Sedimentology and Geochemistry of the 2930 Ma Red Lake–Wallace Lake Carbonate Platform, Western Superior Province, Canada

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ABSTRACT
Chemical sedimentary rocks in the Red Lake–Wallace Lake area of the Canadian Shield form the Earth’s oldest known carbonate platform and, as such, provide a unique opportunity to explore the floor of a 2930 Myr old warm, shallow sea. Peritidal depositional features dominate the platform top, ranging from colloform crusts, teepee structures, and evaporate pseudomorphs in the supratidal; pseudomorph crystal fans and laterally linked domal stromatolites, associated with stromatactis-like structures, sheet cracks and liminoid fenestral fabrics extending from the lower supratidal through the intertidal; and herring-bone cross-stratification, isolated domal stromatolites and herring-bone calcite cement in tidal channels. These lithofacies indicate a low energy, restricted evaporitic environment. Limited subtidal platform top deposits are characterized by laterally linked domal stromatolites and pseudomorph crystal fans on a larger scale than those found in the intertidal areas. A transitional lithofacies to deeper water were deposited further offshore. It consists of ribbon rock (mixed laminae and beds of carbonate, slate and iron oxide sediments), slump structures composed of intraclastic carbonate lithoclasts in a marl matrix and carbonate-associated iron formation. Basinal deposits consist of chert and chert-oxide facies iron formation. Peritidal lithofacies are composed of ferroan dolomite, whereas deep subtidal to upper slope lithofacies are composed of calcite. The dolomites have O and Sr isotopic ratios which were probably reset during dolomitization, whereas only O is altered in the limestones. The δ13C values for all the carbonate samples were 0 ± 1‰ VPDB, with samples formed in deeper water having lighter δ13C values, suggesting the deeper open ocean had a lighter δ13C budget than water in the platform interior. Post Archean Australian Shale normalized rare earth element patterns for the carbonate samples have positive La and Eu anomalies, suprachondritic Y/Ho ratios and slight heavy rare earth element enrichment in most samples. Basin lithofacies are characterized by heavy rare earth element enrichment and positive Eu anomalies. One sample had a significant negative Ce anomaly. These data probably indicate restricted circulation in the supra and intertidal areas and possibly the development of spatially limited areas where oxygen production could move the redox boundary out into the water column.

INTRODUCTION
Carbonate strata deposited in the shallow Archean ocean provide an archive of information on palaeogeography, biologic productivity, the general chemistry of the water from which they formed, and diagenetic pathways (Grotzinger & James, 2000; Webb & Kamber, 2000; Kamber & Webb, 2001). Extensive study of the latest Archean Campbellrand-Malmani carbonate platform of South Africa (Sumner, 1996; Sumner & Grotzinger, 1996, 2004;
The relative lack of carbonate platforms prior to 2 Ga (Fig. 1).

The oldest known thick carbonate platform and is exposed in its relationship to water chemistry during this interval. However, a 200 m thick 2 Ga carbonate platform has been extensively investigated, such as the 259-230 m thick carbonate units in the 3.4 Ga Strelley Pool Formation (Allwood et al., 2010; and references therein), but the relative lack of carbonate platforms prior to 2-8 Ga limits our ability to investigate platform architecture and its relationship to water chemistry during this interval. However, a 200 m thick 2-93 Ga carbonate platform does exist, although it has received very little attention. The Red Lake–Wallace Lake carbonate platform in Superior Province of north-western Ontario has only been the subject of an overview by Hofmann et al. (1985). It is the oldest known thick carbonate platform and is exposed in wave washed outcrops on the shores of Red and Wallace Lakes (Fig. 1).

**REGIONAL GEOLOGY**

The Red Lake and Wallace Lake Greenstone Belts are located in Superior Province on the southern margin of the Uchi Subprovince within the North Caribou Terrane (NCT) (Fig. 1A and B) and are characterized by lithostratigraphically and chronostratigraphically similar volcano-sedimentary sequences (Sanborn-Barrie et al., 2001; Sasseville et al., 2006). Correlative chemical precipitates that formed the Red Lake–Wallace Lake carbonate platform are found within the Wallace Lake Assemblage of the Wallace Lake Greenstone Belt and Ball Assemblage of the Red Lake Greenstone Belt. The Wallace Lake Assemblage is comprised of a transgressive siliciclastic succession, the Conley Formation, overlain by chemical sediments of the East Bay Formation, which in turn is conformably overlain by the dominantly volcanic Overload Bay Formation (Sasseville et al., 2006; Fralick et al., 2008). The base of the Conley Formation consists of a conglomeratic braided fluvial system upwardly gradational into an overlying distributary mouth bar – distal bar assemblage (Fralick et al., 2008). Approximately 800 m of prodelta turbidites cap the formation. These become thinly bedded and finer grained near the top and at the transition to the East Bay Formation interlayer with thinly bedded chert and magnetite. This is overlain by iron formation with chert-rich, millimetre-thick layers or, in other areas, 50 m of dolomitic carbonates (Fralick et al., 2008). These chemical sediments define the western portion of the Red Lake–Wallace Lake carbonate platform at Wallace Lake and are overlain by chloritic sandstones and siltstones, and volcanic rocks of the mafic-ultramafic Overload Bay Formation.

Detrital zircons found within sandstone near the base of the Conley Formation provide a maximum age constraint of 2997 to 2999 Ma (Davis, 1994) and a lower limit is provided by a 2921 Ma crossing felsic dyke (Davis, 1994). The Overload Bay Formation is cut by a 2921 ± 2 Ma dacitic dike and intruded by a 2921 ± 1 Ma tonalite batholith (Tomlinson et al., 2001; Sasseville et al., 2006). The volcano-sedimentary sequence is interpreted as an ocean plateau (Hollings et al., 1999) where plume induced shallowing created sub-aerial conditions that subsided to shallow marine during an interval of restricted volcanism and reduced heat-flow. The thermal subsidence allowed first shallow water siliciclastic deposition, and, as the source area flooded, siliciclastic starved carbonate sedimentation, and finally deeper water chert and iron formation (Fralick et al., 2008). The Overload Bay Formation was deposited during renewed plume volcanism (Hollings et al., 1999).

The Ball Assemblage of the Red Lake Greenstone Belt is comprised of a dominantly calc-alkaline mafic to felsic volcanic sequence with minor komatiite, siliciclastics andstromatolitic carbonates (Sanborn-Barrie et al., 2001). These 200 m thick stromatolitic carbonates are the eastern extension of the Red Lake–Wallace Lake carbonate platform in the Red Lake area. Their age is constrained by overlying and underlying felsic volcanic rocks to
between 2940 ± 2 Ma and 2925 ± 3 Ma (Corfu & Wallace, 1986). Like the Wallace Lake Assemblage, the Ball Assemblage was formed by initial plume-related volcanism and tectonic activity, followed by a hiatus in volcanic activity and a period of siliciclastic starved sedimentation during which time chemical precipitates were deposited. Renewed volcanism occurred at ca 2925 Ma (Sanborn-Barrie et al., 2001).

**METHODS**

A total of 131 carbonate, iron formation, marl and siliciclastic samples were collected from the 10 locations shown in Fig. 1C and D over three separate field seasons during the summers of 1998, 2012 and 2013. The best exposures of these carbonates were along the shore at both Red Lake and Wallace Lake. Samples that showed well-preserved primary features were preferentially selected for sampling. Much of the shoreline exposure was neomorphosed and altered carbonate lacking any discernable primary sedimentary structures. Where well-preserved primary sedimentary structures were identified, the structures were measured and logged.

Many of the collected samples were cut, slabbed and polished. Thin sections were produced from selected samples and characterized by petrographic microscope. Of the 131 samples, 38 were selected for whole rock major and trace element geochemical analysis and 20 of these were analysed for carbon and oxygen isotopes. Samples that contained primary sedimentary features were selected for geochemical analysis while any obvious zones of alteration were excluded. The samples were coarsely crushed using a tungsten carbide mallet and plate and powdered in an agate mill. Carbon and oxygen isotopes were measured from the whole rock powders at G.G. Hatch Isotope Laboratories, University of Ottawa, by methods described in Revez et al. (2001). Major elements and trace elements were measured by inductively coupled plasma (ICP) atomic emission spectroscopy (AES) and ICP mass spectrometry (MS), respectively, at Lakehead University Instrument Laboratories. For major and trace element analysis, 0-500 g aliquots of each sample were digested by open vessel methods with three treatments of nitric and hydrofluoric acid. Final dilution of the samples was to 200 times for AES and 2000 times for MS. Duplicate samples and reference materials were used to evaluate...
accuracy and precision in each run and were within acceptable limits. In addition, three procedural blanks were measured within each run. Minimum detection limits were taken as three times procedural blanks.

Lithofacies description and interpretation

The only previous sedimentological work on the Red Lake–Wallace Lake carbonate platform was a descriptive study of the stromatolites and atikokania (pseudomorphed fanning sea floor precipitates; terminology of Walcott, 1912) present in the Red Lake area (Hofmann et al., 1985). Here, stratigraphic relationships of the stromatolites and pseudomorph fans, as well as their associations with other lithofacies across the platform, are described. Many of the lithofacies are similar to those found in other carbonate platforms from the Palaeoarchean to Neoproterozoic. Some of the outcrops have several metres of carbonate stratigraphy that have groups of lithofacies, and for these, the stratigraphy is summarized in Fig. 2. Along the shoreline, alteration has obscured some areas of stratigraphy and where this has happened, the lithofacies have been inferred from the nearest identifiable structures. Stratigraphic units were grouped by lithofacies and detailed descriptions of these are given in this section.

