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Integrated regional analysis of the Red Lake greenstone belt and its mineral deposits, western Superior Province, Ontario[1]

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Abstract: The Red Lake greenstone belt records a 300 Ma history of episodic volcanism, sedimentation, deformation, and mineralization. The Balmer assemblage, host to current and past-producing gold mines, consists of tholeiitic and komatiitic lava flows intercalated with 2.98–2.96 Ga felsic volcanic, clastic, and chemical sedimentary rocks. The Ball assemblage comprises crustally contaminated komatiite, tholeiitic basalt, 2.94–2.92 Ga calc-alkaline, felsic volcanic rocks, and stromatolitic carbonate. The Slate Bay sedimentary assemblage of wacke, conglomerate and less than 2.91 Ga quartzose arenite records accumulated Balmer- and Ball-age material, prior to the 2.89 Ga intermediate pyroclastic volcanism and sedimentation of the Bruce Channel assemblage. The Confederation assemblage rests unconformably on the Balmer, and consists of basal conglomerate, 2.74 Ga FIII-type rhyolite and tholeiitic basalt with volcanogenic-massive-sulphide-style alteration-mineralization, and younger 2.73 Ga calc-alkaline pyroclastic rocks. Polyphase deformation involved pre-Confederation tilting and at least two episodes of post-Confederation deformation reflected by folds and fabrics of low to moderate finite strain.

Résumé : La ceinture de roches vertes de Red Lake témoigne de 300 Ma de volcanisme épisodique, de sédimentation, de déformation et de minéralisation. L'assemblage de Balmer, hôte de mines d'or actuelles et passées, contient des coulées de laves tholéiitiques et komatiitiques intercalées avec des roches volcaniques felsiques, des roches clastiques et des roches sédimentaires chimiques datant de 2,98 à 2,96 Ga. L'assemblage de Ball comporte des komatiites à contamination crustale, des basaltes tholéiitiques, des roches volcaniques felsiques calco-alcalines de 2,94 à 2,92 Ga, et des roches carbonatées stromatolitiques. L'assemblage sédimentaire de Slate Bay comprend des wackes, des conglomérats et des arénites quartzeuses de moins de 2,91 Ga et atteste l'accumulation de matériaux de l'âge des assemblages de Balmer et de Ball avant le volcanisme pyroclastique intermédiaire et la sédimentation (2,98 Ga) qui ont produit l'assemblage de Bruce Channel. L'assemblage de Confederation repose en discordance sur l'assemblage de Balmer et comporte un conglomérat de base, une rhyolite du type FIII et du basalte tholéiitique (2,74 Ga) avec altération-minéralisation de type sulfures massifs volcanogènes, et des roches pyroclastiques calco-alcalines plus jeunes (2,73 Ga). La déformation polyphasée a comporté un basculement antérieur et au moins deux épisodes de déformation postérieures à la formation de l'assemblage de Confederation, ce dont témoigne la présence de plis et de fabriques associés à des contraintes totales faibles à modérées.

[1] Contribution to the Western Superior NATMAP Project

INTRODUCTION

The Red Lake greenstone belt is characterized by a diverse supracrustal succession that spans approximately 300 Ma — a polyphase tectonometamorphic history and a rich mineral endowment. Field investigations initiated in 1999 as part of the Western Superior NATMAP Project were designed to provide 1) a geological synthesis of an important gold-mining camp with the potential to host significant volcanogenic massive sulphide (VMS) mineralization; 2) an updated overview of the geology, geochronology, and geochemistry along the northern segment of a LITHOPROBE seismic-reflection line (Fig. 1); and, 3) stratigraphic and structural linkage between ongoing Western Superior NATMAP investigations to the west (Wallace Lake, Manitoba; *see* Sasseville and Tomlinson, 2000) and east (Birch–Uchi belt, Ontario; *see* Rogers et al., 2000), thereby providing a wider perspective on ca. 3.0–2.7 Ga tectonomagmatic processes that operated along the southern margin of the North Caribou terrane.

The Red Lake greenstone belt is one of Canada's foremost gold camps, and yet there is no published regional structural analysis of the belt. The earliest comprehensive description of rock units and the first analysis of the structural geology of its mineral deposits were reported by Horwood (1945). Subsequent detailed mapping of individual townships was summarized by Pirie (1981) and Wallace et al. (1986), and studies of shear zones and their relationship to gold deposits by Wilson et al. (1984) and Andrews et al. (1986). A comprehensive overview of the Red Lake greenstone belt within the context of the Uchi Subprovince is provided by Stott and Corfu (1991).

This paper presents the initial results of an integrated stratigraphic, structural, lithogeochemical, and geochronological study of the Red Lake belt. It summarizes field observations and presents new and compiled geochemical and isotopic data that will be used to constrain the tectonic setting of volcanic assemblages and form the basis for lithogeochemical correlations. The geochemistry of felsic volcanic rocks is emphasized to highlight the potential for VMS-style mineralization in the belt (cf. Lesher et al., 1986).

SUPRACRUSTAL ASSEMBLAGES

Mesoarchean strata form the backbone of the Red Lake greenstone belt (Fig. 2) and include three volcanic assemblages: Balmer, Ball, and Bruce Channel. Clastic rocks of the Slate Bay assemblage are likely part of the Mesoarchean strata. Neoarchean volcanic rocks of the ca. 2.75–2.73 Ga Confederation assemblage dominate the northeast and southeast flanks of the belt. The interface between the Mesoarchean Balmer and Neoarchean Confederation assemblages, which bracket a ca. 200 Ma time interval, is exposed at several localities. The structural, lithological, and geochemical character of rocks that straddle this interface provide insight into processes that operated at two widely separated times in the geological history of the area, and the

