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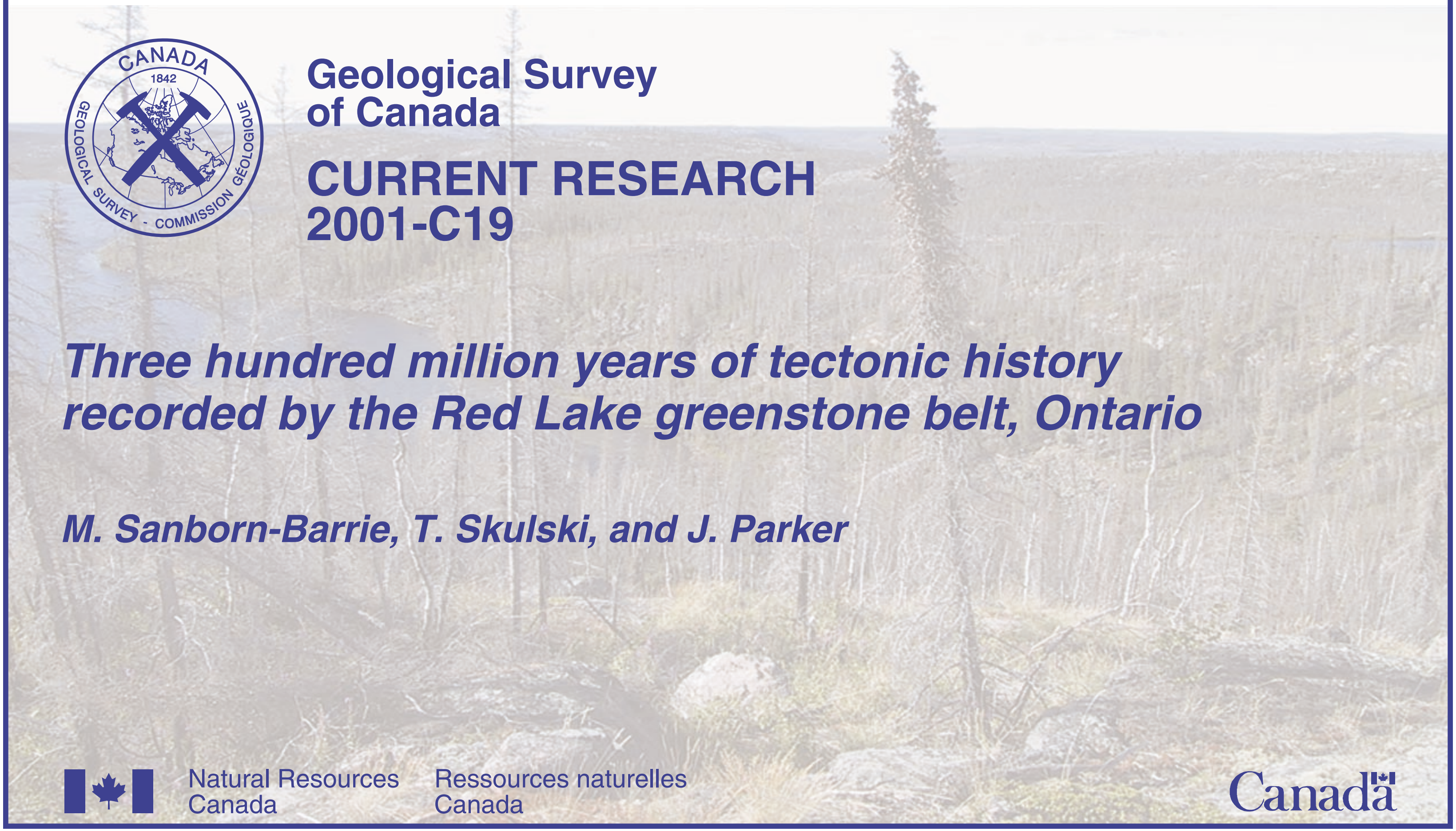

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Three hundred million years of tectonic history recorded by the Red Lake greenstone belt, Ontario[1]

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Sanborn-Barrie, M., Skulski, T., and Parker, J., 2001: Three hundred million years of tectonic history recorded by the Red Lake greenstone belt, Ontario; Geological Survey of Canada, Current Research 2001-C19, 19 p.

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Abstract

The Red Lake belt records ca. 300 Ma of episodic magmatism, sedimentation, and tectonothermal activity along the south margin of the 3 Ga North Caribou terrane. Autochthonous assemblages appear to reflect initial (2.99–2.96 Ga) plume magmatism, 2.94 to 2.91 Ga arc magmatism, 2.90 to 2.89 Ga sedimentation, and protracted Neoarchean continental arc and intra-arc rift-related magmatism (2.75–2.73 Ga). A ca. 2.85 Ga oceanic assemblage containing MORB-like basalt may have been accreted and caused early uplift and erosion prior to Neoarchean magmatism. This was followed by collisional orogenesis at ca. 2.72 Ga, the Uchian phase of the Kenoran Orogeny, which was accompanied by extensive hydrothermal alteration and gold mineralization.

Résumé

La ceinture de roches vertes de Red Lake témoigne de 300 millions d'années de magmatisme, de sédimentation et d'activité tectonothermique épisodiques le long de la bordure méridionale du terrane de North Caribou dont l'âge est de 3 Ga. Les assemblages autochtones témoigneraient d'un début de magmatisme en panache (de 2,99 à 2,96 Ga), de magmatisme d'arc (de 2,94 à 2,91 Ga), de sédimentation (de 2,90 à 2,89 Ga) et d'une longue période de magmatism néoarchéen intra-arc et d'arc continental associé à un rift (de 2,75 à 2,73 Ga). Il y a peut-être eu accrétion d'un assemblage océanique d'environ 2,85 Ga renfermant du basalte semblable au basalte de dorsale médio-océanique, ce qui aurait provoqué un soulèvement et une érosion précoces antérieurs au magmatisme du Néoarchéen. Ces événements ont été suivis d'une orogénèse de collision vers 2,72 Ga, soit la phase uchienne de l'orogénèse kénoréenne, qui a été accompagnée d'altération hydrothermale et de minéralisation aurifère importantes.

INTRODUCTION

The second field season of Western Superior NATMAP activities in the Red Lake greenstone belt focused on integrating geological mapping with new and previously available lithogeochemical, geochronological, and GIS data to further our understanding of 1) the interplay between magmatism, alteration, deformation, and mineralization; 2) the relationships between Meso- and Neoarchean assemblages; and 3) the tectonic setting of the belt through 300 Ma of Archean history. Collectively, these data highlight a protracted history of episodic magmatic activity and sedimentation at the south margin of the North Caribou terrane (**Fig. 1**), and orogenic activity that culminated in collision with the Winnipeg River terrane during the ca. 2.72 Ga Uchian phase of the Kenoran Orogeny (Stott et al., 1989).

EPISODIC MAGMATISM (2.99–2.70 GA)

The Red Lake greenstone belt preserves a volcanic history that spans approximately 300 Ma and is represented by seven volcano-sedimentary assemblages (**Fig. 2**), described below from oldest to youngest. New field, geochemical, and isotopic data relevant to these build on observations presented in Sanborn-Barrie et al. (2000), and provide a more detailed basis for interpreting the origins of the Red Lake belt (*see* Corfu and Stott, 1991; Tomlinson et al., 1998; Hollings et al., 1999) and speculating on the evolution of the North Caribou terrane.

BALMER ASSEMBLAGE

The Balmer assemblage (2.99–2.96 Ga) is dominated by submarine tholeiitic basalt, komatiite, and komatiitic basalt with minor felsic volcanic rocks, iron-formation, and fine-grained clastic rocks (Fig. 2). This lithological association suggests deposition of the earliest recognized supracrustal rocks in a sediment-starved, marine basinal setting. Basaltic flows are typically aphyric or variolitic. Ultramafic flows include pillowed komatiitic basalt (<18% MgO) and spinifex-textured komatiite (**Fig. 3a**). The assemblage has been dated at several localities (Corfu and Andrews, 1987; Fig. 2), with ages of 2992 +20/-9 Ma and 2989 ± 3 Ma for felsic pyroclastic units, and 2964 +5/-1 Ma from massive rhyolite that may be intrusive in origin.

Basalt flows that dominate the Balmer assemblage are tholeiitic and distinguished from other basaltic sequences in the belt by their relatively high Ti contents (<2 weight per cent; eg. **Fig. 4b** vs. **4e**). These rocks encompass a narrow range of primitive-mantle-normalized trace-element contents from light rare-earth-element (LREE)- and large-ion lithophile-element (LILE)-depleted basalt (**Fig. 4b**), to more abundant, flat to slightly LREE- and LILE-enriched basalt with negative Nb anomalies (**Fig. 4a**). They show a negative correlation between Mg content (a differentiation index) and degree of LREE enrichment (e.g. La/Sm). Komatiitic rocks are typically LREE depleted, but show a range of LILE enrichment, and many have negative Nb anomalies (**Fig. 4c**). Analyzed basalts from eastern Red Lake have initial ε_{Nd} values (Tomlinson et al., 1998; R. Stevenson, pers. comm., 2000) ranging from +3.3, typical of depleted mantle at 3 Ga (about >2), to 0.3, typical of sources with a longer lived history of LREE enrichment (e.g. differentiated continental crust), whereas ultramafic samples encompass a wide range of initial ε_{Nd} values from -2.2 to +1.5.

