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Shale and pyrite Re-Os ages from the Hornby Bay and Amundsen basins provide new chronological markers for Mesoproterozoic stratigraphic successions of northern Canada

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ABSTRACT

Here we present Re-Os geochronological data from two carbonaceous shale units from the Hornby Bay and Amundsen basins that provide important chronological markers for Mesoproterozoic stratigraphic successions within northern Canada. Shale from the basal Escape Rapids Formation yields a robust depositional age of 1067.3 ± 13.5 Ma for the lowermost Shaler Supergroup of Amundsen basin with a remarkably unradiogenic initial $^{187}Os/^{188}Os$ value (0.15), implying that it derived from weathering of juvenile source material, such as basalt. Sedimentological features, indicative of large basin conditions, suggest deposition within an extensive epeiric sea that was intermittently mixed with waters from an exterior ocean. This age, and the 720 Ma age of the uppermost Shaler Supergroup, constrain deposition of the ∼4 km-thick succession to a period of approximately 350 myr, recording sedimentation through a complete supercontinent cycle - amalgamation through to break-up of Rodinia. Further, it indicates that the Amundsen basin formed at the same time as the Borden, and Fury and Hecla basins on northern Baffin Island, and the Thule basin in northwestern Greenland, and that these basins were perhaps connected as part of a much larger basin situated in the interior of Rodinia. Diagenetic pyrite from sandstone dykelets in carbonaceous shales of the Fort Confidence Formation yielded a Re-Os model age of 1438 ± 8 Ma, providing a minimum age for deposition of the lower Dismal Lakes Group of the Hornby Bay basin. This age strengthens proposed regional correlation of the Hornby Bay basin with the large intracontinental Athabasca and Thelon basins, located on the Rae craton to the southeast, and is evidence for a Laurentia-wide marine flooding episode ca. 1500 Ma. Both new ages place important constraints on newly discovered eukaryotic microfossils from the Shaler Supergroup and Dismal Lakes Group and calibration points for critical chemostratigraphic data.

1. Introduction

Mesoproterozoic sedimentary and mafic volcanic rocks of the Hornby Bay and Amundsen basins are well exposed in an overall gently northward-dipping section exposed along the Coppermine River, which drains Canada's central-northern mainland, emptying into the Arctic Ocean near the hamlet of Kugluktuk (Figs. 1, 2). The sedimentary fill of the Hornby Bay basin comprises, in ascending order, the Hornby Bay, Dismal Lakes and Coppermine River groups (Fig. 3). The maximum depositional age of the uppermost Hornby Bay Group is approximately 1590 Ma based on the U-Pb age of crosscutting mafic intrusions (Hamilton and Buchan, 2010). The maximum age of the unconformably overlying Dismal Lakes Group is unconstrained, but it is conformably overlain by a ca. 2.5 km-thick succession of basalt flows and succeeding red fluvial sandstone comprising the ca. 1270 Ma Coppermine River Group (Baragar and Donaldson, 1973; Skulski et al., 2018; Fig. 3). The basalts are part of the Mackenzie Large Igneous province, which, in this region, also includes an extensive radiating diabase dyke swarm and layered ultramafic plutonic rocks and granophyre of the 1269 ± 1 Ma Muskox intrusion (Mackie et al., 2009 and references therein). The depositional fill of the unconformably overlying Amundsen basin comprises strata of the lower Shaler Supergroup (Rae Group), which yielded a maximum depositional age of 1150 Ma, based on detrital zircon geochronology (Rainbird et al., 2017). This ca. 4 km-thick succession of mainly carbonate, siliciclastic and subordinate evaporitic sedimentary strata lacks felsic volcanic interlayers suit-

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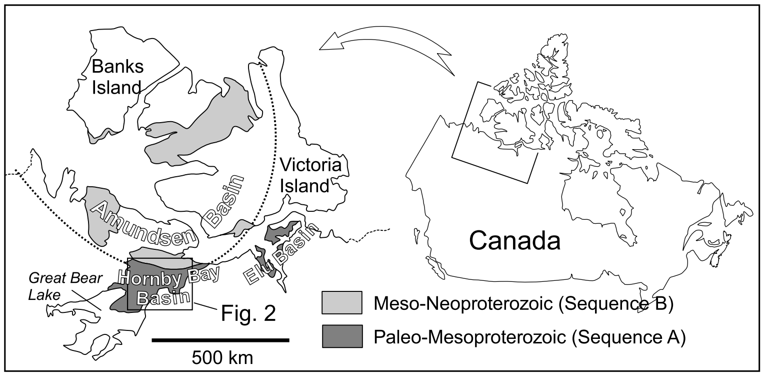

Fig. 1. Location of Amundsen, Hornby Bay and Elu basins in northwestern Canada. Sequences A and B are the lower two (of three) stratigraphic subdivisions of Proterozoic sedimentary basins in northwestern Canada established by Young et al. (1979).

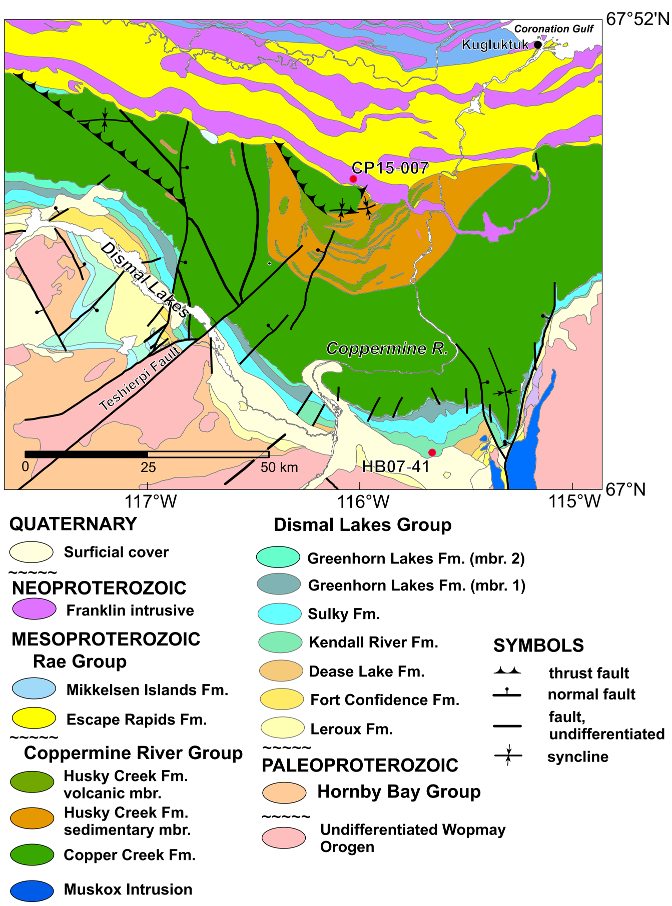

Fig. 2. Geology of the Coppermine area (boxed area in Fig. 1). In general, strata dip gently (less than 10 degrees) northward. Rocks of the Coppermine River Group were folded into a broad open syncline and locally thrust repeated (Skulski et al., 2018), toward the Coronation Gulf. (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

able for direct dating via U-Pb (zircon) geochronology, so other methods of direct dating are required. One such method is Re-Os isotope geochronology of carbonaceous mudstone horizons, which can yield relatively precise depositional ages for Mesoproterozoic shales (Cumming et al., 2013; Kendall et al., 2009; Rooney et al., 2010; Sperling et al., 2014). This method has been successfully applied to date ca. 900-750 Ma shale horizons in the upper Shaler Supergroup (van Acken et al., 2013) but, until now, it has not been attempted with older strata exposed in the Coppermine region. Two prospective organic-rich, mudstone-bearing units targeted in this study are the Fort Confidence Formation, at the base of the Dismal Lake Group, and the Escape Rapids Formation, at the base of the Rae Group (Fig. 3). Samples of thinly parallel-laminated, carbonaceous mudstone interbedded with flaser, wavy and lenticular-bedded sandstone were recovered and analyzed from mineral exploration drill cores. Our reported ages for these horizons provide important pins for regional stratigraphic correlations and global paleogeographic reconstructions as well as direct age constraints for newly discovered microfossil eukaryotes (Loron et al., 2019a, 2019b).