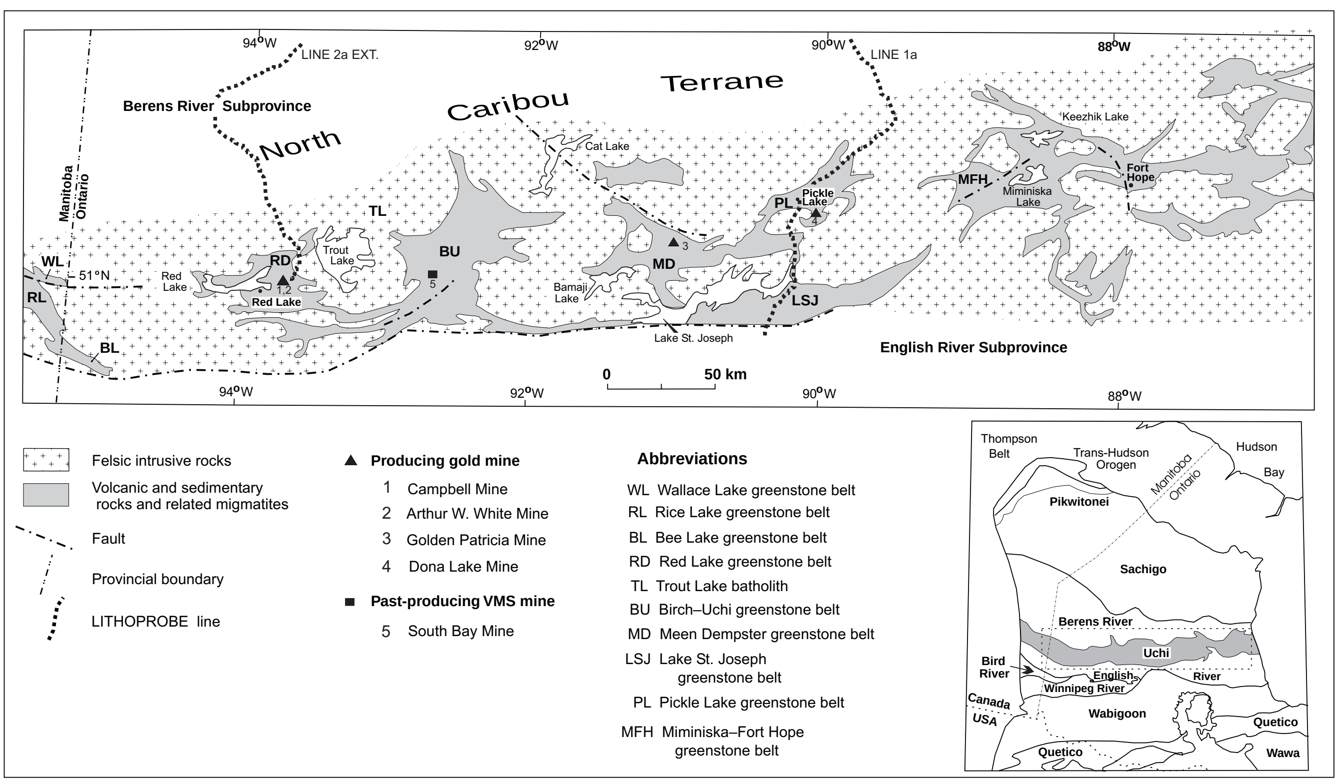


Figure 1. *Greenstone belts and granitic batholiths of the Uchi Subprovince from Stott and Corfu (1991).*

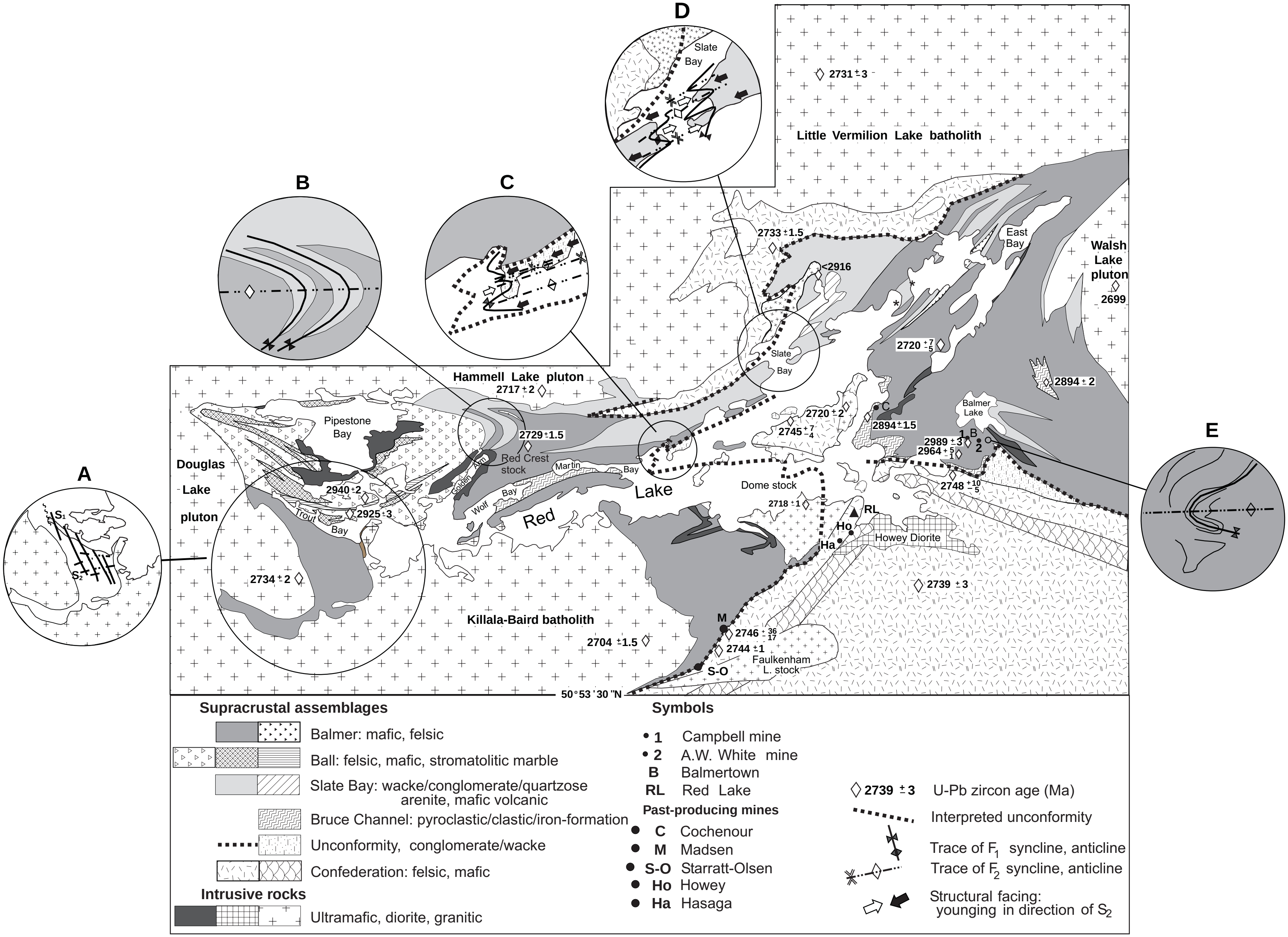


***Figure 2.** Geology of the Red Lake greenstone belt, showing critical U-Pb zircon age determinations of volcanic and plutonic rocks and local structural relationships. Modified from Stott and Corfu (1991).*

processes that brought these crustal blocks together by 2718 ± 1 Ma, the age of the Dome stock that cuts the interface. The importance of these processes in localizing gold mineralization is reflected by the spatial association between this interface and the Madsen, Starratt-Olsen, Hasaga, and Howey gold mines (Fig. 2).

Mesoarchean strata

Balmer assemblage

The Balmer assemblage forms about 50% of the belt (Fig. 2) and is host to all major gold deposits in the Red Lake greenstone belt. It consists of interlayered basaltic and komatiitic flows (Fig. 3a, b) and mafic to ultramafic intrusive rocks, with minor felsic metavolcanic rocks, clastic metasedimentary rocks, and chert-magnetite iron-formation. The assemblage has been dated at several localities in the northeastern part of the belt, with ages of 2992 +20/-9 Ma, 2989 ± 3 Ma, and 2964 +5/-1 Ma (Corfu and Andrews, 1987) determined from rhyolitic units interlayered with mafic and ultramafic metavolcanic rocks. Rocks interpreted as part of the Balmer assemblage on the basis of lithological and geochemical character are exposed in the central and southwestern parts of the belt.

