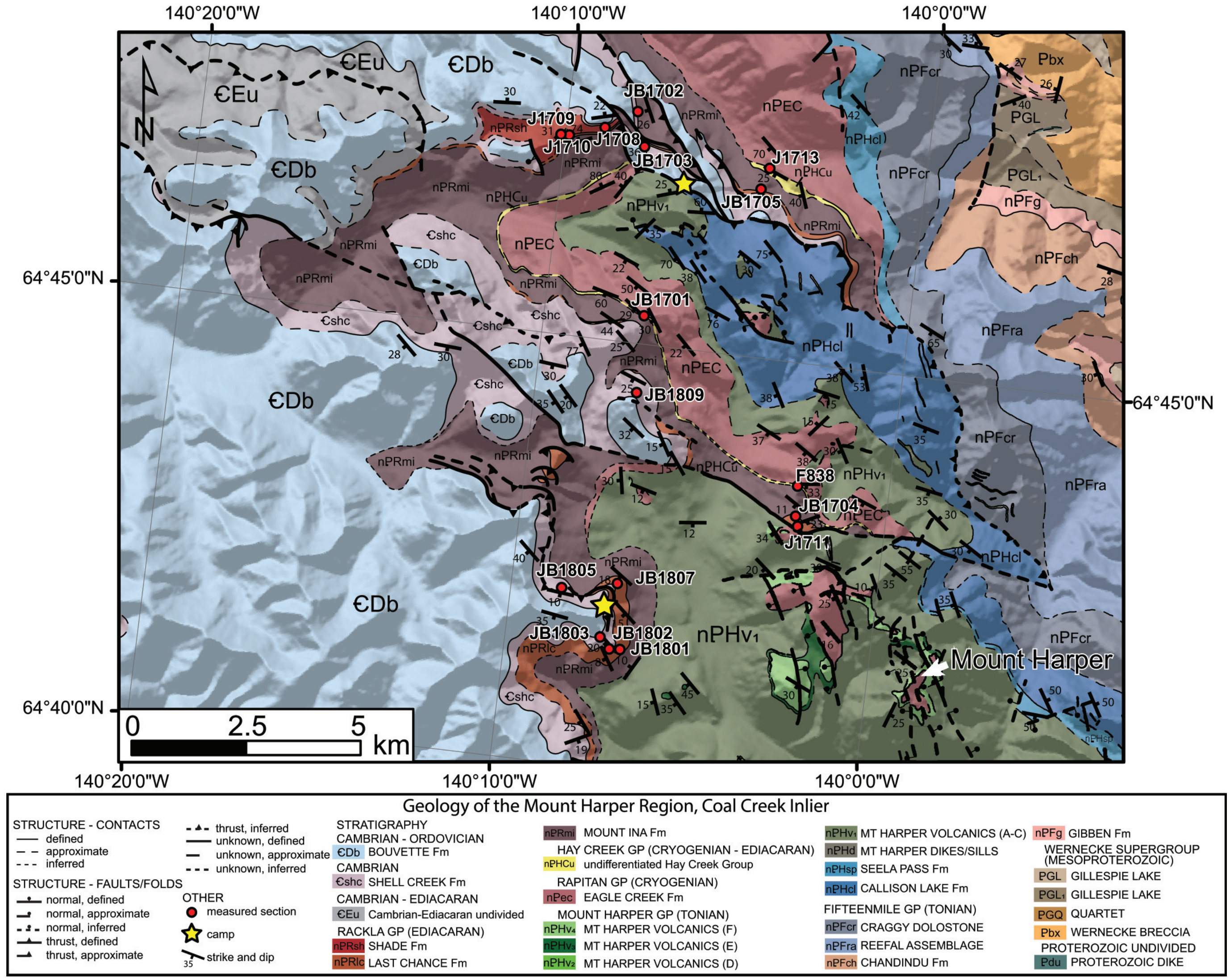
Name	Shell Creek Formation
Name derivation	Named after Shell Creek within the southwestern Ogilvie Mountains, Yukon Territory, Canada; NTS 116C09
Category and rank	Lithostratigraphic Formation
Type area	Exposures within unnamed drainage networks of the westernmost headwaters of Coal Creek, northwest of Mount Harper, Coal Creek inlier, Yukon
Unit type section	Section JB1702 (this study)
	Located in the headwaters of an unnamed tributary to the Monster River approximately 14 km north–northwest of Mount Harper, Yukon Territory, Canada
	Lower boundary: erosional contact with black shale and dark grey siltstone of the underlying Mount Ina Formation (this study; 64.794970, −140.135514)
	Upper boundary: sharp contact with light grey thick-bedded dolograinstone of the Bouvette Formation (Morrow 1999; 64.69087, −140.11849).
Historical list of symbols	Previously referred to as the uppermost part of unit PH5 of the upper Mount Harper Group of Mustard et al. (1988), Thompson et al. (1994), and Mustard and Roots (1997); was subsequently classified as "Cambrian Undivided" in (Macdonald et al. 2011, 2013) and map unit nPu_3 in Strauss et al. (2014)
Unit description	Generally consists of interbedded medium- to thick-bedded, fine- to coarse-grained lithic arenite to quartz arenite, pebble to cobble conglomerate, and siltstone or shale; in the type section, the base of the unit is marked by a prominent erosional contact and begins with 3.2 m of thinly bedded and poorly sorted medium-grained lithic wacke with thin interbeds of subrounded to well-rounded granule to pebble clast-supported conglomerate; conglomerate clasts are crudely imbricated and consist of chert, quartzite, and volcanic lithologies; this is succeeded by 0.4 m of dark-brown-weathering siltstone and 2.8 m of trough cross-stratified medium-grained lithic wacke and poorly sorted medium- to coarse-grained lithic arenite; this is overlain by 0.3 m of trough-cross stratified chert pebble conglomerate with subrounded to well-rounded granule- to pebble-sized clasts with a fine- to medium-grained sandy matrix; the next 7.1 m of strata consist of thick-bedded fine- to medium-grained lithic wacke with thin interbeds of grey–green siltstone and discontinuous lenses of chert pebble conglomerate; 13.8 m above the base of the Formation there is a sharp contact with 2.4 m of grey–green trough cross-stratified fine- to medium-grained lithic arenite interbedded with siltstone; the bases of beds contain abundant syneresis cracks, indeterminate burrows, and *Cruziana*, *Diplocraterion*, *Rusophycus*, and *Planolites* trace fossils; these strata are overlain by 6.2 m of trough cross-stratified fine-grained sublitharenite interbedded with siltstone; this is followed by a 20.8 m thick covered interval of dolostone rubble before an abrupt contact with light grey thin-bedded dolostone of the Bouvette Formation
Dimensions	43.2 m thick at type section.
Unit reference section	JB1809 (this study; 64.68953, −140.11682).
	ca. 144 m thick succession of thin- to medium-bedded grey to brown medium- to fine-grained sublitharenite; the base of the section is marked by more resistant outcrops of sandstone in contact with recessive black shale and grey siltstone of the Mount Ina Formation; above the lower contact, there is 121.5 m of thin- to medium-bedded sublitharenite that contains abundant ripple cross lamination, stoss-preservational ripples, and a 0.6 m thick interval of orange-weathering silty dolostone at 105.0 m; there is 18.0 m of thinly bedded medium- to coarse-grained sublitharenite before 25 m of recessive black- to orange-colored shale and siltstone beneath a sharp contact with massive light grey recrystallized dolostone of the Bouvette Formation
Geologic age	Cambrian (Terreneuvian–Miaolingian) based on trace fossil assemblages (Mustard et al. 1988; Gabriela Mángano and Buatois 2017)
Regional correlations	Slats Creek Formation (Fritz 1985), Taiga Formation (Bell 1986), Illtyd Formation (Bell 1986), Gull Lake Formation (Gordey and Anderson 1993), and unnamed conglomerate (Busch et al. 2019) of the Wernecke and Mackenzie mountains, Yukon and Northwest Territories, Canada

At the base of the Last Chance Formation, the newly defined and informal Gladman member (Table 4) consists of discontinuous thin- to medium-bedded dolomudstone with bedding-parallel and cross-cutting quartz veins, variable silicification, and distinctive "tepee" structures (Kendall and Warren 1987). These tepee structures are marked by the fracturing, buckling, and up-warping of thin dolomudstone beds (ca. 1–2 cm), and they are commonly highly silicified (Fig. 5C). The Gladman member also contains intervals of thick-bedded intraclast rudstone with tabular clasts up to 15 cm long. The upper contact of the Gladman member is marked by a highly irregular surface with up to 40 cm of relief that variably incises into the underlying heavily brecciated and silicified dolostone (Fig. 5D). This surface is draped by tan-weathering massive dolomudstone that contains reworked clasts of recrystallized and silicified dolostone from the underlying Gladman member.

Overlying the Gladman member, the more characteristic strata of the Last Chance Formation are tan- to peach-weathering dolograinstone, interbedded with maroon or green siltstone, intraclast rudstone, and rare stromatolitic doloboundstone. The base of this package (up to ca. 75 m) may include minor siltstone and silty dolograinstone. Above this is a transition into thin- to thick-bedded tan-weathering fine-grained dolograinstone with pervasive SCS and HCS (Fig. 5E) and minor ripple cross-lamination (Fig. 5F). There are several intervals of bright maroon- and green-weathering calcareous siltstone, interbedded with the tan dolograinstone strata, as well as several <1.5 m thick beds of intraclast rudstone with tabular gravel- to cobble-sized dolograinstone clasts. There is also a single interval in the upper ca. 20 m of the Last Chance Formation of a ca. 10 cm thick bed of pink- to light-grey-weathering stromatolitic doloboundstone with laterally linked hemispheroidal stromatolites up to ca. 5 cm in diameter (Fig. 8A).