2. Depositional and tectonic setting of the Hornby Bay and Amundsen basins

The Hornby Bay basin comprises late Paleo- to Mesoproterozoic sedimentary and volcanic rocks (Baragar and Donaldson, 1973) that unconformably overlie metavolcanic, metasedimentary and granitoid rocks of the ca. 1.88-1.84 Great Bear magmatic zone (Wopmay Orogen, Hoffman et al., 2011; Fig. 2). The Hornby Bay basin includes continental sedimentary and volcanic strata of the ca. <1.75-1.59 Ga Hornby Bay Group (Kerans et al., 1981), which is unconformably overlain by mainly shallow marine sedimentary rocks of the <1.59-1.27 Ga Dismal Lakes Group (Hahn et al., 2013; Kerans et al., 1981; Fig. 3). The basin is divided by the Leith Line (Kerans et al., 1981), a north-south structural hinge (centered over western Dismal Lakes) across which sedimentary units of the upper Hornby Bay Group and Dismal Lakes Group thicken westward. The Hornby Bay basin is capped by a gently north-dipping, ~4 km-thick succession comprising continental basalts (Copper Creek Formation) associated with the 1.27 Ga Mackenzie Igneous event (LeCheminant and Heaman, 1989), followed by sharply overlying terrestrial clastic sedimentary rocks and mafic volcanic flows of the Husky Creek Formation (Meek et al., 2019).

The unconformably overlying Rae Group (basal Shaler Supergroup) is exposed along Canada's northern coastal mainland in a grouping of structural inliers whose cuspate distribution define a northwest-opening embayment known as the Amundsen basin (Fig. 1; Christie et al., 1972; Rainbird et al., 1996). Strata composing the Amundsen basin and correlative deposits in the Mackenzie basin (Mackenzie Mountains Supergroup), which is exposed to the west, mainly in the northern Cordillera, represent the main components of a regional, first-order, stratigraphic sequence (Sequence B as defined by Young et al., 1979). These basins are interpreted to have been connected embayments on one side of a much larger cratonic sedimentary basin that lay in the interior of the early Neoproterozoic supercontinent, Rodinia (Rainbird et al., 1996, 2017). These basins were intruded by diabase sills and dykes of the ca. 780 Ma Gunbarrel (Harlan et al., 2003) and ca. 720 Ma Franklin

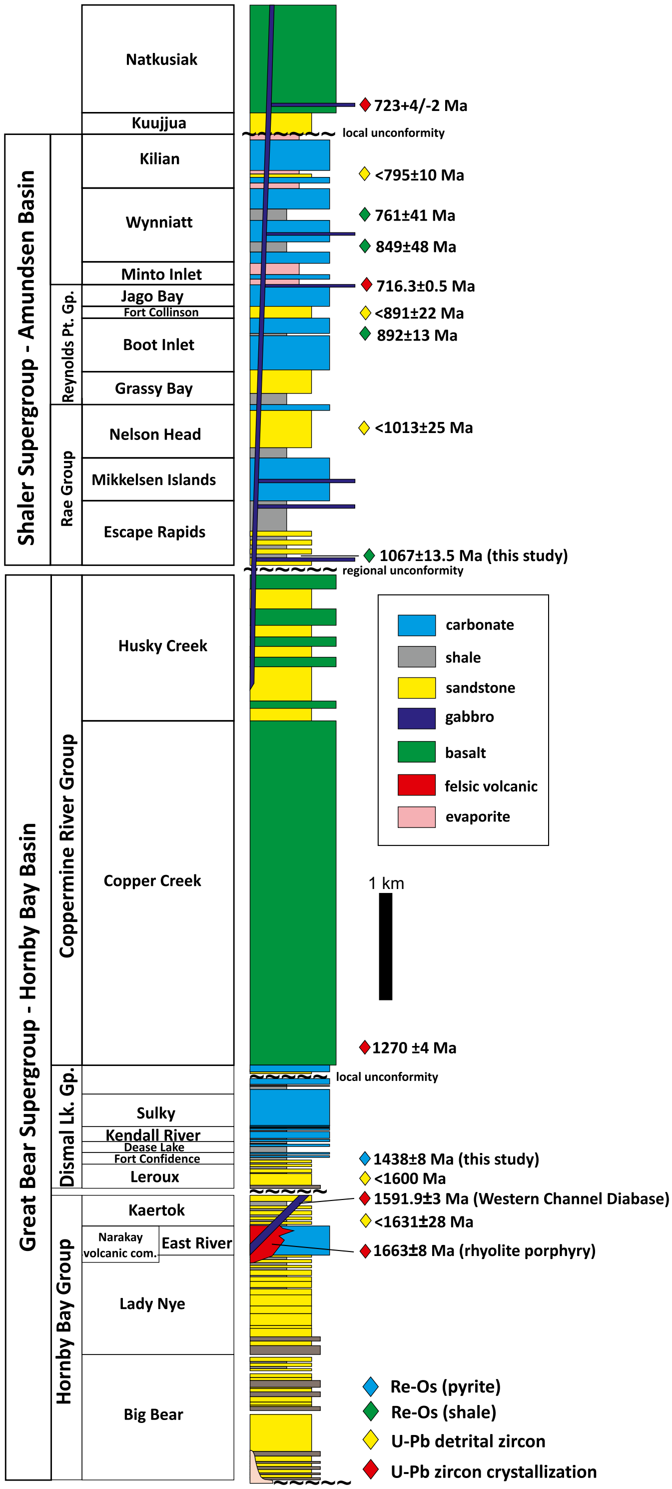

Fig. 3. Generalized stratigraphic column for the Hornby Bay basin (Hornby Bay, Dismal Lakes and Coppermine River groups) and the Amundsen basin (Shaler Supergroup). Strata above the level of the Mikkelsen Islands Formation are exposed only in Brock Inlier (up to and including the Minto Inlet Formation) and Minto Inlier (up to and including the Natkusiak Formation). For location of Brock and Minto inliers, see Fig. 1.