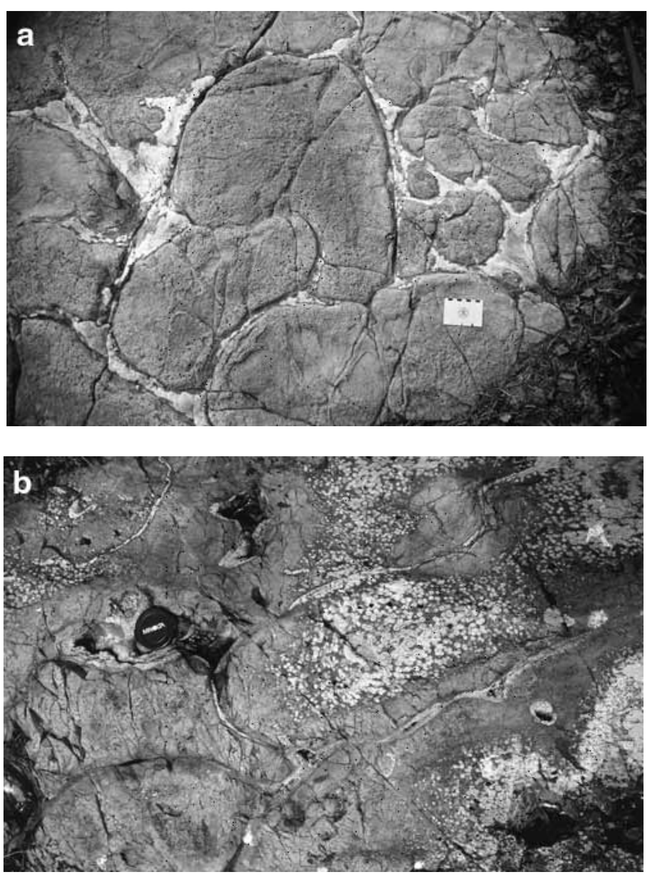


Figure 3. *Pillowed flows of the Balmer assemblage.* ***a)*** *Pillowed komatiitic flow with interpillow chert located on Flat Lake, west of Madsen.* ***b)*** *Variolitic pillowed basalt, eastern Red Lake.*

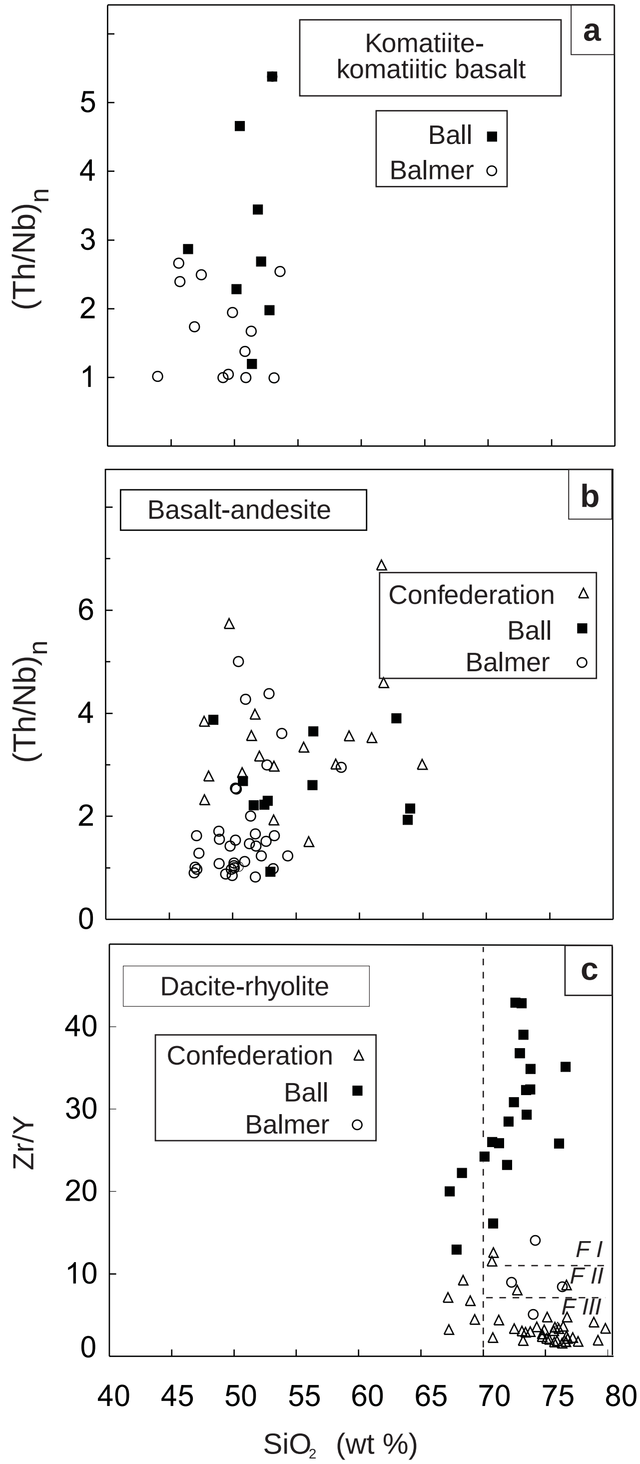


Figure 4. *SiO_2 versus* ***a)*** *$(Th/Nb)_n$ (primitive mantle normalized after Sun and McDonough (1989) in ultramafic volcanic rocks from the Red Lake greenstone belt;* ***b)*** *$(Th/Nb)_n$ in mafic and intermediate volcanic rocks (<65% SiO_2); and* ***c)*** *Zr/Y in felsic volcanic rocks. Fields of FI, FII and FIII rhyolites are from Lesher et al. (1986). The single Balmer rhyolite that lies in the FIII field has low Zr and Y abundances characteristic of FII-type rhyolites (cf. Parker, 1999). Chemical data are from Tomlinson et al. (1998), Hollings et al. (1999) and this study (Geoscience Laboratories, Ontario Geoservices Centre).*

Komatiite and komatiitic basalt samples are of the Al-undepleted variety (Tomlinson et al., 1998; Hollings et al., 1999) and encompass a spectrum of compositions from light rare-earth- element (LREE) depleted with primitive mantle-normalized Th_n=Nb_n<La_n, to komatiitic basalt with flat REE profiles and Th_n>La_n>Nb_n (expressed as $(Th/Nb)_n$ in Fig. 4a). Balmer basalt samples are tholeiitic and have flat to slightly LREE-enriched trace-element profiles with Th>La>Nb (Fig. 4b). Rhyolitic (>70% SiO_2) units intercalated with the mafic rocks are LREE enriched, have flat heavy rare-earth-element (HREE) profiles and Th_n>La_n>Nb_n. Their Zr/Y values and Zr, Y abundances (Fig. 4c) indicate FII-type affinity (Lesher et al., 1986).

The Balmer assemblage has been extensively affected by two styles of alteration. Semiconformable hydrothermal alteration, characterized by Na_2O, CaO, and MgO depletion and variable enrichment in Al_2O_3, SiO_2, CO_2, K_2O, MnO, As, Sb, S, and total Fe (MacGeehan and Hodgson, 1981; Pirie, 1982; Durocher, 1983; Mathieson and Hodgson, 1984; Penczak, 1996), and subsequent metamorphism, has been responsible for the conversion of large volumes of mafic rocks to buff-grey-weathering, biotite-bearing rocks that commonly contain porphyroblasts of andalusite and garnet (Fig. 5). Intensely altered 'bleached' zones and sulphide minerals spatially associated with pillow rims and primary fractures and vesicles suggest that primary features served as conduits for circulating hydrothermal fluids. Superimposed epigenetic vein-type alteration is associated with most of the gold deposits.