Dolograinstone of the characteristic Last Chance Formation transitions to dark-grey-weathering and very finely laminated limestone and dolostone of the newly defined and informal Fireweed member (Table 4, Fig. 7). The basal Fireweed member is covered and (or) highly recessive, but these strata are commonly overlain by ca. 20 m of finely laminated concretionary limestone

Fig. 3. Geological map of the Mount Harper Region, Coal Creek inlier, Yukon, showing measured stratigraphic sections and camp locations for this study. Map created using ESRI ArcGIS version 10.7.1 and is modified from Strauss et al. (2014). Shaded relief elevation data courtesy of Natural Resources Canada. [Color online.]



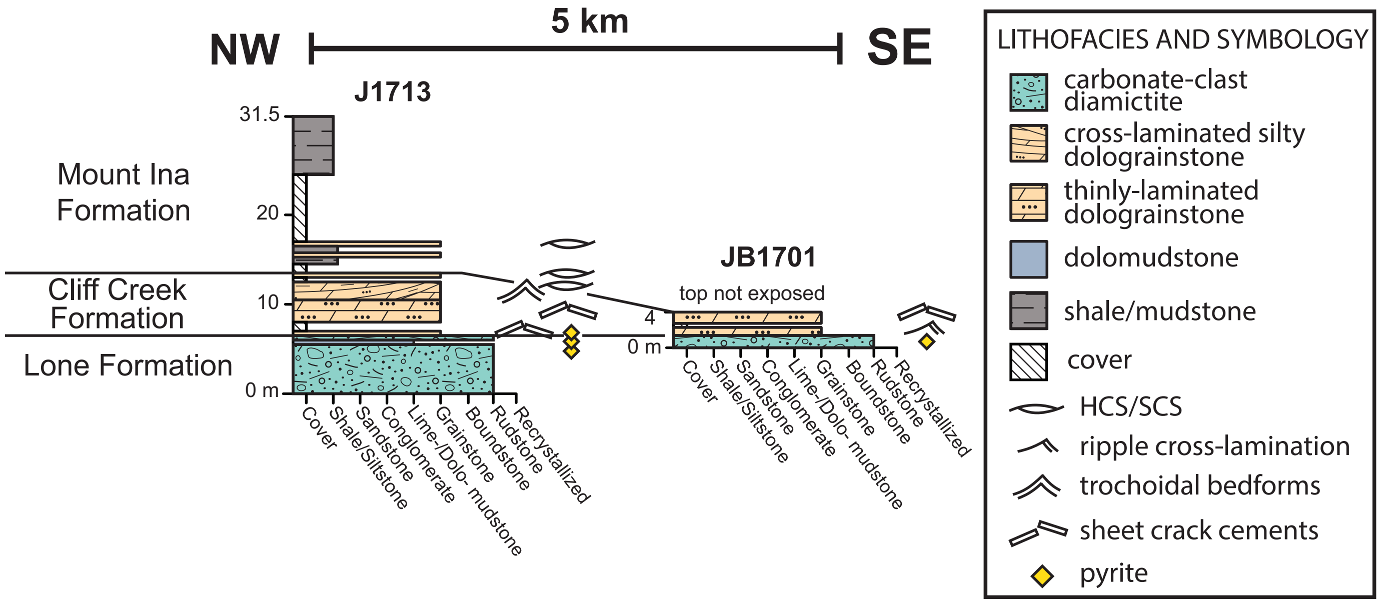
and dolostone with lozenge- to oblate-shaped concretions that are ca. 2–15 cm tall and ca. 5–95 cm wide with rare internal laminae (Figs. 8B, 8C). Dolomitization of these strata is highly localized, often associated with a color change from dark grey to tan/orange, and is most prominent where the sub-Shell Creek unconformity incises into the concretionary carbonate interval. These concretionary carbonate strata also host discontinuous ca. 0.5 m thick intervals or lenses of soft-sediment deformation and intraclast rudstone. Carbonate strata of the Last Chance Formation are disconformably overlain by the siliciclastic-dominated Shade Formation in the southern part of the study area and unconformably overlain by the Shell Creek Formation in the northernmost stratigraphic sections (Figs. 6, 7).

Depositional setting and age

The sedimentological characteristics of the Gladman member of the Last Chance Formation indicate subtidal to supratidal sedimentation along the inner shelf of a carbonate platform or ramp. Tepee structures are often associated with peritidal environments where intense evaporation causes rapid precipitation of carbonate in voids, enlarging fractures and eventually buckling the overlying carbonate sediment (e.g., Assereto and Kendall 1977). In addition, the presence of intraclast rudstone beds, which are commonly thought to form during storm wave action or reworking of shoreline deposits in peritidal or subtidal settings (e.g., Myrow et al. 2004), indicate deposition above maximum storm wave base. A shallow-water setting is supported by widespread silicification of the carbonate facies, which is a common phenomenon observed in proximity to exposure surfaces in Precambrian carbonate successions (e.g., Maliva et al. 2005; Skotnicki and Knauth 2007). Finally, the irregular relief at the Gladman member's upper contact shares many characteristics with "scalloped" erosional surfaces documented in other subaerial exposure surfaces on carbonate platforms (e.g., Read and Grover 1977); thus, the Gladman member probably records shoaling from a shallow marine or peritidal environment to an emergent subaerial environment.

In contrast, the majority of lithofacies in the overlying parts of the Last Chance Formation indicate sedimentation on a storm-dominated carbonate ramp. The predominance of fine-grained dolograinstone with amalgamated HCS/SCS indicates deposition

Fig. 4. Stratigraphic fence diagram of the Lone, Cliff Creek, and basal Mount Ina formations. Thin exposures of the Lone Formation were documented in both sections, while the interbedded nature of the Lone and Cliff Creek formations was only documented at the type section (J1713). In both measured sections, dolostone is eventually succeeded by black shale of the Mount Ina Formation, but this transition is only well exposed at section J1713. HCS/SCS, hummocky and swaley cross-stratification. [Color online.]



under combined flow conditions above storm wave base (e.g., Duke 1985; Nøttvedt and Kreisa 1987). The occurrence of rare beds of reworked intraclast rudstone is also suggestive of deposition above maximum storm wave base (e.g., Myrow et al. 2004). The occurrence of small hemispheroidal stromatolites and intervening calcareous siltstone facies in the Last Chance Formation may indicate episodic deepening into the mid-outer ramp relative to the HCS-dominated and amalgamated dolograinstone, which were deposited in an inner ramp setting, or they may simply reflect background quiescent sedimentation within the inner-middle ramp setting. The occurrence of abundant cross-stratified grainstone is similar to other Ediacaran storm-dominated carbonate margins, such as the Nama Group of Namibia (Dibenedetto and Grotzinger 2005).

The laminated concretionary facies of the Fireweed member probably records suspension sedimentation beneath maximum storm wave base in an outer shelf setting. The formation of carbonate concretions is thought to occur during early diagenesis and could be related to microbial processes (e.g., Berner 1968; Raiswell 1976) or mixing between meteoric and marine porewaters (e.g., Hudson and Friedman 1974). Soft-sediment deformation may occur from buoyancy instability due to deposition of material with density contrasts, downslope shear from slumping or slope failure, fluid escape from post-depositional compaction or seismicity, or syn-depositional current shear from turbidity currents (Gladstone et al. 2018). There is no indication of turbidity current flow or coherent structures indicating downslope slumping in these carbonate-dominated strata, so buoyancy instability or fluid escape are favored interpretations. There is also the localized presence of discontinuous intraclast rudstone intervals, which suggest reworking by rare storm-generated events.

The Last Chance Formation hosts a large negative carbon isotope excursion that has been correlated globally with the ca. 567–574 Ma Shuram carbon isotope excursion (Macdonald et al. 2013; Rooney et al. 2020). The depositional age of the Fireweed member has recently been constrained by a Re–Os age of 567.3 ± 3.0 Ma, which was obtained 16.4 m above the contact with underlying peach dolostone of the Last Chance Formation (section J1711, Fig. 7; Rooney et al. 2020).

Shade Formation (new), Rackla Group (Ediacaran)

Lithostratigraphy

Fine-grained siliciclastic rocks of the Shade Formation disconformably overlie carbonate strata of the Last Chance Formation (Table 5). This unit was previously referred to as the uppermost part of unit PH4 of the upper Mount Harper Group of Mustard (1988), Thompson et al. (1994), and Mustard and Roots (1997) and part of the "upper group" by Macdonald et al. (2011, 2013). Strata of the Shade Formation at the type section consist of 103 m of poorly exposed brown- to yellow-weathering siltstone and shale/mudstone interbedded with very-fine-grained quartz arenite and sublitharenite (Fig. 7). This siliciclastic package is in places dolomite cemented and contains normal grading, ripple cross-lamination, occasional flute casts, and rare full to abbreviated Bouma subdivisions (Bouma 1962). The Shade Formation was only observed in two measured sections and in most locations is absent beneath the sub-Shell Creek unconformity (Fig. 7). In all measured sections, the Formation's upper contact is marked by an erosional contact with up to 2 m of relief beneath siliciclastic rocks of the Cambrian Shell Creek Formation (Fig. 7).