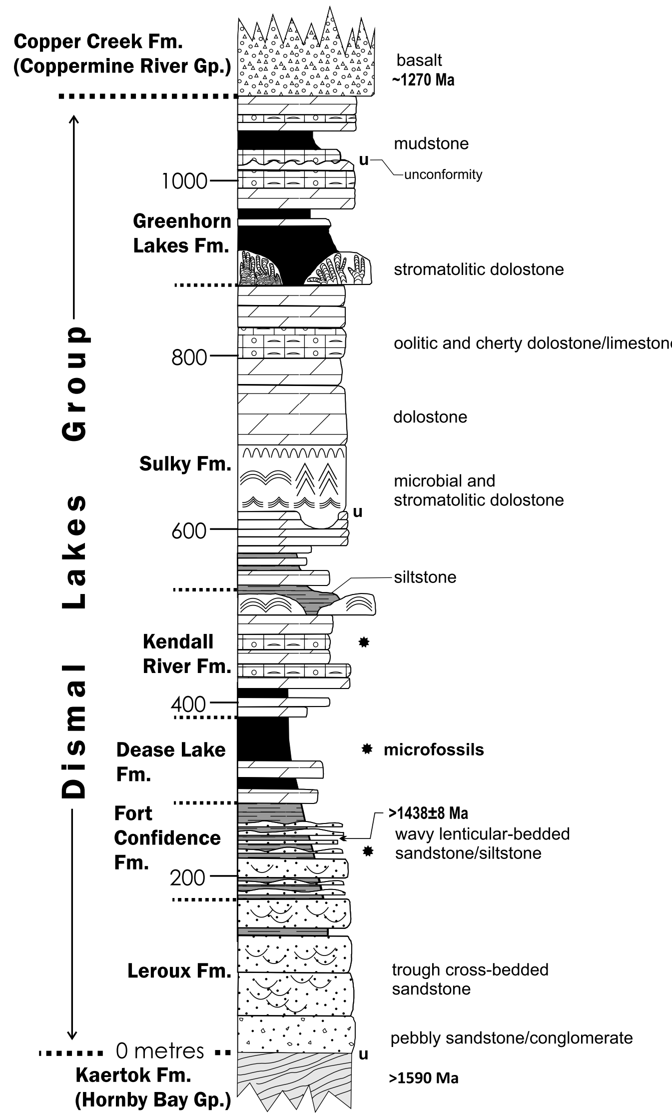

Fig. 4. Generalized stratigraphic section of the Dismal Lakes Group (modified from Kerans et al., 1981 and Frank et al., 2003).

Large Igneous provinces (Heaman et al., 1992). Cambrian and Ordovician clastic and carbonate sedimentary rocks unconformably overlie the Coppermine River and Rae groups along the western margin of the Coppermine area and in the Brock Inlier to the west.

3. Sedimentology and stratigraphy of the Fort Confidence and Escape Rapids Formations

3.1. Fort Confidence Formation

The Dismal Lakes Group consists of fluvial to shallow-marine siliciclastic rocks (LeRoux and overlying Fort Confidence formations), which pass upward into shallow and deeper water carbonate rocks (in ascending depositional order: Dease Lake, Kendall River, Sulky and Greenhorn Lakes formations; Ross and Kerans, 1989; Fig. 4). The LeRoux Formation conformably overlies the Kaertok Formation, west of the Teshierpi Fault; elsewhere it rests unconformably on granite of the Great Bear magmatic zone and older units of the Hornby Bay Group (Fig. 2; Kerans et al., 1981). It ranges in thickness from 10 to >150 m and is composed of a lower unit of white, crossbedded, quartz arenite and quartz-pebble conglomerate deposited by westerly flowing rivers and an upper unit of crossbedded and ripple-bedded quartz arenite deposited in a tidally influenced shallow marine setting (also see Hahn et al., 2013). The Fort Confidence Formation gradationally overlies the LeRoux Formation and is up to 200 m thick. It is composed of scour-based, wavy-lenticular to flaser-bedded white sandstone interbedded with dark, carbonaceous, parallel-laminated mudstone

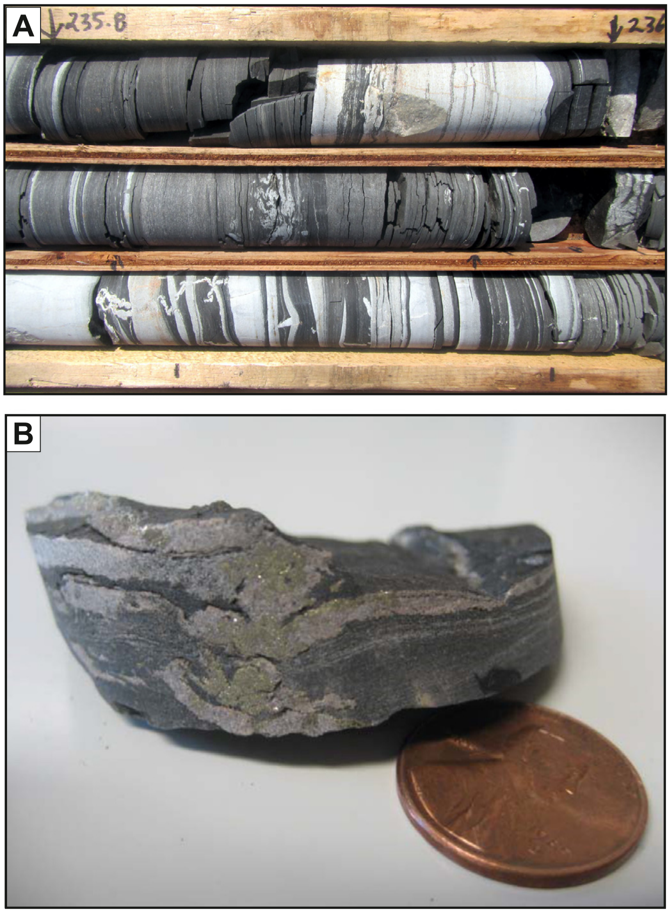

Fig. 5. (a) Image of core from diamond drill hole HB07-41 showing strata of the Fort Confidence Formation similar to those that were sampled for Re-Os geochronology. Width of core is approximately 5 cm. (b) Image of core sampled for Re-Os geochronology showing coarse pyrite in folded sandy lens within carbonaceous shale from the Fort Confidence Formation. American 1 cent coin, for scale. Drill hole location: 67°04′20.0″N, 115°43′27.9″W (NAD83, Zone 11).