Wavy Laminae

The wavy laminae lithofacies are characterized by flat, wavy and crinkly laminae and massive orange weathering carbonate separated, at somewhat regular intervals, by millimetre-scale, light coloured chert laminae (Fig. 3). Sheet cracks, stromatactis-like cavities, roll-ups, crinkly laminae, irregular folding, teepee structures, probable desiccation cracks, small millimetre-scale fibrous colloid cement crusts, pseudomorphs after gypsum and colleniella occur locally.

Sheet cracks are found in some ancient carbonate deposits (Kennedy et al., 2001; Aubrecht et al., 2009; Hoffman & McDonald, 2010; Fralick & Riding, 2015) and, in the present study, consist of irregular, bedding parallel elongate, spar filled voids ranging in length from 2 to 10 cm and commonly 1 cm in height (Fig. 3B). The spar crystals are perpendicular to the void walls and often over lain by dark micritic sediment which outlines the crystal terminations. The remaining void is sometimes filled with blocky megaquartz. The characteristics of the spar are reminiscent of the void filling cement, radiaxial fibrous calcite (Kendall & Tucker, 1973; Kendall, 1985; Aubrecht et al., 2009). The sheet cracks are similar to those found in Maronian cap dolostones (Kennedy et al., 2001; Hoffman & McDonald, 2010).

Fig. 2. Stratigraphic sections corresponding to outcrop locations described in Fig. 1C and D: A is outcrop 1, B is outcrop 5, C is outcrop 6, D is outcrop 7, E is outcrop 8 and F is outcrop 9. Massive carbonate, silicified wackestone and contorted laminae are not mentioned in text as they are poorly preserved and positive identification was putative.
The stromatolites of the Red Lake–Wallace Lake carbonate platform commonly occur as laterally linked domal (LLD) stromatolites, isolated domal (ID) stromatolites and large low relief domes. The LLD and ID stromatolites of the Red Lake area have been termed *statifera* and *colleniella*, respectively, by Hofmann et al. (1985). The stromatolites are composed of coarse to fine laminoid fenestral fabric (terminology of Logan (1974)) defined by translucent white chert interbedded with orange weathering carbonate. Silicified areas of the stromatolites commonly preserve 1 to 3 mm birds eye vugs. Modern examples of birds eye fabric can be found in Shinn (1968, 1983), Flugel (2010), and references therein. *Statifera* are generally associated with wavy laminae, laminated carbonate and pseudomorph fans. In addition, herring-bone cross-strata are found in transitional facies between *statifera* and *colleniella*. Stromatolites, like those found in the Red Lake and Wallace Lake Carbonate Platform, are widely represented in the literature in larger carbonate platforms that date from the Neoarchean to the Proterozoic (Wilks & Nisbet, 1985; Grotzinger, 1986; Demicco &
Limestone of the middle Proterozoic Apache Group. reported by Skotnicki & Knauth (2007) for the Mescal areas proximal to intraclastic breccia. Similar dissolution tures that occur as cavities in stromatolitic laminae in roan dolomite. In addition, similar to that which surrounds the voids, in this case fer-surfaces, and are filled with what appears to be sediment have a cement rim, flat upper surfaces, irregular lower surfaces, and sharply over lain by the next generation of stromatolites or wavy laminae lithofacies. In many cases, statifera are gradational to wavy laminae lithofacies (i.e., stromatolites lose relief up section and become flat to wavy laminated carbonate beds). Statifera commonly have cherty reticulate stromatactis-like structures that conform to the curvature of the upper portions of the concave surfaces of stromatolitic layering (Fig. 4A, B and C). These stromat-actis-like structures are like those found in the Doushan-tuo Cap Carbonate by Jiang et al. (2006) in that they have a cement rim, flat upper surfaces, irregular lower surfaces, and are filled with what appears to be sediment similar to that which surrounds the voids, in this case fer-roy dolomite. In addition, statifera host dissolution features that occur as cavities in stromatolitic laminae in areas proximal to intraclastic breccia. Similar dissolution cavities to those present in the stromatolites have also been reported by Skotnicki & Knauth (2007) for the Mescal Limestone of the middle Proterozoic Apache Group.

Colleniella have similar dimensions and characteristics (laminoid fenestral fabric, birds eye vugs and reticulate stromatactis-like structures) to, and occur in close associ-ation with, statifera (Fig. 4D). They differ from statifera in that they are isolated domal stromatolites hosted in other sedimentary facies rather than forming stromatolite biostromes. This stromatolite type is best preserved at outcrop 5 where it is overlain by herring-bone crossbedding composed of intraformational mud chips. The her-ring-bone crossbedding can be seen in the dip direction of the elongate rip-up clasts, where the clasts are ferroan dolomite 2 to 3 mm in thickness and 2 to 10 mm in length within a siliceous matrix. Individual herring-bone cross-stratified beds are ca 5 cm in thickness. Other colle-niella associations in this area are herring-bone calcite (HBC) and statifera. The other occurrences of colleniella are poorly preserved but occur with laminated carbonate, small crystal fans and statifera.

Herring-bone calcite, that is associated with colleniella, is a cement that occurs as 1 to 3 cm thick laterally con-tinuous layers (Fig. 5) and rarely 1 to 3 cm thick coatings on probable intraclastic breccia. Herring-bone calcite is characterized by irregular banding composed of serrated, sub-millimetre-scale layers of fibrous calcite or dolomite cement with crystals elongate and perpendicular to banding. In outcrop, banding is dominantly produced by preferential weathering of some layers creating an alternating high and low banded topography. In thin section, dolomitization and recrystallization are prolific leaving behind equant crystals and patches of fibrous spar that only faintly retain the banded extinction which is charac-teristic of HBC. Herring-bone calcite is a common cement found in large carbonate platforms throughout the Archean and Proterozoic (Ricketts & Donaldson, 1981; Sumner & Grotzinger, 1996). It occurs in some Phanerozoic carbonates, although only in restricted pore spaces (Sumner & Grotzinger, 1996; de Wet et al., 2004).

Large low relief dome-type stromatolites form mounds on the order of 2 m in diameter and 1 m of topographic relief. The layering of these domes is more regular and smooth than those of statifera and colleniella, but in general they have similar characteristics to these other stromatolites.

Crystal fans

Crystal fans occur in the Red Lake–Wallace Lake carbonate platform in varying sizes and lithofacies associations. Some of these have been termed atikokania by Hofmann et al. (1985), based on the similarity of the fans with atikokania of the Mosher Carbonate (e.g., Walcott, 1912; Sumner & Grotzinger, 2000; Fralick & Riding, 2015), and here we present new occurrences and evidence for the widespread pervasiveness of these fans in the Red Lake–Wallace Lake carbonate platform. In all areas in which the crystal pseudomorphs occur, they have an acicular radiating habit and are preserved by preferential silicification of the needle-like crystals in a fine-grained ferroan dolomite or calcite matrix. Similar structures found in Archean carbonates are usually interpreted as pseudo-morphs after aragonite (Sumner & Grotzinger, 2000, 2004; Fralick & Riding, 2015). The difference between fans in different occurrences is in their lithofacies associa-tions, density of packing and size of individual fans.

The most abundant occurrence of these fans is as verti-cally stacked radiating needle-like crystals ca 2 to 7 cm in height (Fig. 6A and B). The proximity of nucleation points of individual fans is such that adjacent fans truncate each other imparting a more vertical orientation to the crystals rather than a botryoidal morphology. This density of packing has been previously described for similar crystal pseudomorphs from other Archean carbonate platforms (Sumner & Grotzinger, 2000, 2004; Fralick & Riding, 2015). These stacked fan beds generally range
from 5 to 10 cm in thickness, but can form beds up to a few metres thick. The beds of stacked fans alternate with beds 2 to 10 cm thick of flat to wavy carbonate laminae like those found in the wavy laminae lithofacies. This type of crystal fan occurrence is associated with *stratifera* and wavy laminae lithofacies. The interbedding of these fans with laminated carbonate and their stromatolite association is common in the ca 2.54 Ga Campbellrand-Malmani Platform (Sumner & Grotzinger, 2004) and the ca 2.6 Ga Cheshire Formation (Sumner & Grotzinger, 2000). For the purposes of referencing the occurrence of these fans with laminated carbonate, their density of packing, and association with other lithofacies (with *stratifera* and wavy and irregular laminae facies) these fans are termed type 1 fans.

Another fan type (type 2) also occurs as more broadly fanning pseudomorphs with laminae that conform to the
botryoidal shape of the fans. These fans are rare in the Red Lake–Wallace Lake carbonate platform and poorly preserved. They are also similar to those found in the subtidal lithofacies assemblage of the Cambrian Malmani platform (Sumner & Grotzinger, 2000, 2004; Riding, 2008).

Atikokania are larger, with fans ranging from 5 to 30 cm in height and are densely packed and stacked (Fig. 6C and D). The stacked fan beds produce a dome-like structure about 2 m in diameter and 1.5 m in height.