Depositional setting and age

The fine-grained siliciclastic strata of the Shade Formation may record evidence of upper slope sedimentation due to the presence of partial to full Bouma sequence turbidites and flute casts. The Formation's general poor exposure in the Coal Creek inlier precludes a detailed reconstruction of its depositional environment, but this siliciclastic package probably records a deepening relative to the underlying concretionary carbonate unit of the Fireweed member, perhaps from an outer shelf to a upper slope setting that is dominated by sediment gravity-flow processes. There are no absolute age constraints for the Shade Formation in the Coal Creek inlier; however, its stratigraphic position overlying the ca. 567 Ma Fireweed member (Rooney

Fig. 5. (A) Matrix-supported carbonate clast diamictite of the Lone Formation; rock hammer is 33 cm in length. (B) Cliff Creek Formation silicified dolostone with "giant wave ripples" disrupted by sheet crack cements; hammer is 33 cm in length. (C) Tepee structures within silicified dolostone of the Gladman member (Last Chance Formation); pencil is 13 cm in length. (D) Irregular contact between silicified and brecciated dolostone of the upper Gladman member and dolomudstone of the Last Chance Formation; hammer is 33 cm in length. (E) Hummocky cross-stratified dolograinstone of the Last Chance Formation; hammer is 33 cm in length. (F) Silty dolograinstone with hummocky cross-stratification and ripple cross-lamination in the Last Chance Formation; coin is 1.8 cm in diameter. [Color online.]

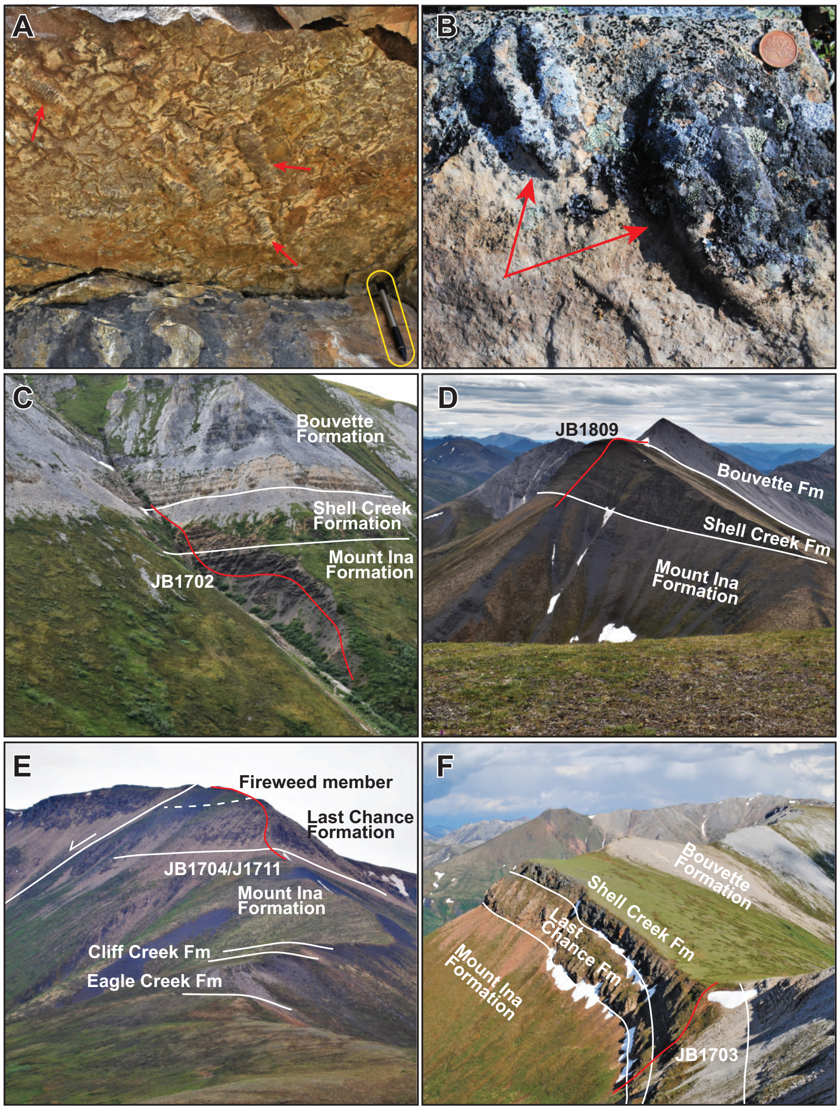
et al. 2020) and below the Cambrian Shell Creek Formation suggests this unit was deposited in the late Ediacaran to early Cambrian (section J1711, Fig. 7; Rooney et al. 2020).

Cambrian Shell Creek Formation (new)

Lithostratigraphy

The Shell Creek Formation overlies a major erosional surface in the Coal Creek inlier (herein referred to as the sub-Shell Creek unconformity) and consists of interbedded shale, siltstone, sandstone, and conglomerate (Table 6, Fig. 9). This unit was previously referred to as unit PH5 of the upper Mount Harper Group of Mustard (1988), Thompson et al. (1994), and Mustard and Roots (1997); it was subsequently classified as "Cambrian Undivided" by Macdonald et al. (2011, 2013). The Shell Creek Formation displays significant facies variation and thickness changes across the study area. In the northern part of the Coal Creek inlier, this unit is no more than 45 m thick and unconformably overlies siltstone of the Shade Formation, carbonate of the Last Chance Formation, or black shale/mudstone of the Mount Ina Formation (Fig. 9). Shell Creek strata in this location consist of interbedded medium- to thick-bedded fine- to very-coarse-grained sandstone, pebble to cobble conglomerate, and siltstone/shale (Fig. 9). Dark-grey-weathering conglomerate intervals are composed of locally imbricated subrounded to well-rounded granule- to pebble-sized clasts of chert, quartzite, and mafic volcanic rocks with crude cross-stratification (Figs. 8D, 8G, 8H). Conglomerate packages are commonly interbedded with grey–green siltstone, shale, and trough cross-stratified fine- to medium-grained lithic arenite and sublitharenite (Figs. 8E, 8G), the bases of which contain syneresis cracks and *Cruziana, Diplocraterion, Rusophycus,* and *Planolites* trace fossils (Figs. 6A, 6B; Mustard et al. 1988). Bedding geometries are commonly lenticular to stratiform with local irregular bases, and in some cases form

Fig. 6. (A) Base of a sandstone bed in the Shell Creek Formation with abundant complex trace fossils, including *Cruziana* (red arrows), *Planolites*, and other indeterminate ichnogenera; pencil in yellow is 13 cm long. (B) *Rusophycus* trace fossils on a float block from the Shell Creek Formation; coin is 1.8 cm in diameter. (C) Measured section JB1702 in the northern part of the study area where proximal facies of the Shell Creek Formation sit unconformably on the Mount Ina Formation. (D) Measured section JB1809 in the western part of the study area where distal facies of the Shell Creek Formation rest unconformably on the Mount Ina Formation. (E) Measured sections JB1704/J1711 of the Last Chance Formation overlying the type section of the Mount Ina Formation (F838, Macdonald et al. 2013). (F) Measured section JB1703 where the Shell Creek Formation sits unconformably on the Last Chance Formation. [Color online.]



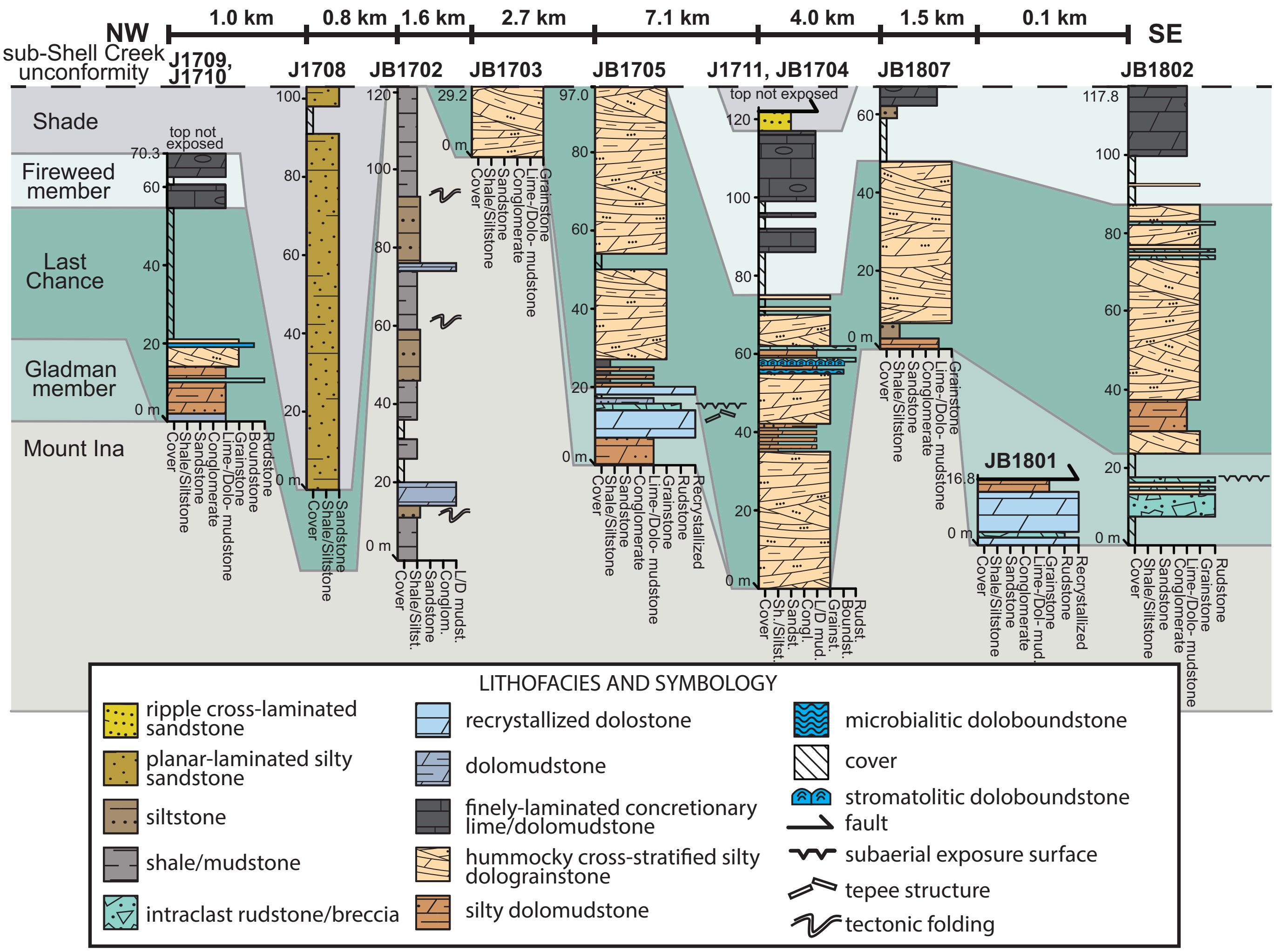
amalgamated bed-sets up to ca. 1.5 m thick (Fig. 8G). There is a general fining-upwards trend in these coarser-grained facies of the Shell Creek Formation, where the conglomerate and sandstone facies are generally succeeded by siltstone and shale beneath the overlying Bouvette Formation (Fig. 9).