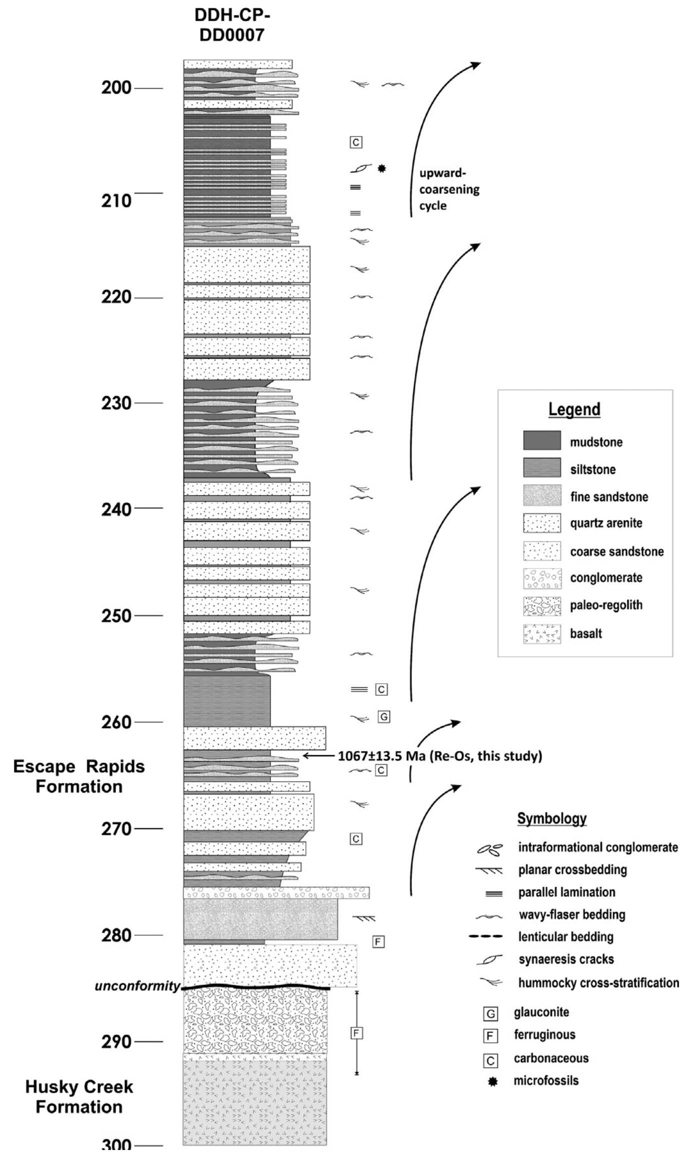

Fig. 6. Detailed stratigraphic section for the basal Hihotok member of the Escape Rapids Formation derived from detailed sedimentological and stratigraphic logging of diamond drill hole CP15-007 and showing stratigraphic location of carbonaceous shale sampled for Re-Os geochronology. Drill hole location: 67°36′52.4″N; 116°02′51.6″W (NAD83, Zone 11).

and siltstone (Figs. 4 and 5a). The carbonaceous layers were targeted for Re-Os sulphide geochronology. Thicker sandstone layers exhibit hummocky upper profiles and cross-bedding and are graded, suggesting storm-influenced deposition. Many of the mudstone interlayers contain folded sandstone dykelets that represent infilled desiccation cracks indicating intermittent subaerial exposure, perhaps on a tidal flat. Some of the sandstone dykelets contain relatively coarse, disseminated authigenic pyrite (Fig. 5b) and were sampled for Re-Os geochronology (see below). The Fort Confidence Formation grades upward into strata of the Dease Lake Formation (Fig. 4), which includes variegated (red and green) mudstone and siltstone with interbedded quartz arenite and sandy to oölitic dolostone, considered to have been deposited in tidal flats, coastal sabkhas and lagoons (Kerans et al., 1981). Regional facies transitions and thickness variations suggest a gradual marine transgression from west to east, increase in carbonate deposition, including thick stromatolitic units indicating deeper water conditions, and eventual shut-off of siliciclastic input from the east. The remainder of the overlying Dismal Lakes Group (Kendall River, Sulky and Greenhorn Lakes formations) is characterized by marine carbonate platform deposition (see Kerans et al., 1981, for details; Fig. 4).

3.2. *Escape Rapids Formation*

The Escape Rapids Formation, basal unit of the Rae Group (Fig. 3), is exposed throughout the Amundsen basin but the Coppermine River valley is the only region where the lower (Hihotok) member of the formation and its contact with underlying strata is exposed (Skulski et al., 2018). The contact is best exposed along the banks of the Coppermine River, where it forms a low-angle (<10°) unconformity with the underlying Husky Creek Formation (Meek et al., 2019; Skulski et al., 2018). Here, the contact is marked by a thin pebble lag that separates parallel-laminated red siltstones (Husky Creek Fm.) from cross-laminated to small-scale, cross-bedded, pinkish-green sandstones of the overlying Escape Rapids Formation. The sandstone passes upward into parallel-laminated, grey siltstones with organic-rich mudstone interlayers that were sampled for micropaleontological study (Loron et al., 2019b). These strata, in turn, pass upward into several meters of fine-grained, rusty weathering, green sandstone with well-developed, large-scale hummocky and swaley crossbedding, indicating storm influence. A stratigraphic section was not measured at this locality but a correlative section was observed and logged from mineral exploration drill core collared about 20 km west of the outcrop locality described above (see below and Fig. 6). In the

Table 1
Elemental abundances for Re and Os and isotopic compositions for pyrite from the Fort Confidence Formation.

Sample	Re (ppb)	±2σ	Os (ppt)	±2σ	^{192}Os (ppt)	±2σ	^{187}Re/^{188}Os	±2σ	^{187}Os/^{188}Os	±2SE	rho*	Model Age (Ma)	±2σ
HB-7-41-183.0-A	6.512	0.027	105.03	36.99	1.95	0.51	6643	1729	163	42	0.998	1450	22
Sample	Re (ppb)	±2σ	^{187}Re (ppb)	±2σ	^{187}Os** (ppt)	±2σ	Total common Os (pg)	Model Age (Ma)	±2σ				
HB-7-41-183.0-B	7.456	0.027	4.687	0.017	113.4	0.2	1.7	1438	8				

Sample A uses conventional ^{185}Re-^{190}Os spike
Sample B uses mixed-double spike ^{185}Re + ^{188}Os + ^{190}Os.
ppb = parts per billion.
ppt = parts per trillion
SE = standard error
*rho = error correlation function.
**Includes ^{187}Re decay constant uncertainty.

drill core, basal sandstone of the Escape Rapids Formation rests on a basaltic lava flow (top of Husky Ck. Formation) with a well-developed oxidized regolith overlying hematite-altered and calcite-veined basalt. The basal unit is a ~15 m thick, thick-bedded, white to light pink, poorly sorted, coarse to very coarse-grained sandstone with faint crossbedding, siltstone rip-up clast horizons and several ~10 cm-thick interlayers of variegated red/green, parallel-laminated siltstone. This is capped by a 1 m-thick conglomerate composed of angular to sub-rounded clasts of green and red siltstone. It is difficult to interpret from the two-dimensional perspective of a drill core, but the conglomerate could represent a transgressive lag because it overlies coarse, cross-bedded sandstones, possibly deposited in a fluvial setting, and underlies a series of ca. 10- to 20-m-thick, upward-coarsening cycles that are reminiscent of a prograding delta or sandy shoreface (Fig. 6). Most of the cycles commence with parallel-laminated green to black carbonaceous siltstone and mudstone (pro-delta), which grades upward into flaser and wavy-lenticular bedded sandstone interbedded with parallel-laminated black siltstone (delta slope) and then white to grey, fine- to medium-grained quartz arenite with possible hummocky cross-bedding (delta top/storm- and tide-influenced shoreface). Some of the carbonaceous layers in the lower cycle were sampled for Re-Os geochronology (see description below). A continuation of the Hihotok member is exposed in an outcrop section, ~100 m thick, intruded by a 30-40 m thick, Franklin gabbro sill on the west side of the Coppermine River, below Escape Rapids (see Skulski et al., 2018, for details).

