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Earth's earliest known extensive, thick carbonate platform suggested by new age constraints

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ABSTRACT

Proterozoic and Phanerozoic carbonate platforms have provided considerable information on how the flora, fauna and water chemistry of warm, shallow seas evolved through time. This contrasts with the relative scarcity of Archean examples of these extensive repositories of biochemical and chemical sediments. Until now the late Neoarchean Campbellrand-Malmani and Hamersley carbonate platforms have provided the only examples of extensive, thick Archean carbonate deposits. Scattered outcrop areas of Mesoarchean carbonate, up to 400 m thick, are present in western Superior Province, but past geochronology has assigned significantly different ages to them. A reappraisal of previously dated felsic volcanic rocks as sandstones, combined with new U-Pb zircon geochronology conducted on intermediate to felsic tuffs, determined that four of these carbonate occurrences, now scattered over 2300 km^2, were deposited between 2.87 Ga and 2.85 Ga. The realization that an extensive, thick carbonate platform, and deeper water chronostratigraphic equivalents (Slate Bay Assemblage), are probably present in this area provides a basis for future comprehensive studies of the relationships between the various types of depositional processes and compositions of seawater chemistry developed on and above the Mesoarchean seafloor.

1. Introduction and background

Thick successions of Phanerozoic and Proterozoic carbonates, termed carbonate platforms, provide an exhaustive archive of life through these time intervals, and the precipitates they contain track changes in ocean chemistry (Chilingar, 1956; Ronov, 1968; Sandberg, 1985; Hardie, 1996; Balthasar and Cusack, 2015; Hood and Wallace, 2018). The communities of organisms that lived on these deposits and became part of their superstructure form the basis for much of what we know of marine paleoecology. The calcite and aragonite they precipitated sampled the geochemistry of the seawater from which they formed, and can potentially preserve a record of primary elemental compositions (e.g. rare earths: Webb and Kamber, 2000; Nothdurft et al., 2004; Webb et al., 2009). This provides a means of ascertaining spatial and chronologic changes in both local conditions and at the Earth systems scale, though alteration during diagenesis can be problematic for more mobile elements and isotopes (Brand and Veizer, 1980; Fralick et al., 2024). Unlike later eons, the Archean has relatively few very thick accumulations of limestone and dolostone deposited in shallow water that formed extensive carbonate platforms. This limits our knowledge of how shallow seafloor carbonate deposits, and their biota and water chemistry, changed through that time period. During the 1.5 billion year

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duration of the Archean only eight thick carbonate platforms are known to have developed (Riding et al., 2014).

Prior to 2.95 Ga no known carbonate accumulations are thicker than 100 m, e.g. the 3.4 Ga, 15 m thick, member 2 of the Strelley Pool Chert, Australia (Lowe 1980; 1983; 1994; Hoffman et al., 1999; Allwood et al., 2006), and 26 m of carbonate in the 3.4 Ga Kromberg Formation, South Africa (Lowe and Knauth, 1977; Byerly et al., 1996). This changed in the Mesoarchean as oceanic plateau volcanism (Hollings et al., 1999; Fralick et al., 2008), in what was to become western Superior Province, provided stable areas for the deposition of shallow water siliciclastics and stromatolitic carbonates (Thurston and Chivers, 1990). The largest of these outcrop areas is the ~400 m thick (Fig. 2 in Afroz et al., 2023) Red Lake carbonate platform, reported to be underlain and overlain by felsic tuffs with U-Pb ages of 2.940 and 2.925 Ga respectively (Corfu and Wallace, 1986). The ~2871 Ma (Rogers, 2002) Woman Lake carbonate platform lies ~100 km to the east-northeast of the Red Lake carbonates. This 100 m thick limestone succession is underlain by a felsic tuff and has an upper intrusive contact with gabbro. Two smaller carbonate occurrences outcrop on the shores of Narrow and Shabu Lakes (Fig. 1). All of these carbonates are present essentially within the same ~130 km long greenstone belt, which outcrops around the Trout Lake batholith (Fig. 1). The third thick, ~500 m, succession of carbonates in western Superior Province is the Steep Rock Lake Platform approximately 230 km to the south (Wilks and Nisbet, 1988; Fralick and Riding, 2015). Zircon from volcanic rocks in the overlying Dismal Ashrock gave an age of 2780±1 Ma (Tomlinson et al., 2003), which, if not inherited, would be a younger age limit for the Steep Rock Group.

The global record contains no other known thick carbonate platforms until 2639 Ma, when the 120 m thick Vanivilas Formation in the Chitragurga Group, Dharwar Craton was deposited (Srinivasan et al., 1989). This was followed by the first known very extensive carbonate platforms: ~2600 Ma, 225 m thick Carawine Dolomite, Hamersley Group (Murphy and Sumner, 2008); 2600–2520 Ma, ~1900 m thick Campbellrand-Malmani carbonate platform (Schröder et al., 2009); and 2597–2504 Ma, 475 m thick, Paraburdoo Member, Hamersley Group (Murphy and Sumner, 2008). The development of extensive carbonate deposits in the latest Neoarchean continued into the Proterozoic with cap carbonates of the 2.4 – 2.3 Ga glacial cycles (Bekker et al., 2001, 2003, 2005; Mohanty et al., 2015; Kurucz et al., 2021) and younger Paleoproterozoic carbonate successions (Grotzinger, 1986; Zentmyer et al., 2011; Fralick et al., 2017).

The Mesoarchean carbonate platforms that have been identified consist of small fragments of what may have been significantly larger entities. Red Lake is the most extensive, with an 11 km strike length (Hofmann et al., 1985; Afroz et al., 2023). Woman Lake carbonates only consist of four small outcrop areas, one km apart (Hofmann et al., 1985). The other small occurrences of carbonate occur 10 km northwest of Woman Lake (Narrow Lake), and 23 km northwest of Woman Lake