Figure 5. *Hydrothermally altered pillowed basalt from the immediate footwall (McVeigh zone) of the Madsen gold deposit. Andalusite porphyroblasts are concentrated in bleached margins of pillows.*

Figure 6. *Stromatolitic marble of the Ball assemblage, western Red Lake.*

Ball assemblage

Diverse volcanic rocks and interlayered chemical sedimentary rocks of the Ball assemblage underlie the northwestern part of the Red Lake greenstone belt (Fig. 2). Volcanic rocks include komatiitic to tholeiitic basalt, intermediate pyroclastic rocks, and massive to spherulitic rhyolite. Chemical sedimentary rocks include chert-magnetite iron-formation and dolomitic marble-chert beds which, in the south, contain stromatolites (Fig. 6) (Hofmann et al., 1985). Uranium-lead ages of rhyolitic units immediately below and above stromatolitic marble beds are 2940 ± 2 Ma and 2925 ± 3 Ma, respectively (Corfu and Wallace, 1986), and bracket the time of stromatolite growth in shallow-water conditions.

Komatiite and komatiitic basalt of the Ball assemblage are Al-undepleted (Hollings et al., 1999), and along with the majority of basalt samples, have slightly LREE-enriched profiles, with Th_n>La_n>Nb_n ($(Th/Nb)_n$ in Fig. 4a, b). In contrast, a single tholeiitic basalt sample is LREE-depleted with Th_n<Nb_n<La_n (Fig. 4b). Stratigraphically higher andesitic to rhyolitic rocks of the Ball assemblage are calc-alkaline, and are LREE-enriched, HREE-depleted with Th>La>Nb (andesite) and Th>La>Nb (dacite, rhyolite). Ball rhyolites have Zr/Y values and Zr, Y abundances typical of FI-type (Fig. 4c).

Slate Bay assemblage

The Slate Bay area (Fig. 2) is underlain by clastic metasedimentary rocks. From south to north these are dominated by 1) well bedded feldspathic wacke interbedded with lithic wacke and argillite; 2) lenses of pebble to cobble conglomerate with well rounded clasts (Fig. 7a); and, 3) compositionally mature (quartz-rich), texturally immature pebble conglomerate, grit and quartzose arenite (Fig. 7b). Quartz-rich clastic rocks contain clasts of vein quartz, felsic volcanic rocks, and fuchsitic material suggesting felsic and ultramafic sources. Their maximum depositional age is ca. 2916 Ma, the age of the youngest detrital zircon analyzed (Corfu et al., 1998).

Quartz-rich pebble conglomerate and quartzose wacke exposed in northeastern Red Lake (* in Fig. 2) may be correlative with those of the Slate Bay assemblage.

Bruce Channel assemblage

The Bruce Channel assemblage is presently recognized in the eastern Red Lake belt, proximal to gold-mineralized mafic volcanic rocks of the Balmer assemblage. It consists of intermediate pyroclastic rocks (Fig. 8a), including well bedded

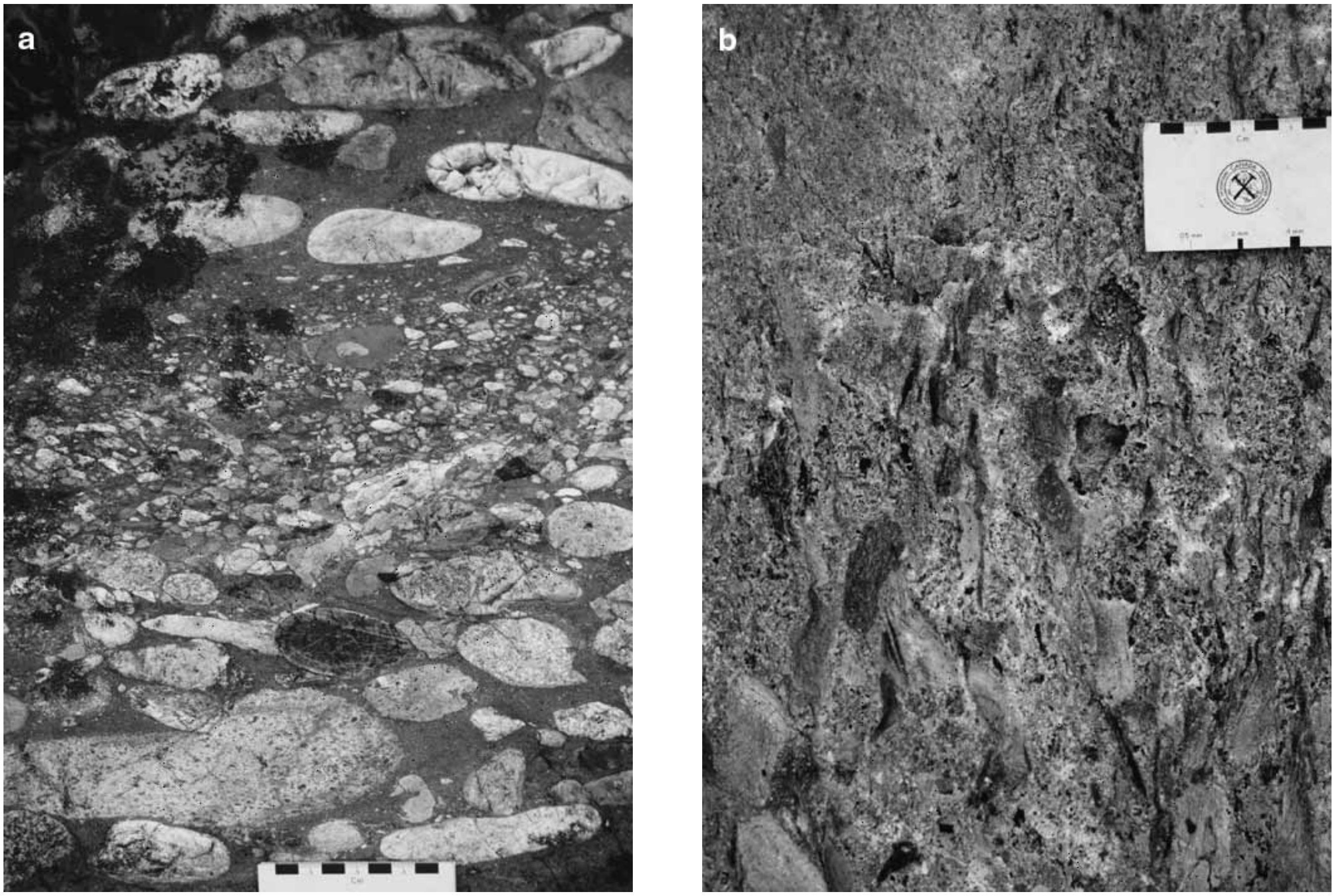


Figure 7. *Slate Bay assemblage.* ***a)*** *Well sorted polymictic conglomerate, central Slate Bay.* ***b)*** *Conglomeratic quartzose arenite, northern Slate Bay.*