In the southern part of the Coal Creek inlier, the thickness of the Shell Creek Formation increases by over a factor of three to a maximum of ca. 165 m (Figs. 3, 9). Here, the unit unconformably overlies either carbonate of the Last Chance Formation, or black shale of the Mount Ina Formation. Shell Creek lithofacies in these sections consist of thin- to medium-bedded grey to brown fine- to medium-grained sublitharenite and siltstone with abundant ripple cross-lamination, occasional stoss-preservational structures, and common normal graded sandstone horizons with erosional bases (Fig. 8F). Siltstone typically occurs as partings or drapes between thin beds of fine-grained sandstone. Notably, trace fossils were not observed in these strata. The top of the Shell Creek Formation is marked by a ca. 25 m thick interval of recessive black- to orange-weathering shale and siltstone, which outcrops beneath massive light grey dolostone of the Bouvette Formation.

Depositional setting and age

Cross-stratified conglomerate and sandstone facies of the northern Shell Creek exposures are interpreted to be marginal marine in origin. Paleocurrent indicators from sandstone and conglomerate horizons in this unit indicate paleoflow ranging from northerly to westerly (present-day coordinates), although an overall northerly trend was reported by Mustard (1990). The polydirectional inclination of the foresets observed in the trough cross-stratified sandstone may indicate a tidal or oscillatory wave-current influence; thus, we interpret these coarser-grained

Fig. 7. Stratigraphic fence diagram of the Shade, Last Chance, and Mount Ina formations beneath the sub-Shell Creek unconformity. At least ca. 190 m of strata is truncated by the sub-Shell Creek unconformity at section JB1702, while preservation of the majority of the Ediacaran succession occurs at section JB1802. Broadly, the sub-Shell Creek unconformity incises more strata to the northwest compared with the southeast in the study area. [Color online.]



deposits to reflect sedimentation within a wave-influenced deltaic system. These coarse-grained strata could alternatively comprise subaqueous marine fan delta deposits, but the consistent thickness of these strata and the distance over which they transition to finer-grained facies argues against this interpretation. The ripple cross-lamination and stoss-preservational ripples in the southern exposures, some of which resemble combined-flow bed configurations of Arnott and Southard (1990; Fig. 8F), indicate deposition by oscillatory and combined-flow regimes and are interpreted to represent deposition in a wave-influenced fluvio-deltaic to shallow marine environment (e.g., Raaf et al. 1977).

The diagnostic trace fossils *Cruziana*, *Rusophycus*, and *Diplocraterion* provide a maximum depositional age for the Shell Creek Formation of Cambrian Stage 2 (Terreneuvian; Mustard et al. 1988; MacNaughton and Narbonne 1999; Gabriela Mángano and Buatois 2017). The Shell Creek Formation directly underlies the Bouvette Formation, where the occurrence of putative archeocyathids (Thompson et al. 1994; Mustard and Roots 1997) suggest an upper age constraint of Cambrian Stage 4 (Series 2; Zhuravlev and Wood 1996; Rowland and Shapiro 2002); however, the fossil report of Fritz (1982) from this locality suggests these specimens are reworked with specimens of *Tabulaconus* spp. and coral-like forms that resemble *Halysites*, thereby providing an ambiguous Furongian maximum depositional age for the Bouvette Formation. As a result, the potential age range of the Shell Creek Formation extends from the Terreneuvian to the Miaolingian.

$\delta^{13}C_{carb}$ and $\delta^{18}O_{carb}$ chemostratigraphy

The Cliff Creek Formation has $\delta^{13}C_{carb}$ values that begin at −0.5‰ and decrease incrementally to a minimum of −3.7‰, before returning to −3.0‰ in the highest exposure (Fig. 10; also see data in Ahm et al. 2019). The $\delta^{18}O_{carb}$ data from these strata average −6.6‰ and display a strong positive correlation with the $\delta^{13}C_{carb}$ values ($r = 0.58$). The Gladman member of the Last Chance Formation has a range of $\delta^{13}C_{carb}$ values between 2.7‰ and −4.8‰ (Fig. 10) and attendant $\delta^{18}O_{carb}$ values are from 1.3‰ to −5.5‰ with no obvious trend, except for an abrupt decrease to −5.6‰ at the contact with the overlying Last Chance Formation. Gladman member $\delta^{18}O_{carb}$ and $\delta^{13}C_{carb}$ values have a strong positive correlation (average correlation coefficient for all sections = 0.77). The $\delta^{13}C_{carb}$ values are highly depleted in the Last Chance Formation and range from −3.1‰ to −9.3‰, with a nadir at the base of the Formation (directly above the Gladman member, where present). Carbon isotope values of the Last Chance Formation tend to gradually increase to more enriched values and then rapidly transition to highly positive values of 5.3‰ in

Fig. 8. (A) Hummocky cross-stratified silty dolograinstone interbedded with a single bed of stromatolitic doloboundstone (red arrow) in the upper Last Chance Formation (camera lens cap is 6 cm in diameter). (B) Finely laminated dolomudstone with lozenge-shaped concretions (red arrows) in the Fireweed member of the Last Chance Formation; hammer is 33 cm long. (C) Plan view of a large carbonate concretion within the Fireweed member; hammer is 33 cm long. (D) Crudely stratified polymict cobble conglomerate with imbricated clasts interbedded with siltstone of the Shell Creek Formation; hammer is 33 cm long. (E) Trough cross-stratified sandstone interbedded with recessive siltstone of the Shell Creek Formation; hammer is 33 cm long. (F) Planar and cross-laminated fine-grained sandstone with local starved ripples in the Shell Creek Formation; coin is 2.5 cm in diameter. (G) Planar laminated and trough cross-stratified pebble conglomerate and sandstone of the Shell Creek Formation; pencil is 13 cm long. (H) Polymict conglomerate of the Shell Creek Formation; coin is 1.8 cm in diameter. [Color online.]