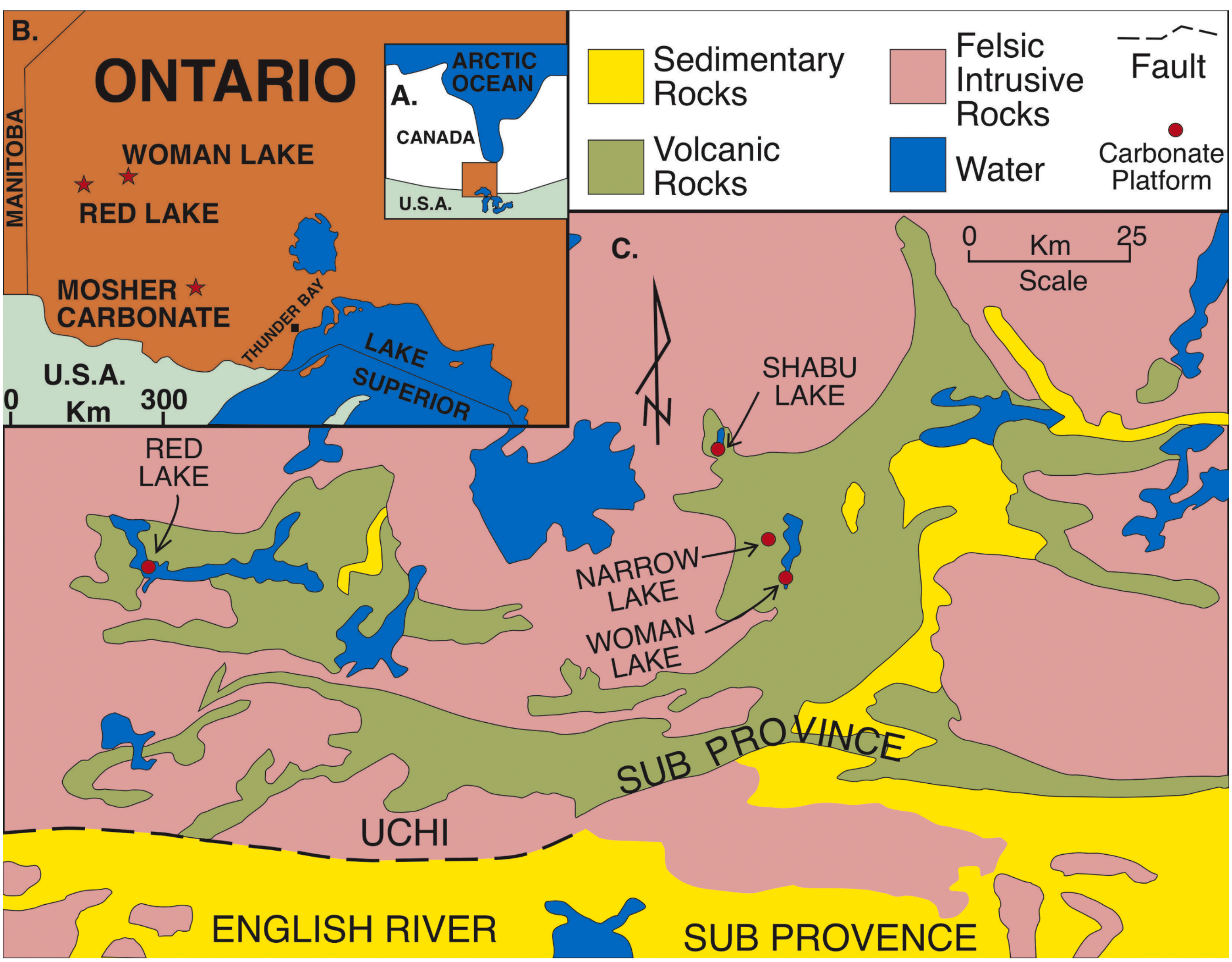

Fig. 1. A) Location of Fig. 1B. B) Location of Red Lake and Woman Lake carbonate platforms. C) Geology of the western Uchi Subprovince, of the Superior Province, showing the location of carbonate successions at Red Lake, Woman Lake, Narrow Lake and Shabu Lake.

(Shabu Lake) (Fig. 1). The four carbonate successions are in the Uchi subprovince and are relatively close together at the present day. However, the region has been extensively folded, with near vertical layering and strong schistosity (Stott and Corfu, 1991). Regional to localized shear zones are common, with on the larger scale, deep seismic northward dipping reflectors underlying the Uchi subprovince (Hynes and Song, 2006), possibly related to stacking of crustal slabs during the Kenoran Orogeny. This tectonized assemblage was intruded by batholiths and smaller igneous bodies. Under these circumstances the original distances between the carbonate successions were probably greater than at present. In addition, although there is some overlap, each of these four Mesoarchean carbonate successions differs in their biogenic and non-biogenic lithofacies. Thus, their chronostratigraphic relationships to one another are important factors in understanding the characteristics of the Mesoarchean seafloor during this time period.

Here we provide new U-Pb age determinations based on zircon from volcanic and volcanogenic sedimentary rocks associated with the Mesoarchean Red Lake (sample BL-12–37) and Woman Lake (sample WM-123) carbonate platforms, and from smaller carbonate occurrences at Narrow Lake (NZ-1) and Shabu Lake (SB-1) aa well as the Steep Rock Group, which although distant from the others, has similar basement characteristics. We outline the chronostratigraphic framework of each area and provide preliminary interpretations of its carbonate facies, several of which appear to lack modern analogs.

2. Stratigraphy

2.1. Red lake carbonate platform

Drilling conducted in 2010 and 2012 in search of mineral deposits has shown that this platform is at least ~400 m thick (Fig. 2 in Afroz et al., 2023). It rests conformably on ~100 m of ripple laminated and cross-stratified sandstones (Figs. 2, 3A, C, D), pebbly sandstones, and pebble to cobble conglomerates composed predominantly of rhyolite clasts (Fig. 3B). The sandstones overlie a thick succession of mafic to ultramafic volcanic rocks. Laterally linked and isolated domal stromatolites, layers of small crystal fan fabric and finely laminated dolomite dominate the western shallower areas of the platform (McIntyre and Fralick, 2017) (Fig. 4A). Further offshore to the east: 1) large calcite crystal fan mounds (Fig. 4B); 2) laminated carbonate, in places with thin magnetite laminae between the carbonate laminae; and 3) slump deposits of carbonate debris with carbonaceous slate and/or magnetite matrices, dominate (McIntyre and Fralick, 2017; Afroz et al., 2023). The lower ~100 m of carbonate is overlain by a major transgressive-regressive cycle, which deposited up to 120 m of carbonaceous, sulfidic slate; chert; oxide facies iron formation; and sulfide facies iron formation (Afroz et al., 2023). Two hundred and fifty meters of carbonate with scattered siliciclastic intervals and rarer felsic tuff overlie this. In the drill sections, the platform is seen to be capped by