**Laminated carbonate**

Laminated carbonate consists of flat layered orange weathering carbonate laminae. In polished sections, laminated carbonate is characterized by light coloured chert and dark grey millimetre-scale limestone bands. This type of occurrence is associated with large low relief domes and crystal fans.

**Ribbon rock**

Ribbon rock consists of wavy and laminated, fine- to medium-grained (0.05 to 0.5 mm), light and dark coloured carbonate couplets, occurring with irregular chert laminae, carbonate-shale couplets and rare magnetite laminae (Fig. 7A). Laminated light and dark carbonate couplets consist of light coloured, medium-grained (0.2 to 0.5 mm), carbonate laminae with millimetre-scale thicknesses separated by fine-grained (<0.2 mm), dark carbonate laminae with sub-millimetre-scale thicknesses. Carbonate and shale couplets alternate on a centimetre- to decimetre-scale. Magnetite laminae are rare but occur in locally abundant areas. Irregular folding occurs in some areas and is similar to folded structures described by Mclearth & James (1978). The ribbon rock lithofacies is similar to ribbon and parted limestone and carbonaceous rhythmite of the Victor Bay Formation (Sherman et al., 2000). In addition to areas where ribbon rock is preserved in stratigraphic section (Fig. 2A), these lithofacies also characterize outcrop 4 (Fig. 1D).

**Intraclastic carbonate lithoclasts and marl lithofacies**

In the Red Lake–Wallace Lake carbonate platform, these lithofacies occur as clasts of fine- to medium-grained (0.05 to 0.5 mm) calcite in a marl or carbonate matrix (Fig. 7B). The clasts of the disaggregated calcite beds are variable in morphology, but are generally elongate and deformed clasts up to 8 cm long and 0.2 to 3 cm thick. These are hosted in a marl matrix of fine-grained (0.01 to 0.2 mm) calcite and biotite in variable proportions and rare magnetite. The constituents of this lithofacies have the appearance of disaggregated ribbon rock facies. In addition to the occurrences of this lithofacies in stratigraphic sections in
In outcrop 3 (Fig. 1D) where it overlie interbedded decimetre-scale chert and shale beds.

**Carbonate-associated oxide facies iron formation**

Carbonate-associated oxide facies iron formation (OF-IF) is characterized by yellowish carbonate laminae interbedded with dark magnetic laminae (Fig. 7C). The laminae are planar to wavy, occasionally irregularly folded, and have light coloured carbonate disks throughout. The carbonate laminae of sub-millimetre thickness occur in packages separated by thin layers of dark, fine-grained material. These carbonate packages are up to 1 cm in thickness and have disseminated magnetite grains throughout. The dark magnetic laminae are composed of euhedral magnetite grains in a matrix of carbonate. In some instances, individual carbonate laminae grade into magnetite and are sharply overlain by carbonate producing chemically graded rhythmites. Thin, millimetre-scale, slate beds occur locally.

**Chert-oxide facies iron formation**

The chert-OF-IF is characterized by fine-grained, millimetre-scale laminations of light coloured chert and magnetite. Laminations are usually even and continuous, but deformation sometimes causes folding of the laminae. These lithofacies gradationally overlie the Conley Formation of the Wallace Lake area at outcrop 1. The gradation from the Conely Formation to the chert-OF-IF is characterized by a change from chloritic sandstones to siltstone at the top of the Conley Formation, which is transitional to siltstone, chert and oxide laminae, and overlain by chert-OF-IF. At Red Lake, chert-OF-IF occurs as layers 2 to 7 cm thick interbedded with ferroan dolomite layers of similar thicknesses.

**GEOCHEMISTRY: RESULTS AND INTERPRETATION**

The geochemical results are given in Tables S1–S3. They show that most of the samples are dolomite with only the atikokania crystal fans, laminated carbonate below them, ribbon rock and one sample of herring-bone cement composed of calcite (Table 1). The intraclastic carbonate lithoclasts forming the slump deposits and marl lithofacies associated with iron formation contain both dolomite and calcite portions. Strontium values are generally higher in the calcite atikokania fans, with amounts 10 times greater than the dolomite type 1 fans (Fig. 8). The calcite
also contains larger amounts of Ba and Pb. This is expected as Sr, Ba and Pb will substitute for calcium, especially in aragonite (McIntyre, 1963; Kretz, 1982), whereas elements with smaller radii, such as Fe, Mn, Ni, Cu and Co, should have greater concentrations in the dolomite (Swart, 2015). The Red Lake–Wallace Lake samples do not show the latter trend, with insignificant differences in Ni, Cu and Co concentrations between the dolomite and calcite (Table 1). As the amounts in both minerals are very small, this may reflect low concentrations of these elements in the 2.93 Ga ocean. The Mn and Fe are lowest in the atikokania, but are highest in the calcite layers directly below it. This is probably related to a local variation in water chemistry rather than a mineralogical difference.

There is also a difference in the $\delta^{18}$O values of the dolomite and calcite, with dolomite values of $-15.2 \pm 1.2^\circ/o_V-PDB$ and calcite values of $-11.7 \pm 1.2^\circ/o_V$ (Fig. 9). The $^{87}$Sr/$^{86}$Sr ratios are also dependent on mineralogy, as the five dolomite samples analysed were 0.7032 ± 0.0002, whereas three calcite samples were 0.7017, 0.7018 and 0.7020 (Satkoski et al., 2017). The values for calcite are very close to the hypothetical value for sea water at 2.9 Ga (Veizer & Jansen, 1979; Taylor & McLennan, 1985; Veizer et al., 1989a,b; Godderis & Veizer, 2000; Veizer, 2003; Satkoski et al., 2017). As all samples had very low levels of Rb, and it was adjusted for, the Sr isotopic results strongly indicate that the $^{87}$Sr/$^{86}$Sr for the calcite samples reflect sea water composition and have not been significantly reset, whereas the dolomite samples have had their Sr isotopic ratios altered, probably during dolomitization, the only known diagenetic or metamorphic event that affected the dolostones but not the limestones. The higher $^{87}$Sr/$^{86}$Sr ratios for the dolomite were likely caused by interaction with meteoric fluids that had been involved in weathering reactions with older crustal rocks. As higher water/rock ratios are commonly needed to alter the carbon isotopic signature than the stronontium isotopic signature (Veizer et al., 1989b; Jacobsen & Kaufman, 1994; Veizer, 2003), it is reasonable to assume that $\delta^{13}$C in the calcite samples reflects the original composition of the water-mass from which the calcium carbonate precipitated. As the dolomite samples have similar $\delta^{13}$C values to the calcite (Fig. 9A), it is also reasonable to assume that dolomitization did not alter the C isotopic values. Conversely, oxygen isotopic values commonly reset at lower water/rock ratios than those necessary to alter the Sr isotopic values. Therefore, it is likely that the $\delta^{18}$O values for dolomite have been reset, but it is unknown whether or not the $\delta^{18}$O for calcite are primary (Fig. 9).

Stromatolitic units in the 2.7 Ga Cheshire and Manjeri Formations of Zimbabwe have $\delta^{18}$O values (Abell et al., 1985a) similar to the calcite samples from Red Lake and Wallace Lake, although their $\delta^{13}$C values are mostly slightly negative as opposed to those from Red Lake–Wallace Lake calcite, which are slightly positive. The $\delta^{18}$O and $\delta^{13}$C values for the Red Lake–Wallace Lake dolomite are similar to Archean Mushandike stromatolites from Zimbabwe (Abell et al., 1985b). Abell et al. (1985b) believed that this difference between the Cheshire and Mushandike was caused by progressively higher metamorphic grades. However, this explanation cannot be applied to the Red Lake samples as both the dolomite and calcite have experienced the same grade of metamorphism. Furthermore, Abell et al. (1985b) believed that the C and O isotopic values for the Cheshire Formation represented those of the water from which the limestone precipitated, with little later modification. The similar $\delta^{18}$O values in the Red Lake–Wallace Lake calcite samples may, by comparison, also be close to their starting compositions.

Carbon isotope values obtained from the 2.55 Ga (Altermann & Nelson, 1998) Campbellrand carbonate platform of South Africa tend to be slightly more negative than the Red Lake–Wallace Lake samples with an average of $-0.5^\circ/o_V$, (Fischer et al., 2009). The Campbellrand $\delta^{18}$O values are heavier than those from the Red Lake–Wallace Lake samples with samples from two drill cores having $\delta^{18}$O values averaging $-7.6^\circ/o_V-PDB$ and $-8.5^\circ/o_V-PDB$ with upper limits on both holes of $-5.5^\circ/o_V$ and $-7.6^\circ/o_V$ and lower limits of $-16.7^\circ/o_V$ and $-10.8^\circ/o_V$ respectively (Fischer et al., 2009). The Hamersley carbonate platform of Australia is similar with $\delta^{13}$C values of $0 \pm 1.2^\circ/o_V$ and $\delta^{18}$O values ranging between $-5$ to $-15^\circ/o_PDB$ (Becker & Clayton, 1972; Veizer et al., 1990). The older 2.8 Ga Steep
Rock Carbonate Platform shows greater similarity to Red Lake–Wallace Lake calcite samples with δ¹³C values of 1.6 ± 0.7‰ and δ¹⁸O values of −8.9 ± 1.7‰°V-PDB, although it was noted that the one sample below −12‰° δ¹⁸O was altered (Fralick & Riding, 2015). Thus, the δ¹⁸O values obtained from the Red Lake–Wallace Lake calcite samples have similarities with those from other Archean carbonate platforms, but the O isotope values for the dolomite samples are lower and probably represent post-depositional alteration, possibly by meteoric fluids during dolomitization.