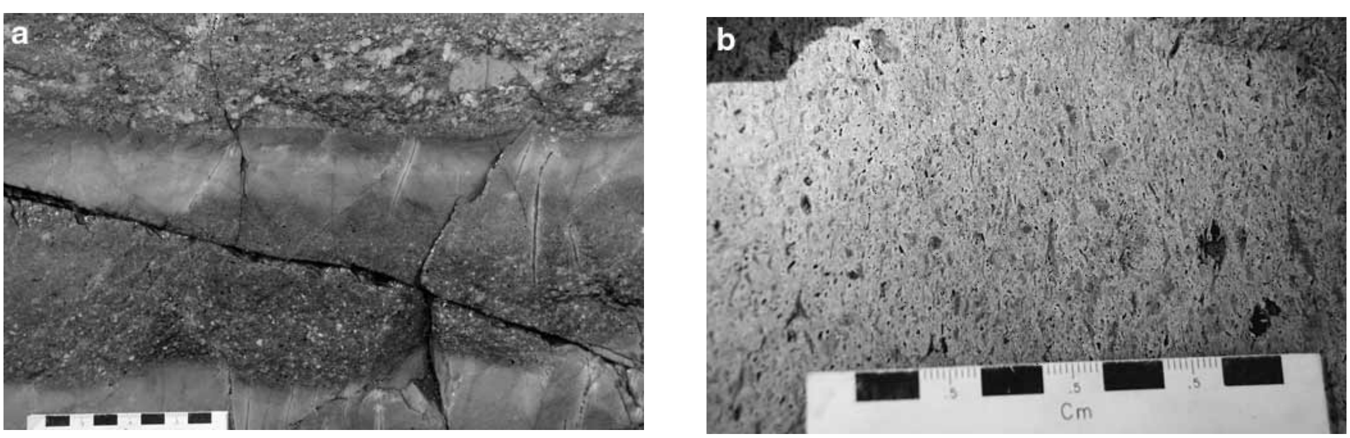


Figure 8. *Bruce Channel assemblage near Cochenour.* ***a)*** *Thinly bedded, rhyodacitic tuff to ash beds.* ***b)*** *Pumaceous upper part of pyroclastic deposit.* ***c)*** *Ungraded pebble conglomerate overlain by thinly bedded volcanic-derived, crosslaminated wacke and parallel-laminated siltstone.*

lapilli tuff with normally graded lithic fragments at the base of beds and inversely graded pumaceous upper beds (Fig. 8b). These have U-Pb zircon ages of 2894 ± 1.5 Ma (Corfu and Wallace, 1986) on the east shore of Bruce Channel, and 2894 ± 2 Ma (Corfu and Andrews, 1987) northeast of Balmer Lake (Fig. 2). In the latter area, Stott and Corfu (1991) interpreted a thick section of basalt to belong to the Bruce Channel assemblage; however, this remains to be tested through lithogeochemistry. Although internal folding is present, overall younging criteria established that clastic rocks overlie the pyroclastic rocks. The clastic rocks are texturally variable, and include poorly sorted, poorly bedded pebble conglomerate overlain by thinly bedded wacke (Fig. 8c). Magnetite-chert iron-formation at the top of the Bruce Channel assemblage is traced along much of its length and is the principal means of correlating rocks exposed along the east shore of Bruce Channel with those in the easternmost part of the belt (cf. Stott and Corfu, 1991).

Units that may be correlative with the Bruce Channel assemblage were recognized in the central Red Lake belt (Fig. 2). In Martin Bay, these include dacitic flows and pumaceous pyroclastic rocks capped by wacke with well preserved primary dewatering structures. Further southwest in Wolf Bay (Fig. 2), intermediate volcanic rocks are overlain by a substantial thickness (~1 km) of thinly bedded iron-formation and iron-formation breccia, overlain by plagioclase crystal-rich tuff, carbonate, and graphitic argillite. Sampling will test whether rhyodacitic flows and tuffs north of McKenzie Island are also part of the Bruce Channel assemblage.

Neoarchean Strata

Confederation assemblage

The Confederation assemblage is a significant volcanic assemblage found throughout the Uchi Subprovince, deposited during a period of extensive volcanic activity between 2750 and 2730 Ma (Stott and Corfu, 1991). At Red Lake, this assemblage consists of intercalated felsic to mafic metavolcanic flows, pyroclastic rocks, and metasedimentary rocks of volcanic provenance. In the southeastern part of the greenstone belt (Fig. 2), a thick succession of felsic metavolcanic rocks dominated by pyroclastic tuff, lobe-hyaloclastite rhyolite flows (Fig. 9a, b), and rhyolite flow breccia strikes northeast to east, dips steeply south and faces southward. The rhyolite flows are overlain and interlayered with pillowed mafic flows, quartz-feldspar crystal tuff, and intermediate to felsic pyroclastic rocks. Stratigraphically higher sections include feldspar-porphyritic andesitic flows and associated dykes (Fig. 9c).

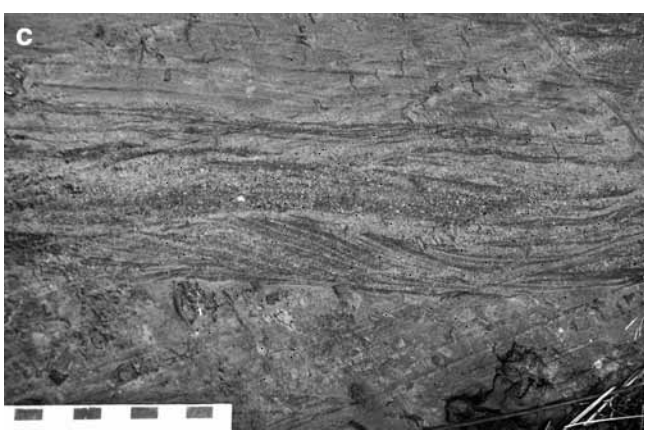


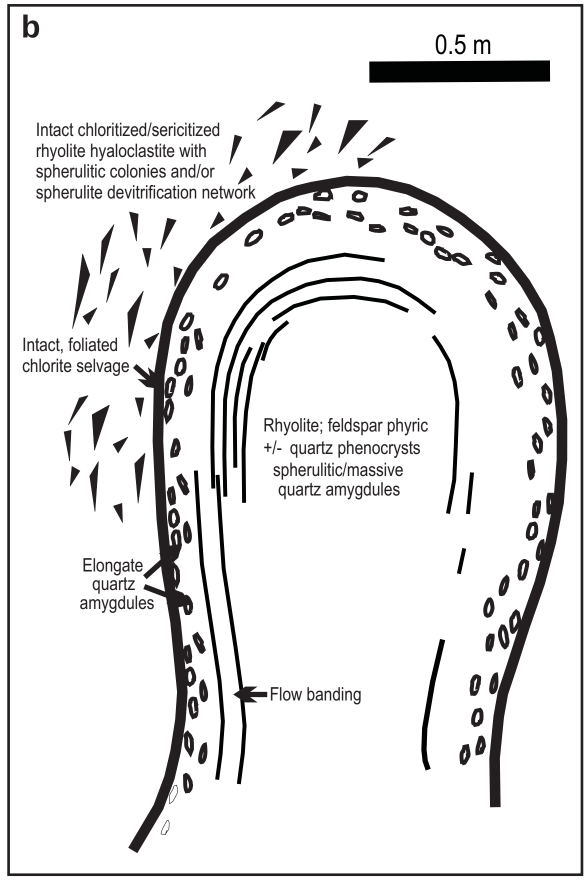
Figure 8. *(cont.)*

Felsic rocks of the Confederation assemblage from the southeastern flank of the Red Lake greenstone belt have U-Pb zircon ages that range from 2748 +10/-5 Ma to 2739 ± 3 Ma (Corfu and Wallace, 1986) (Fig. 2), whereas a younger U-Pb zircon age of 2733 ± 1.5 Ma (Corfu and Wallace, 1986) has been determined from its northern flank. In the center of the belt, pyroclastic rocks previously interpreted to represent an isolated occurrence of ca. 2830 Ma rocks (Corfu and Wallace, 1986), have been reinterpreted as part of the Confederation assemblage, with an U-Pb zircon age of 2745 +7/-4 Ma (Corfu et al., 1998).