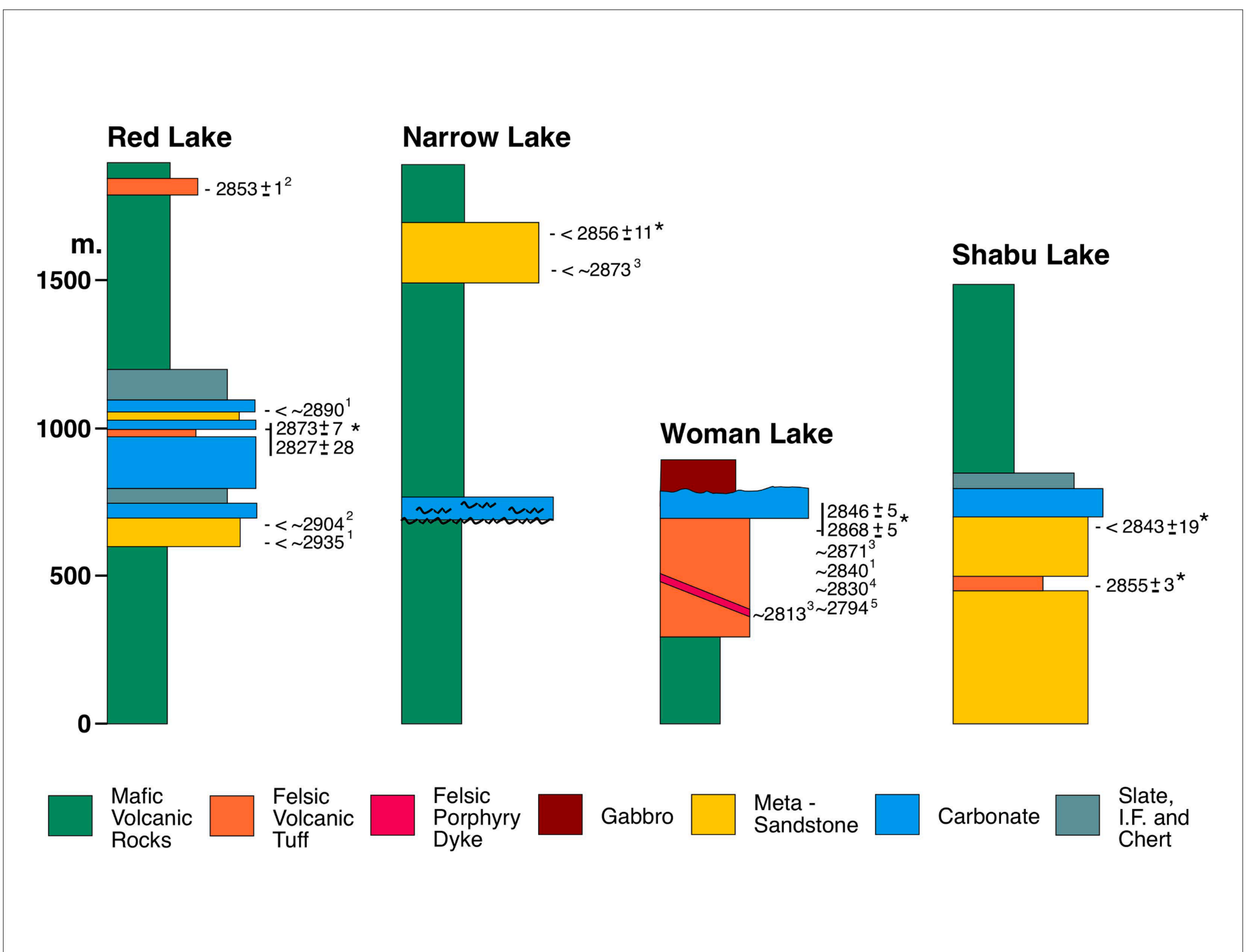

Fig. 2. General stratigraphy and geochronology of the four carbonate outcrop areas. Geochronology: [1] Corfu and Wallace (1986); [2] Skulski, in Sanborn Barrie et al. (2004); [3] Rogers (2002); [4] F. Corfu pers. comm. in Hofmann et al. (1985); [5] Nunes and Thurston (1980); * this study.