BALL ASSEMBLAGE

The Ball assemblage (2.94–2.92 Ga) of northwestern Red Lake (**Fig. 2**) may be in tectonic contact with the Balmer assemblage, as these assemblages young toward one another. The Ball assemblage comprises a calc-alkalic sequence of basalt, andesite, dacite, and rhyolite intercalated with minor komatiite and komatiitic basalt flows (**Fig. 3b**), conglomerate, quartzite, and locally stromatolitic marble. Felsic volcanic rocks bracket the age of stromatolite growth between 2940 ± 2 Ma and 2925 ± 3 Ma (Corfu and Wallace, 1986) and constrain two mafic-ultramafic submarine volcanic intervals, one prior to 2940 Ma and the other after 2925 Ma.

Ball assemblage calc-alkalic volcanic rocks encompass a wide range in silica and have relatively low Ti contents (<0.5 weight per cent). Increasingly felsic compositions of the basalt–rhyolite continuum reflect a progressive increase in LREE and LILE enrichment and an increase in the magnitude of negative Nb anomalies (**Fig. 4d, e, f**). Despite their large compositional spectrum, the calc-alkalic rocks have initial ε_{Nd} values that range from +0.8 to +1.1 (Henry et al., 2000; this study). These uniform isotopic values are lower than estimated values of depleted mantle and suggest derivation from a LREE-enriched mantle source. Ball assemblage komatiite and komatiitic basalt flows are characterized by flat to LREE-enrichment profiles, enrichment in LILE, and large negative Nb anomalies (**Fig. 4f**). A sample of peridotite from the large ultramafic intrusive body exposed in Pipestone Bay (Fig. 2) has a trace-element profile similar to that of the komatiite flows and an initial ε_{Nd} value of +2.2, consistent with depleted mantle at ca. 2.9 Ga.

SLATE BAY ASSEMBLAGE

The Slate Bay assemblage (<2.92 Ga) is a clastic-dominated sequence that disconformably overlies the Balmer assemblage. Clastic rocks include feldspathic wacke interbedded with lithic wacke, argillite, and lenses of conglomerate, and compositionally mature conglomerate, grit, and quartzose arenite. Quartz-rich rocks contain clasts of vein quartz, felsic volcanic rocks, and fuchsitic material indicating derivation from felsic and ultramafic sources, respectively. They contain Balmer- and Ball-age detrital zircons and their maximum depositional age is ca. 2916 Ma, the age of the youngest detrital zircon analyzed (Corfu et al., 1998).

BRUCE CHANNEL ASSEMBLAGE

The Bruce Channel assemblage (2.89 Ga) appears to disconformably overlie the Balmer assemblage in eastern Red Lake (**Fig. 2**) and comprises 2894 Ma intermediate volcaniclastic fragmental rocks, locally overlain by a fining-upward sequence of chert-pebble conglomerate, crossbedded wacke, siltstone, and quartz-magnetite iron-formation. The volcanic sequence is relatively thin (<500 m) and represents explosive volcanism followed by subsidence and deposition of clastic sediments and younger chemical sediments in a marine setting. Calc-alkalic volcanic rocks of the Bruce Channel assemblage are dacitic to rhyodacitic and are characterized by LREE- and LILE-enriched trace-element profiles, with negative Nb anomalies (Fig. 5). A sample of dacite has an initial ε_{Nd} value of +2 (Henry et al., 2000), similar to estimated depleted mantle.

TROUT BAY ASSEMBLAGE

New field, geochronological, and geochemical data from the southwest part of the belt indicate that rocks previously correlated with the Balmer assemblage (Stott and Corfu, 1991) represent a distinct volcano-sedimentary sequence, the Trout Bay assemblage (2.85 Ga; Fig. 2). This assemblage consists of a lower sequence of basalt overlain by clastic rocks, intermediate tuff, and chert-magnetite iron-formation. These are intruded by gabbro and lesser ultramafic rocks that are economically important in terms of their nickel, copper, and platinum-group-element potential (Parker, 2000a). The lower sequence is overlain by a thick sequence of pillowed, LREE-depleted, tholeiitic basalt capped by thinly bedded oxide-facies iron-formation. Separating the lower and upper sequences is a unit of fragmental rock that generally appears to be pyroclastic in origin.

Intermediate tuff from the lower sequence yielded a U-Pb magmatic crystallization age of 2853 ± 1 Ma, based on analyses of five single zircon grains (Fig. 6). The dated sample has calc-alkalic geochemical affinity, is enriched in LREE and LILE, and has a negative Nb anomaly (Fig. 7a).

Pillow basalt from the upper Trout Bay assemblage is notable in the Red Lake belt for its very low overall trace-element abundances and depletion in LILE and LREE (Fig. 7a). Two samples of depleted basalt have initial ε_{Nd} values of +2 and +1.8, consistent with derivation from a depleted-mantle source. Gabbroic rocks intrusive into the lower Trout Bay sequence, and likely related to the upper depleted basalt, have flat to depleted LREE profiles, but higher overall trace-element abundances (**Fig. 7b**). A minimum age constraint on the upper depleted-basalt sequence is given by a preliminary U-Pb zircon age of 2745 to 2735 Ma for a crosscutting dyke that is likely an apophysis of the 2734 ± 2 Ma Douglas Lake pluton (**Fig. 2**).

HUSTON ASSEMBLAGE

A regionally extensive unit of polymictic conglomerate marks an angular unconformity between Mesoarchean and Neoarchean strata. Along the unconformity, the character of the Huston sedimentary assemblage (<2.89 >2.74 Ga) varies from a thin veneer of clastic detritus (e.g. Austin 'tuff' at Madsen) to a thick (~0.5 km) succession of well bedded argillite and turbiditic wacke. This suggests an erosional surface of considerable relief on which deposition of sedimentary detritus under locally marine conditions took place prior to Neoarchean volcanism.

A sample of amphibolite-facies polymictic conglomerate (Austin tuff) from the Madsen mine yielded Balmer- and Ball-age detrital zircons (**Fig. 8**) and a younger 2912 Ma grain that provides a maximum age of sediment deposition. A reversely discordant titanite multigrain fraction yielded a preliminary age estimate for amphibolite-facies metamorphism at 2714 ± 19 Ma, and a minimum age for sediment deposition. Three single zircons yielded younger $^{207}Pb/^{206}Pb$ ages of ca. 2.7 Ga and may date a late hydrothermal event, possibly related to the adjacent 2704 Ma post-tectonic Killala-Baird batholith (Fig. 2; Corfu and Andrews, 1987).

CONFEDERATION ASSEMBLAGE

New field, geochemical, and geochronological data extend the known occurrence of the Confederation assemblage (2.75–2.73 Ga) and allow its subdivision into three temporally and spatially distinct volcanic sequences. These are the 2745 to 2742 Ma McNeely calc-alkalic sequence in central Red Lake, the <2744 to 2739 Ma Heyson tholeiitic sequence in southeastern Red Lake, and the 2734 to 2731 Ma Graves calc-alkalic sequence in the north (**Fig. 2**).

The McNeely sequence unconformably overlies the Balmer assemblage and is dominated by intermediate tuff breccia and lapilli tuff that, on McNeely Bay and McKenzie Island (Fig. 2), yielded zircon U-Pb ages of 2748 +10/-5 Ma (Corfu and Wallace, 1986) and 2745 +7/-4 Ma (Corfu et al., 1998), respectively. New U-Pb ages on intermediate tuff from central Red Lake and Martin Bay are 2742 +5/-2 Ma (**Fig. 9a**) and 2742 +3/-2 Ma (**Fig. 9b**), respectively. The McNeely sequence is calc-alkalic and comprises intermediate to felsic rocks and low Ti (<1 weight per cent) plagioclase-phyric, amygdaloidal pillow basalt that are enriched in LREE and LILE, with prominent negative Nb anomalies, and relatively depleted in heavy rare-earth elements (HREE) and high field-strength elements (HFSE; **Fig. 10a**). A dacitic tuff has an initial ε_{Nd} value of +1.2 (Henry et al., 2000). Intrusive rocks of McNeely age cut Balmer and Bruce Channel strata, consistent with eruption of this calc-alkalic sequence on a Mesoarchean continental margin. These include a 2757 +9/-4 Ma felsic dyke (Corfu and Wallace, 1986) and the synvolcanic 2742 +3/-2 Ma Brewis porphyry (Corfu and Andrews, 1987).