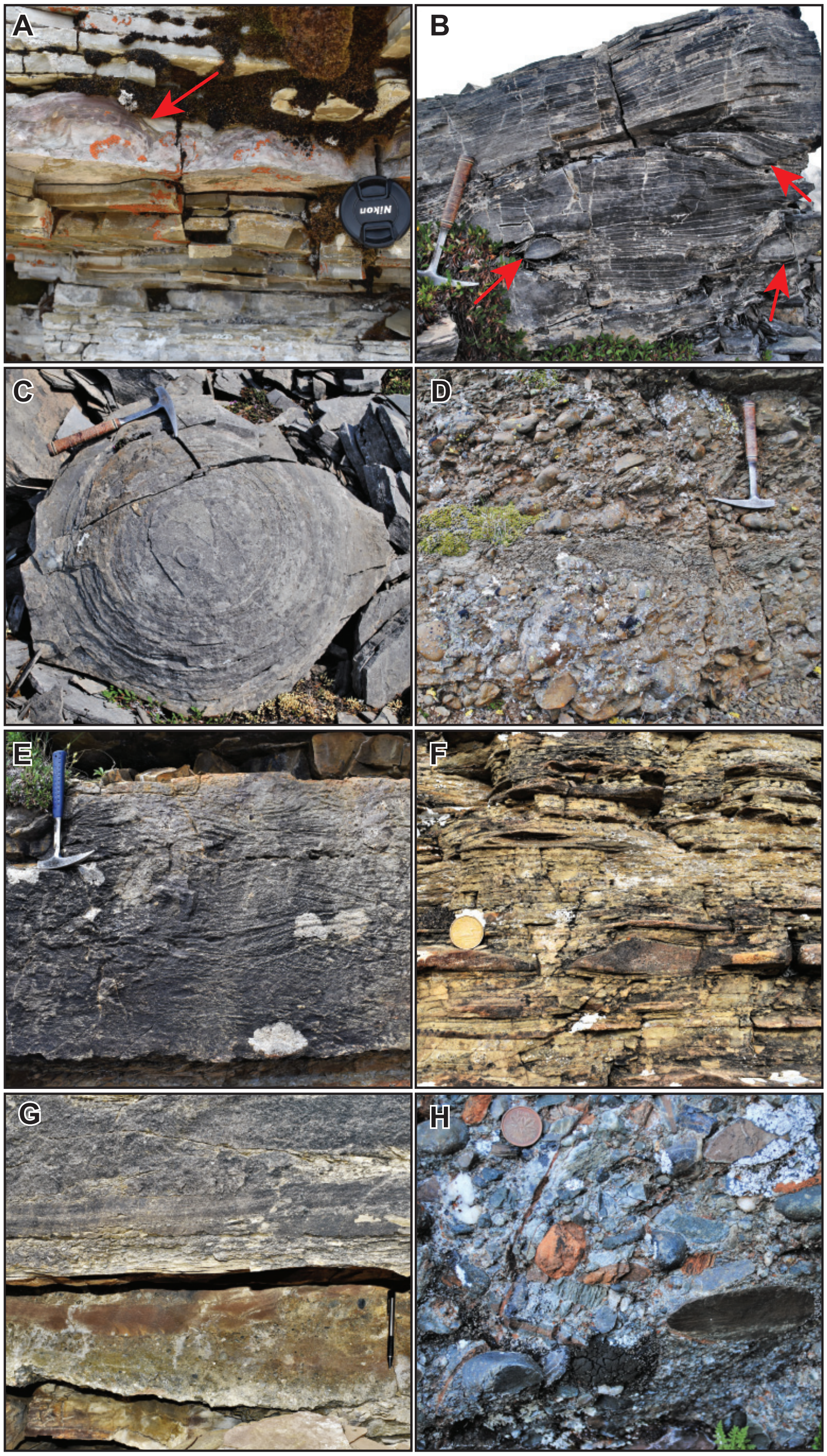
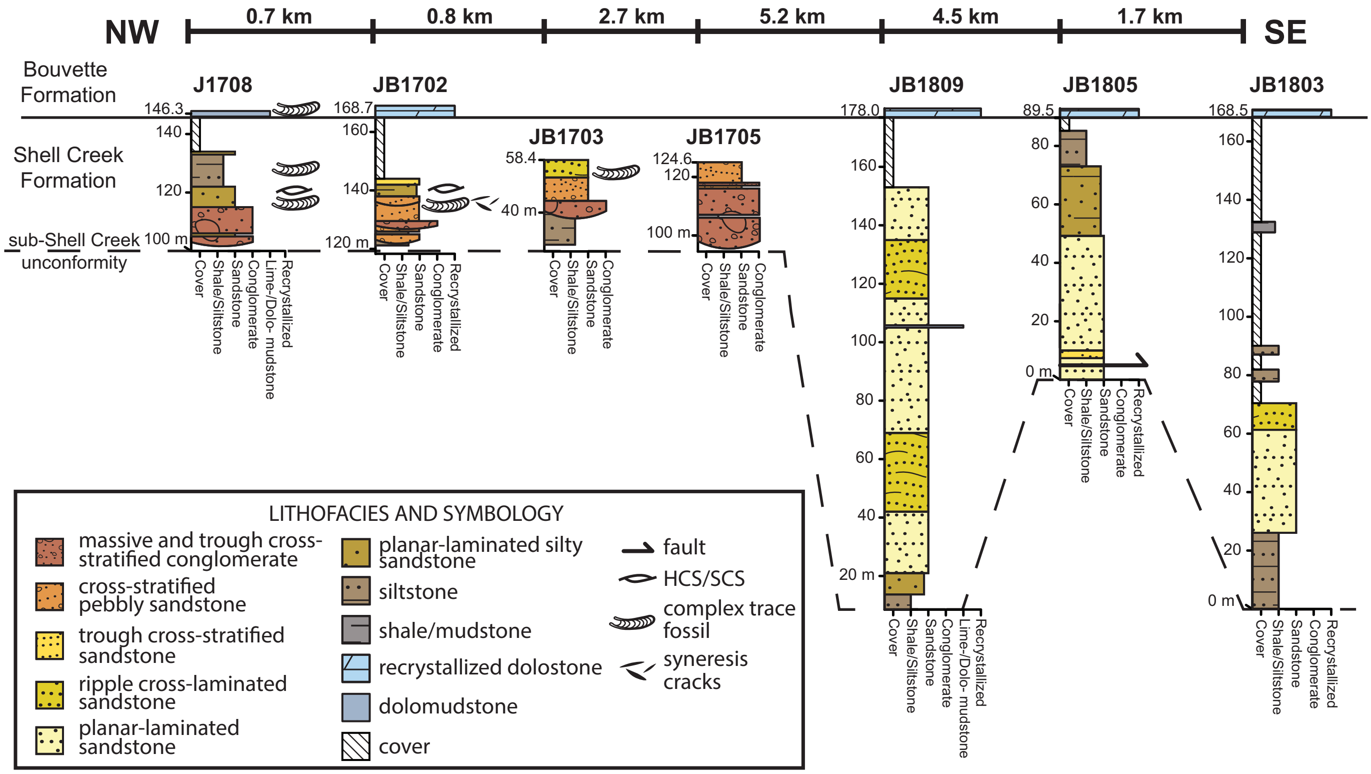


Fig. 9. Stratigraphic fence diagram of the Bouvette and Shell Creek formations above the sub-Shell Creek unconformity. The Shell Creek Formation increases in thickness by roughly a factor of three from ca. 40 m in the northwestern part of the study area to ca. 165 m in the southeastern part of the study area. This change in thickness is accompanied by a shift in lithofacies from conglomerate- and sandstone-dominated strata in the northwest to fine-grained sandstone- and siltstone-dominated strata in the southeast. HCS/SCS, hummocky and swaley cross-stratification. [Color online.]



the concretionary dolostone and limestone of the Fireweed member (Fig. 10). $\delta^{18}O_{carb}$ data (ranging from −2.8‰ to −12‰) exhibit varying relations with $\delta^{13}C_{carb}$ in the Last Chance Formation and Fireweed member, correlating both positively and negatively. Notably, there exists a $\delta^{13}C_{carb}$ gradient in the Last Chance Formation between northwestern and southeastern locations, where the southeastern measured sections are depleted by as much as 5.2‰ in $\delta^{13}C_{carb}$ relative to the sections to the northwest (Fig. 10).

Discussion

Stratigraphic correlations within the Yukon block

Cryogenian–Ediacaran

The Lone Formation is distinguished here for the first time from the underlying Sturtian (ca. 717–660 Ma) Eagle Creek Formation (Rapitan Group; Macdonald et al. 2018) by its distinct matrix/clast composition and interbedded nature with cap dolostone strata of the Cliff Creek Formation. This interbedded relationship implies a Marinoan ca. 635 Ma age for this deposit (e.g., Calver et al. 2004; Condon et al. 2005; Hoffman 2011), which is also supported by the presence of idiosyncratic sedimentary structures in the Cliff Creek Formation, such as cuspate bedforms and sheet crack cements (e.g., Hoffman 2011). In addition, $\delta^{13}C_{carb}$ values from the Cliff Creek Formation fall within the range of values seen in global $\delta^{13}C_{carb}$ compilations of Marinoan cap carbonates (−1.9‰ to −3.6‰), where global variation is thought to reflect a spectrum of fluid- or sediment-buffered diagenetic conditions (Fig. 11; Ahm et al. 2019). Thus, the Lone Formation is correlative with the terminal Cryogenian Stelfox member of the Ice Brook Formation in the Wernecke and Mackenzie mountains (Aitken 1991*b*; Hoffman and Halverson 2011; Macdonald et al. 2018; Moynihan et al. 2019), and the Cliff Creek Formation is correlative with the informal Ravensthroat formation of the Mackenzie Mountains (James et al. 2001). In the Tatonduk inlier of the Yukon–Alaska border area, matrix-supported diamictite and overlying dolostone with sheet crack cements have previously been assigned to the Hay Creek Group (units 3–4 of the upper Tindir Group, Young 1982; Macdonald et al. 2011). We propose all these equivalent Marinoan glacial and cap carbonate strata in the Yukon block should now be termed the Lone and Cliff Creek formations.

As highlighted previously, the base of the Ediacaran Mount Ina Formation is probably correlative with the early Ediacaran Sheepbed Formation of the Wernecke and Mackenzie mountains (Gabrielse et al. 1973; Dalrymple and Narbonne 1996; Macdonald et al. 2013; Rooney et al. 2015). These units share many similar lithological characteristics, including dominance by >100 m thick exposures of recessive black shale and mudstone (e.g., Dalrymple and Narbonne 1996; Moynihan et al. 2019). The Mount Ina Formation does not contain any of the coarser-grained lithofacies that are abundant in the upper Sheepbed Formation in the Wernecke Mountains (Moynihan et al. 2019), which could reflect different depositional sites along the Sheepbed – Mount Ina slope system (Dalrymple and Narbonne 1996).

Despite some sedimentological and thickness differences, brecciated dolostones of the Gladman member of the Last Chance Formation are correlated here with mixed siliciclastic–carbonate strata of the upper Nadaleen Formation in the Wernecke Mountains (Moynihan et al. 2019). Two recently reported Re–Os radiometric dates constrain the upper Nadaleen Formation's depositional age to ca. 575 Ma (Fig. 11; Rooney et al. 2020).

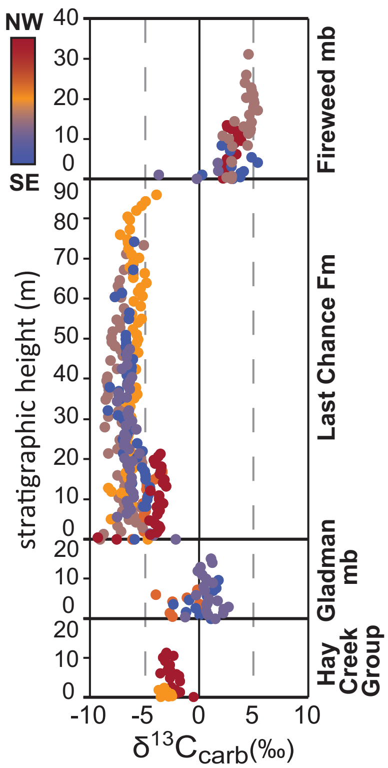


Fig. 10. Compilation of all $\delta^{13}C_{carb}$ data from the Lone, Cliff Creek, and Last Chance formations measured for this study with data colored by relative location in the study area. No spatial trend is obvious in the Hay Creek Group and Gladman or Fireweed members of the Last Chance Formation, but there is a ca. 5‰ gradient in the most depleted values of the Last Chance Formation between the northwestern (J1710) and southeastern (JB1704) stratigraphic sections. These highly depleted $\delta^{13}C_{carb}$ values in the Last Chance Formation are correlated with the globally recognized Shuram carbon isotope excursion. [Color online.]