4. Geochronology

4.1. Fort Confidence Formation: Re-Os pyrite geochronology

4.1.1. Sampling and analytical procedures

Samples of carbonaceous shale were obtained in 2017 from uranium exploration core (diamond drill hole HB07-41) drilled in 2007 by Unor Inc. (now Hornby Bay Mineral Exploration Ltd.) but all samples tested yielded less than 0.5 ng/g Re, meaning that the amount of Re and radiogenic ^{187}Os is insufficient for reliable analysis. However, sandy lenses and folded desiccation-crack infills from the drill core contain coarse, disseminated pyrite, which we interpret to have formed during diagenesis (Fig. 5b). A sample of pyrite recovered from core taken at 183.0 m was tested for Re content and found to contain 4 ng/g Re. On this basis, a sample containing 0.3 g of pyrite was separated by metal-free crushing and hand picking, for a full Re-Os isotope analysis at the University of Alberta. The sample was weighed and transferred to a thick-walled, borosilicate glass Carius tube. A mixed ^{185}Re + ^{190}Os spike was added to the sample and it was dissolved at 240 °C for 48 hours, followed by chemical separation and purification of Os and Re and mass spectrometric methods described in detail by Morelli et al. (2005). The total procedural blanks were measured to be less than 3 picograms Re and 0.5 picogram Os (<0.01 picograms ^{187}Os). The decay constant used for ^{187}Re is that of Smoliar et al. (1996) of λ^{187}Re constant of 1.666×10^{-11} yr^{-1}.

4.1.2. Results

The single full Re-Os analytical result is presented in Table 1. The sample of pyrite shows a high ^{187}Re/^{188}Os ratio, and a highly radiogenic ^{187}Os/^{188}Os value of 163. With a single Re-Os analytical datum, information regarding the age of the sample can be made only by assuming a value for the initial ratio of ^{187}Os/^{188}Os present in the sample when it formed, and calculating a single-analysis model age. For samples with multiple Re-Os analyses, the initial ^{187}Os/^{188}Os ratio is defined by linear regression of the data by the isochron method. For sample HB07-41, 183.0 m, the following model age can be calculated with the single Re-Os analytical datum. Assuming an intermediate crust-mantle value of initial ^{187}Os/^{188}Os value of 0.50, the datum yields a model age of 1450 ± 22 Ma (2σ).

The nature of Os in this pyrite is such that 99.7% of all ^{187}Os present in the sample is the radiogenic ^{187}Os, derived from decay of ^{187}Re since formation of the pyrite. For samples such as this, a more suitable analytical method involves the use of a mixed double-Os spike (^{188}Os + ^{190}Os + ^{185}Re; Markey et al., 2007), which provides a more precise determination of radiogenic Os abundance for calculating a model age. Using this spike, a second aliquot of pyrite was separated and analyzed (HB07-41,183.0 m-B, Table 1). For this analysis, the Re-Os model age is again calculated assuming an initial Os ratio of 0.5 for the small amount of common Os present, and yields a value of 1438 ± 8 Ma (2σ). This is interpreted to be the most reliable determination of the age of formation of pyrite in this sample. The model ages derived from both Re-Os analyses agree within analytical uncertainty and provide a good check on both analytical protocols and geological effects. The Re-Os geochronometer in pyrite is considered to be robust at post-depositional conditions well above greenschist grade of metamorphism and provides a reliable timing estimate for sulfide mineral formation (Morelli and Creaser, 2006). The age uncertainty for the Fort Confidence Formation pyrite includes the 0.35% uncertainty in the ^{187}Re decay constant (Smoliar et al., 1996).

4.2. Escape Rapids Formation: Re-Os sedimentary rock geochronology

4.2.1. Sampling and analytical procedures

Samples from the Hihotok member, near the base of the Escape Rapids Formation were collected in 2017 from core drilled by the mineral exploration company, Kaizen Discovery in 2015. A series of samples were taken from a ~1 m-long section located at 261 m of diamond drill hole CP15-007 (for log, see Fig. 6) and

Fig. 7. Images of core from diamond drill hole CP15-007 showing strata of the Escape Rapids Formation that were sampled for Re-Os geochronology. Actual sampled horizon is outlined by the dotted line shown in enlarged image at bottom. Width of core is approximately 5 cm.

are composed of black, thinly parallel-laminated mudstone/siltstone interlaminated with <1 cm cross-laminated white sandstone starved ripples (Fig. 7). The samples were analyzed for sedimentary rock geochronology at the Yale University Metal Geochemistry and Geochronology Center following methods from Selby and Creaser (2003) with modifications from Cumming et al. (2013). All samples were greater than 20 g, and thinner than 3 cm vertically, to minimize variations in initial $^{187}Os/^{188}Os$ values. Although sampled vertically, all initial $^{187}Os/^{188}Os$ values for the Escape Rapids Formation display very little internal variation (Table 2). Between 0.75 and 1.1 g of sample was digested and equilibrated in 10 ml of $Cr^{VI}O_3$-H_2SO_4 together with a mixed tracer (spike) solution of ^{190}Os and ^{185}Re in Carius tubes at 220 °C for 48 hours. The $Cr^{VI}O_3$-H_2SO_4 digestion method was employed as it has been shown to preferentially liberate hydrogenous Re and Os yielding more accurate and precise age determinations for sedimentary rocks (e.g., Kendall et al., 2009). Total procedural blanks during this study were 38.3 ± 2.1 pg and 0.10 ± 0.07 pg for Re and Os respectively, with an average $^{187}Os/^{188}Os$ value of 0.25 ± 0.05 (1σ, $n = 4$). The major source (>90%) of Re blank is the $Cr^{VI}O_3$ used to make up the $Cr^{VI}O_3$-H_2SO_4 solution.

4.2.2. Results

The Escape Rapids Formation samples display moderate enrichments of Re and Os in comparison with average continental crust with values ranging from 0.7 to 1.2 ng/g and 54 to 74 pg/g, respectively (Table 2). Uncertainties for $^{187}Re/^{188}Os$ and $^{187}Os/^{188}Os$ were determined by error propagation of uncertainties in Re and Os mass spectrometry measurements, blank abundances and isotopic compositions, and reproducibility of standard Re and Os isotopic values. Regression of the Escape Rapids Formation Re-Os isotopic composition data and 2σ calculated uncertainties using *Isoplot V. 4.15* with the $\lambda^{187}Re$ constant of 1.666×10^{-11} a^{-1} (Ludwig, 1980, 2011; Smoliar et al., 1996) yields a Model 1 isochron age of 1067.3 ± 13.5 Ma, 2σ, $n = 5$, with an MSWD (Mean Square of Weighted Deviates) of 0.75 and an initial $^{187}Os/^{188}Os$ value of 0.15 ± 0.02 (Fig. 8a). The age uncertainty for the Escape Rapids Formation includes the 0.35% uncertainty in the ^{187}Re decay constant (Smoliar et al., 1996).