Basalt and andesite from low in the Confederation succession are primarily tholeiitic, whereas basalts from higher stratigraphic levels are calc-alkaline. Both suites are characterized by parallel REE profiles that are slightly enriched in LREE, have flat HREE, and $Th_n > La_n > Nb_n$. Normalized Th/Nb values for these rocks overlap the upper range of values found in basalts of the Balmer and Ball assemblages, and extend to higher values (Fig. 4b). Relative to the mafic rocks, dacite and rhyolite have parallel REE profiles reflecting uniform enrichment of trace elements, with negative Eu anomalies (not depicted). Rhyolitic rocks from the southeastern belt have Zr/Y values and Zr, Y abundances characteristic of FIII- and FII-type felsic volcanic rocks (Fig. 4c) (Parker, 1999). The parallel trace-element profiles of compositionally diverse Confederation volcanic rocks are consistent with comagmatic derivation by fractional crystallization.

GRANITOID ROCKS

Granitoid rocks in the Red Lake area record three main episodes of felsic plutonism. The first coincided with the end of Confederation volcanism and is represented by the 2734 ± 2 Ma Douglas Lake pluton (Corfu and Stone, 1998), the 2731 ± 3 Ma Little Vermilion Lake batholith, and the 2729 ± 1.5 Ma Red Crest stock (Corfu and Andrews, 1987) (Fig. 2). The Douglas Lake pluton is dominated by biotite tonalite that is LREE-enriched, HREE-depleted, with normalized $Th_n > La_n > Nb_n$, interpreted to have formed by partial melting of mafic crust (Corfu and Stone, 1998). The Little Vermilion Lake batholith is part of a hornblende tonalite-granodiorite suite that is characterized by LREE enrichment, is slightly less depleted in HREE than the Douglas Lake pluton, and may have assimilated older sialic crust (Corfu and Stone, 1998).



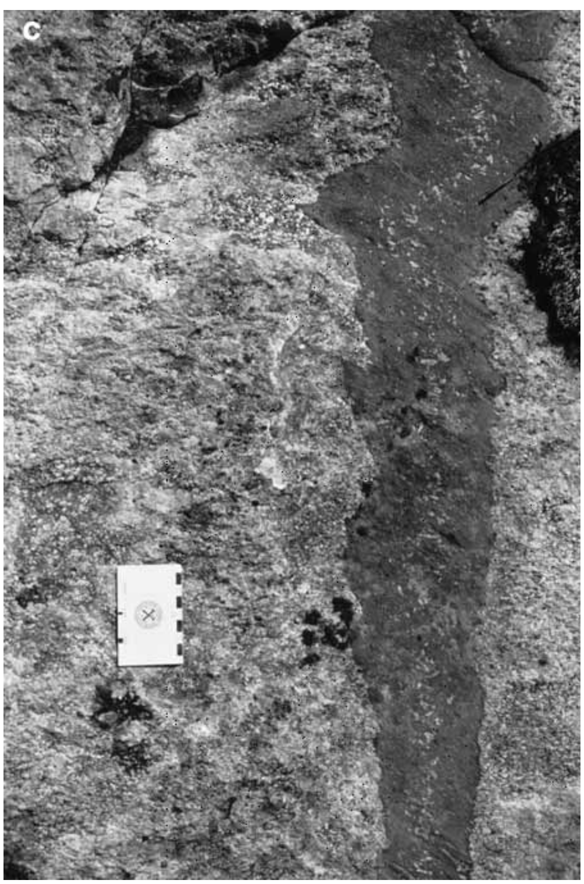


Figure 9.

Confederation assemblage. ***a)*** *Rhyolite lobe.* ***b)*** *Schematic diagram of massive rhyolite lobe and rhyolite breccia after Gibson (1999).* ***c)*** *Rhyolite tuff tuff breccia cut by plagioclase-phyric andesite dyke.*

A second episode of plutonism at 2.72 Ga is represented by the 2717 ± 2 Ma Hammell Lake pluton (McMaster, 1987) and a number of plutons internal to the belt including the 2720 ± 2 Ma McKenzie Lake stock, 2718 ± 1 Ma Dome stock, 2720 +7/-5 Ma Abino granodiorite, and a post-tectonic, post-ore quartz-feldspar porphyry dyke in the A.W. White mine dated at 2714 ± 4 Ma (Corfu and Wallace, 1986; Corfu and Andrews, 1987).

A final magmatic event at 2.7 Ga is represented by K-feldspar-megacrystic granodiorite of the 2704 ± 1.5 Ma Killala-Baird batholith (Corfu and Andrews, 1987), the ca. 2699 Ma Walsh Lake pluton (Noble, 1989) at the eastern margin of the belt, and a 2699 ± 4 Ma post-ore dyke at Madsen. Although subsequent localized brittle deformation, alteration, and gold mineralization (cf. Menard et al., 1999) is indicated by an U-Pb zircon age of 2701 ± 1.5 Ma for the Wilmar granodiorite dyke (Corfu and Andrews, 1987), which is cut by a stockwork of gold-bearing quartz-tourmaline veins, a rapid decline in thermal and hydrothermal activity in the Red Lake belt at ca. 2.7 Ga is indicated by the small time difference between zircon and titanite ages of these late- to post-tectonic plutons (Corfu and Andrews, 1987).

STRUCTURAL GEOLOGY

The Red Lake greenstone belt is an east-trending belt characterized by steeply dipping panels of volcanic and metasedimentary rocks. Shallowly dipping strata are observed locally in the central and eastern parts of the belt. Although hydrothermal alteration of volcanic strata is moderate to intense, penetrative strain is typically moderate to weak, such that in substantial parts of the belt primary volcanic and sedimentary structures are well preserved (cf. Fig. 3, 5–9).