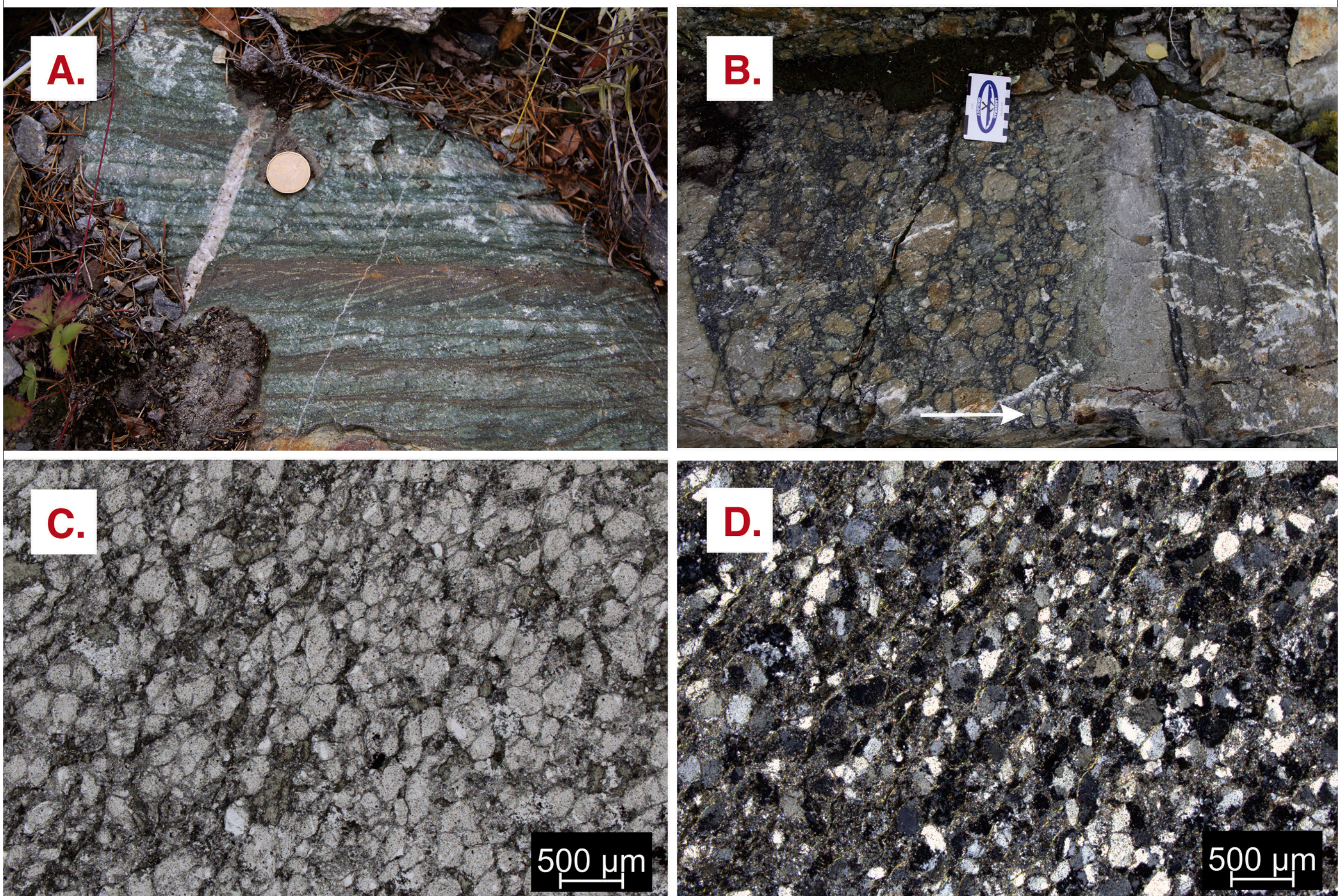

Fig. 3. Photographs from an approximately 100 m thick succession of sandstones and conglomerates lying conformably on ultramafic volcanic flows and gradationally transitioning into the Red Lake Carbonate Platform stromatolitic dolostones. A) Herringbone planar cross-stratified sandstones in a succession of sand-dominated tidal rhythmites. Green coloration is caused by common Cr-micas, probably derived from weathering and erosion of adjacent ultramafic volcanic rocks. Diameter of coin 2.7 cm. B) Monomictic felsic clast conglomerates with clay and sand-rich matrices. The thicker unit has erosive remnants of pebble conglomerate at its base, overlain by two cobble-to-pebble graded layers, with overlying very coarse-grained sandstones. Thin packages of sand-dominated tidal rhythmites separate some sandstones and conglomerates (top to right). C. (plane polarized) and D. (crossed polarized) photomicrographs of a medium-grained sandstone from strata underlying the carbonate. Extensive grain to grain pressure solution has affected the lower amphibolite sandstone. However, the rounded nature of the original grains is visible where the effects of pressure solution are not present. Quartz dominates the grain population with lesser amounts of rock fragments. A well-developed fine-grained matrix lies between the grains.

mafic and ultramafic flow rocks. The sub-vertical, southward younging succession contains smaller folds causing localized reversals. Further to the south the narrow Trout Bay has fine-grained siliciclastics overlying the carbonates on its north shore. Strata on the south shore are siltstones, chert and oxide facies iron formation overlain by a thick succession of mafic to intermediate volcanic strata with southward younging graded cobble to pebble agglomerates.

2.2. Woman lake carbonate platform

Here a probable Plinian eruption deposited a 300 m thick welded felsic tuff containing relict shards, fiamme draped over lithic fragments, and pumice (Thurston, 1980). This directly underlies the carbonate (Fig. 2). The basal strata of the ~100 m thick limestone platform consist of strandline deposits dominated by stratiform stromatolites interlayered with thin, probably storm-generated, grainstones that conformably overlie the felsic tuff (Ramsay, 2020). These transition up-section to laterally linked low domal stromatolites, which are themselves transitional to larger domes and low bioherms composed of walled pseudocolumnar stromatolites. The biogenic deposits are interlayered with grainstones. The upper half of the succession is composed of thrombolite-like facies containing narrow isolated columnar stromatolites and stromatactis-bearing low domal stromatolites (Fig. 4C), and overlain by pseudocolumnar stromatolites interlayered with cross-stratified and parallel laminated clastic carbonates (Fig. 4D) (Ramsay, 2020). The upper contact is with an intrusive gabbroic body (Fig. 2).

2.3. Narrow lake carbonate

Narrow Lake (Fig. 1) is narrow and 6 km long with carbonate and mafic volcanic remnants sheared together on its northern shore. Away from the highly deformed shear zone, minor scattered outcrops contain hummocky cross-stratified grainstone. Mafic volcanic flows form a thick, 2959±2 Ma (Nunes and Thurston, 1980), succession on the south side of the lake. The mostly highly sheared carbonate is overlain by a ~