The presence of significant amounts of siliciclastic material in the carbonate samples can also affect the concentrations of elements of interest in the chemical sediments. Plotting relatively chemically immobile elements common in siliciclastics but not in carbonates against elements of interest will result in a positive correlation if there is a significant amount of siliciclastics in the samples. The Red Lake–Wallace Lake carbonate samples contain low amounts of Al and Ti, which show no correlation with Sr (Fig. 10A and B). In addition to affecting the concentration of elements such as Sr in the samples, contamination with siliciclastics can alter their Rare Earth Element (REE) pattern. Such contamination will limit primary sea water signatures, such as La, Ce, Eu, Gd and Y anomalies and cause flattening of the REE patterns (Kamber & Webb, 2001; Peter, 2003). Yttrium/holmium ratios can be used to test for siliciclastic contamination.

Fig. 8. The atikokania samples and laminated carbonate directly below an atikokania mound are calcite and contain considerably more Sr than the dolomite samples. The samples of slumped intraclastic material are mixtures of high Sr calcite and dolomite, whereas ribbon rock and herring-bone cement samples are low Sr calcite.

Fig. 9. (A) Cross-plot of O and C isotopic ratios. The carbonate associated with oxide facies iron formation (OF-IF) and a slump deposit have lower δ¹³C values than the shallower water deposits, with the majority of shallow water deposits of both calcite and dolomite having similar δ¹³C values. (B) Most calcite samples have higher δ¹⁸O values than the dolomite samples. Symbols are the same as in Fig. 8.
contamination altering REE patterns. Crustal rocks typically have $Y_{p.p.m.}/Ho_{p.p.m.}$ ratios of ca 26 while ratios in carbonate precipitates are commonly greater than 44 and modern sea water has ratios between ca 44 and 120 (Nozaki et al., 1997; Kamber & Webb, 2001; Bolhar et al., 2004). Thus, contamination of carbonate by siliciclastics should lower their $Y/Ho$ ratios. By plotting $Y/Ho$ against insoluble elements that concentrate in siliciclastics, the development of a negative correlation will indicate significant contamination by siliciclastic material (Kamber & Webb, 2001; Bolhar et al., 2004). The two slate samples have $Y/Ho$ ratios of 25 and 26, i.e. chondritic ratios expected of crustal rocks. The iron formation samples have $Y/Ho$ ratios of 33 $\pm$ 4, and the carbonates of 67 $\pm$ 22. There is no correlation between $Y/Ho$ and either $Al_2O_3$ or $TiO_2$ indicating no significant contamination for most samples (Fig. 10C and D), as expected with such low levels of elements that concentrate in siliciclastics. However, three of the samples may contain sufficient siliciclastic material to significantly influence their geochemistry. One of the herring-bone cement samples has considerably more $Al_2O_3$ and $TiO_2$ than the other chemical precipitates, and the two samples of magnetite from carbonate-associated iron formation have relatively high amounts of $Al$ and $Ti$, and $Ti$ respectively, which indicate possible significant siliciclastic impact on their geochemistry. (C and D) $Y/Ho$ weight ratios in most crustal rocks are ca 26, similar to the two siliciclastic samples. Most iron formation samples are between this value and 40, with the carbonate samples between 40 and 130. These are the ratios expected for those rock types. Significant amounts of siliciclastic contamination would lower the ratios for the chemical sediments, which, in general, do not appear to be the case. Symbols are the same as in Fig. 8.

Fig. 10. (A and B) Sr does not vary systematically with elements contained in the siliciclastic component of the samples, such as $Al$ and $Ti$. This indicates that siliciclastic levels in the majority of the samples are below the amount necessary to significantly impact the Sr content. However, a sample of herring-bone cement and the samples of magnetite from the carbonate-associated iron formation have relatively high amounts of $Al$ and $Ti$, and $Ti$ respectively, which indicate possible significant siliciclastic impact on their geochemistry. (C and D) $Y/Ho$ weight ratios in most crustal rocks are ca 26, similar to the two siliciclastic samples. Most iron formation samples are between this value and 40, with the carbonate samples between 40 and 130. These are the ratios expected for those rock types. Significant amounts of siliciclastic contamination would lower the ratios for the chemical sediments, which, in general, do not appear to be the case. Symbols are the same as in Fig. 8.

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Danielson et al., 1992). Some Archean chemical sediments also have positive La and Gd anomalies.

Rare earth elements were normalized using Post Archean Australian Shale (PAAS) and their patterns plotted. The REE patterns for magnetite and chert are similar, although with decreased abundance in the chert. They are also similar to other published REE patterns for Archean iron formations (Barrett et al., 1988; Fralick et al., 1989; Derry & Jacobsen, 1990; Danielson et al., 1992; Alibert & McCulloch, 1993; Bau & Moller, 1993; Bau & Dulski, 1996). Both the magnetite and chert are heavy REE enriched, have a substantial positive Eu anomaly and no Ce anomaly (Fig. 11A and B). The OF-IF associated with carbonate has a somewhat different pattern with positive La and Gd anomalies, reduced Eu anomalies, and, aside from one sample, are not heavy REE enriched with a somewhat flat pattern (Fig. 11C). The samples of ribbon rock, both the wavy and more planar laminated carbonate, sheet crack cement, herringbone cement, intraclastic carbonate lithoclasts and marl, type-1 fans, stromatolites and atikokania have patterns very similar to the iron formation samples (Figs 12, 13 and 14). The notable differences being generally lower slopes, positive La anomalies in the carbonates and some carbonate samples have positive Gd anomalies. The one sample that shows a different pattern is the laminated carbonate directly below the atikokania, which has a negative Ce anomaly and extensive heavy REE enrichment (Fig. 14D). The positive slope that results from the enrichment forms the carbonate end member of a continuum when the overall slope of the patterns is plotted against slope of the medium to heavy REEs (Fig. 15). A herring-bone cement sample is the only carbonate sample that has as high an overall slope, along with the iron formation magnetite and chert samples. A slate sample with slight light REE enrichment forms the other end of this continuum. The carbonate samples are spread out between these two end points with the magnetite from carbonate-associated OF-IF clustering at the slate end.

![Fig. 11. Rare earth element patterns for the rock types associated with iron formation. (A and B) The magnetite and chert layers in samples from banded iron formation are depleted in light rare earth elements (REEs) and have substantial positive Eu anomalies. They do not have significant La, Ce or Gd anomalies. (C) The carbonate-associated and oxide facies iron formation (OF-IF) samples were from the iron formation layers and mostly consist of magnetite and chert with minor carbonate. They have flat to light depleted patterns with positive La, Eu and Gd anomalies and appear quite different from the iron formation not associated with carbonate layers. This may reflect their higher siliciclastic content (Fig. 10). (D) The carbonaceous slate samples are both light REE enriched and depleted, with moderate middle REE enrichment and one has a distinct positive Eu anomaly.](image-url)
Fig. 12. The samples of various forms of laminated carbonate, wavy laminae, and ribbon rock (A), cement (B) and slumped material (C) are all similar with light rare earth element (REE) depletion, positive Eu anomalies and flat to slightly positive Gd anomalies. The sample of herring-bone calcite higher on the graph than the other has a much steeper slope and is also the only calcite sample in the figure, as the other herring-bone calcite has been dolomitized.
Comparing the Red Lake–Wallace Lake samples to those from the next oldest carbonate platform, the 2.8 Ga Steep Rock succession (Figs 13 and 14) highlights some similarities and differences. The Red Lake–Wallace Lake carbonates generally have larger positive Eu anomalies, fewer Gd anomalies, more subdued La anomalies and lower slopes. The most notable exception to this is the sample of laminated carbonate immediately below atikokania, which has a REE pattern very similar to that of the Steep Rock samples with negative Ce anomalies (compare Fig. 14B, C and D).

DISCUSSION

Stromatolite biogenicity

The stromatolites of the Red Lake–Wallace Lake carbonate platform likely formed by biomediated carbonate precipitation in a low energy intertidal environment. The laminae of the stromatolites are irregular and crinkly with variable thicknesses characteristic of the fine-grained crusts of Riding (2008), and these crusts are a prerequisite for identifying Archean lithified microbial mats (Awramik & Grey, 2005; Fralick & Riding, 2015). In addition, lamnoid fenestral fabrics and bird’s eye vugs are ubiquitous in the stromatolites and can form from the desiccation and decomposition of microbial mats or sediment shrinkage during desiccation (Logan, 1974; Shinn, 1968; Demicco & Hardie, 1994; Flugel, 2010).