The overlying Heyson sequence (Fig. 2) comprises a thick succession of tholeiitic felsic volcanic rocks dominated by pyroclastic tuff, lobe-hyaloclastite rhyolite flows, and rhyolite flow breccia. These are overlain and interlayered with pillowed mafic flows, quartz-feldspar crystal tuff, and younger plagioclase-phyric, high-TiO_2 basaltic andesite and associated dykes. Heyson basalt and andesite are primarily tholeiitic, but locally overlie calc-alkalic dacitic tuff at Madsen, and are intercalated with calc-alkalic volcanic rocks on Keg Lake. The tholeiitic lavas have trace-element profiles characterized by LREE and LILE enrichment, large negative Nb anomalies, and flat HREE and HSFE abundances (**Fig. 10b**). A sample of Heyson basalt has an initial ε_{Nd} value of +0.77, whereas an overlying ca. 2739 Ma rhyolitic tuff has an initial ε_{Nd} value of +2.9.

The ca. 2733 Ma Graves sequence (Corfu and Andrews, 1987) in northern Red Lake was erupted on polymictic conglomerate that overlies, and sourced, Slate Bay and Balmer assemblages and mesozonal granitoid rocks. Locally the conglomerate contains tuffaceous components and appears to grade transitionally into the overlying Graves sequence, suggesting concomitant clastic and pyroclastic activity 10 Ma after initiation of Neoarchean volcanism in southeastern Red Lake. Accordingly, this conglomerate appears to reflect younger uplift, erosion, and sedimentation than that recorded in the central and southern parts of the belt. The Graves sequence includes andesitic to dacitic pyroclastic rocks and synvolcanic diorite and tonalite, and likely represents a shallow-water to subaerial arc complex. Synvolcanic plutons include the granodioritic 2731 ± 3 Ma Little Vermilion Lake batholith in the north (Corfu and Wallace, 1986) and biotite tonalitic to granodioritic 2734 ± 2 Ma Douglas Lake pluton in the southwest (Corfu and Stone, 1998). The Graves sequence is calc-alkalic and, like the McNeely sequence, is characterized by LREE and LILEenrichment, negative Nb anomalies and depletion in HREE and HFSE (**Fig. 10c**). Henry et al. (2000) report an initial ε_{Nd} value for the Douglas Lake pluton of 0, likely indicating significant assimilation of older continental crust.

DEFORMATION

The Red Lake greenstone belt is polydeformed with an early (pre-2.748 Ga), nonpenetrative deformational event (D_0) and at least two recognizable generations of ductile structures (D_1, D_2) imposed after ca. 2.742 Ga volcanism. Early deformation involved overturning of Balmer pillow basalt, as documented by opposing facing on either side of the regionally extensive angular unconformity in the Madsen and central Red Lake areas. Coplanar bedding orientations in oppositely facing Balmer and Confederation rocks suggest overturning of the Balmer assemblage involved recumbent folding.

The main stages of penetrative deformation resulted in the formation of two generations of folds and associated L-S fabrics throughout the belt. The F_1 folds are established by opposing structural facing (younging in the direction of the superimposed axial planar S_2 fabric) and are recognized mainly in clastic-dominated assemblages (Bruce Channel, Slate Bay, and Huston) where bedding structures highlight fold development (**Fig. 11a**). The D_1 planar fabrics strike northerly and are best developed in volcanic rocks of the Balmer, Ball, and Trout Bay assemblages.

The main penetrative structures recognized throughout the Red Lake belt are attributed to D_2 deformation (**Fig. 11b**). These include sets of northeast-striking, moderately to steeply plunging F_2 folds that, like F_1, are best developed in clastic rocks. Weakly to moderately developed L-S fabrics associated with F_2 folds (D_2) trend east to northeasterly and are developed in all sedimentary and volcanic units as well as the Dome Stock.

Although D_2 structures are dominantly east- to northeast-striking, a corridor of variably strained rock with a dominant east-southeast strike extends from Cochenour through the Balmertown area. This heterogenous strain corridor hosts the major gold deposits of the Red Lake camp (*see* Dubé et al., in press) and is marked by moderately developed ductile L-S fabrics with a consistent planar orientation of 120°/75°N and a mineral lineation that plunges 45° to 65° to the southwest. Subsequent semibrittle and brittle structures have both localized and offset gold mineralization (Dubé et al., in press). The relationship between the regional S_2 and 'mine-trend' fabrics is best reconciled in the McKenzie Island area where a progressive change in orientation can be documented (**Fig. 12**) from west of McKenzie Island, where S_2 strikes 070°, to the north end of the island where 090°-striking planar fabrics prevail, to east of the island where the mine-trend fabric strikes 110°. In those localities, this variably oriented foliation is of similar strain and bears the same relationship to pervasive ankerite alteration (Parker, 2000b). Because there is no evidence of an overprinting relationship between the S_2 and mine-trend fabrics, we consider these to have formed coevally during D_2. Given the absence of mylonitic rocks or strain gradients within these strain corridors, these are not interpreted as belt-scale conjugate shear zones, in contrast to the model of Andrews et al. (1986).

Timing constraints on deformation

The D_0 event, manifested primarily through overturning of parts of the Balmer assemblage, predates 2744 ± 1 Ma, the age of tholeiitic rocks of the Heyson sequence that unconformably overlie and young away (southeast) from northwest-younging Balmer basalt. A maximum age of D_0 appears to be 2894 Ma, because the Bruce Channel assemblage is interpreted to disconformably overlie the Balmer assemblage, as evidenced by same-facing, coplanar strata of the Bruce Channel assemblage overlying mafic volcanic rocks of the older Balmer assemblage.

A maximum age of D_1 is ca. 2742 Ma, given that F_1 and F_2 folds affect intermediate tuff of the McNeely sequence in central Red Lake (Fig. 12). At present it does not appear that F_1/S_1 structures are recorded by the ca. 2733 Ma Graves sequence, which suggests a minimum age of ca. 2733 Ma for D_1 and highlights the potential role of D_1 deformation in uplift, erosion, and subsequent deposition of polymictic conglomerate that underlies and possibly interfingers with the Graves sequence. Emplacement of the 2734 Douglas Lake pluton and 2731 Little Vermilion Lake batholith is consistent with the timing of D_1; however, the belt-wide presence of D_1 structures suggests that D_1 involved regional-scale, east-west (present-day co-ordinates) shortening.

The timing of D_2 is established by field relationships involving ca. 2.72 Ga intra-belt plutons. The 2.718 ± 1 Ga Dome Stock contains S_2 foliated xenoliths of local country rock, but is itself weakly to moderately foliated with a throughgoing northeast-striking (060°/80°N average) fabric, coplanar with the regional S_2 foliation (**Fig. 11b**). Deviation in the orientation of interpreted D_2 fabrics from the regional (east- to northeast-striking) S_2 trend to the east-southeasterly striking mine trend (described above) may have been influenced by the syntectonic 2720 ± 2 Ma McKenzie Island stock and/or evolved through a change in local boundary conditions in the eastern Red Lake belt related to ca. 2.72 Ga magmatism.

TECTONIC SETTING OF THE RED LAKE BELT AND EVOLUTION OF THE NORTH CARIBOU TERRANE

The Red Lake greenstone belt records a ca. 300 Ma history of Archean crustal growth (**Fig. 13**) at the south margin of the North Caribou terrane, a ca. 3 Ga terrane that sustained protracted reworking (outlined below) that culminated in the 2.7 Ga Kenoran Orogeny. Prior to Balmer volcanism, the North Caribou protocraton comprised 3.02 Ga island arc mafic-felsic volcanic crust and 3.01 to 3.0 Ga tonalitic crust (Corfu and Wood, 1986; Thurston et al., 1991; Turek and Weber, 1994). Trace-element and isotopic data for Balmer basalt support some degree of interaction with continental crust (*see* Tomlinson et al., 1998; Hollings et al., 1999). Accordingly, Balmer volcanism at 2.99 Ga is inferred to have taken place on this volcano-plutonic substrate (**Fig. 13a**), leading to the development of a voluminous mafic-ultramafic submarine sequence. Intercalated komatiite and basalt of the Balmer assemblage have been interpreted as the products of a mantle plume in which the hot, deep, mantle-derived axis produced komatiitic magma, and mixing with asthenospheric mantle produced tholeiitic basalt magma (Tomlinson et al., 1998; Hollings et al., 1999). Anomalously low negative ε_{Nd} values (-2) for komatiitic rocks reported by Tomlinson et al. (1998) have been attributed to second-stage melting of a LREE-enriched mantle (Tomlinson et al., 1998) or crustal contamination (Hollings et al., 1999).

Balmer volcanism at Red Lake was contemporaneous with komatiitic volcanism at Wallace Lake and with mafic-felsic volcanism in the Birch-Uchi belt (2975–2964 Ma; Nunes and Thurston, 1980; Rogers et al., 2000), McInnes belt (2974–2969 Ma; Corfu et al., 1998), and North Caribou belt (2981 Ma; de Kemp, 1987) (Fig. 13a). However, ca. 2.99 to 2.97 Ga komatiite is absent from these latter belts, suggesting absence of a plume axis component. Plume-related magmatism may have triggered rifting of the North Caribou terrane, with komatiite of the Balmer assemblage reflecting a locus of maximum crustal extension at Red Lake and Wallace Lake.