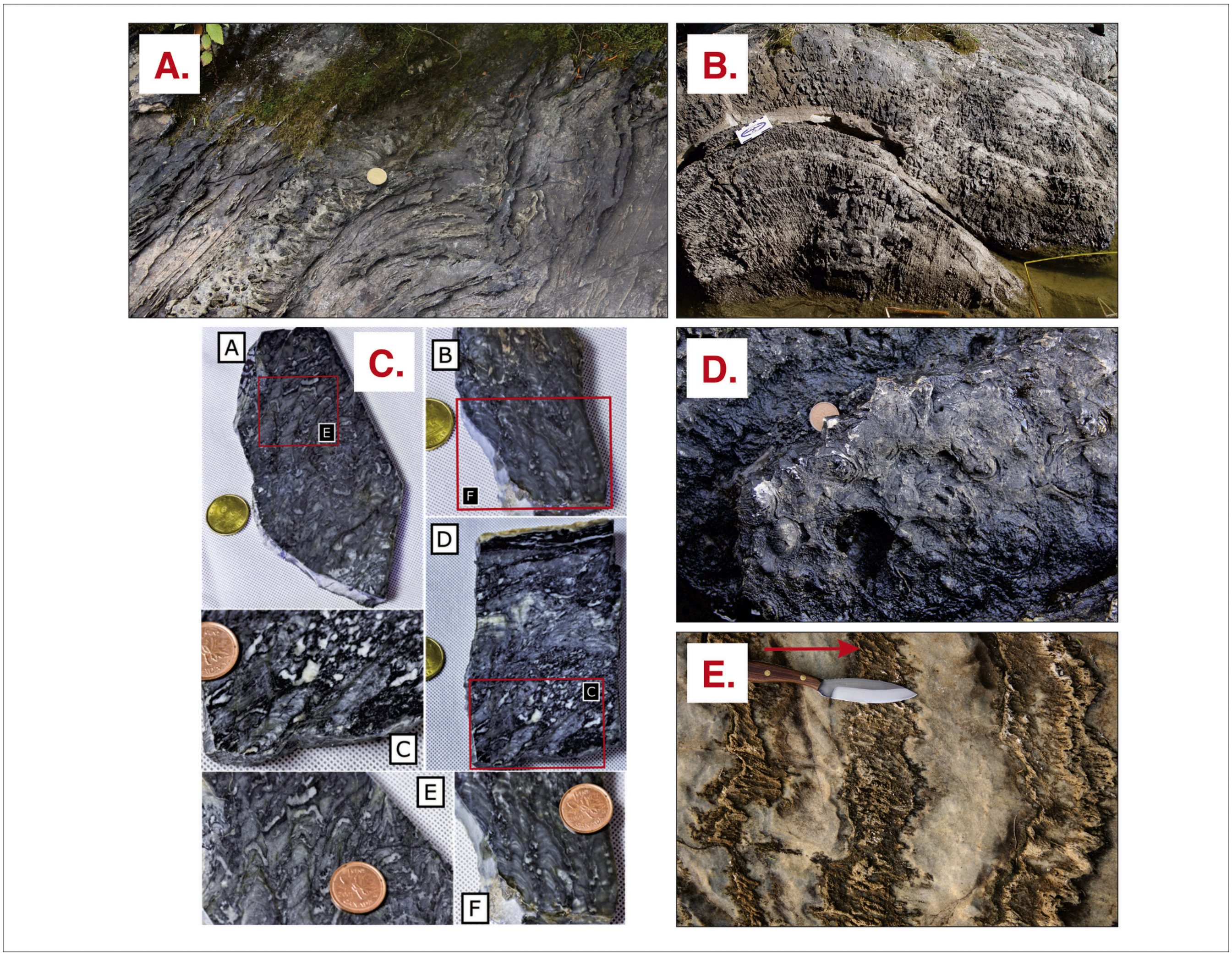

Fig. 4. A.) Red Lake Carbonate Platform. Stromatolitic mounds erosively truncated and overlain by a flat layer of crystal fan fabric. The fans are succeeded upwards by laminated carbonate. B.) Red Lake mounds composed of crystal fan fabric deposited further offshore from those shown in A. C.) Woman Lake Carbonate Platform. (a) Tall, slightly sinuous and very slender stand-alone columnar stromatolites amongst irregular, thrombolitic microbialite with abundant fenestrae and stromatactis (e). Coin is 2.7 cm. in diameter. (b) Narrow columnar stromatolites with gradational contacts between laminae. Some initiate atop a wider column, producing a branched appearance (f). (c) Small, slender columns overlain by abundant clotted and irregular lobate fenestrae, then smooth laminae reminiscent of low domal stromatolites, followed upwards by laminated carbonate with elongate fenestrae. Coin is 1.3 cm across. D.) Woman Lake partly silicified low domal stromatolites: some laterally linked, others mutually spaced. E) Shabu Lake Carbonate Assemblage. Layers of massive recrystallized micrite alternating with crystal fan fabric. Outer walls of the fans are silicified. Knife is 20 cm. long.

700 m mafic volcanic succession, which is in turn overlain by ~200 m of beds composed of graded, medium- and fine-grained sandstones that form what is probably a turbidite assemblage (Fig. 2). Due to shearing and a lack of way-up indicators in the volcanic units, original stratigraphic positioning is difficult to ascertain (Fralick et al., 2009)

2.4. *Shabu lake carbonate*

Approximately 100 m of carbonate on Shabu Lake (Figs. 1, 2) is underlain by >1 km of massive bedded, mafic, medium-grained sandstones interrupted by areas of mafic volcanic rocks (Sanborn-Barrie et al., 2004) and one area of felsic tuff. The carbonate assemblage consists of 1to 20 centimeter-thick layers of crystal fan fabric, separated by equally thick, massive, micritic carbonate (Fig. 4E). This is overlain by ~50 m of interbedded chert, sulfidic and carbonaceous slate, together with oxide facies iron formation.

2.5. *Mosher carbonate*

This carbonate succession is present in the Wabigoon subprovince, 230 km south of the others. The approximately 500 m of limestone present here conformably overlies sandstones and conglomerates deposited in channels cut into the underlying tonalite (Wilks and Nisbet, 1988). It is interpreted to be an isolated oceanic platform (Fralick et al., in press) rimmed by giant hybrid mounds composed of alternating layers of cuspate fenestral fabric and crystal fan fabric, with a stromatolite dominated central lagoon (Riding et al., 2014; Fralick and Riding, 2015), and is overlain by ultramafic pyroclastic debris.

3. Sampling and methodology

Core samples were collected from an interbedded tuff interlayered in the middle portion of the Red Lake carbonate strata present in drill hole BL-12–37 (see Afroz et al., 2023, Figs. 1 and 2, for the location and stratigraphic column). The Woman Lake carbonate platform rests conformably on a crystal tuff that was sampled for this study (WM-123, on the shore of Woman Lake, 1.44 km north of outcrop #8 of Hofmann et al. (1985), (15U 517,684.0E, 5,666,916.1 N). A 10 m thick crystal tuff (SB-1) interlayered within a sandstone assemblage ~200 m below the carbonate strata on the western shore of Shabu Lake (503,698.5E, 5,684, 813.4 N) was sampled, as well as the sandstones directly below the carbonate, for detrital zircons. Sandstone samples for detrital zircon U-Pb geochronology (NZ-1) were also collected on Narrow Lake (515, 740.0E, 5,672,941.5 N).

At Steep Rock, samples were collected from sandstone in the upper portion of the Wagita Bay formation, conformably underlying the Mosher Carbonate (Sample DD07–5: Zone 15, NAD 27, 604023mE, 54o6559mN) and from lapilli tuff in the Dismal Ashrock (Sample DD07–7:Zone15, NAD 27, 603490mE, 5406575mN), which overlies it. Both samples are from the SE arm of Steep Rock Lake.

Details of Methodology are presented in Supplementary Data File SD-1. Tabulated results are given in Supplementary Data File SD-2. Age results are quoted with 95 % confidence or 2 sigma errors. Error ellipses are plotted at 2 sigma.

4. Results

4.1. Red lake carbonate platform

Data on zircon from a fine-grained felsic tuff interlayered with carbonates in drill-hole BL12–37 (for location see Afroz et al., 2023) are clustered, but scatter somewhat outside of error (MSWD 1.8, Fig. 5A), which could be due to a mixed age population. Assuming that the age population contains two modes, the algorithm of Sambridge and Compston (1994, "Unmix Ages" application in Isoplot) gives the major age component as 2873±7 Ma (90 %) and a minor component at 2827 ±28 Ma (10 %). One slightly older grain is omitted because of the possibility of inheritance. A sandstone also collected at Red Lake (RLZ-1) yielded a mixed age population (Fig. 6A) that appears to contain at least 4 modes: 2837±4 Ma (4 %), 2876±45 Ma (6 %), 2908±16 Ma (28 %) and 2938±5 Ma (38 %). Although populations are small so errors are large the youngest two modes appear similar to those from the felsic tuff.

4.2. Woman lake carbonate platform

Zircon grains from a felsic tuff that directly underlies the carbonate sequence, sample WM-123, gave ages that mostly cluster somewhat