The internal features of the reticulate stromatactis-like structures and sheet cracks are similar to those found in the Doushantuo Cap Carbonates (DCC) (cf. Jiang et al., 2006). The stromatactis-like structures of the Red Lake–Wallace Lake carbonate platform differ from those of the DCC in that they are regularly confined by stromatolitic layers, whereas those in the DCC form extensive networks in plastically deformed detrital carbonate. Jiang et al. (2006) interpreted the stromatactis-like structures and sheet cracks to represent deformation caused by the injection of fluid into partially lithified sediment of low
Fig. 14. Samples of atikokania (A) are light rare earth element (REE) depleted with positive La, Eu and lesser Gd anomalies, and flat Ce. Compared to samples of Steep Rock crystal fans (C) and cuspatate fenestrae fabric (C.F.F.) (D) the Steep Rock samples have higher slopes, larger La and Gd anomalies, lower Eu, and most exhibit a negative Ce anomaly. The Steep Rock samples were probably deposited during periods of restricted circulation onto that carbonate platform (Riding et al., 2014; Fralick & Riding, 2015), whereas the atikokania and other REE patterns from the Red Lake–Wallace Lake platform are more similar to the Steep Rock columnar stromatolites (Fig. 13D) that were deposited during less restricted circulation. However, laminated carbonate from directly under an atikokania mound has a REE pattern (B) comparable to the Steep Rock platform samples deposited during a period of more restricted circulation.

Fig. 15. Post Archean Australian Shale (PAAS) normalized (SN) ratios of Gd/Yb and Pr/Yb, representing slope of the heavy rare earth elements (REEs) and slope of the entire pattern, respectively. The chert and magnetite from the banded iron formation as a group have the highest slopes. The groups composed of slate, and magnetite from carbonate-associated iron formation have the lowest slopes. The carbonate samples form a continuum between these two end members. Symbols are the same as Fig. 8.
permeability. A similar process can be envisioned for the stromatactis-like structures in the Red Lake–Wallace Lake carbonate platform in which gases within the stromatolitic layering are confined by irregularly developed sparry crusts and the underlying leathery mats were deformed by pressurisation of gases within the stromatolites resulting in rounded and irregular voids with flat upper surfaces. Similarly, sheet cracks could have formed by fluid injected along layers of carbonate laminae. In addition, the limited extent of the structures implies localized fluid production in both stromatolites and wavy laminae lithofacies after deposition. However, the plastic deformation of stromatolitic laminae and wavy laminae indicates that fluid production occurred prior to or contemporaneous with lithification. Localized fluid production within the stromatolitic laminae would require the decomposition of organic material either by abiotic processes with CO₂ as a by-product (cf. Larralde et al., 1995) or by several microbial pathways that are known to be operating by as early as the Neoarchean and have gaseous by-products (cf. Czaja et al., 2010).

In summary, the development of thick microbial mats on the shallow sea floor was accompanied by periodic sparry crust precipitation, periodic in situ desiccation and partial early cementation of the microbial mat to produce laminoid fenestral fabrics and bird’s eye vugs, and then burial and mat decomposition to produce stromatactis-like structures and sheet cracks through in situ gas production.

**Evidence for low energy restricted environment**

**Stromatolite morphology**

The energy of the environment in which the earliest stromatolites formed is important in understanding limiting factors affecting the geographic extent of the earliest life. Was life limited to environments that were shallow,
restricted, low energy, and sheltered from destructive physical or chemical elements, or did life require current flux where high nutrient supply facilitated the development of microbial ecosystems? By examining the characteristics of stromatolite morphology related to the environment and applying this to the physical characteristics of the stromatolites in the present study and those of temporally related carbonate platforms provides insight into this question.

Dupraz et al. (2006) and Tice et al. (2011) show that stromatolite morphology is dependent on the physical characteristics of microbial mats (i.e. mat cohesion and response to current induced shear stress and the affinity of nutrients to the mats surface), sediment supply, and the limited diffusion and concentration of nutrients through and in the water that is in contact with the surface of microbial mats. Variations in these factors can produce four main morphologies given a range of peritidal environments (Dupraz et al., 2006; Tice et al., 2011). In the first scenario, in which current-induced shear stress is greater than mat cohesion on topographic highs, mats are limited to topographically low hydraulically protected areas, producing thin discontinuous mat lenses in a detrital matrix. If, on topographic highs, mat cohesion is greater than current induced shear stress and mat cohesion between domes tends to be less than current induced shear stress, erosion of laminae and/or deposition of detritus in between domes will produce isolated domal stromatolites and branching stromatolites. The detritus supply is particularly important in the development of columnar and branching stromatolites (Dupraz et al., 2006). If sediment supply is limited and the mat is resistant to erosion on topographic highs and lows, the dominant limiting factor in stromatolitic growth is nutrient diffusion and water depth. Diffusion-limited processes (boundary Reynolds number, nutrient concentration and nutrient-mat affinity) may severely limit the growth of the mat between domes leading to massive and linked stromatolitic forms. Finally, if the nutrient-mat affinity is large, columnar stromatolites may form in the absence of sediment supply. As implied by the above discussion, given a consistent mat cohesiveness, the stromatolitic forms were presented in order of decreasing current energy.

In Archean carbonate formations, stromatolitic morphologies are consistent with the theoretical considerations above, such that, stromatolitic morphologies reflect the energy of the environment and higher energy environments tend to produce more diverse morphologies. The ca 3 Ga Chobeni Formation is a stromatolite bearing mixed siliciclastic-carbonate formation formed in a high energy tide-dominated shallow marine environment (Beukes & Lowe, 1989; Siahi et al., 2016). Stromatolitic forms are diverse from supratidal stratiform, intertidal domal and subtidal/tidal channel linked to partially linked branching columnar, and laterally linked and isolated conical (conophyton) (Siahi et al., 2016). Siahi et al. (2016) recognize the importance of physical processes in the morphology of the stromatolites in noting that strong tidal and storm currents provide an ideal environment for the formation of the conical and sporadic domal stromatolites. Columnar, domal and conical stromatolites occur as isolated forms or linked groups unevenly distributed in fine to coarse-grained clastic sediment between...
the domes and groups of stromatolites (Beukes & Lowe, 1989; Siahi et al., 2016). This is consistent with mat survival rather than nutrient availability as a limiting factor in stromatolite development, and these stromatolitic forms are expected in a high energy environment.

Younger stromatolitic carbonate are morphologically diverse, yet conical, columnar, domal, and stratiform morphologies are still ubiquitous in carbonate platforms through the Neoarchean (e.g. Sumner & Grotzinger, 2004; Sakurai et al., 2005; Awramik & Buchheim, 2009; Fralick & Riding, 2015). In the ca 2.8 Ga Mosher Carbonate columnar stromatolites, δ13C values, Sr, Ba, Mn and Fe concentrations in the columnar and laterally linked domal stromatolites lie on a mixing line between evaporitic facies and facies that are interpreted as having formed when open marine water circulated through the platform (Fralick & Riding, 2015). The columnar stromatolites represent the open marine end-member component and laterally linked domal stromatolites trend more towards formation during periods of more restricted water circulation (Fralick & Riding, 2015), suggesting that laterally linked domal stromatolites were affected by diffusion limited nutrient availability whereas columnar stromatolites formed during periods of higher energy which probably resulted in a clastic sediment supply. The variability in the stromatolitic forms may have been related to varying current energy.

The ca 2.72 Ga Tumbiana Formation is a lacustrine high energy, near-shore, shallow water, mixed carbonate-siliciclastic depositional environment, in which stromatolite morphology varies as a function of environmental energy (Awramik & Buchheim, 2009). In the highest energy, environment stromatolitic forms are rare consisting of isolated small domes and columns. With decreasing energy, stromatolite abundance increased and morphotypes included large columns, domes (linked clusters) and clusters of branching centimetre-scale columns. The increase in abundance of stromatolites within lower energy environments suggests that mat survival played an important role in the presence or absence of stromatolitic forms, and where microbial mats could propagate out of hydraulically protected areas, they form high energy morphotypes.

In the three stromatolitic carbonate occurrences discussed above, stromatolitic diversity and the survival of microbial mats is dependent on the energy of the environment, and all of these are indicative of mid to high energy environments. In contrast, the Red Lake–Wallace Lake carbonate platform lacks many of the higher energy stromatolitic forms and stromatolitic diversity found in other Archean carbonate platforms suggesting a lower energy depositional environment. The main stromatolitic morphology, laterally linked domal stromatolites (stratifera), necessarily requires limited clastic sedimentation and an environment where diffusion of nutrients is the limiting process in stromatolite development. Whereas Colleniella are associated with herring-bone cross-stratification and formed within tidal channels. Because of the limited exposure of outcrops of colleniella, it is not possible to determine if these stromatolites began development within a tidal channel facies or were stratifera in which the development of stronger current activity destroyed low areas between the individual domes. Therefore, the extent to which colleniella can be used as an indicator of the depositional environment of the platform is limited. However, the paucity of higher energy stromatolitic morphologies, such as branching and non-branching columnar stromatolites, and the pervasive appearance of stratifera is indicative of sedimentation within a near-shore, low energy environment, possibly a very low slope coast with lagoons, similar in some ways to today’s Trucial Coast.

In addition to an absence of high energy stromatolitic morphologies, the Red Lake–Wallace Lake carbonate platform lacks conical stromatolites. These stromatolitic forms have generally been interpreted as deep to shallow subtidal deposits formed on platform slopes (Grotzinger, 1989). Batchelor et al. (2004) have shown, through modelling, that the conical form occurs when phototactic microbial growth in stromatolites is much more rapid than mineral accretion. Consequently, conical stromatolites should only form within the photic zone. If the lack of conical stromatolites in the Red Lake–Wallace Lake carbonates is not the result of preferential preservation of other facies, using the reasoning of Batchelor et al. (2004), mineral accretion was too great to allow this stromatolitic form to occur. This supports a relatively restricted environment of carbonate precipitation. In addition, the ribbon rock and intraclastic carbonate lithoclasts and marl lithofacies are interpreted as platform proximal slope lithofacies. A lack of conical stromatolites in this environment indicates that these lithofacies formed below the photic zone and/or the platform slope was too unstable to allow the development of microbial mats. This would suggest a steep-sided flat-topped geometry for the platform.