The Gladman member has enriched $\delta^{13}C_{carb}$ values that are similar to the uppermost Nadaleen Formation (Fig. 11; Moynihan et al. 2019), and it shares a number of sedimentological similarities with proximal sections in the northern Goz Creek area of the Wernecke Mountains (Fig. 11; Pyle et al. 2004; Macdonald et al. 2013). In addition, both units occupy equivalent stratigraphic positions between postglacial siliciclastic strata of the Sheepbed/Mount Ina formations and Shuram-bearing carbonate strata of the Gametrail/Last Chance formations (Fig. 11). The bulk of the Last Chance Formation, which is characterized by highly depleted $\delta^{13}C_{carb}$ values down to −9‰, is correlative with the Gametrail Formation of the Wernecke Mountains (Fig. 11; Aitken 1989; Macdonald et al. 2013; Moynihan et al. 2019; Rooney et al. 2020). Similar to the underlying Gladman member, proximal HCS-bearing dolograinstone facies of the upper Last Chance Formation share sedimentological characteristics with Gametrail strata in the northern Goz Creek area (Goz A and B, Pyle et al. 2004; Macdonald et al. 2013; Rooney et al. 2020).

The Fireweed member of the upper Last Chance Formation and the overlying Shade Formation both postdate the ca. 575–567 Ma Shuram carbon isotope excursion and are therefore potentially correlative with the lower Blueflower Formation of the Wernecke and Mackenzie mountains (Aitken 1989; Macdonald et al. 2013; Moynihan et al. 2019). The Blueflower Formation of the northern Goz Creek area is similarly composed of ca. 100 m of mixed siliciclastic and carbonate strata deposited in outer shelf to upper slope settings (Fig. 11; Pyle et al. 2004, Macdonald et al. 2013; Rooney et al. 2020). Thinly laminated concretionary carbonates, similar to those in the Fireweed member, also form part of the Blueflower Formation in the Nadaleen River area (Moynihan et al. 2019). There are no reported $\delta^{13}C_{carb}$ measurements from the basal Blueflower Formation in the northern Goz Creek region, although data from the southern Goz Creek region (Goz D) range from −2‰ to 0‰ (Macdonald et al. 2013; Rooney et al. 2020). Enriched $\delta^{13}C_{carb}$ values of the Fireweed member (2‰ to ‰) are more similar to isotopic data from the lower carbonate member of the Blueflower Formation in the Rackla area of the Wernecke Mountains and the Sekwi Brook area of the Mackenzie Mountains (ca. 0‰ to 4‰; Macdonald et al. 2013; Moynihan et al. 2019); thus, the Fireweed member of the Last Chance Formation in the Coal Creek inlier is most likely correlative with the basal Blueflower Formation as currently defined.

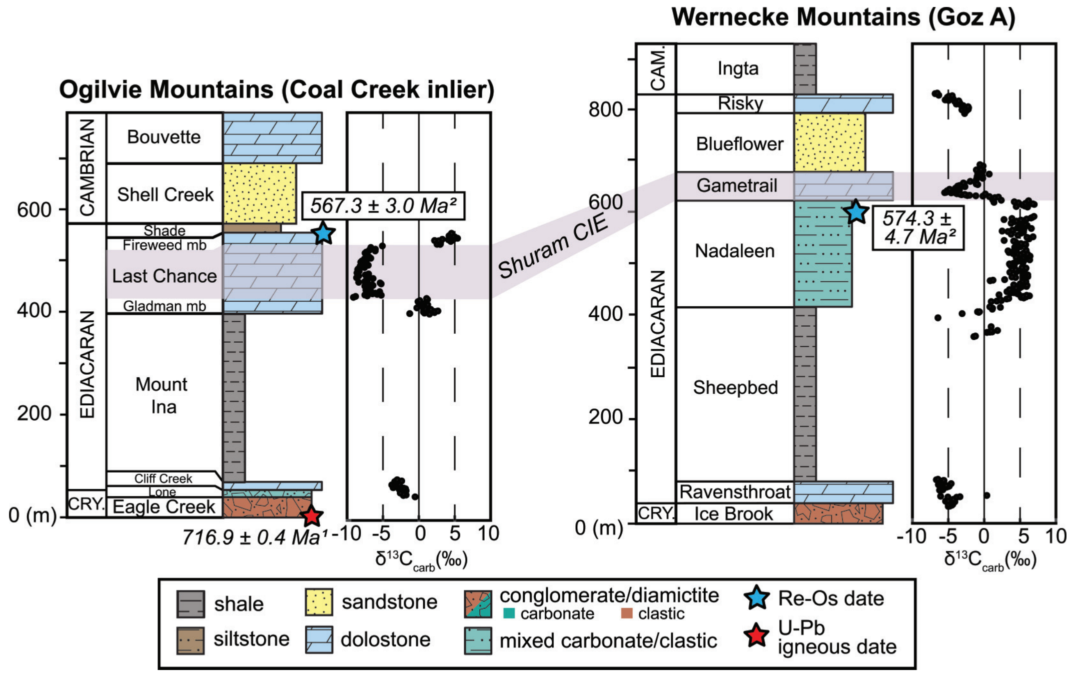
Strata of the Tatonduk inlier assigned to the "upper group" by Macdonald et al. (2011) (formerly units 4b and 5 of the upper Tindir Group, Young 1982) include ca. 40–75 m of parallel-laminated siltstone, sandstone, dolomitic marl, black shale, and organic-rich limestone, which thicken to ca. 700 m along the Tatonduk River in Alaska. Due to the absence of direct age constraints or carbon isotope data from these strata, direct correlations with the Rackla Group in the Coal Creek inlier remain ambiguous.

Cambrian

Elsewhere on the Yukon block, the lower–upper Cambrian Illtyd, Slats Creek, and Taiga formations occupy a similar stratigraphic position to the Shell Creek Formation beneath the Bouvette Formation (Fritz 1985, 1997; Bell 1986; Morrow 1999). The lower Cambrian (*Bonnia–Olenellus* Zone, Stage 4, Series 2) Illtyd Formation overlies various Proterozoic units (Rapitan and Quartet groups) with an angular unconformity and is composed of ca. 1 km of interbedded lime mudstone, argillaceous lime wackestone, oolitic grainstone, and doloboundstone (Norris 1982*a*, Fritz 1991; Morrow 1999). These strata are regionally overlain by the middle Cambrian (*Glossopleura* Zone; Miaolingian) Slats Creek Formation, which is a laterally discontinuous ca. 500 m thick mixed carbonate–siliciclastic unit that is thickest around the Richardson trough (ca. 1600 m) and thins dramatically (ca. 12 m) onto the Yukon block (Fritz 1997; Morrow 1999). The overlying middle–upper Cambrian (*Glossopleura–Crepicephalus* Zone; Miaolingian) Taiga Formation consists of ca. 100 m of interbedded silty dolostone, intraclast conglomerate, and planar-bedded dolostone that conformably overlies the Slats Creek Formation in the Richardson trough, but further west in the Hart River map area, it unconformably overlies various Proterozoic units (Norris 1982*b*; Fritz 1997; Morrow 1999). The Slats Creek Formation is potentially correlative with the Shell Creek Formation, as they are similar in age and record abrupt lithofacies and thickness changes related to regional extension, although an overlap in age with the Illtyd and Taiga formations (Fritz 1997) cannot be excluded.

In the western Wernecke Mountains near the southeastern edge of the Yukon block, the Narchilla, Gull Lake, and two unnamed map units occupy an equivalent stratigraphic position to the Shell Creek Formation (Gordey and Anderson 1993; Morrow 1999; Busch et al. 2019). The latest Ediacaran – early Cambrian (Terreneuvian, Series 2) Narchilla Formation consists of a thick package of maroon shale and siltstone that conformably overlies the upper Ediacaran Algae Formation in the type area but becomes erosive to the north (Gordey and Anderson 1993; MacNaughton et al. 2016; Moynihan et al. 2019). The overlying middle Cambrian (Miaolingian) Gull Lake Formation consists predominantly of fine-grained siliciclastic rocks with a discontinuous basal conglomerate unit with up to block-sized clasts of

Fig. 11. Newly formalized Ediacaran–Cambrian units of the Coal Creek inlier shown with correlative Ediacaran–Cambrian strata of the Goz A region of the Wernecke Mountains; $\delta^{13}C_{carb}$ data shown for all carbonate units with the location of the Shuram carbon isotope excursion (CIE) highlighted between the two locations (modified after Macdonald et al. 2013 and Rooney et al. 2020). [1]Macdonald et al. 2013, [2]Rooney et al. 2020. [Color online.]



carbonate, mafic volcanic, and sandstone lithologies, some of which bear archeocyathids and *Bonnia–Ollenelus* Zone trilobites (Gordey and Anderson 1993; Abbott 1997; MacNaughton et al. 2016). Two unnamed carbonate units underlie the Bouvette Formation in the Nadaleen River area (Busch et al. 2019). These are (1) a Miaolingian-Furongian fine-grained limestone and shale succession, and (2) a rudstone and breccia succession that includes a tongue of volcaniclastic conglomerate and sandstone that yielded Guzhangian (ca. 500 Ma) detrital zircon grains (Yukon Geological Survey Geochronology Database samples 11MC059 and 12-MC-162, Yukon Geochronology 2018). The Gull Lake Formation, the base of which marks a prominent sequence boundary that is correlative with the sub-*Bonnia–Ollenelus* unconformity elsewhere in Yukon (Moynihan et al. 2019), could be correlative with the Shell Creek Formation. Alternatively, the Shell Creek Formation could correlate with one or more younger units, including the <500 Ma unnamed rudstone/breccia of Busch et al. (2019).