The diverse lithological association of the Ball assemblage suggests construction of a shallow marine, central volcanic edifice with periods of quiescence and stromatolite growth. Enrichment in LILE and LREE and relative depletion in HFSE in the isotopically juvenile mafic to felsic sequence suggests an arc-like setting (**Fig. 13b**) for calc-alkalic volcanism (*see* Hollings et al., 1999). Two units of komatiitic rocks separated by 15 Ma indicate the influx of anomalously hot melts, possibly during two intervals of extension during arc formation. Intra-arc extension may be due to the influence of a mantle plume (*see* Hollings et al., 1999) or to a change in plate dynamics (e.g. change in velocity of the upper plate during rollback). Arc-like geochemical characteristics (**Fig. 4f**) of these isotopically juvenile ultramafic rocks support mixing between sub-arc-mantle and depleted-mantle components. Diverse, calc-alkalic-dominated, komatiite-bearing sequences similar to the Ball assemblage occur elsewhere in the North Caribou terrane including the ca. 2928 Ma Power assemblage (McInnes), the ca. 2926 Ma Setting Net assemblage (Favorable Lake), and 2945 Ma subaerial pyroclastic rocks of the North Sandy assemblage (Corfu et al., 1998, and references therein). The northerly trend (present-day co-ordinates) of coeval calc-alkalic-dominated volcanic centres may reflect a contiguous continental arc built during eastward subduction below the western margin of the North Caribou terrane at ca. 2.94 to 2.91 Ga.

Circa 2.9 Ga volcanism is widespread across the North Caribou terrane (**Fig. 13c**). At Red Lake it is represented by calc-alkalic volcanic rocks of the 2.894 Ga Bruce Channel assemblage. Synchronous volcanism is inferred for the Pickle Crow assemblage (**Fig. 1**) from ca. 2892 Ma inherited zircon in the crosscutting 2860 Ma Pickle Crow porphyry (Corfu and Stott, 1991). Slightly older felsic volcanism at 2901 Ma is recorded in the Hornby Lake belt (Corfu et al., 1998), whereas younger magmatism is recorded in the Favourable Lake and North Caribou belts. The Bruce Channel assemblage has arc-like geochemical attributes (LILE- and LREE enrichment, HFSE depletion, juvenile Nd isotopic composition) and may represent a time when the locus of arc volcanism expanded to include the present-day southern margin of the terrane.

In the Red Lake greenstone belt, the ca. 2853 Ma Trout Bay assemblage appears to be a distinct lithotectonic element characterized by strongly LREE-depleted submarine tholeiitic basalt of the upper sequence, in likely tectonic (front-to-front) contact with the older Ball assemblage. This depleted basalt sequence was later cut by the Douglas Lake pluton, which has an isotopic composition consistent with interaction with continental crust at 2735 Ma (ε_{Nd} =0; Henry et al., 2000). The Trout Bay assemblage may represent a back arc or oceanic plateau crust, tectonically juxtaposed with the North Caribou terrane between 2853 and 2735 Ma. This may have taken place during subduction and/or related strike-slip faulting along its southern margin, evidence of which is recorded by ca. 2.84 to 2.82 Ga arc-like volcanic rocks distributed across the Uchi Subprovince (**Fig. 13d**; Stott and Corfu, 1991). Possibly related to such an event is largely nonpenetrative deformation (D_0) that appears to be diachronous across this region at pre-2.86 Ga in Pickle Lake (Stott and Corfu, 1991), ca. 2.85 Ga in the Birch-Uchi belt (N. Rogers, pers. comm., 2000) and between 2.894 and 2.750 Ga in Red Lake.

A regional angular unconformity separates rocks of the Balmer and Bruce Channel assemblages from Neoarchean rocks of the Confederation assemblage and, as such, is widely bracketed between 2894 Ma and 2744 Ma. An angular unconformity has also been described in the Bamaji Lake area to the east (**Fig. 1**), where 2805 Ma volcanic and plutonic rocks are separated from 2781 Ma felsic tuff by conglomeratic rocks (Stott and Corfu, 1991). Unconformably overlying rocks record a Neoarchean history of renewed arc volcanism (**Fig. 13e**). Mafic to felsic shallow-marine, calc-alkalic volcanic rocks of the 2745 to 2742 Ma McNeely sequence have LILE- and LREE-enrichment and HFSE-depletion characteristic of arc-related volcanic rocks. Eruption of isotopically juvenile, submarine tholeiitic felsic±mafic volcanic rocks of the <2744 to 2739 Ma Heyson sequence at Red Lake, and chemically and isotopically similar and coeval volcanism at Confederation Lake to the east (Rogers et al., 2000), is interpreted to record intra-arc rifting on the continental margin. Volcanogenic massive-sulphide mineralization is associated with this rifting event in the Birch-Uchi belt. A final phase of Andean-style arc magmatism at ca. 2.73 Ga, recorded at Red Lake by the Graves sequence and throughout the Berens arc, is diachronous along the North Caribou margin between 2.73 Ga and 2.72 Ga. A switch from an extensional to compressional setting for the Neoarchean arc may be reflected by diachronous penetrative D_1 deformation across the area from pre-2.74 Ga in the Pickle Lake area, to between 2.732 and 2.724 Ga in the Confederation Lake area (N. Rogers, pers. comm., 2000), to between 2.742 and 2.718 Ga in the Red Lake belt (Fig. 13e). Continued subduction culminated in collision of the Winnipeg River terrane, the Uchian phase of the Kenoran Orogeny (Stott et al., 1989), at ca. 2718 Ma in the Red Lake and Birch-Uchi belts (**Fig. 13f**) and slightly younger to the east and possibly west (*see* Percival and Bailes, in press). Relationships in the Red Lake belt indicate that D_2 was a protracted event involving brittle-ductile reworking during extensive hydrothermal alteration and metamorphism (Parker, 2000b; Dubé et al., in press), which ultimately led to syn- to late-tectonic precipitation of gold to form one of Canada's foremost gold mining camps.

ACKNOWLEDGMENTS

We thank Alexandre Zagorevski and Lea-Marie Bowes-Lyon for their dedicated assistance in all aspects of field work, including a significant component of independent mapping by A. Zagorevski.

Carmen Storey and Lynn Kosloski of the Red Lake office of the Ministry of Northern Development and Mines provided us with valuable logistical and geological support. We thank the exploration staff at Placer Dome North America, Goldcorp Inc., Rubicon Minerals Corp., and Claude Resources Inc. for access to properties and the free exchange of ideas in the field. We also acknowledge Stuart Morris, Raymond Swanson, Benoît Dubé, Tim Twomey, Ian Russell, Raymond Casey, and Roland Landry who kindly helped ensure the seamless success of a two-day field trip in the Red Lake belt this summer. We are grateful to the support staff of the Geochronology Laboratory of the GSC. This paper was improved through reviews by Cees van Staal and Marc St-Onge.

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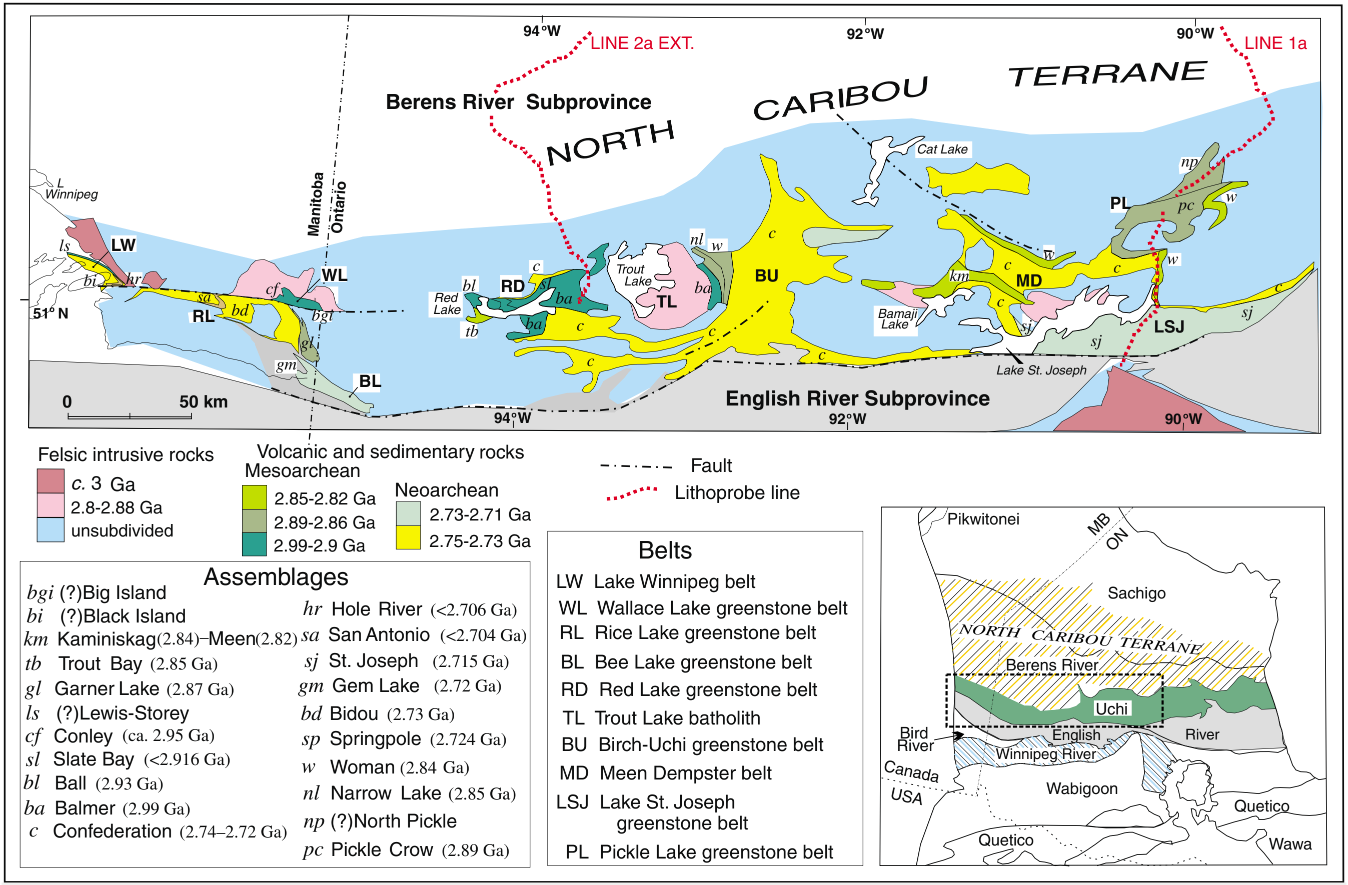