Pseudomorphic crystal fans

Large Archean and Proterozoic sea floor precipitates occurred as crystal fan structures that are ubiquitous in platform carbonates and formed in restricted to open marine settings in upper intertidal to deep subtidal platform margin environments (e.g. Grotzinger, 1986; Sumner & Grotzinger, 1996, 2000, 2004; Grotzinger & James, 2000; Allwood et al., 2007; Riding, 2008; Fralick &
Riding, 2015). Although variations in the types of Precambrian crystal fans can occur in the morphology, size and primary mineralogy, the earliest centimetre-scale crystal fans in Archean carbonate platforms formed in restricted low energy environments (Allwood et al., 2006; Fralick & Riding, 2015). In addition, neither the Chobeni Formation or Tumbiana Formation, which have both been interpreted as high energy environments, has crystal fans (cf. Beukes & Lowe, 1989; Sakurai et al., 2005; Awramik & Buchheim, 2009; Siahi et al., 2016). Although crystal fans in younger Archean carbonate platforms may have formed in open marine, high energy settings (cf. Grotzinger, 1986; Sumner & Grotzinger, 1996, 2000, 2004; Grotzinger & James, 2000), there is no indication that pseudomorph crystal fans formed in high energy and/or open marine environments prior to 2.8 Ga.

Although they are densely packed, the crystal fans of the Red Lake–Wallace Lake carbonate platform form delicate needle-like crystals with no evidence of current resistance. In addition, the similar morphology of the crystal fans found in the shallow to deep areas of the Red Lake–Wallace Lake carbonate platform indicates that the fans were not isolated to a single environment but span the entire peritidal range, and that the height of the fans was possibly controlled by water depth. Extrapolating from environments where similar fans formed at this time, it is likely that this platform wide fan development occurred only during periods where the platform was subject to restricted and evaporitic conditions.

**Depositional environments**

The lithofacies of the Red Lake–Wallace Lake carbonate platform have been grouped into six lithofacies assemblages in which the sedimentary structures have been related to specific depositional environments (Fig. 16). These depositional environments are supratidal, upper–mid-intertidal, lower intertidal, tidal channel and shallow subtidal, subtidal, and platform slope and distal environments.

**Supratidal lithofacies assemblage**

The wavy laminae lithofacies is characterized by millimetre-scale wavy and crinkly laminae containing teepee structures, tufa, cement crusts, pseudomorphs after gypsum, and desiccation cracks, features that are typical of supratidal environments in the Proterozoic and Archean (Grotzinger & Reed, 1983; Clough & Goldhammer, 2000; Bekker & Erikkson, 2003; Sumner & Grotzinger, 2004; Allwood et al., 2007). In addition, flat lying laminoid fenestral fabrics associated with wavy laminae were likely produced by desiccation of microbial mats in such an environment. The deformation features of these mats, roll-up structures and irregular folding, are from flooding of the supratidal flat. The presence of soft sediment deformation features indicates that some areas in this environment remained wet while at times relatively dry conditions elsewhere produced teepee structures, gypsum, desiccation cracks and colloform crusts. Wet conditions may have persisted in supratidal ponds as was suggest by Clough & Goldhammer (2000) in the Katakturuk Dolomite or the “wet” sedimentary structures may represent upper intertidal zone environments on a platform with limited topographic relief.

**Upper–mid-intertidal lithofacies assemblage**

Type 1 fans found in Red Lake–Wallace Lake carbonate platform are identical to crystal pseudomorphs occurring in the tidal flat environment of the Campbellrand–Malman Platform (Sumner & Grotzinger, 2004) and the subtidal environment in the Cheshire Formation (Sumner & Grotzinger, 2000). Because the height of the fans appears to be controlled by water depth, the height and their association with the wavy laminae lithofacies places the fans in the upper to mid-intertidal flat environment. Type 1 fans are unique only in their association with thin carbonate laminae between the fan layers which may be a transition to wavy laminae lithofacies. In addition to crystal fans, large bioherms of *statifera* appear to be upwardly transitional to wavy laminae lithofacies. That is, the domal stromatolites lose relief up section to form wavy and irregular laminae characteristic of wavy laminae lithofacies. Although, *statifera* in the Red Lake–Wallace Lake carbonate platform are interpreted as lower intertidal facies, water depth may control the height of the domes. As the growth of the stromatolites reduces accommodation space, they lose topographic relief, begin to flatten, and form upper intertidal to supratidal lithofacies assemblages. Thus, low relief domes in these areas represent transitions from large *statifera* to wavy laminae lithofacies in the upper to mid-intertidal flat environment.

**Lower intertidal lithofacies assemblage**

Although not a definite environmental indicator (Hofmann et al., 2004), other Precambrian LLD stromatolites are interpreted as tidal flat to shallow subtidal depositional structures (Grotzinger, 1986; Clough & Goldhammer, 2000; Sumner & Grotzinger, 2004). Here, the *statifera* contain laminoid fenestral fabric and birds eye vugs indicative of some desiccation from periodic subaerial exposure or formation in an environment that was evaporitic (Logan, 1974; Shinn, 1968; Demicco & Hardie, 1994; Flugel, 2010). In addition, the *statifera* are
associated with intertidal to supratidal lithofacies; type 1 fans and wavy laminae lithofacies. Furthermore, the domes are gradational to upper intertidal/supratidal environments. *Statifera* are also closely associated with tidal channel facies assemblages. Thus, *statifera* are interpreted as forming and were the dominant structure in the lower intertidal to shallow subtidal environment of the Red Lake–Wallace Lake carbonate platform.

**Tidal channel and shallow subtidal lithofacies assemblage**

Tidal channel lithofacies were identified by the presence of intraclastic mud-chip conglomerate with herring-bone cross-stratification. This lithofacies assemblage also contains some HBC and *colleniella*. As discussed above, the transition from laterally linked to isolated domal stromatolites is controlled by increasing turbulence in the water. Such an interpretation has also been applied to other Precambrian stromatolitic carbonates (e.g. Grotzinger, 1986; Hofmann *et al*., 2004). Because most sedimentary structures in the Red Lake–Wallace Lake carbonates are indicative of an ambient low energy environment, the formation of *colleniella* is strongly suggestive of a unique microenvironment and most likely necessitates their formation in tidal channels. In addition, in the Red Lake–Wallace Lake carbonates, HBC is only found associated with the tidal channel lithofacies assemblage. If this association is not from preferential preservation in this area, then HBC may have formed in a zone of mixing between more shallow-supratidal/intertidal water and offshore water. This interpretation is supported by the variable trace element geochemistry in HBC (Fig. 12). It should also be noted that *statifera* are found in this assemblage, which may indicate their proliferation into the subtidal environment away from the influence of stronger currents in tidal channels.

**Subtidal lithofacies assemblage**

The subtidal environment is characterized by structures such as atikokania and *statifera* that require low turbulence to form. As discussed above, the size of crystal fans may be controlled by water depth, and the large size of atikokania that form metre-scale domes likely require that they form part of the subtidal assemblage. Type 2 crystal fans appear to be draped by sediment as they formed. These are not well preserved. However, these fans are like those found in the Campbellrand-Malmani Platform within the subtidal zone (cf. Sumner & Grotzinger, 2004) and are similarly interpreted here. In addition to the crystal fans and *statifera*, large low relief domes are also interpreted as having formed in the subtidal environment likely stratigraphically below *statifera*. The laminae of the domes have a weak laminoid fenestral fabric with respect to *statifera* and wavy laminae facies. This likely indicates a relatively lower degree of desiccation in an evaporitic environment rather than being periodically sub-aerially exposed and these likely formed in an evaporitic lagoonal setting.

As is noted above, the proliferation of *statifera* in the Red Lake–Wallace Lake carbonate platform has important implications for the depositional environment of the platform. *Colleniella* developed in microenvironments characterized by tidal channels and are isolated due to the higher turbulent water flow in this environment. In addition, in other Archean carbonates crystal fans are associated with low energy structures (Allwood *et al*., 2007; Fralick & Riding, 2015). However, truncation surfaces in some stromatolites and roll-up structures in the supratidal zone indicate possibly infrequent storm events.

**Platform slope and distal lithofacies assemblages**

The platform slope lithofacies assemblage is defined by ribbon rock, disaggregated calcite beds and marl, carbonate-associated iron formation, OF-IF, chert and slate. In the ribbon rock facies, the carbonate beds of the carbonate-shale couplets are likely thin bedded, platform derived detrital carbonate overlain by shale derived from sediment fallout, and the irregular bedding associated with these couplets is characteristic of syn-depositional folding by creep in an upper slope, peri-platform environment (McIearth & James, 1978). The intraclastic carbonate lithoclasts and marl contain fragments representing mixtures of the constituents of the ribbon rock lithofacies and these lithofacies are closely related. Eberli (1988) found the frequency of slope failure was increased and the angle of repose needed to produce slope failure decreased when peri-platform oozes hosted platform derived detrital carbonate as opposed to uniform sediments. Similarly, the density contrasts between different beds in the ribbon rock likely resulted in more prolific slope failure and slumping on the upper platform slope. Thus, intraclastic carbonate lithoclasts and marl lithofacies are likely slump-related structures on the upper platform slope.