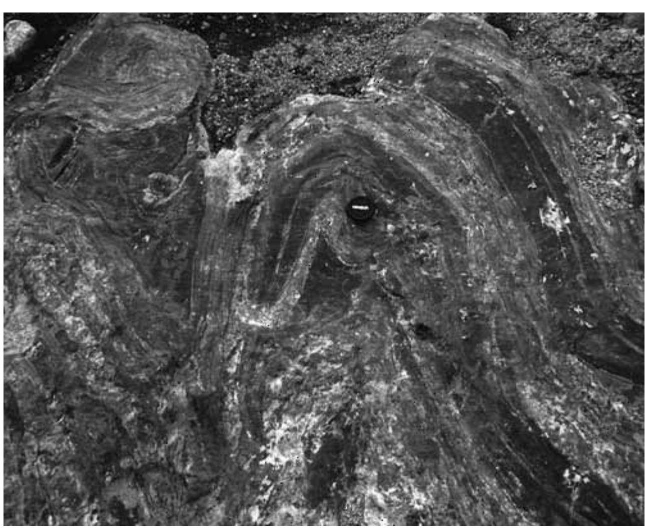


Figure 10. *Refolded folds in chert-magnetite iron-formation, A.W. White Mine area (see inset E, Fig. 2).*

D_1 and D_2

Throughout the greenstone belt, evidence of two main episodes of deformation is widespread. In the southwest, overprinting planar tectonic fabrics (S_1, S_2) are developed in Balmer strata (Fig. 2, inset A). S_1 is a north-northwest-striking bedding-parallel foliation, whereas S_2 is an east-striking foliation that crenulates S_1. These fabrics are axial-planar to F_1 and F_2 folds, respectively, developed in overlying clastic rocks of uncertain age. Along the northwestern margin of the belt (Fig. 2, inset B), map patterns are consistent with two phases of deformation likely correlative with F_1 and F_2 above: that is, first generation north-trending folds refolded about east-striking F_2 axial traces. The penetrative east-striking S_2 foliation recorded in the Ball assemblage throughout the Pipestone Bay area, which locally cuts a bedding-parallel S_1 cleavage in the hinge zone of an east-striking F_2 fold, is axial-planar to the inferred F_2 fold of inset B. In the central Red Lake belt, opposing structural facing at several localities (Fig. 2, inset C, D) is consistent with two phases of folding. At these localities, metasedimentary rocks of post-Confederation (inset C) and post-Ball age (inset D) are characterized by a single moderately developed S_2 foliation that strikes east-northeastward and dips steeply southeastward. S_1 is not developed. In eastern Red Lake near Balmertown (Fig. 2, inset E; Fig. 10), refolded folds in banded iron-formation reveal an initial generation of north-trending F_1 folds that have been refolded by west- to northwest-trending F_2 folds.

Pre-D_1

Pre- to syn-Confederation-age tilting of Mesoarchean strata is indicated by the presence of an angular unconformity between the Balmer and Confederation assemblages at several localities (*see* ‘Discussion’ below).

Regional-scale shear zones

During the 1980s, a number of structural studies in the Red Lake belt focused on defining shear zones to which gold mineralization was considered to be spatially and genetically linked (Lavigne and Crocket, 1983; Durocher and Burchell, 1983; Durocher and Hugon, 1983; Andrews et al., 1986; Hugon and Schwerdtner, 1988). These studies led to the formulation of a belt-scale system of transcurrent deformation zones (Fig. 11), the limits of which were postulated to contain a higher than normal abundance of ductile and brittle-ductile fault zones characterized by a single sense of shear. These studies have had significant impact on mineral exploration in the belt in that they purported that strain localization was a dominant control on gold mineralization.

The concept of regional-scale deformation zones was reassessed during this mapping program and preliminary interpretations pertinent to the concept are as follows.

1. Mylonites are very rare, and generally there is excellent preservation of primary structures.

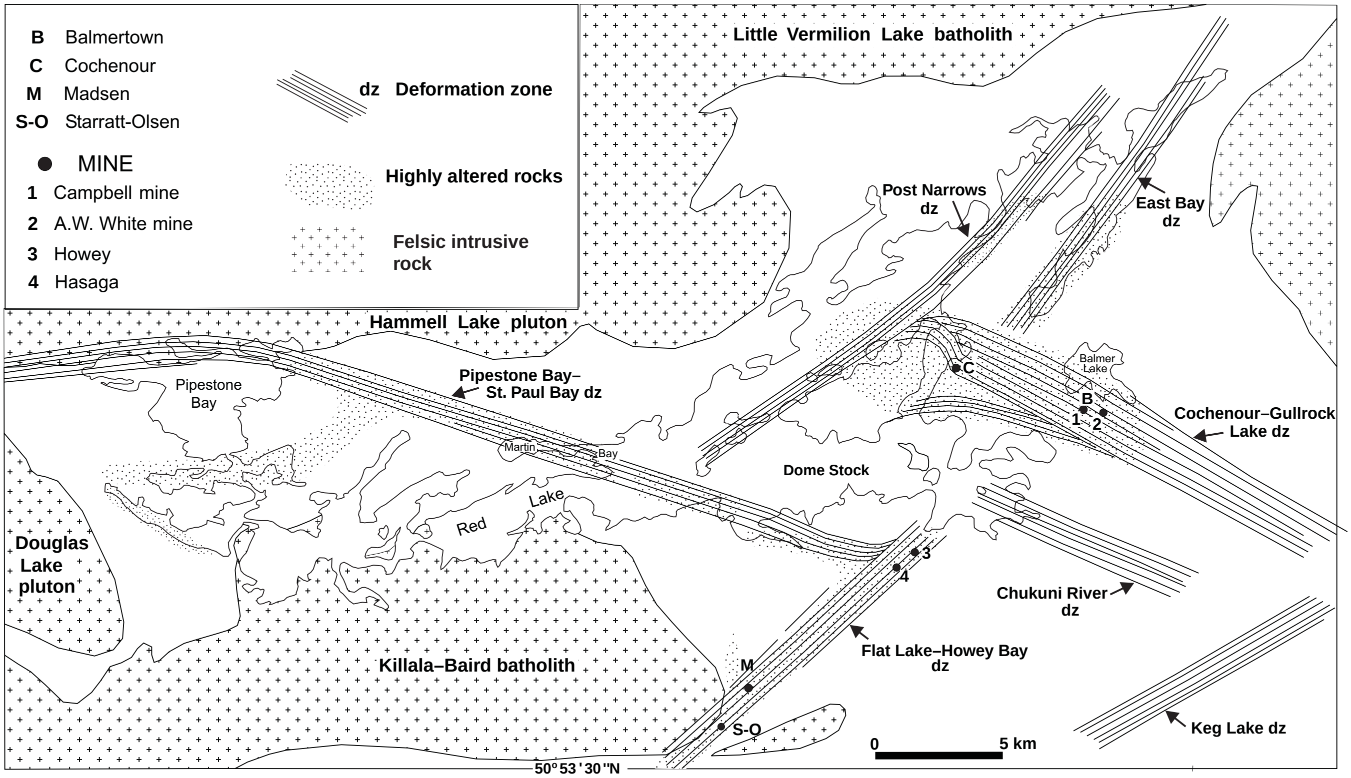


Figure 11. *System of belt-scale transcurrent shear zones proposed by Hugon and Schwerdtner (1988), from Andrews et al., 1996.*

2. Observed high-strain zones within defined high-strain corridors are not necessarily oriented parallel to these corridors.

3. Alteration and gold mineralization may have been partly controlled by primary permeable horizons, such as unconformities, rather than only focused along regional-scale ductile shear zones. Proximity to an unconformity (*see* Fig. 2) may represent an underestimated first-order parameter in designing exploration strategy in the district.