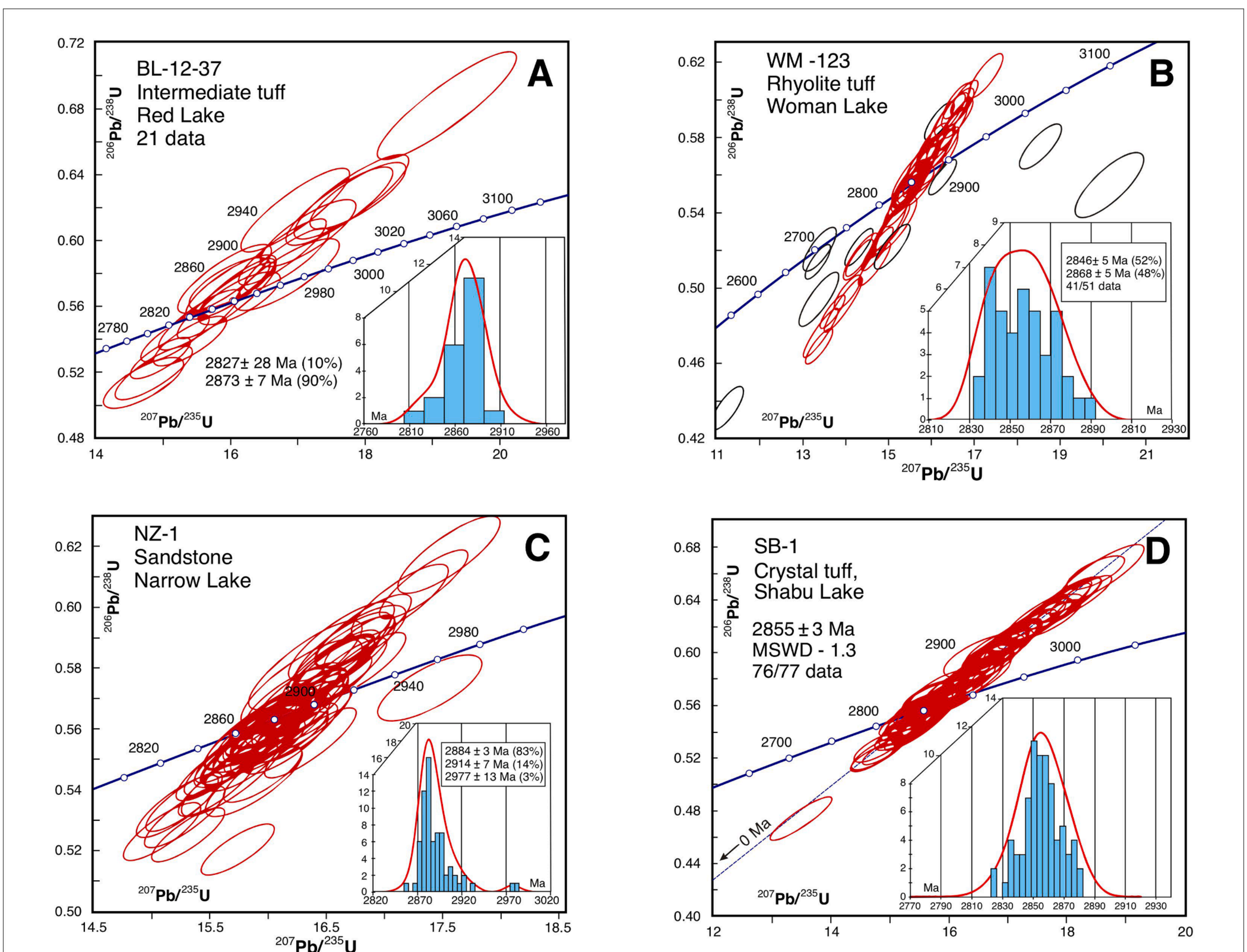

Fig. 5. Concordia plot showing U-Pb data on zircon derived from A) BL-12–37, a felsic volcanic ash layer interbedded in the middle of the carbonate succession on Red Lake; B) WM-123, a felsic volcanic ash directly underlying the Woman Lake Carbonate Platform; C) NZ-1, detrital zircon derived from sandstone overlying the carbonate on Narrow Lake; D) SB-1, a felsic volcanic ash approximately 600 m below the carbonate strata on Shabu Lake. Inserts show $^{207}Pb/^{206}Pb$ age probability density (PPD) distributions and histograms for data from each zircon population, as well as interpreted age modes (see text). Dark ellipses in B are not included in the PPD.

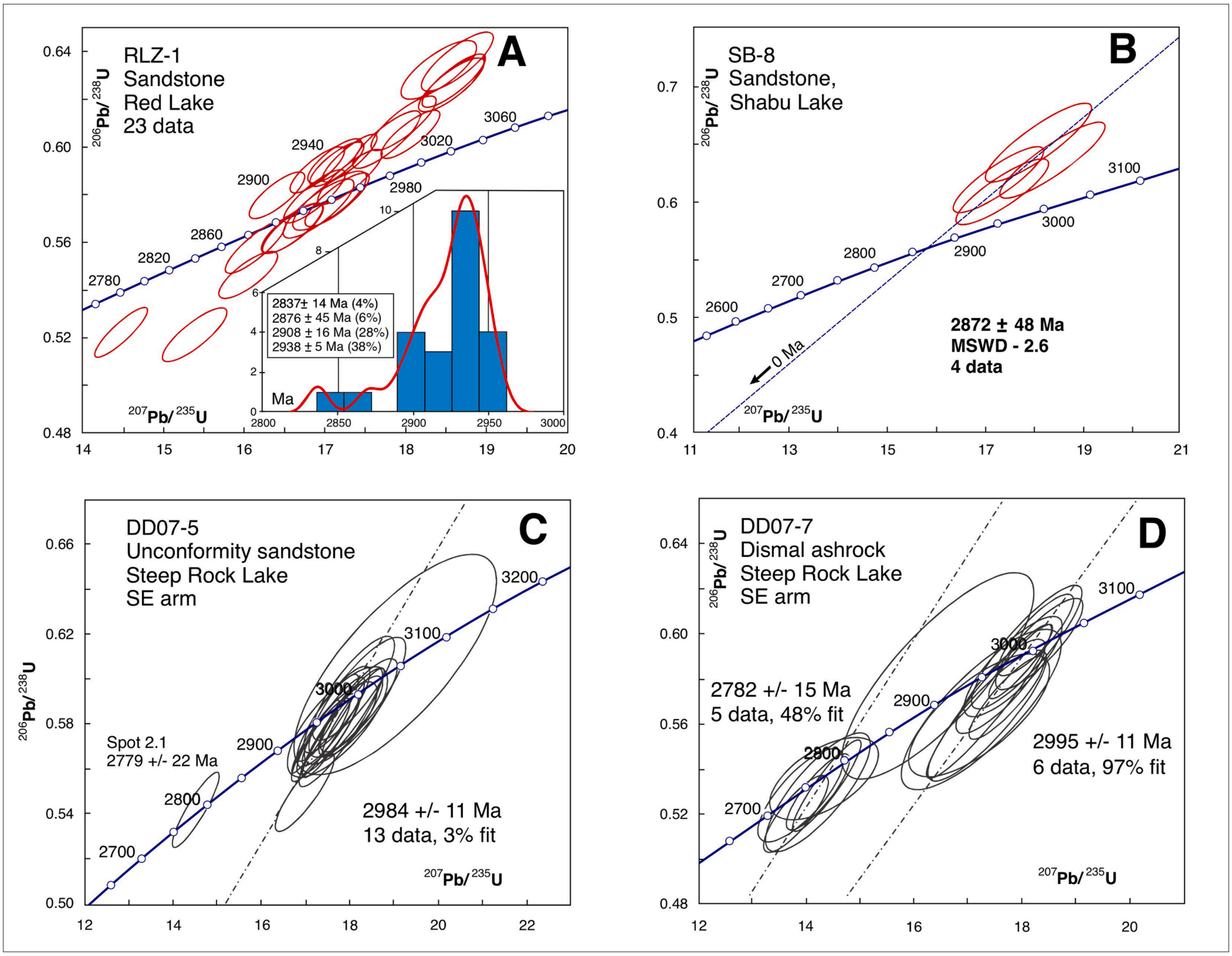

Fig. 6. A) Concordia plot showing U-Pb data on zircon from RLZ-1, a sandstone interlayered within the carbonate succession at Red Lake. The insert shows the PDD and age histogram as well as four interpreted age modes for the detrital population. B) Concordia plot showing U-Pb data on 4 zircon grains recovered from sample SB-8, collected from sandstones underlying the carbonates at Shabu Lake. C) Concordia plot showing U-Pb data on detrital zircon recovered from sample DD07–5, the Wagita Bay sandstone underlying the Mosher carbonate. D) Concordia plot showing U-Pb data on zircon recovered from sample DD07–7, the Dismal Ashrock overlying the Mosher carbonate.