5. Discussion

5.1. Age and regional correlation of the Dismal Lakes Group

The 1438 ± 8 Ma age for diagenetic pyrite within the Fort Confidence Formation is from a horizon that is ~250 m stratigraphically above its unconformable contact with the Hornby Bay Group (Fig. 4), which has a maximum age of 1590 Ma, based on crosscutting mafic intrusions (Hamilton and Buchan, 2010; Fig. 3). The ca. 1440 Ma age is considered as a minimum age because it derives from diagenetic pyrite, so the depositional age of the basal Dismal Lakes Group (Leroux and Fort Confidence formations) is between 1590 and 1440 Ma. It might be relevant to consider that this age is within error of the age of uranium mineralization and related hydrothermal activity (1453 ± 18 Ma) reported from the Port Radium deposit, located on eastern Great Bear Lake, about 100 km southwest of our sampling locality (Gandhi et al., 2018). Given that the Hornby Bay Group was deformed, uplifted and eroded during the Forward orogeny (Cook and MacLean, 1995), all before deposition of the Leroux Formation, the depositional age of the Fort Confidence Formation is conceivably closer to its minimum age. However, potentially correlative carbonaceous shales of the Douglas Formation of the Athabasca basin in northern Saskatchewan have an inferred depositional age of 1541 ± 13 Ma, also based on Re-Os geochronology (Creaser and Stasiuk, 2007). Both the Douglas and Fort Confidence formations are interpreted to be representative of a continent-scale marine flooding episode that culminated with deposition of extensive platformal carbonate deposits in the Elu, Hornby Bay, Athabasca and Thelon basins (Subsequence A3 of Hahn et al. (2013). The diagenetic age for the Fort Confidence Formation is thus potentially 100 myr younger than its depositional age. The Dismal Lakes Group is conformably overlain by ca. 1270 Ma basalts of the Coppermine River Group, so at least 170 myr are required for deposition of the Dease Lake, Kendall River, Sulky and Greenhorn Lakes formations, the main carbonate units of the Dismal Lakes Group (Fig. 4). Some of this time undoubtedly can be accounted for in lacunae represented by two local unconformities within the ~1 km-thick stratigraphic section.

Table 2
Elemental abundances for Re and Os and isotopic compositions for the Escape Rapids Formation.

Sample	Re (ppb)	$\pm 2\sigma$	Os (ppt)	$\pm 2\sigma$	^{192}Os (ppt)	$\pm 2\sigma$	$^{187}Re/^{188}Os$	$\pm 2\sigma$	$^{187}Os/^{188}Os$	$\pm 2\sigma$	rho[a]	Osi[b]
259.92	0.73	0.006	73.0	0.3	26.6	0.1	54.794	0.499	1.1307	0.008	0.304	0.147
259.98	0.62	0.005	59.6	0.3	21.6	0.1	56.798	0.524	1.1731	0.009	0.393	0.153
260.77	1.24	0.004	73.7	0.4	24.6	0.1	100.175	0.604	1.9494	0.014	0.604	0.151
260.96	0.69	0.003	54.4	0.3	19.2	0.1	71.665	0.455	1.4355	0.010	0.558	0.149
260.19	0.69	0.003	61.9	0.3	22.2	0.1	62.181	0.382	1.2694	0.008	0.538	0.153

[a] rho = error correlation function.
[b] Initial $^{187}Os/^{188}Os$ 1068 Ma.

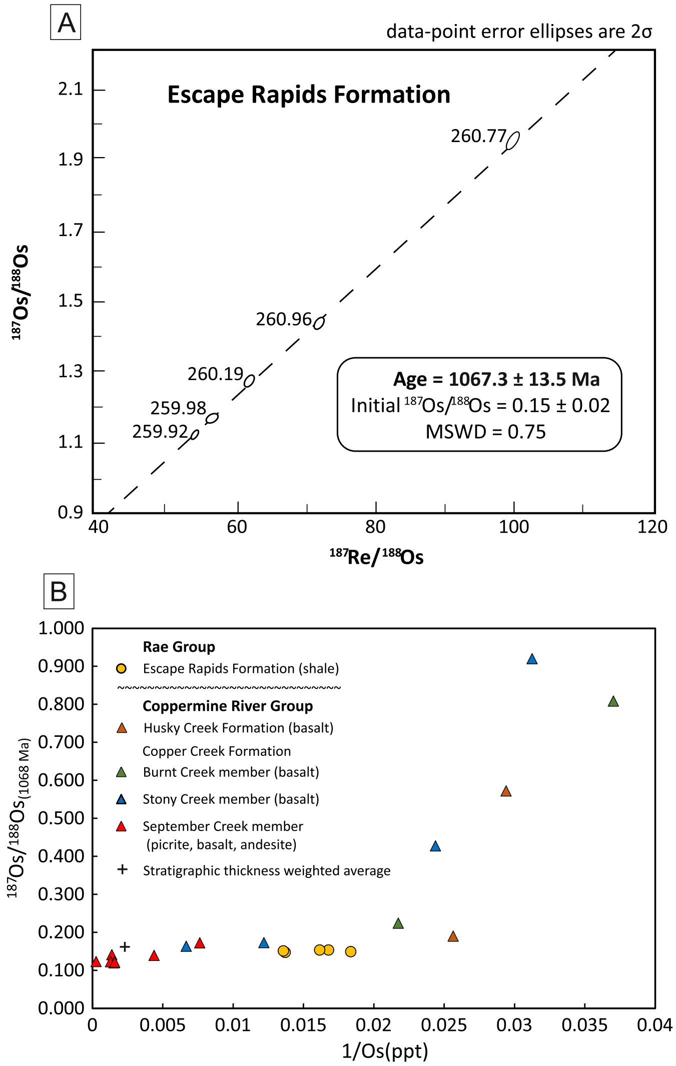

Fig. 8. (a) $^{187}Os/^{188}Os$ vs. $^{187}Re/^{188}Os$ isochron diagram for the Escape Rapids Fm. Re-Os geochron samples (numbered with drill core metreage) display a moderate enrichment in Re and Os with values ranging from 0.7 to 1.2 ng/g and 54 to 74 pg/g, respectively. Regression of the Re and Os isotopic composition data yields a Model 1 age of 1067.3 ± 13.5 Ma, 2σ, $n = 5$, with a mean square of weighted deviates of 0.75 and an initial $^{187}Os/^{188}Os$ value of 0.15 ± 0.02, the age uncertainty includes the uncertainty in the ^{187}Re decay constant. (b) Reciprocal Os abundance versus $^{187}Os/^{188}Os$ at 1067 Ma. Escape Rapids Formation shales (this study) are shown along with Coppermine River Group basalts (Day et al., 2013) that are subdivided using stratigraphic nomenclature of Skulski et al. (2018). Calculation method of the volcanic stratigraphic thickness weighted average $^{187}Os/^{188}Os$ at 1067 Ma and osmium metal values are provided in supplemental data table and text.