In the White Uplift of northeastern Yukon, poorly understood early Cambrian calcareous quartzite and interbedded red shale and siltstone (Dyke 1996) are interpreted as equivalent to the Shell Creek Formation. These strata rest with angular unconformity on poorly documented Proterozoic strata and are overlain by the Cambrian–Silurian Vunta Formation, which is correlated with the Bouvette Formation (Norford 1964).

Ediacaran–Cambrian stratigraphic trends in the Coal Creek inlier

Stratigraphic sections of Ediacaran–Cambrian strata in the Coal Creek inlier capture several distinct trends. The Cryogenian–Ediacaran Lone and Cliff Creek formations and Ediacaran Mount Ina Formation display no obvious sedimentological differences between measured sections, while the overlying Gladman member of the Last Chance Formation is present only locally in the study area (Fig. 7). Highly silicified carbonate intraclast rudstone and breccia of the Gladman member (Fig. 5C) were observed in all measured sections of this unit, and the one section that preserves the upper contact (JB1705) displays an erosional boundary interpreted as a subaerial exposure surface (Fig. 5D). These features suggest the limited preservation of the Gladman member could be the result of subaerial exposure and erosion during regional base level regression, a common phenomenon observed on emergent carbonate platforms (e.g., Maslyn 1977). Above this erosional surface, strata of the Last Chance and Shade formations display no significant sedimentological differences between the measured sections (Fig. 7).

The most notable stratigraphic feature of the Ediacaran–Cambrian units in the Coal Creek inlier is the extent of truncation that occurs beneath the sub-Shell Creek unconformity. The thickness of strata truncated by the unconformity ranges from a maximum of ca. 190 m to a minimum of ca. 100 m (Fig. 7). In other locations on the Yukon block, the Shade Formation's stratigraphic equivalent, the Blueflower Formation, is locally over 700 m thick and is consistently overlain by the terminal Ediacaran Algae or Risky formations (e.g., Aitken 1989; Pyle et al. 2004, Macdonald et al. 2013; Moynihan et al. 2019). Equivalents of the Algae and Risky formations are absent in the Coal Creek inlier and the variably preserved thicknesses of the Shade Formation suggests it may be mostly missing beneath the sub-Shell Creek unconformity (Fig. 11). The Shade Formation siliciclastic rocks were observed in only two stratigraphic sections (J1708 and J1711); it is notably thick at section J1708, while it is completely absent 1.6 km to the east (JB1702) and absent or not exposed 1 km to the west (J1709/J1710; Fig. 7). Although observed over a relatively short distance, this significant thickness change in the Shade Formation occurs across a thrust fault with unknown displacement, raising the possibility that at the time of deposition there existed a greater distance separating the two measured sections (Fig. 3). Despite this, composite section J1709/J1710, only 1 km to the west of section J1708, occurs along the same structural panel with no intervening faults; these sections all contain the concretionary carbonate unit of the Fireweed member but preserve no overlying siliciclastic strata of the Shade Formation (Figs. 3, 7). One possible explanation for this relationship is post-depositional uplift in the latest Ediacaran or early–middle Cambrian, which may have caused variable incision into the Shade Formation during the development of the sub-Shell Creek unconformity.

To achieve the observed stratigraphic truncations beneath the sub-Shell Creek angular unconformity (Fig. 11), the Ediacaran units must have been tilted between 0.9° and 2.1°, without accounting for shortening across major contractional structures in the study area, or 0.7°–1.6° allowing for 30% shortening (Supplementary Material S3[1]). These estimates of regional tilting are consistent with observations of tilted fault blocks (ranging from 1° to 4°, average of 2°) in pre-rift strata from the Red Sea rift in the Gulf of Suez (e.g., Cross et al. 1998). Notably, the spatial trend of truncation beneath the sub-Shell Creek unconformity seems to occur from northwest to southeast, with less truncation of the Ediacaran strata to the southeast (Figs. 3, 9).

The Shell Creek Formation also displays significant facies variations and thickness changes from northwest to southeast (Fig. 9). In the northern sites where the unit is ca. 40 m thick, it consists of thick-bedded polymict conglomerate and coarse- to medium-grained lithic arenite (Figs. 8D, 8E), while in the southern localities, the Shell Creek Formation thickens to ca. 165 m and is composed of a fairly homogeneous package of interbedded siltstone and sandstone (Fig. 8F); thus, between the northern and southern exposures of the Shell Creek Formation, there is a thickness change of over 100 m within a distance of ca. 5 km. Thickness and facies changes of this magnitude over such short distances (<10 km) are commonly observed in steep-margined transtensional or extensional basins (e.g., Ravnås and Steel 1998). In these systems, deltaic or alluvial systems commonly interfinger with and transition down-dip into lacustrine or marginal-marine environments. Importantly, these successions display distinctive changes in the sedimentary facies from distal to proximal settings accompanying thickness changes and have been documented in many basins around the world (e.g., Colella and Gawthorpe 1990). For example, similar facies distributions and thickness changes have been observed in early-rift and syn-rift strata from the well-studied Gulf of Suez, where alluvial conglomerate and sandstone sourced from uplifted rift shoulders of local tilt-blocks transition abruptly into terrigenous and marine bioclastic sandstone successions with an accompanying increase in thickness (e.g., Plaziat et al. 1998).

Similar coarse-grained siliciclastic packages, which often form small juxtaposed systems infilling submarine valleys before overflowing as extensive terrigenous sheets, have been interpreted in several locations as deposits of terrestrial alluvial fan and braided stream plains that pass into marine fan deltas within the Red Sea rift system (e.g., Bosworth et al. 1998). It is possible the Shell Creek Formation represents a subaqueous fan delta system rather than a braided delta that transitions to an open marine system; however, the latter is preferred due to the consistent thicknesses of the conglomerate packages and the distance (ca. 5 km) over which occurs the transition from coarse- to fine-grained deposits and the occurrence of marine trace fossils in these strata. Studies of subaqueous alluvial fan aprons show that this transition from the fan apex conglomerate to distal fan siltstone can occur within ca. 2 km (e.g., Prior and Bornhold 1989; Horton and Schmitt 1996); this scale is inconsistent with our data from the Shell Creek Formation.

Ediacaran–Cambrian basin evolution in the Coal Creek inlier

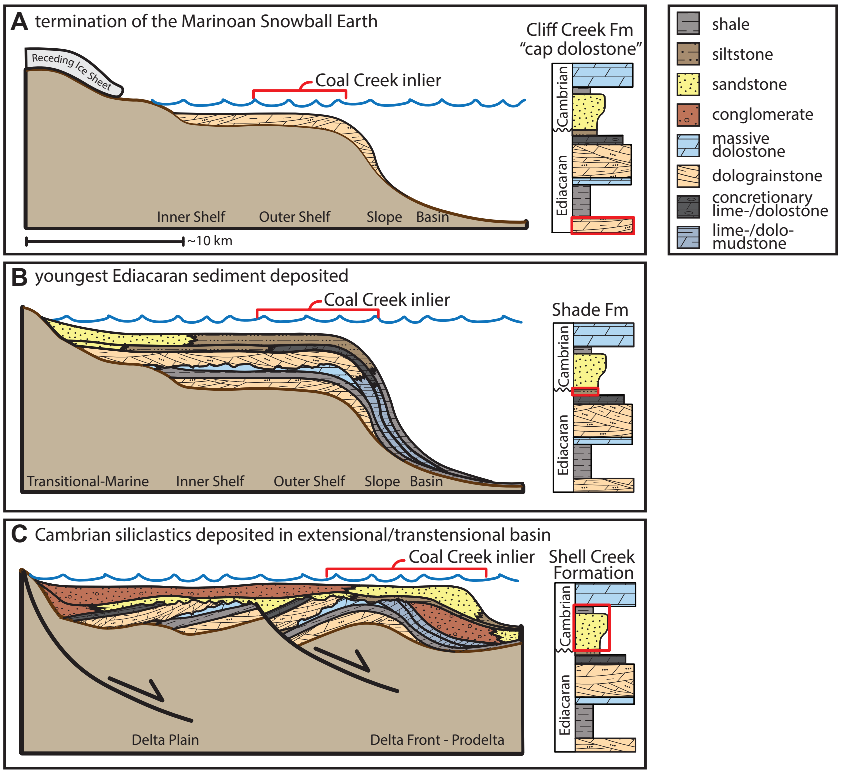
Based on the field observations and regional stratigraphic relations described above, the Ediacaran–Cambrian depositional history of the Coal Creek inlier begins with deposition of the Lone Formation in the aftermath of the Marinoan Snowball Earth glaciation (Fig. 12A). The sparsely preserved glacial diamictite in the Lone Formation is interbedded with cap dolostone facies of the Cliff Creek Formation (ca. 635 Ma), which contain sedimentary structures suggestive of deposition in an inner-shelf setting that was rapidly flooded during postglacial transgression (cf., Creveling and Mitrovica 2014). During this transgression, a thick package of black shale and mudstone of the Mount Ina Formation was deposited between ca. 632 and ca. 575 Ma before the appearance of shallow water carbonate facies in the Last Chance Formation (Tables 3, 4; Rooney et al. 2015, 2020).