Figure 1. Greenstone belts and granitic batholiths of the Uchi Subprovince (*after* Stott and Corfu, 1991).

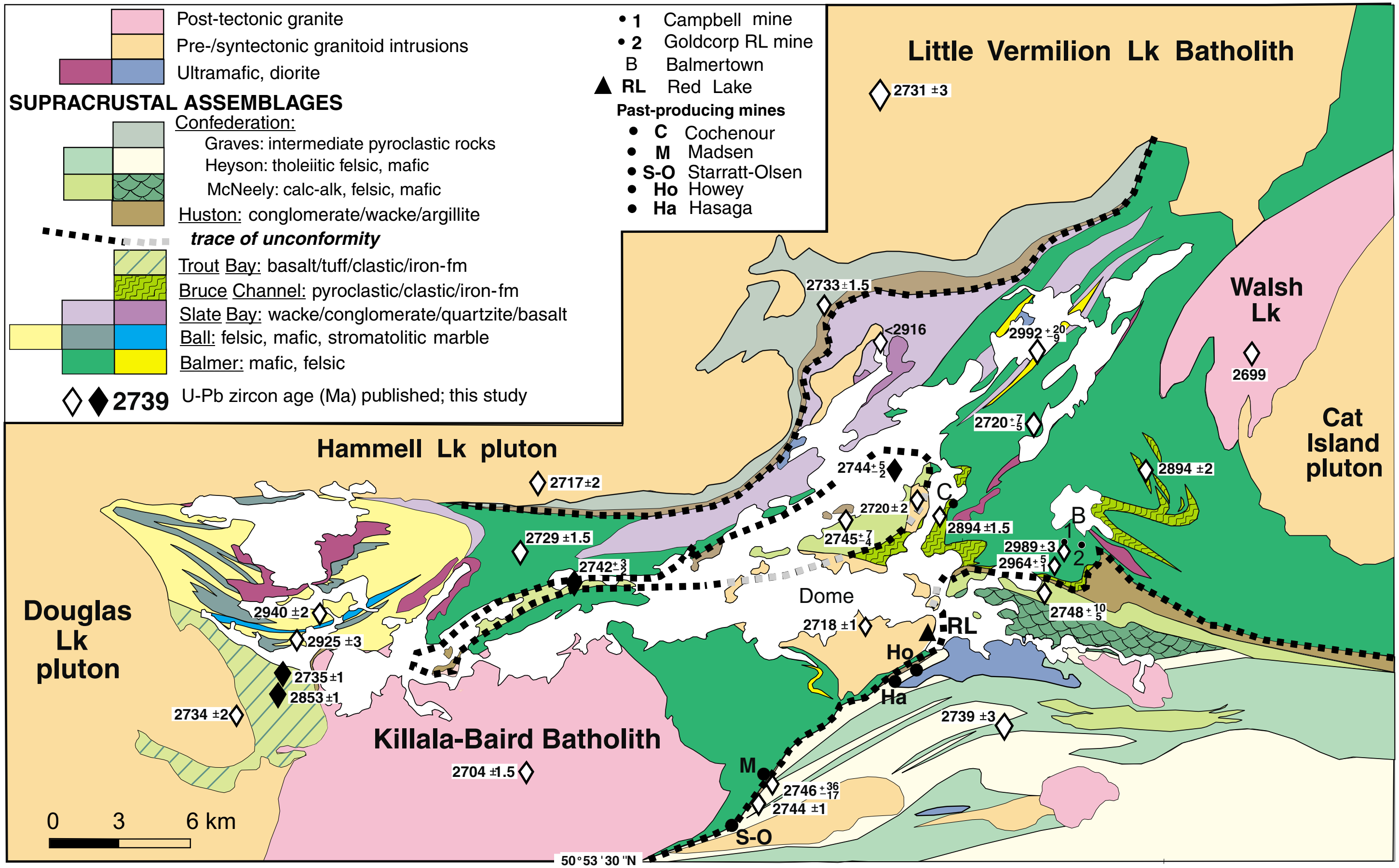

Figure 2. Geology of the Red Lake greenstone belt, showing critical U-Pb zircon age determinations of volcanic and plutonic rocks (*modified from* Stott and Corfu, 1991).

Figure 3. Spinifex-textured ultramafic rocks of the Red Lake belt. **a**) bladed olivine komatiite, Balmer assemblage, Golden Arm; **b**) acicular clinopyroxene komatiitic basalt, Ball assemblage, Miles Creek.

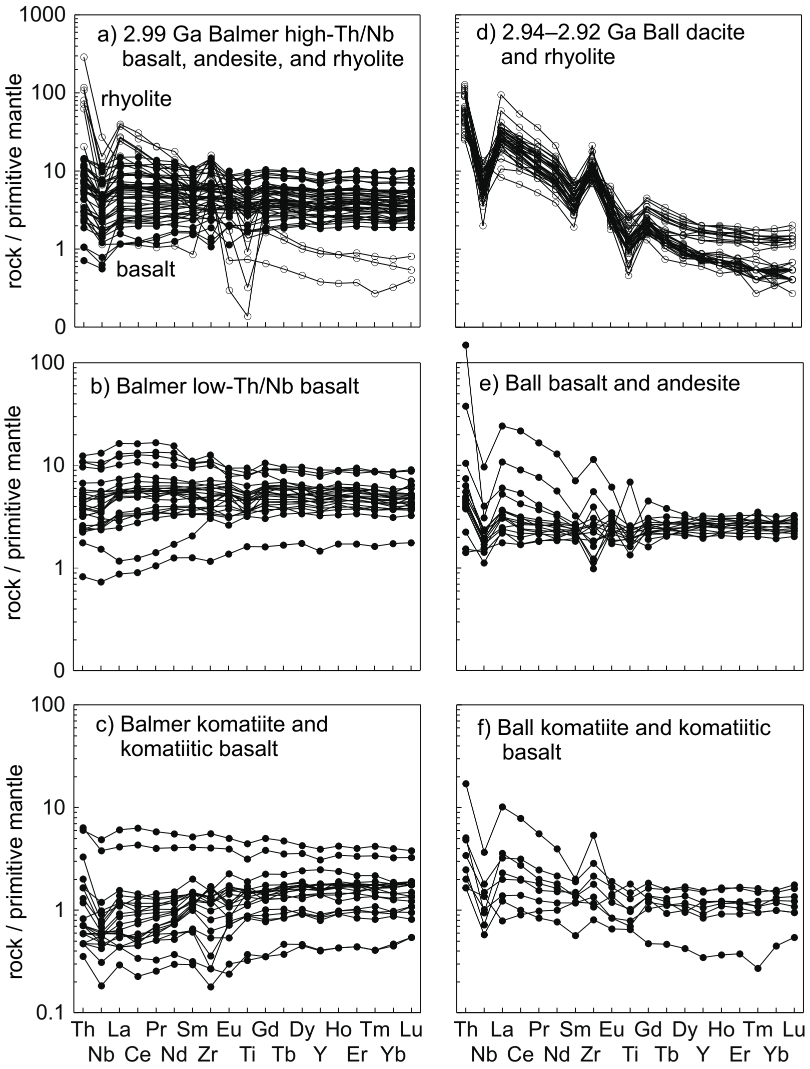

Figure 4. Primitive-mantle-normalized trace-element profiles for Balmer and Ball assemblage volcanic rocks (normalization factors are *after* Sun and McDonough, 1989). Chemical data from this study and *after* Tomlinson et al. (1998) and Hollings et al. (1999).