outside of error around 2.85 Ga (Fig. 5B). The main cluster of data contains at least two sub-equal age components that Unmix calculates as 2846±5 Ma and 2868±5 Ma. Scattered older and younger analyses are also present with the two youngest averaging 2725 Ma.

4.3. Narrow lake carbonate

There are no felsic volcanic rocks closely associated with the carbonates on Narrow Lake. Therefore, a sample from sandstones stratigraphically above the carbonates (Fig. 2) was collected for detrital zircon U-Pb geochronology (NZ-1). The probability density distribution of ages has a major mode at the young end, with minor older Mesoarchean components (Fig. 5C). Applying the Unmix algorithm gives 2884±3 Ma as the principal and youngest component with minor components at 2914±7 Ma and 2977±13 Ma. The youngest zircon is 2856±11 Ma (1 sigma).

4.4. Shabu lake carbonate

Sample SB-1 is from a felsic tuff interlayered with the underlying mafic sandstone succession (Fig. 2). The age population appears to be unimodal with an average of 2855±3 Ma (MSWD −1.3, Fig. 5D). Sample SB-8 was collected from sandstones underlying the carbonates. These are mostly composed of mafic to intermediate debris. Due to the composition of the source area, these samples provided very few zircons and only 4 detrital zircon U-Pb ages were obtained. The group of 4 has an average age of 2872±48 Ma (Fig. 6B).

Mosher Carbonate zircon data from sample DD00–5, the sandstone underlying the carbonate, mostly cluster around an average age of 2984 ±11 Ma (Fig. 6C) with slight excess scatter. One grain gave a younger age of 2779±22 Ma. Data on zircon from DD00–7, the overlying Dismal Ashrock, mostly forms two concordant clusters with average ages of 2995±11 Ma and 2782±15 Ma (Fig. 6D).

5. Discussion

At Red Lake, sedimentation progressed from shallow water stromatolitic dolostones (Fig. 4A) developed on tidally reworked sandstones ((Fig. 3A) that transitioned to offshore aragonite crystal fan mounds (Fig. 4B), interlaminated carbonate and magnetite, and slide deposits of intraformational carbonate clasts with carbonaceous mud and/or magnetite matrices (McIntyre and Fralick, 2017; Riding et al., 2022). Chert, carbonaceous sulfidic mud and oxide iron formation were deposited offshore from the carbonate platform (Afroz et al., 2023).

Transgressive, regressive, transgressive cycling caused stacking of the lithofacies (Fig 2 in Afroz, 2023). Approximately 700 m above the carbonates a dacitic tuff interlayered with clastic and epiclastic strata in a mafic to intermediate volcanic succession produced a U-Pb zircon age of 2853±1 Ma (T. Skulski, in Sanborn-Barrie et al., 2004). This limits the age of the felsic tuff in the carbonate to older than 2853±1 Ma, which is consistent with the major age component of 2873±7 Ma (90 %) for sample BL-12–37 and is within error of its minor component, 2827±28 Ma (10 %). Twelve kilometers to the east of the carbonate outcrops siltstones and sandstones of the Slate Bay assemblage, with detrital zircon ages of 2903 Ma, 2904 Ma (T. Skulski, in Sanborn-Barrie et al., 2004), and 2916 Ma (Corfu et al., 1998) are associated with lapilli tuffs with U-Pb zircon ages of 2855 Ma and 2852 Ma (T. Skulski, in Sanborn-Barrie et al., 2004), suggesting that this could be a lateral deeper water equivalent of the carbonate shelf. The new age data on tuff from within the carbonates (Fig. 5A), combined with the 2.85 Ga age of overlying tuffs (T. Skulski in Sanborn-Barrie, 2004), suggests that the upper Ball assemblage, possibly together with all of the Ball, Trout Bay, and Slate Bay assemblages are part of the same Mesoarchean chronostratigraphic series.

Corfu and Wallace (1986) measured ID-TIMS U-Pb ages on zircon grains derived from “rhyolite lapilli tuff” below the stromatolitic carbonates on Red lake and a “rhyolite flow” above them, finding 2935.1, 2939.0, 2940.2, 2943.0 Ma and 2890.3, 2917.4, 2913.0, 2918.7, 2925.4 Ma, respectively). These define discordia lines with a low probability of fit. Hydraulically cleaned outcrop areas, and ten drill-holes with over 1500 m of core through the carbonate platform and adjacent rocks, have provided more data on the stratigraphy and sedimentology than available to Corfu and Wallace (1986). It is now apparent that the carbonates are underlain, not by rhyolite lapilli tuff, but by ripple laminated and cross-stratified sandstone containing debris from the underlying volcanic rocks (including some samples with over 1000 ppm Cr), which were assigned a maximum depositional age of 2904 by Skulski (in Sanborn-Barrie et al., 2004). The rhyolite flow thought to overlie the carbonate is actually sandstone that is interlayered within the carbonate succession (Afroz et al., 2023). A selection of core samples from those sandstones (RLZ-1) gave detrital zircon ages that are mostly clustered between 2.84 Ga and 2.94 Ga (Fig. 6A), reducing the older limit on deposition that was defined by Corfu and Wallace (1986).

Carbonates at Woman Lake directly overlie a felsic volcanic succession, (WM123, Fig. 2), without intervening siliciclastics. The main zircon population appears bimodal with ages of 2.85 Ga and 2.87 Ga. consistent with the ages at Red Lake. The sampled unit is described in detail in Thurston (1980) and appears to be a primary volcanic deposit that was never redeposited. Nevertheless, the evidence for mixed age populations, both here and in the Red Lake sample (BL-12–37), suggest that a younger felsic eruption at approximately 2.85 Ma incorporated 2.87 Ma felsic eruptive materials. Zircon from a felsic dyke that cross-cuts the tuff was dated at 2813 Ma (Rogers, 2002), which, if not inherited, should establish a minimum age (Fig. 2). In this case the two approximately 2.72 Ga Neoarchean zircons present in the volcanic sample may represent either contamination or hydrothermally introduced zircon (e.g. Davis et al., 2022).