5.2. Regional stratigraphic correlation of the Rae Group and estimate for the duration of deposition of a first-order megasequence (Sequence B)

The ca. 1070 Ma age for the Escape Rapids Formation is nearly 100 million years younger than the previous age constraint, a maximum depositional age of 1150 Ma based on detrital zircon geochronology (Rainbird et al., 2017). The Re-Os age derives from a horizon that is only 20 m above the basal contact with the Coppermine River Group (Fig. 6) and thus it provides an important lower depositional age for the Shaler Supergroup and initiation of the Amundsen basin. The top of the Shaler Supergroup, represented by basalts of the Natkusiak Formation (Fig. 3), is part of the 720 Ma Franklin Large Igneous Province, so the duration of deposition of this ~4 km-thick succession was approximately 350 myr. The Shaler Supergroup therefore fits the predicted duration of a first-order megasequence set (*sensu* Krapež, 1996), and is thus interpreted as the stratigraphic record of a complete supercontinent cycle (assembly and break-up of supercontinent Rodinia; e.g. Nance et al., 2014). Sedimentary strata include thick, stromatolitic and arenaceous carbonate rocks suggesting shallow but open marine conditions that alternate with both supratidal and basinal evaporite rocks deposited in times of basin restriction as well as terrestrial sandstones deposited by large rivers entering the basin from the southeast (Rainbird et al., 2017). The Shaler Supergroup and stratigraphically correlative strata are preserved in structural inliers across northern Canada and are interpreted to have been deposited in a broad, relatively shallow, epeiric sea that lay within the interior of Rodinia (Amundsen basin; Fig. 9). This extensive basin had many embayments and arms, some likely connected via seaways to an exterior ocean. Remnants of it are preserved on other continents, such as Australia (e.g. Centralian Superbasin of Walter et al., 1995), Siberia (Yudoma-Uchur-Maya region; Khudoley et al., 2001) and west Africa (Taoudeni basin; Bertrand-Sarfati and Moussine-Pouchkine, 1988), which rifted away from Laurentia with the break-up of Rodinia. Components of this basin in northern Canada include the Mackenzie basin in the northern Canadian Cordillera (Turner and Long, 2012) and the Bylot basins, exposed on northern Baffin Island, northwest Greenland and Ellesmere Island (Gibson et al., 2019; Long and Turner, 2012; Fig. 9). Recent Re-Os dating of carbonaceous shales of the Arctic Bay and Victor Bay formations in the Bylot Supergroup of Borden basin (Gibson et al., 2018), are within error, the same age as the Escape Rapids Formation. Therefore, the Amundsen and Borden basins were contemporaneous, at least during the early stages of their development, and possibly even connected during periods of greater marine influence (deposition of platformal carbonates during periods of global sea-level highstand and connection to an exterior ocean). They might also have been connected with the Fury and Hecla basin to the south and the Thule basin to the north (e.g. Long and Turner, 2012; Fig. 9), which contain shales at approximately the same stratigraphic levels.

5.3. Os isotope composition of seawater ca. 1070 Ma: local or global signal?

The Os isotope composition of seawater at the time of sedimentation is interpreted to reflect an input balance between radiogenic sources ($^{187}Os/^{188}Os$ ~1.4; weathering of upper continental crust via riverine input) and unradiogenic sources ($^{187}Os/^{188}Os$ ~0.13; cosmic dust; hydrothermal vents and weathering of mafic or ultramafic rocks) with a modern day Os isotope composition of ~1.06 (Peucker-Ehrenbrink and Ravizza, 2012). The initial $^{187}Os/^{188}Os$ value from a sedimentary rock isochron therefore represents the seawater Os isotope composition at the time of deposition (ca. 1070 Ma, for the basal Escape Rapids Formation). The geochronological analysis of the Escape Rapids Formation yielded a remarkably unradiogenic initial $^{187}Os/^{188}Os$ value of 0.15. This value is close to the mantle value of ~0.13, (Meisel et al., 2001), suggesting that the predominant source of Os flux into the Amundsen basin at this time was weathering of juvenile material such as basalts, which are abundant in the directly underlying Coppermine River Group (Skulski et al., 2018; Figs. 2, 3). By comparison, isochron regressions from shales higher in the Shaler Supergroup (Boot Inlet and Wynniatt formations; Fig. 3) produced initial $^{187}Os/^{188}Os$ values ranging from 0.63-0.68 (van Acken et al., 2013).

On a mixing diagram of reciprocal [Os] versus $^{187}Os/^{188}Os$ values at 1067 Ma (Fig. 8b), the Escape Rapids Formation shale samples have $^{187}Os/^{188}Os$ values similar to lower Coppermine River Group basalts (Day et al., 2013), and Os metal abundances that lie within the range of the basalts. Lower Coppermine River basalts have an order of magnitude higher Os metal abundances relative to the overlying volcanic succession, and thus from a mass balance

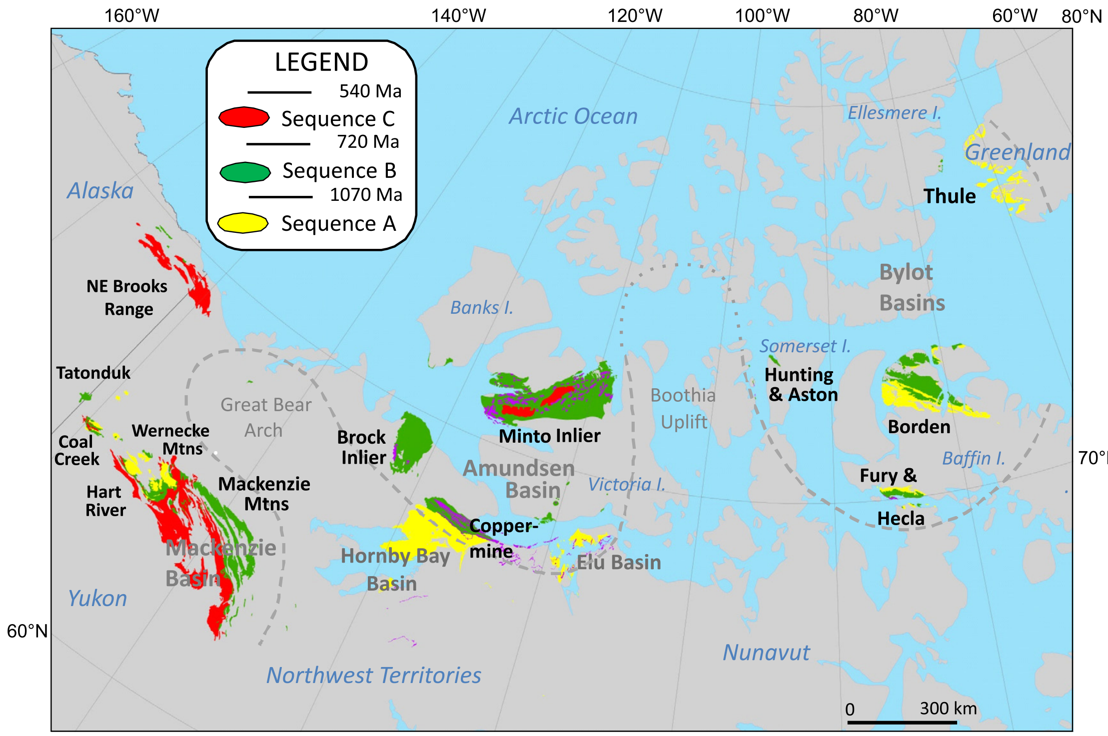

Fig. 9. Regional distribution of Meso-Neoproterozoic sedimentary rocks and basins in northern Canada and northwestern Greenland. A, B, C, sequence subdivision from Young et al. (1979). Dashed grey line represents depositional zero-edge of hypothesized epeiric sea basin.

perspective, it is not surprising that these older strata, exposed during pre-Rae Group folding and thrusting (Skulski et al., 2018), may have dominated the isotopic composition of derived clastic sediments. This is shown by calculating the stratigraphic thickness weighted average $^{187}Os/^{188}Os$ at 1067 Ma and osmium metal abundance of the Coppermine River Group (Fig. 8b), which lies within the field of lower Coppermine River Group basalts (September Creek member). Baragar et al. (1996) and Day et al. (2013) showed that Mackenzie dykes are comagmatic and locally feeders to basalt flows of the Coppermine River Group. The high concentration of Mackenzie dykes in the Slave Craton, located between volcanic inliers in the Coppermine River and Bathurst Inlet (Elu basin; Fig. 1) areas, gives a qualitative indication of the large volume of basalt that may have been eroded on the Amundsen basin margin. Riverine transport of oxidized Os derived from weathered basalt, and subsequent reduction of metal cations at the organic-rich seawater-sediment interface could account for the Os isotopic composition of Escape Rapids Formation shale.