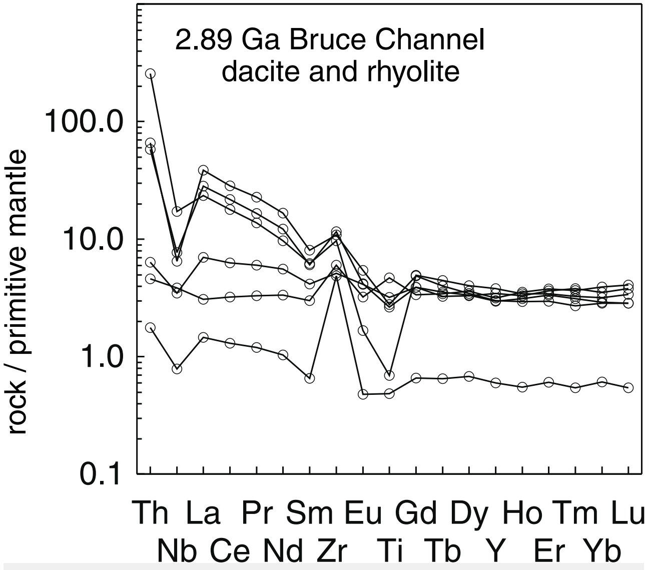

Figure 5. Primitive-mantle-normalized trace-element profiles of Bruce Channel volcanic rocks (data from this study).

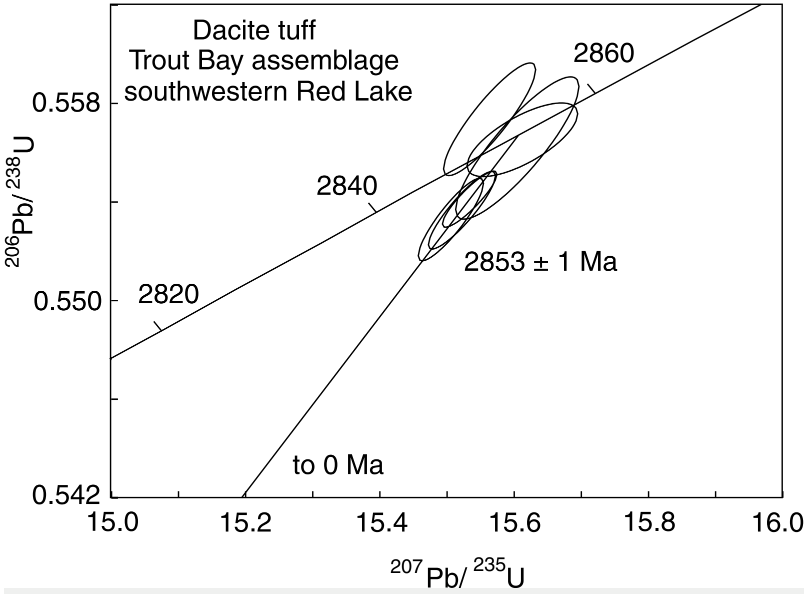

Figure 6. Uranium-lead concordia diagram of intermediate tuff from the lower sequence of the Trout Bay assemblage (UTM 15 415169E, 5650620N).

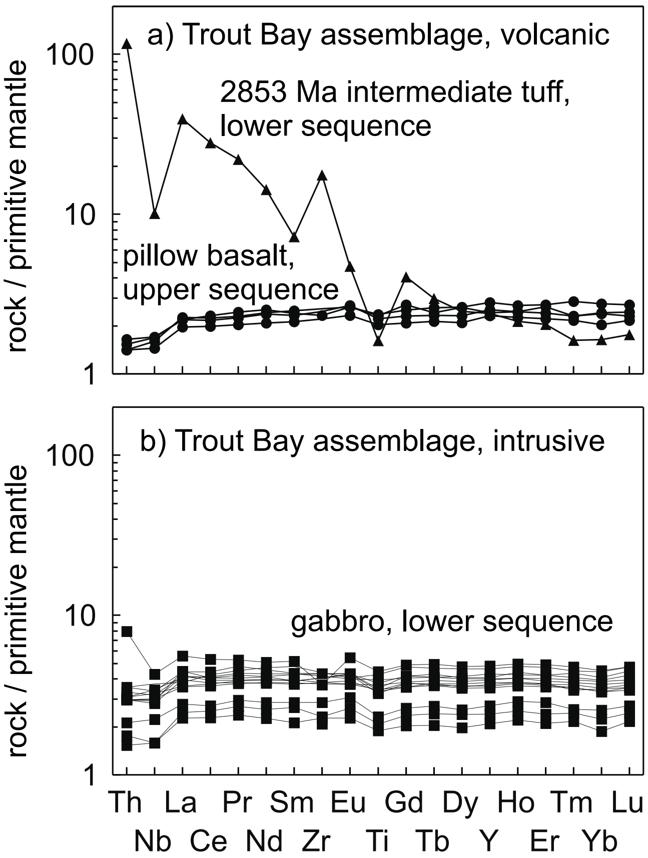

Figure 7. Primitive-mantle-normalized trace-element profiles of the Trout Bay assemblage (data from this study).

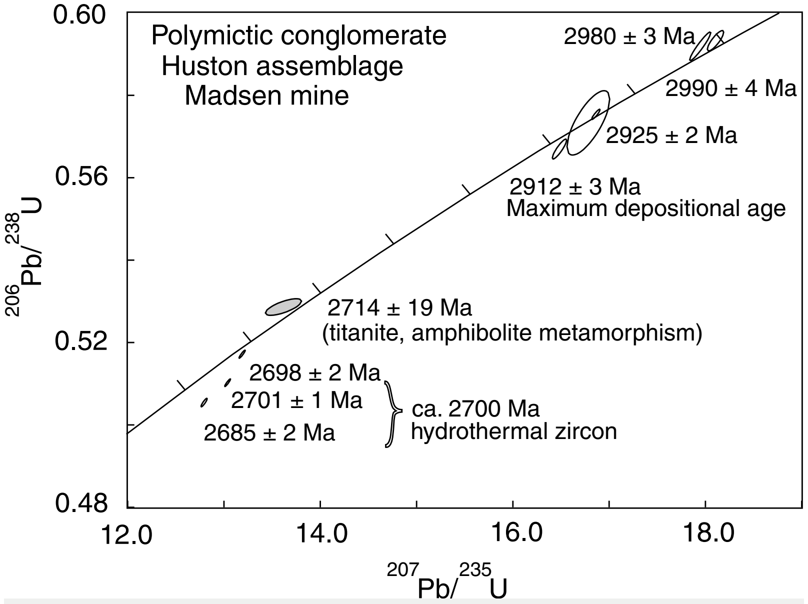

Figure 8. Uranium-lead concordia diagram of polymictic pebble conglomerate (Austin tuff), Huston assemblage, Madsen mine (UTM 15 435855E, 5646887N).

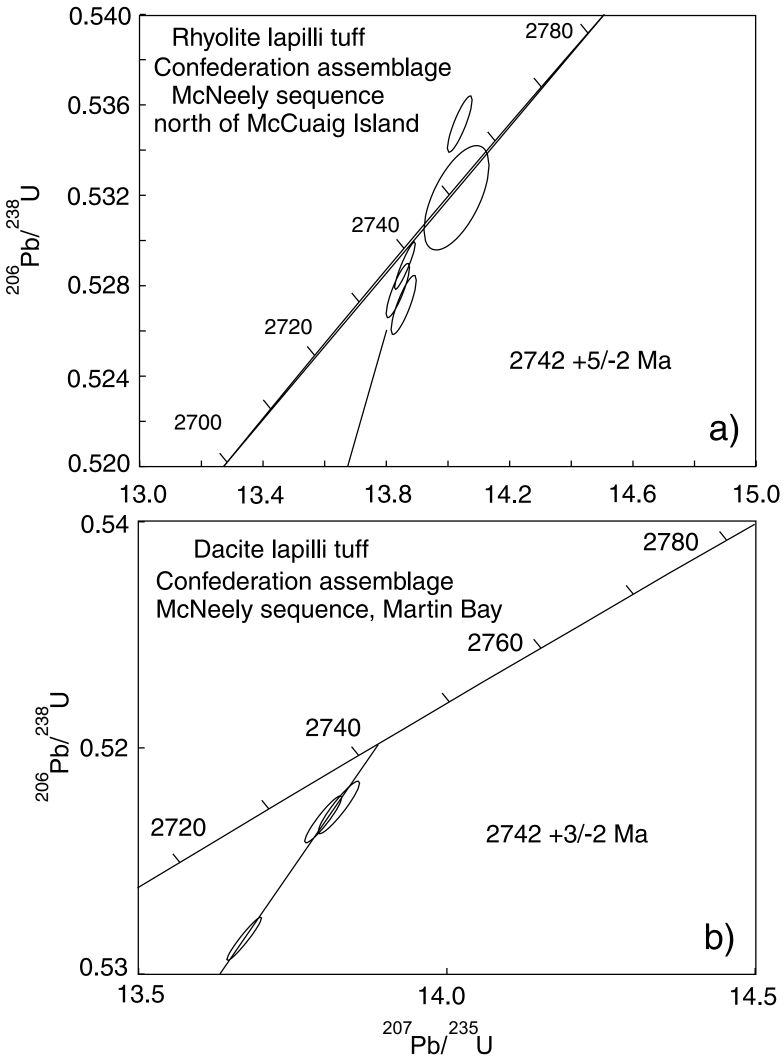

Figure 9. Uranium-lead ages of the McNeely sequence, Confederation assemblage. a) U-Pb concordia diagram of rhyolite tuff from central Red Lake (UTM 15 441671E, 5660288N), and b) U-Pb concordia diagram of dacite lapilli tuff, Martin Bay (UTM 15 427507E, 5655386N).