Compared to the Red Lake platform, at Woman Lake the subaerial tuff represents lowstand and the carbonate only records a transgressive systems tract. Unfortunately, the gabbro intrusion ends the sequence there. The mineralogy of the carbonates at Woman Lake differs from the majority of those at Red Lake. Apart from sporadic ferroan dolomite near the base, calcite dominates the entire succession (Ramsay, 2020; Ramsay et al., 2020, 2021), suggesting very low levels of Fe^{2+} in solution (Herzog et al., 1989; Katz et al., 1993; Sumner and Grotzinger, 1996; Sumner, 1997; Canfield, 2005; Riding et al., 2014, 2022). This could reflect an increase in the area of the shallow water shelf, extending the distance to the offshore chemocline. Negative Ce anomalies, produced when water from which the sediment precipitated passed through oxygenated areas (De Baar et al., 1983; Bolhar et al., 2004; Bolhar and Van Kranendonk, 2007), also suggest increased biologic production of O_2 during Woman Lake deposition, corresponding to increased shelf area. Red Lake carbonates only appear to have one area where negative Ce anomalies developed (McIntyre and Fralick, 2017), whereas 89 of 152 of Woman Lake carbonate samples analyzed have negative Ce anomalies, and these become more abundant as relative sealevel increased up section, suggesting a progressively larger area of shallow water deposition (Ramsay, 2020; Ramsay et al., 2020, 2021).

Carbonates at Narrow Lake overlie a highly sheared contact with a thick mafic volcanic assemblage. Approximately 700 m above the carbonates are sandstones, siltstones and slate, with abundant detrital zircon whose main and youngest population defines an age of 2884±3 Ma, with a spread from 2.87 Ma to 2.93 Ma (Fig. 5C), which contains a youngest zircon with an age of 2856±22 Ma. This implies derivation from a variety of felsic to intermediate igneous rocks of these ages

The carbonate succession at Shabu Lake was deposited after 2855±3 Ma. It contains crystal fan fabric in laterally continuous beds composed of single layers of fans (Fig. 4E), rather than stacked layers of fans forming mounds as, for example, at Red Lake (Fig. 4B) (McIntyre and Fralick, 2017). The fans grew by precipitation at the sediment - water interface and alternate with massive micrite layers that probably represent nucleation and rainout of precipitates from the overlying water. The factors causing this alternation of water column and substrate precipitation are unknown. This offshore facies is overlain by chert, oxide facies iron formation and sulfidic slate, representing a change from carbonate precipitation to that of oxidized and reduced iron. The exclusive presence of iron sulfides in carbonaceous slates may reflect the need for degrading carbonaceous organic matter to be present to essentially eliminate virtually all oxygen, allowing sulfides, rather than oxides, to form. This condensed siliciclastic, chert, and oxide iron formation association resembles that of deeper water deposits that accumulated offshore from the Red Lake Carbonate Platform (Afroz et al., 2023), and also constitute the drowning succession at the Steep Rock isolated platform (Riding et al., 2014; Fralick and Riding, 2015). Similar offshore, deep-water facies are associated with the huge, Neoarchean Campbellrand-Malmani Carbonate Platform (Klein and Beukes, 1989; Schröder et al., 2006; Knoll and Beukes, 2009).

Volcanogenic strata associated with the Red Lake and Woman Lake carbonate platforms have similar 2.87 to 2.85 Ga ages, which may reflect ongoing tuffaceous volcanism through this time period, with incorporation of the older material into the layer produced by the younger volcanic eruption whose material was sampled. The 2855±3 Ma crystal tuff on Shabu Lake records the younger portion of this interval without incorporation of older material. The youngest zircon in the Narrow Lake sandstone sample may have also been derived from this period of felsic volcanic activity.

The Mosher Carbonate at Steep Rock must be younger than the underlying Wagita Bay sandstones. Most of the detrital age population of the sandstones approaches the 3.0 Ga age of the nearby basement (Marmion Batholith) and greenstones at Lumby Lake to the north (Tomlinson et al., 2003; Davis and Jackson, 1988), but a single age constrains deposition to be younger than 2779 ± 22 Ma (Fig. 6C). The zircon population from the Ashrock tuff that overlies the carbonates also shows a detrital component derived from the basement, but a coherent cluster of ages gives 2782 ± 15 Ma (Fig. 6D). This agrees with the more precise zircon age reported by Tomlinson et al. (2003). If this population records volcanism, and the basal contact is not a thrust fault as suggested by Kusky and Hudleston (1999), it establishes an early Neoarchean age for the Mosher Carbonate.

After deposition of the Red Lake, Woman Lake, Narrow Lake and Shabu Lake carbonates, which appear to be approximately the same age and may constitute one large dismembered carbonate platform, there are no significant preserved carbonates in Superior Province till accumulation of the 2.78 Ga (Fig. 6C, D) Mosher Carbonate forming the Steep Rock Carbonate Platform. It appears that changes occurred in the lithofacies being deposited over the intervening 70 My. These include the common occurrence of cuspate fenestrae microbialite fabric in Neoarchean carbonates compared to its absence in the Mesoarchean carbonates described here, and the presence of thrombolite-like build-ups in the Mesoarchean, but not in the Neoarchean. Hopefully the new age data will spur further investigations into secular changes in the Archean seafloor environment.

6. Conclusions

U-Pb zircon geochronology suggests that the 400 m thick carbonate platform at Red Lake, the 100 m carbonate platform preserved at Woman Lake, and the thinner carbonate successions at Narrow and Shabu Lakes, could all be parts of one Mesoarchean carbonate platform in the Uchi subprovince of the Canadian Shield. This would then be the oldest extensive, thick carbonate platform known on Earth. As such, it could provide a great deal of information on how shallow marine Mesoarchean carbonate facies were organized from the strandline to the shelf break, and offshore into siliciclastic sediments and iron-bearing precipitates. In addition, recognition of the likely existence of the platform provides a workshop for research on Mesoarchean seawater geochemistry.

Statement of commercial gain

This manuscript represents pure science with no commercial value. The authors will see no monetary or other gain due to its publication

CRediT authorship contribution statement

Philip Fralick: Writing – original draft, Visualization, Validation, Supervision, Resources, Investigation, Conceptualization. **Donald W. Davis:** Writing – review & editing, Visualization, Validation, Investigation, Formal analysis. **Munira Afroz:** Writing – review & editing, Resources. **Brittany Ramsay:** Writing – review & editing, Resources. **Laureline Patry:** Writing – review & editing, Resources. **Dylan Wilmeth:** Resources. **Martin Homann:** Resources. **Pierre Sansjofre:** Resources. **Robert Riding:** Writing – review & editing, Resources. **Stefan V. Lalonde:** Supervision, Resources, Project administration, Funding 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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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.epsl.2025.119273.

Data availability

Data is in supplemental files supplied.

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