The Gladman member of the basal Last Chance Formation contains evidence for abrupt shoaling in the Coal Creek inlier, as recorded by the preservation of a thin and poorly developed carbonate system with evidence for subaerial exposure. The overlying thick package of inner- to outer-shelf carbonate strata of the Last Chance Formation was deposited on a storm-dominated ramp prior to a shift to more quiescent sedimentation beneath maximum storm wave base on the outer shelf recorded by the Fireweed member (Fig. 12B). The thick package of HCS grainstone is here interpreted as reflecting deposition on a ramp, rather than a platform, based on the spatial constraint of equivalent slope deposits ca. 10 km to the south in the Selwyn basin. This would require a platform margin position too distant to reasonably allow for storm-generated waves to produce the abundant HCS observed in the Coal Creek inlier (e.g., Duke 1985). A poorly understood ca. 567 Ma transition into fine-grained siliciclastic sedimentation is preserved in the Shade Formation. The terminal Ediacaran sedimentary history of the Coal Creek inlier is not preserved due to subsequent tilting of the Ediacaran succession during formation of the sub-Shell Creek unconformity, which occurred between the latest Ediacaran (<567 Ma) and Series 2 of the early–middle Cambrian (Figs. 12B, 12C).

Rapid thickness and facies changes occur in overlying siliciclastic strata of the Shell Creek Formation (Fig. 12C), which are here interpreted to have been deposited during the middle Cambrian (Miaolingian) in a transtensional or extensional basin. Evidence for active tectonism in these early–middle Cambrian siliciclastic rocks of the Coal Creek inlier are consistent with the formation of the middle Cambrian (Miaolingian) Dempster volcanic rocks and the ca. 499 Ma Old Cabin Formation (Mamrol et al. 2016; MacNaughton et al. 2016). These alkaline volcanic rocks crop out close to the Yukon block – Selwyn basin boundary and were presumably localized by the deep structure(s) that accommodated rifting and controlled the location of the platform-basin interface through the lower Paleozoic (Roots 1987; Gordey and Anderson 1993; Goodfellow et al. 1995; Abbott 1997; MacNaughton et al. 2016). Age constraints are insufficient to demonstrate temporal coincidence, but it is possible that the extensional tectonism recorded in the Shell Creek Formation overlapped with strike-slip deformation associated with rotation of the Yukon block (Eyster et al. 2017).

Regional unconformities separating Ediacaran and Cambrian units have been recognized at different stratigraphic levels in the North American Cordillera (commonly termed the "sub-Cambrian" unconformity). In many locations, the "sub-Cambrian" unconformity likely represents a composite surface including multiple late Ediacaran – early Cambrian erosional events that progressively truncate more stratigraphic units in proximal locations (e.g., MacNaughton et al. 2000). On the Yukon block, angular unconformities of regional extent have been recognized beneath the *Bonnia–Olenellus* (Stage 4, Series 2) and *Elvinia* (Jiangshanian Stage, Furongian) Laurentian trilobite zones (Gordey and Anderson 1993; Fritz 1997; Moynihan et al. 2019). The angular nature of the sub-Shell Creek unconformity is here interpreted as a consequence of extension-related tilting; we tentatively correlate this surface with the regional sub-*Bonnia–Olenellus* unconformity, which is overlain by the Illtyd Formation in the eastern Yukon block (Fritz 1997; Morrow 1999). A regionally widespread (sub-Jiangshanian) unconformity beneath the Bouvette and Rabbitkettle

Fig. 12. Schematic model for Ediacaran–Cambrian basin evolution of the Coal Creek inlier. Note stratigraphic thicknesses are not to scale and facies distributions are inferred outside of the "Coal Creek inlier" extent (shown with red bar). Tilting of strata in panel C is exaggerated for illustration purposes. (A) Basal Ediacaran Cliff Creek Formation "cap dolostone" is deposited during postglacial transgression within an outer shelf setting. (B) Upper Ediacaran fine-grained siliciclastic rocks and concretionary carbonate of the Last Chance and Shade formations are deposited in an outer shelf to upper slope setting. (C) Syn-tectonic coarse- to fine-grained siliciclastic rocks of the Shell Creek Formation are deposited in a wave-influenced deltaic environment within a transtensional or extensional basin following block rotation and uplift that produced the angular "sub-Shell Creek" unconformity. [Color online.]



formations (Gordey and Anderson 1993; Norris 1997; Busch et al. 2019) may be expressed locally as the disconformity between the Shell Creek and Bouvette formations.

Cryogenian – middle Cambrian rifting in the Northern Canadian Cordillera

The Coal Creek inlier is one of three structural culminations that lie close to the southern boundary of the Yukon block (Fig. 1). These culminations are interpreted to have formed by Mesozoic structural inversion of Windermere Supergroup depocenters (Roots and Thompson 1992). In the Coal Creek inlier, early Windermere rifting is recorded by the Mount Harper and Rapitan groups. The position of the Coal Creek, Hart River, and Wernecke inliers along the southern boundary of the Yukon block (Fig. 1) and the interpreted nature of their basin development — as localized, steep-sided basins distributed linearly along a major lithospheric boundary — is suggestive of a component of strike-slip deformation during their formation (Strauss et al. 2015).

Early Windermere rift basins are overlain by Ediacaran strata that are more widely distributed and in many cases lack evidence for syn-sedimentary tectonism (e.g., Aitken 1991*a*). Stratigraphic and sedimentological information from this study and elsewhere (e.g., Nadaleen River area and Tatonduk/Hart River inliers) indicates that Ediacaran strata were deposited on a generally southward-facing slope along the boundary between the Yukon block and Selwyn basin. A dearth of evidence for rift-related structures in Ediacaran – early Cambrian strata has been noted elsewhere along the Cordilleran margin (Aitken 1991*b*; Levy and Christie-Blick 1991). The apparent lack of upper crustal extension during this interval may indicate a tectonic lull separating pulses of rifting, but this could also reflect the nature of western Laurentian rifting processes. While many researchers have focused on the segmented, asymmetric nature of the rifted Cordilleran margin (Lister 1986; Cecile et al. 1997; Lund 2008; Lund et al. 2010), Beranek (2017) and Campbell et al. (2019) noted similarities between the Cordilleran and North Atlantic margins and emphasized the role of depth-dependent stretching in their formation. Depth-dependent stretching may result in little upper crustal deformation during some phases of rifting (Kusznir and Karner 2007; Huismans and Beaumont 2014) and consequently leave little trace in the stratigraphic record.

The stratigraphic and sedimentological data presented herein demonstrate renewed upper crustal extension on the southern flank of the Yukon block during the early–middle Cambrian. Tilting of Ediacaran strata and accompanying deposition of the Shell Creek Formation may have overlapped with alkaline volcanism along the Yukon block – Selwyn boundary during the Guzhangian. Furthermore, the timing of Shell Creek Formation deposition and associated active tectonism also coincides with early to late Cambrian extension and syn-rift sedimentation in the Misty Creek embayment and Richardson trough, two important Paleozoic depocenters that flanked the Ogilvie and Mackenzie platforms (Cecile 1982; Cecile et al. 1997). These data provide additional support for the contention that extensional deformation was widespread in the northern Canadian Cordillera through this time interval (Gordey and Anderson 1993; Post and Long 2008; Dilliard et al. 2010; Moynihan et al. 2019). For example, the Sekwi

Formation (*Nevadella* to *Bonnia–Olenellus* Zone) contains geographically restricted facies distributions and large allochthonous blocks interpreted as syn-tectonic in origin from the eastern Selwyn basin (Dilliard et al. 2010) and the Slats Creek Formation (*Glossopleura* Zone) contains abrupt lithofacies and thickness changes in the southeastern Yukon block related to regional extension (Fritz 1997). Similarly, the Mount Roosevelt Formation of the Kechika graben (northeastern British Columbia) contains coarse-grained siliciclastic rocks deposited in an active fault-controlled extensional basin in the early–middle Cambrian (Post and Long 2008).

Given the evidence for regionally widespread extensional tectonism, we favor interpretations that the prolonged and episodic rifting that led to formation of the Cordilleran continental margin continued into the middle Cambrian, and that continental separation and final breakup of Rodinia took place after deposition of the northern Cordilleran Windermere Supergroup (Post and Long 2008; Beranek 2017; Campbell et al. 2019; Moynihan et al. 2019). This is ca. 15–20 million years younger than the interpreted age of ca. 520 Ma for the transition from rifting to post-rift thermal subsidence that occurred in the southern Canadian Cordillera and western United States (Bond et al. 1985; Devlin and Bond 1988; Hein and McMechan 1994; Lickorish and Simony 1995; Warren 1997), which implies diachronous, south-to-north formation of the Cordilleran continental margin of Laurentia.

Conclusions

The integrated sedimentological, stratigraphic, and geochemical data from Ediacaran–Cambrian strata of the Coal Creek inlier, Yukon, Canada, presented above clarifies the tectonic setting of the uppermost Windermere Supergroup on the Yukon block and elucidates the rift-related sedimentation history for this region. Based on these observations, mixed siliciclastic and carbonate strata of the newly defined Lone, Cliff Creek, Mount Ina, Last Chance, Shade, and Shell Creek formations reflect deposition on a thermally subsiding Ediacaran margin that subsequently experienced tilting, erosion, and early–middle Cambrian extension prior to the initiation of Cambrian–Devonian passive margin sedimentation.

An angular unconformity in the Coal Creek inlier separates Ediacaran strata from the early–middle Cambrian Shell Creek Formation, which implies that regional tilting is constrained to <567 and >529 Ma. To account for the observed incision into Ediacaran strata, the sub-Shell Creek angular unconformity requires underlying strata to have been tilted ca. 1.5° during extension-related block rotation. These data support stratigraphic evidence presented elsewhere in northwestern Canada that the transition from active rifting to thermal subsidence occurred roughly 15 million years later in the northern Canadian Cordillera relative to the southern Canadian Cordillera and western United States.

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