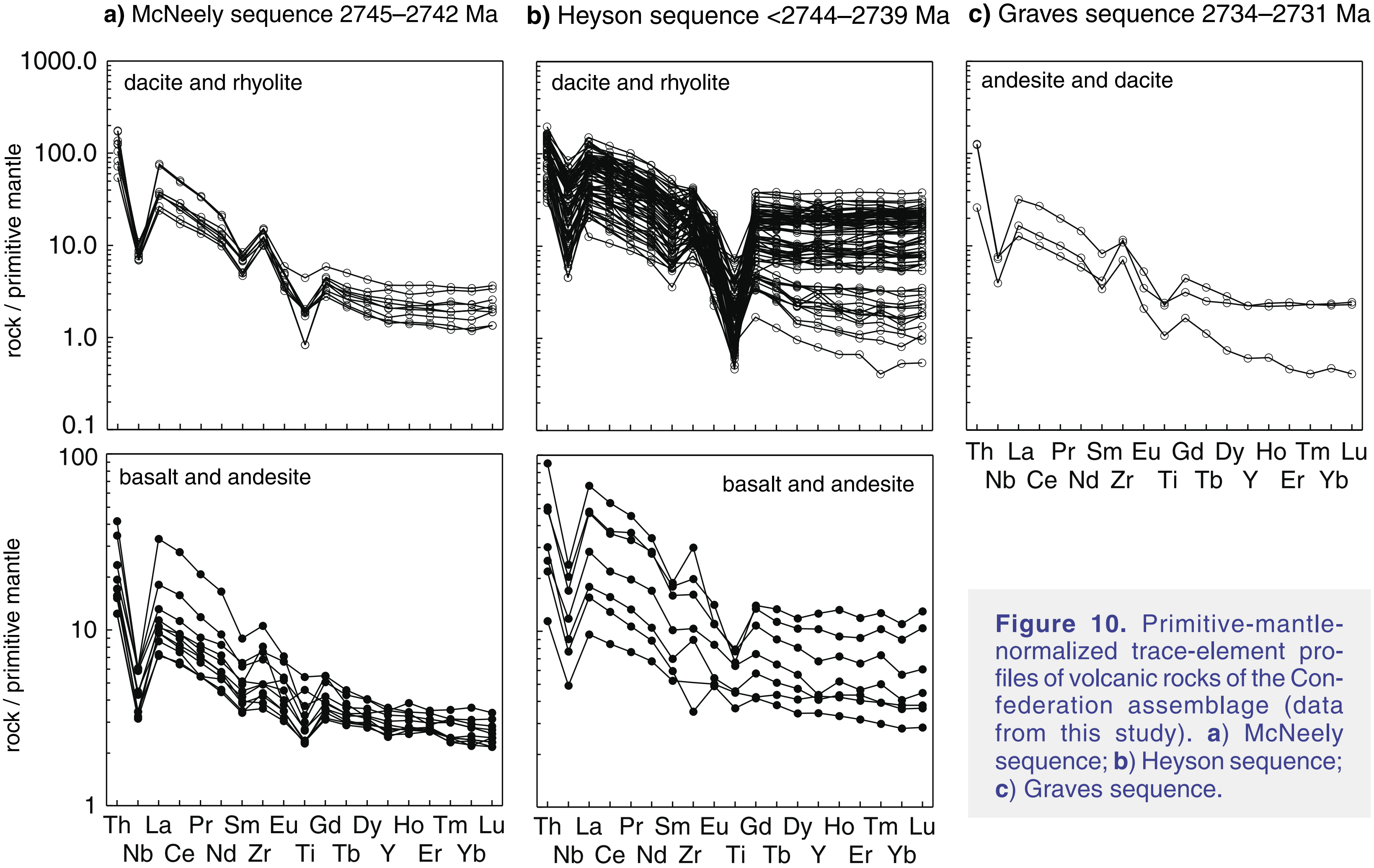

Figure 10. Primitive-mantle-normalized trace-element profiles of volcanic rocks of the Confederation assemblage (data from this study). **a**) McNeely sequence; **b**) Heyson sequence; **c**) Graves sequence.

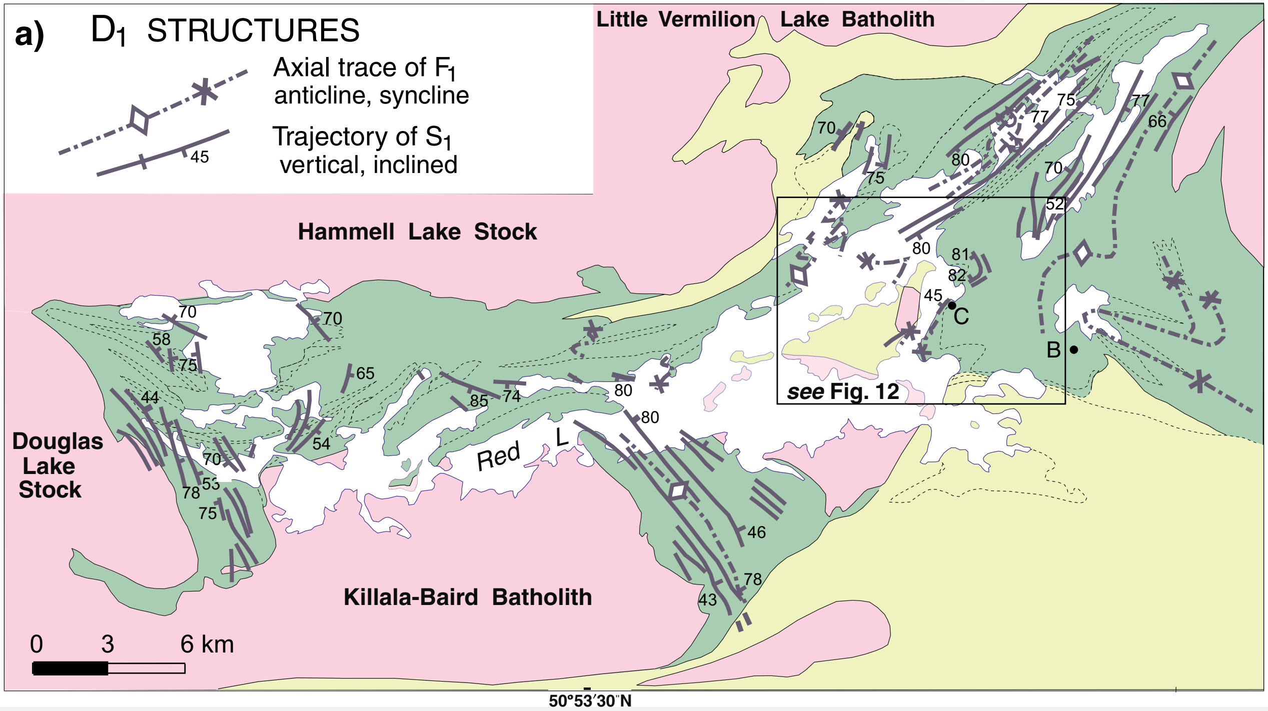

Figure 11a. D$_1$ structure from the Red Lake belt. B = Balmertown; C = Cochenour; RL = Red Lake