The slump structures are found overlying slate-chert beds and carbonate-associated iron formation. These latter lithofacies are considered to have formed on the platform slope below ribbon rock facies. The carbonate beds are interpreted as being platform derived, chert and shale pelagic in origin, and iron formation produced from oxy-hydroxide precipitation at a weak oxidative chemocline between the platform and more distal environments. The absence of slumping, carbonate laminae and turbidity current deposits in laminated chert and chert-oxide iron
formation indicates that these lithofacies formed in deeper water than the carbonate-associated iron formation and considered a platform distal lithofacies.

**Geochemistry**

As the geochemistry of chemical sediments, and in particular their REE contents, can reflect the water from which they precipitated (Barrett et al., 1988; Derry & Jacobsen, 1990; Murray et al., 1992; Danielson et al., 1992; Alibert & McCulloch, 1993; Bau, 1993; Bau & Moller, 1993; Bau & Dulski, 1996; Kamber & Webb, 2001; Kato & Nakamura, 2003; Van Kranendonk et al., 2003; Bolhar et al., 2004; Klein, 2005; Planavsky et al., 2010; Bekker et al., 2010), they are key to understanding the ambient water masses associated with various sea floor precipitates and cements. The geochemistry also provides insight into the later alteration history of the sediment through the concentrations and isotopic ratios of elements more prone to exchange with the surrounding fluid, such as Sr, Ba and O.

Compared to limestones of the 2.8 Ga Steep Rock carbonate platform, which have not been significantly altered (Veizer et al., 1982; Fralick & Riding, 2015), the Sr and Ba concentrations in the Red Lake dolomites are low (Table 1). The $^{87}$Sr/$^{86}$Sr ratios for the Red Lake dolomite samples are, on average, 0.0014$_{10}$, higher than those for the calcite samples and $^{18}$O values are significantly lower for the dolomite samples than the calcite samples (Fig. 9). This indicates that Sr, Ba and O were exchanged during alteration and the higher Sr isotopic ratios requires an alteration fluid that only affected the dolomitized samples and was derived, at least in part, from a cratonic source. The dolomitization itself is the prime candidate for this. However, there is no significant difference between the $^{13}$C values for the dolomite and calcite samples (Fig. 9), indicating that the dolomitization did not alter these.

Three of the samples are removed from the main grouping of $^{13}$C values (Fig. 9). These samples, the carbonate associated with iron formation and one of the slump deposit samples, formed in deeper water. Although data from previous studies have estimated the carbon isotopic composition of Archean sea water to have $^{13}$C values of $+1.5 _{0}$ (Veizer et al., 1989b and references therein), there is growing evidence that deeper water carbonates associated with other Archean carbonate platforms commonly have lower $^{13}$C values, such as those from the Hamersley (Becker & Clayton, 1972; Kaufman et al., 1990), Transvaal Supergroup (Beukes et al., 1990; Schneiderhan et al., 2006; Fischer et al., 2009) and Steep Rock (Fralick & Riding, 2015). Kaufman et al. (1990) believed that deep Archean sea water had a $^{13}$C value of ca $-5.5 _{0}$ and diagenetic reactions between organic carbon and iron hydroxide had further lowered it in their samples. A lower $^{13}$C value for deeper sea water was also suggested by Fralick & Riding (2015) who obtained $-5.5 _{0}$ for a sharp sided siderite layer with no associated iron oxides. However, Fischer et al. (2009) and Heimann et al. (2010) have interpreted the lower values of the siderite in the Kuruman Formation overlying the Campbellrand carbonate platform as due to syn-depositional precipitation of siderite by microbial dissimilatory iron reduction of OF-IF. The carbonates of the Red Lake–Wallace Lake platform can offer insight into the nature of the cause of the variation in $^{13}$C values. The carbonate-associated oxide facies IF reflects the transitional facies between shallow carbonate deposits and distal chert-oxide facies IF. These contain the most negative $^{13}$C values of all the carbonate samples, $-3.1 _{0}$ and $-3.9 _{0}$. One of the slump samples, which was also deposited in deeper water, has the next lowest $^{13}$C value of $-1.0 _{0}$. Because the carbonate in the carbonate-associated OF-IF is calcite and the carbonate in the slump is ferroan dolomite, the more negative values of these carbonates relative to the peritidal carbonates cannot be attributed to the microbial pathways described by Fischer et al. (2009) and Heimann et al. (2010) for siderite precipitation. It is more likely that the decreasing values for $^{13}$C going from the Red Lake–Wallace Lake carbonate shelf downslope to the slump deposits and the iron formation-associated carbonate indicates a gradient in the carbon isotopic ratio with depth.

There is a change in $^{13}$C values between the shallow water carbonates in the Mesoarchean and the Neoarchean; the ca 3.0 Ga Pongola carbonates have shallow water $^{13}$C values of 2 $\pm$ 1$_{0}$ (Veizer et al., 1990) and the 2.8 Ga Steep Rock platform has shallow water carbonates with $^{13}$C values of 1.6 $\pm$ 0.7$_{0}$ (Fralick & Riding, 2015), whereas the 2.55 Ga Campbellrand and Gamohaan have shallow water $^{13}$C values averaging $-0.5$ and $-1.0 _{0}$ (Fischer et al., 2009; Heimann et al., 2010), respectively. The heavy carbon enrichment in the Mesoarchean shallow carbonate deposits is also reflected in $^{13}$C values for the shallow water carbonates of the Red Lake–Wallace Lake platform, which are 0.5 $\pm$ 0.4$_{0}$.

The REEs have been used extensively to infer attributes of the solutions from which chemical sediments have precipitated. Variations in Y/Ho ratios and PAAS normalized La, Ce, Eu and Gd anomalies, plus the slope of the pattern, all provide clues to fluid composition. The Y/Ho weight ratio in crustal rocks of about 26 (Kamber & Webb, 2001) is maintained as the two elements behave very similarly in this system (Nozaki et al., 1997; Bau, 1999). However, in aqueous solution Y and Ho behave differently. Dependent on the availability of particulate matter (Nozaki et al., 1997) and solution-surface...
complexation behaviour (Bau, 1999; Luo & Byrne, 2004; Quinn et al., 2004, 2006) the Y/Ho weight ratio of modern sea water varies between 44 and 120 (cf. Nozaki et al., 1997; Kamber & Webb, 2001). Similarly, the distribution of light REEs and heavy REEs depends on solution chemistry and the availability of particulate matter (Lee & Byrne, 1992; Bau, 1999; Luo & Byrne, 2004; Quinn et al., 2004, 2006). In solutions dominated by dissolved carbonate, REE carbonate complexation is dependent on pH and \([\text{CO}_3^{2-}]_t\) (total dissolved carbonate) (Luo & Byrne, 2004; Quinn et al., 2004, 2006). At lower pH, trivalent metal ions are more soluble and the formation of \(\text{H}_2\text{CO}_3\) likely limits activation sites for complexation, resulting in REE carbonate complexation being relatively unselective at low pH and \([\text{CO}_3^{2-}]_t\) concentration (Quinn et al., 2004, 2006).

With increasing pH and \([\text{CO}_3^{2-}]_t\), heavy REEs and Y preferentially form solution complexes with carbonate ions, but the degree of carbonate complexation of heavy REEs relative to Y is increased, making it more likely that Y will come out of solution rather than Ho possibly resulting in super-chondritic Y/Ho ratios in precipitates. Also, solution complexation constants decrease from Nd to La in a curved path that is exponential with increasing pH and/or \([\text{CO}_3^{2-}]_t\), and the ability of Gd to form surface complexes, compared to its neighbours, decreases as well (Ohta & Kawabe, 2001; Quinn et al., 2004, 2006).

Surface complexation of REEs with precipitating iron hydroxides is also dependent on pH (Bau, 1999; Quinn et al., 2004, 2006) and \([\text{CO}_3^{2-}]_t\) (Sholkovitz et al., 1994; Quinn et al., 2004, 2006). Bau (1999) found that middle REEs were enriched in the hydroxides/oxides and Y was lower than Ho, also leading to higher Y/Ho ratios in the fluid.

Particulate organic matter is also important in REE scavenging. Lee & Byrne (1992) performed a study of REE complexation with organic ligands and found that heavy REEs formed surface complexes with organic surface ligands to a greater degree than light REEs. They also discovered that Gd complexed with organic surface ligands to a lesser degree than its neighbouring REEs. Similarly, Nozaki et al. (1997) found that Y behaves in a similar manner to light REEs in having low stability with organic surface complexes. However, Sholkovitz et al. (1994) discovered that precipitating oxides on particulate matter preferentially removed light REEs from solution.