In the modern ocean, sulfate concentrations are high enough ($\sim$28 mM) to ensure that unradiogenic Os from hydrothermal vents is largely precipitated out as sulphides prior to meeting seawater. This effect may be responsible for the radiogenic $^{187}Os/^{188}Os$ value of 1.06 recorded in the oceans today (Peucker-Ehrenbrink and Ravizza, 2012). However, existing Re-Os data from other Stenian (1200-1000 Ma) basins coupled with our data from the Escape Rapids Formation display remarkably unradiogenic seawater $^{187}Os/^{188}Os$ values (e.g., Rooney et al., 2010), supporting geochemical proxy records (Gilleaudeau and Kah, 2015) that advocate for lower seawater sulfate concentrations during this time. These low-sulfate waters would permit more of the hydrothermally sourced unradiogenic Os to reach the seafloor and mix into the water column, driving seawater $^{187}Os/^{188}Os$ compositions towards unradiogenic values for much of the Stenian.

The sedimentology of the Escape Rapids Formation supports deposition in a very large basin with marine influence. For example, wavy-lenticular and flaser bedding indicates the action of tides, which can only be generated in ocean basins and large-scale hummocky and swaley crossbedding indicate big storms (e.g. hurricanes) along the shorelines of waterbodies with considerable fetch. The sedimentology of the lower Escape Rapids Formation coupled with its unradiogenic initial Os composition suggests deposition in a marine-influenced basin dominated by local terrigenous influx from weathered continental flood basalts and derived volcaniclastic rocks. Potentially correlative shale of the ca. 1050 Ma Arctic Bay Formation (Bylot Supergroup of Borden basin; Gibson et al., 2018) yielded highly radiogenic initial Os values (1.56-0.97), interpreted to reflect extreme basin restriction and concomitant reduced influence from the hydrothermal input, combined with increased local contribution to the basin from weathering of highly evolved crystalline basement rocks (Gibson et al., 2019). What these contrasting Os isotope data show is an effect of deposition from waters in an interior (epeiric sea) basin that was strongly influenced by terrigenous influx, especially in parts of the basin that may have been embayments, cut-off from regional circulation and connection to an exterior ocean. It also shows the composition of waters in such basins at this time was highly variable and not necessarily reflective of the composition of global oceans (cf. Kendall et al., 2009; Rooney et al., 2010). This basin heterogeneity would also have been enhanced by the short residence time of Os in seawater ($<$50 kyr).

5.4. Significance for the timing of early eukaryotic evolution

The Re-Os ages from both the Fort Confidence and Escape Rapids formations are important for situating recently discovered microfossil assemblages in a better-calibrated chronostratigraphic context, relative to other important Mesoproterozoic microfossil assemblages, which have less well constrained depositional ages (e.g. Javaux and Knoll, 2017). More than twenty-five species of eukaryotes were recently reported from the lower Shaler Supergroup by Loron et al. (2019b), mainly from the Rae Group, including four new genera and five new species, which is an unprecedented record for this time interval (1070-900 Ma). The new fossils include *Ourasphaira giraldae*, interpreted to be Earth's oldest fossil fungi by more than 500 myr (Loron et al., 2019a). Furthermore, the likelihood that basalt weathering contributed to the chemistry of seawater in Amundsen basin as established from Os isotope data, has implications on the local availability of bio-limiting elements such as Fe, Ni, P, and Cu that are enriched and easily remobilized in basaltic source terrains.

The ca. 1440 Ma minimum depositional age for the Fort Confidence Formation comes from within the same horizon that recently yielded a moderate diversity of 12 eukaryotic taxa, including one new species and two unnamed forms (C. Loron, personal communication), making them some of the oldest, well-constrained examples currently known. The Re-Os ages are also vital for improving the uncertainty in secular curves presenting high-resolution stable isotope data for these strata (Frank et al., 2003; Greenman et al., 2020; Hahn et al., 2013; Thomson et al., 2015), which, in turn, have been used to construct and calibrate global reference curves and stratigraphic correlations (Halverson et al., 2018).

6. Conclusions

The Re-Os isotopic data from carbonaceous shale units in the Hornby Bay and Amundsen basins provide much-needed chronological markers for Mesoproterozoic stratigraphic successions from northern Canada. The 1438 $\pm$ 8 Ma age, derived from diagenetic pyrite in carbonaceous shales of the Fort Confidence Formation, provides a minimum depositional age for the lower Dismal Lakes Group, a $\sim$1 km-thick carbonate platform succession, which was deposited between 1.59 Ga and 1.27 Ga. It also bolsters previously proposed regional correlation of the Hornby Bay basin with the Elu, Athabasca and Thelon basins and evidence for a continent-scale marine flooding episode ca. 1500 Ma.

A shale from the Escape Rapids Formation from the Amundsen basin yields a robust Re-Os depositional age of 1067.3 $\pm$ 13.5 Ma for the lowermost Shaler Supergroup of Amundsen basin with a remarkably unradiogenic initial $^{187}Os/^{188}Os$ value, suggesting that the shale's composition derived from weathering of local juvenile source material, such as basalt and volcaniclastic sandstone from the underlying Coppermine River Group. Together with sedimentological features indicative of open marine conditions, this suggests deposition within an intracontinental (epeiric sea) basin that was intermittently open to an exterior ocean. Comparison with Os isotope data from coeval basins, both regionally and globally, reveals that the composition of seawater in them was heterogeneous and strongly influenced by basin paleogeography and local terrigenous influx. This is an area of on-going and future research that will benefit from incorporating other independent isotopic tracers (e.g. Nd, Sr) to assess the relative contributions of riverine and oceanic fluxes to observed seawater composition.

The ca. 1070 Ma age for the Escape Rapids Formation constrains deposition of the overlying $\sim$4 km-thick Shaler Supergroup to a period of approximately 350 myr, recording sedimentation through a complete supercontinent cycle - amalgamation through to break-up of Rodinia. Further, this age indicates that the Shaler Supergroup correlates in time with the Bylot Supergroup and Fury and Hecla Group on northern Baffin Island, and the Thule Supergroup in northwestern Greenland and that these basins likely were connected as part of a much larger epeiric sea basin situated within the interior of Rodinia. Both new ages place important constraints on newly discovered eukaryotic microfossils from the Shaler Supergroup and Dismal Lakes Group and calibration points for critical chemostratigraphic data from a time period that is underrepresented globally.

CRediT authorship contribution statement

Robert Rainbird: Conceptualization, Writing - Original Draft, Reviewing and Editing, Funding Acquisition, Field data acquisition. **Alan Rooney**: Formal analysis, Re-Os geochronology, Writing-Reviewing and Editing. **Robert Creaser**: Formal analysis, Re-Os geochronology, Writing, Reviewing and Editing. **Tom Skulski**: Writing, Reviewing and Editing, Field data acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.epsl.2020.116492.

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