🟥 Granitoid rocks

🟩 Mesoarchean supracrustal rocks

🟨 Neoarchean supracrustal rocks

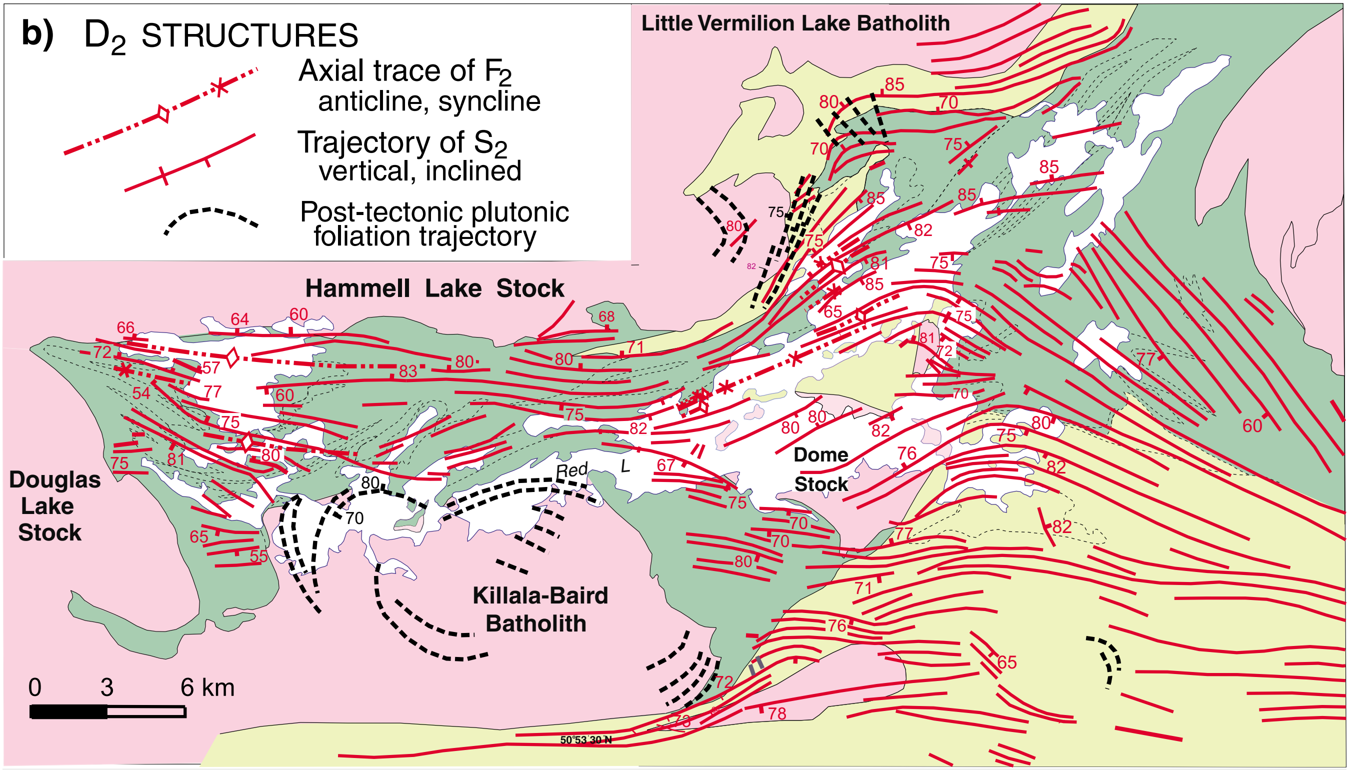

Figure 11b. D_2 structures and post-tectonic granitoid fabrics from the Red Lake belt. B = Balmertown; C = Cochenour; RL = Red Lake

🟥 Granitoid rocks

🟩 Mesoarchean supracrustal rocks

🟨 Neoarchean supracrustal rocks

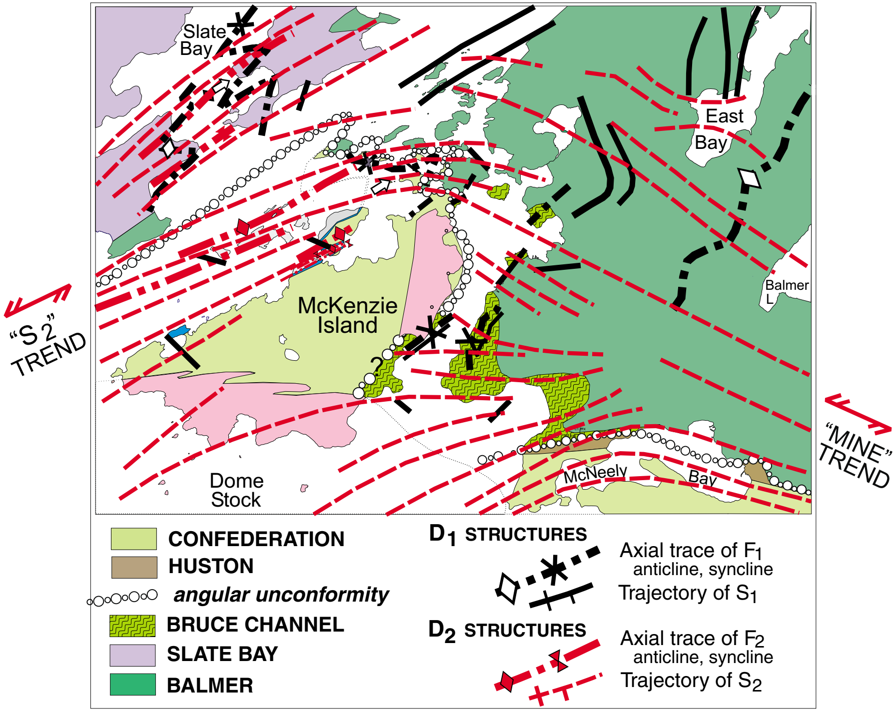

Figure 12. Structural geology of the McKenzie Island area.

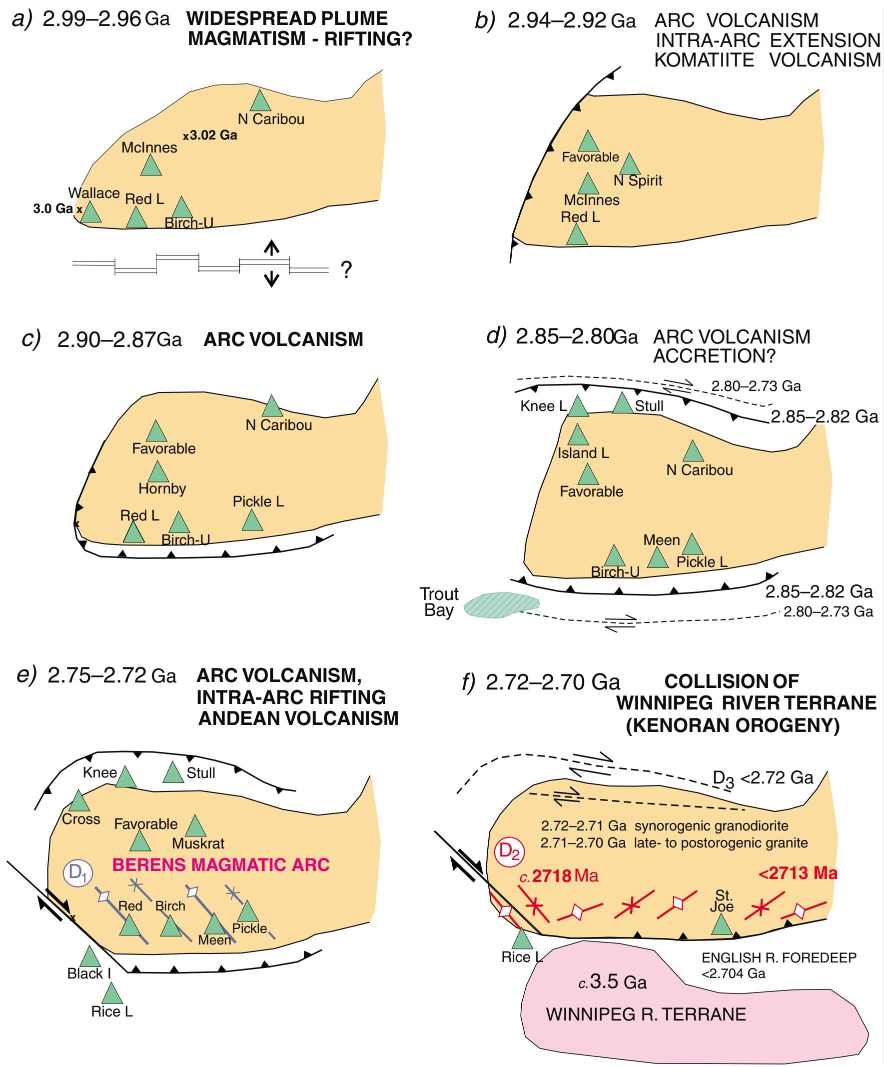

Figure 13. Geodynamic setting of the Red Lake greenstone belt and evolution of the North Caribou terrane. **a)** Plume-related magmatism on 3 Ga North Caribou protocraton; **b)** arc magmatism and intra-arc extension leading to komatiite eruption; **c)** arc magmatism encompasses the southern North Caribou terrane; **d)** arc volcanism and accretion of oceanic rocks of the Trout Bay assemblage; magmatic quiescence at this time may reflect a change from arc volcanism to transpression; **e)** Neoarchean arc volcanism and intra-arc rifting reflecting subduction along the northern and southern margins; a shift from extensional to compressional arc magmatism at 2.73 Ga coincides with the development of the Andean-style Berens River arc, D_1 deformation and uplift; **f)** 2.72 to 2.70 Ga diachronous collision of the Winnipeg River terrane.