Neoarchean and Palaeoproterozoic carbonates tend to be dominated by super-chondritic Y/Ho ratios, \(\text{Pr/Yb}_{\text{PAAS}}\) lower than or close to unity, positive Eu, La, and less commonly Gd anomalies, and no Ce anomalies (cf. Kamber & Webb, 2001; Bolhar et al., 2004, 2005; Kamber et al., 2004; Allwood et al., 2010; Planavsky et al., 2010). Neoarchean iron formations have similar trends, although commonly with lower Y/Ho ratios, \(\text{Pr/Yb}_{\text{PAAS}} < 1\), and Gd and La anomalies are subdued to absent (cf. Bau & Dulecki, 1996; Bolhar et al., 2004, 2005; Planavsky et al., 2010; Thurston et al., 2012). The Red Lake–Wallace Lake Carbonate Platform REE patterns for both iron formation and carbonates are similar to those in Neoarchean and Palaeoproterozoic deposits, with super-chondritic Y/Ho, Yb/PrPAAS close to unity to less than one, positive La (except the iron formation) and Eu anomalies, variable Gd anomalies and no Ce anomalies, except in one sample (Figs 11, 12, 13 and 14). The carbonate-associated iron formation samples are somewhat different with Gd anomalies of the same magnitude as their less pronounced Eu anomalies and flatter REE patterns.

From the previous discussion, it can be concluded that the enhanced ability of heavy REEs to form carbonate complexes would leave more free light REEs in solution and available for adsorption onto particulate matter (Bolhar et al., 2004; and references therein). This would have led to a depletion of the light REEs in Archean sea water, similar to today. The positive La and Gd anomalies in the carbonate samples may be due to their lower ability to complex with carbonate in solution and particulate matter, respectively. The super-chondritic Y/Ho ratios could be either the result of differences in the two element’s ability to complex with carbonate in solution or differences in scavenging processes by particulate matter resulting in preferential removal of Ho upon delivery to the ocean (Zhang et al., 1994; Nozaki et al., 1997). Although the slope of the REE curves is less for the Red Lake–Wallace Lake chemical sediments, these trends are similar to average modern sea water.

The Red Lake–Wallace Lake samples have pronounced positive Eu anomalies and no negative Ce anomalies, except for one sample (Fig. 17). Positive Eu anomalies are common in Archean and early Palaeoproterozoic chemical sediments. Europium is the only REE that can exist in the \(^{125}\) state, and as such can substitute for Ca and Sr in minerals such as plagioclase. The REEs were leached from the ocean crust during hydrothermal circulation and these fluids developed a positive Eu anomaly (Klinkhammer et al., 1983, 1994; Derry & Jacobsen, 1990; Danielson et al., 1992). The REE contribution from this hydrothermal circulation dominated over REEs delivered in continental runoff during the Archean and, thus, the oceans at this time had excess Eu compared to other REEs. The lack of a negative Ce anomaly (Fig. 17) is the result of extremely low concentrations of oxygen present at this time. Cerium can exist in the \(^{144}\) state and when oxidized forms cerianite or is adsorbed onto iron hydroxides removing it from solution. On the modern Earth, oxidized soils have positive Ce anomalies and groundwater commonly develops negative Ce anomalies, leading to the ocean having a pronounced negative anomaly. In the
Archean, without common oxidizing agents Ce remained in the Ce $^{3+}$ state and behaved similarly to the other REEs. However, one sample has a negative Ce anomaly, an elevated Y/Ho ratio, and a higher positive slope than the others.

The sample of laminated calcite lying directly under an atikokania mound has a REE pattern very similar to patterns from crystal fan and cuspatc fenestrate fabric samples from the 2.8 Ga Steep Rock carbonate platform (Fig. 14B, C and D). It is possible that the mounds provided a localized restricted environment where oxygen, produced by prolific stromatolite development, could build up without being overwhelmed by tidal flushing of relatively anoxic ocean water. This would have allowed a redox boundary to exist at the edge of this locally restricted area, Ce to preferentially be deposited there, and the more central area develops a negative Ce anomaly. One of the atikokania samples directly overlying the laminated carbonate has a positive Ce anomaly, further reinforcing this scenario. It is noteworthy that this sample and those deposited in areas of restricted circulation on the Steep Rock platform (Fralick & Riding, 2015) have steeper REE slopes than those deposited in less restricted settings. This may be caused by photosynthetic activity resulting in an increase in pH, which could then drive a draw-down of the HCO$_3^-$ with delivery of HREEs complexed with it. The sample of laminated carbonate from directly under an atikokania mound is also enriched in iron oxides, which would have also delivered HREEs.

The sample discussed above is in contrast to the REE patterns for other carbonate samples from the Red Lake–Wallace Lake Carbonate Platform (Figs 12, 13A and B, and 14A), which have similar slopes to columnar stromatolite samples from the Steep Rock Platform (Fig. 13D). Of the carbonate samples, the stromatolite samples have the lowest slopes (Pr/Yb$_{\text{SN}}$ average 0-7), and the chert-OF-IF samples, which should reflect the basin water chemistry, have the greatest slopes (Pr/Yb$_{\text{SN}}$ average 0-2) (Fig. 15). The siliciclastic samples also have low slopes and it is possible that the low slopes of some of the chemical sediments are caused by siliciclastic contamination. This is probably applicable to the two samples of magnetite from the carbonate-associated iron formation, which in addition to flattened patterns, have low Y/Ho ratios and elevated concentrations of titanium. One of the samples of carbonate from the carbonate-associated iron formation and a stromatolite sample also have suspiciously flat slopes similar to the siliciclastics. However, the array of points, representing the carbonate samples, which stretch between the siliciclastic and iron formation end members on Fig. 15 likely is not caused by siliciclastic contamination as the samples have very low contents of Al$_2$O$_3$ and TiO$_2$. This leaves the possibility that they are forming a continuum between oceanic sourced water and continentally sourced water. The majority of points are closer to the oceanic field, but even with this for continentally derived water to have an influence on at least a somewhat arid, tidally influenced coastline, current activity must have been sluggish. A setting similar to the present-day Trucial coast would be appropriate, although with somewhat increased runoff from the land.

**CONCLUSIONS**

The lithofacies assemblages of the Red Lake–Wallace Lake carbonate platform encompass structures that characterize supratidal flat to platform distal environments. Most of the preserved platform carbonates are peritidal in origin and formed in a low energy environment (possibly related to a low slope coastline with lagoon development) by a combination of the build-up of microbial mats within related biomediated sedimentary structures and in situ sea floor precipitation of sparry crusts. The low slope peritidal area would have had a variable topography produced by differential growth rates in biomediated structures which possibly allowed localized restricted conditions in which oxygen levels could build up. Dissolution features are present in some areas indicating periodic sub-aerial exposure of portions of the platform. The transition from subtidal to upper slope environment is not preserved. The upper platform slope is characterized by a combination of detrital platform derived carbonate and pelagic sedimentation that often resulted in slumping. The platform slope proper is similar to the upper slope but has an increase in pelagic sediment in combination with the introduction of OF-IF. The distal environment is limited to the deposition of chert-OF-IF. The perversiveness of peritidal lithofacies assemblages and slumping in the slope environment indicates that the platform was flat-topped and steeply sided.

The sediments of the Red Lake–Wallace Lake carbonate platform precipitated from oceanic water that had relative REE concentrations similar to today’s oceans (i.e. supradritic and variable Y/Ho ratios, PAAS normalized REE patterns that are positively sloping, and positive La and Gd anomalies). The notable exceptions include (1) the Mesoarchean ocean had a larger REE input from hydrothermal alteration of oceanic crust than today’s, and (2) the lack of Ce anomalies in the chemical sediments indicates that the oceans were largely anoxic. In addition, the water from which the platform precipitated was chemically stratified; the deep water precipitates had a large chemical input from hydrothermal alteration of oceanic basalts while the shallow water precipitates formed from water with mixed deeper water signatures.
and chemical input from continental runoff. A significant finding, and in combination with the large areal extent of the platform, suggests that these carbonates precipitated on the margins of an extensive oceanic platform.

Dolomitization of many samples has reset O and Sr isotopic ratios but left C isotopic ratios largely unchanged from those in the precursor carbonate phase. In calcite samples, Sr and C isotopic ratios reflect this precursor phase and 87Sr/86Sr ratios are in agreement with estimates for Archean sea water at 2.9 Ga. The δ13C values of the platform slope carbonates are light with respect to those of the peritidal areas, in agreement with Kaufman et al. (1990) and Fralick & Riding (2015) in that this suggests deep Archean ocean water was isotopically light relative to shallow water and further suggesting a chemically stratified water body.

The intermittent development and preservation of stromatolitic carbonates in the Archean from the earliest ca 3450 Myr old Strelley Pool Chert to the latest ca 2540 Myr old Campbellrand-Malmani carbonate platform spans almost 1 billion years of Earth’s history. Despite extensive study of these carbonates, and those in the interim, we do not know details of important facts concerning Earth’s surface processes during the Archean; the nature of the atmosphere, chemical and physical dynamics of the oceans, and how life fit into these systems are still largely mysteries. The sedimentary rock record is too sporadic and, in places, altered to allow high resolution of Earth’s physical and chemical processes during this time interval, yet it is clear, and not unexpected, that such processes changed with frequencies on scales that were similar to those observed in the Phanerozoic rock record. Here, we document the physical and chemical character of a ca 2930 Myr old carbonate platform, the oldest yet discovered, and of which life formed an integral part, in hopes to fill some of the missing gaps.

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**Supporting Information**

Additional Supporting Information may be found online in the supporting information tab for this article:

**Table S1.** Whole rock geochemistry, major elements, isotopes.

**Table S2.** Whole rock geochemistry, trace elements.

**Table S3.** Whole rock geochemistry, rare earth elements.