ALTERATION AND MINERALIZATION

Volcanogenic massive-sulphide mineralization

The Confederation assemblage in the Red Lake greenstone belt has several geological attributes that make it a significant target for volcanogenic massive-sulphide (VMS) exploration. The metavolcanic rocks are the same age as VMS-productive metavolcanic successions elsewhere in the Superior Province (Fyon et al., 1992). Many felsic metavolcanic rocks of southeast Red Lake have FIII-type trace-element abundances (Parker, 1999), a signature common to most VMS-productive metavolcanic successions in the Superior Province (e.g. the South Bay VMS deposit (Fig. 1)). Primary textural features of the Confederation assemblage, such as coarse, pyroclastic deposits and lobe-hyaloclastite rhyolite flows indicate deposition in subaqueous conditions proximal to volcanic centres. In addition, several sulphidic chert-argillite exhalite units, interlayered with FIII-type felsic metavolcanic rocks, are associated with synvolcanic alteration and contain anomalous zinc, copper, lead, and silver-sulphide mineralization (Parker, 1999). The nature, composition, and shallow-water environment of deposition of felsic rocks of the Confederation assemblage, combined with presence of aluminous alteration, clearly emphasize the potential for gold-rich, high-sulphidation, VMS-type deposits in the district. The subaerial pyroclastic nature of the Bruce Channel assemblage may also represent another interesting exploration target for epithermal systems, particularly in the presence of aluminous alteration.

At the west end of the Red Lake greenstone belt, the Balmer assemblage hosts two subeconomic, zinc-rich deposits. Volcano-sedimentary rocks in this area were deposited in a subaqueous environment, and associated felsic metavolcanic rocks have FII-type geochemical affinities, supporting their economic potential (Lesher et al., 1986). The assemblage has undergone extensive semiconformable synvolcanic alteration resulting in carbonatized, Na-depleted zones, typical of alteration stratigraphically below Mattabi-type VMS deposits.

Gold

The Red Lake greenstone belt is one of the largest gold camps in Canada, with historical production of more than 18 million ounces of gold, essentially produced from three deposits, the Campbell-Goldcorp deposit (>13 million ounces of gold (Fig. 1), the Cochenour-Willans Mine (1.2 million ounces of gold), and the Madsen Mine (2.4 million ounces of gold). Gold deposits in the Red Lake district are atypical of most Archean, greenstone, shear-zone-hosted, vein-type deposits and remain the subject of much debate in terms of deposit type, genesis, and timing relative to regional deformation and metamorphism (e.g. Penczak and Mason, 1997; Tarnocai et al., 1998). The first phase of a GSC–Red Lake gold project, initiated to better understand these inter-relationships, focused on the Madsen Mine, which is currently being explored by Claude Resources (*see also* Dubé et al., 2000).

Madsen Mine

The Madsen gold deposit is an Archean, stratabound, disseminated, replacement-style deposit located at the interface between the Balmer and Confederation assemblages (Fig. 2, 12). The deposit is hosted by hydrothermally altered Balmer basalt and mafic-derived fragmental rocks, and comprises two main ore horizons, the McVeigh and Austin. An inner zone of hydrothermal alteration, which hosts the ore, is characterized by metasomatic layering composed of hornblende-actinolite, biotite, quartz, calcite, tourmaline±K-feldspar, with 3–5% disseminated pyrrhotite, pyrite, and local arsenopyrite. This alteration zone is surrounded by an aluminous, calc-silicate-bearing outer zone characterized by andalusite, garnet, biotite, staurolite, and amphibole in mafic volcanic rocks.

Deformation within the deposit is highly heterogeneous, but overall of low to medium intensity with local centimetre- to metre-scale high-strain zones. Two main generations of structures are documented: a weak to moderately developed, variably oriented, bedding-parallel foliation (S_0-S_1), and a moderately to strongly developed, east-northeast-striking, southeast-dipping S_2 foliation with moderately north-east-plunging L_2 mineral lineations and local centimetre- to metre-wide, sinistral, high-strain zones. S_2 is axial-planar to locally developed, shallowly to moderately east-northeast-plunging F_2 folds. Alteration zones and mineralization are folded, partly transposed, and disrupted by D_2 structures, indicating pre- to early-D_2 age.

The Madsen deposit is located at an unconformity (described below) between the Balmer and Confederation assemblages. The unconformity appears to have acted as a

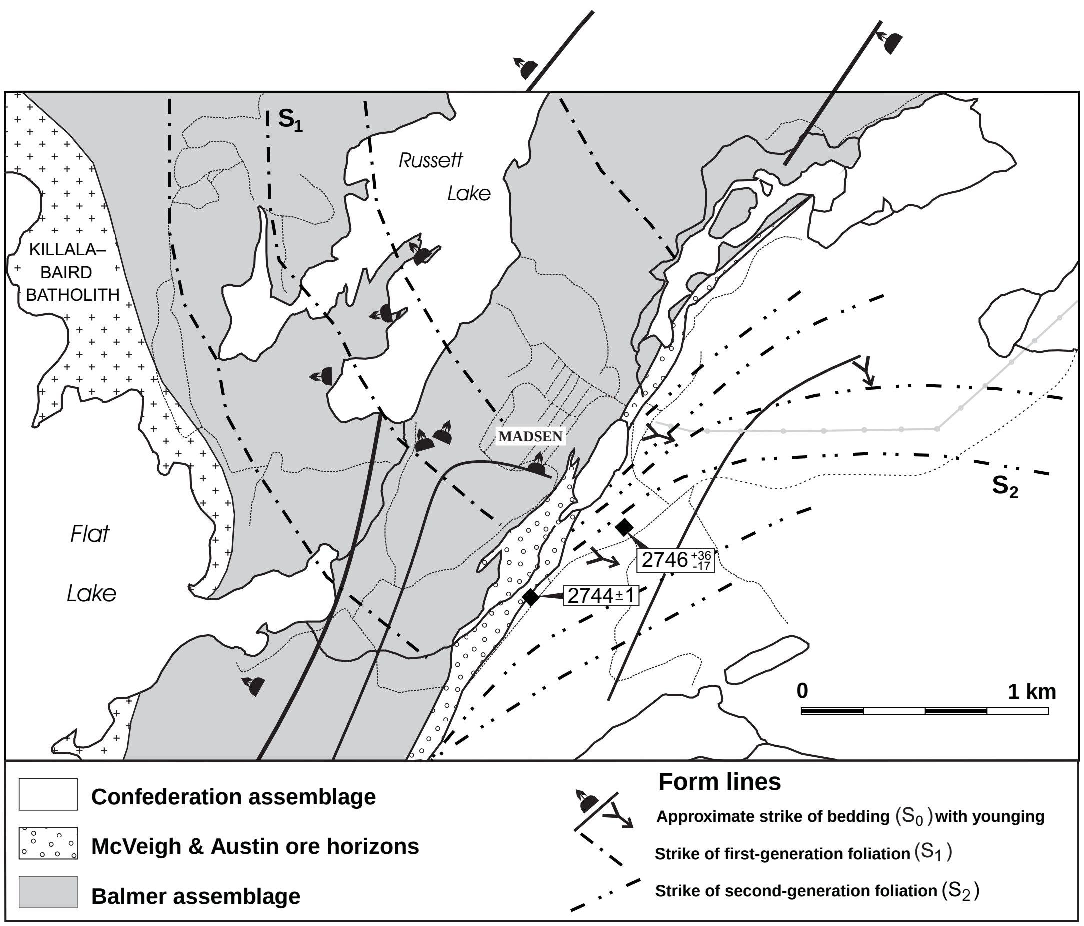


Figure 12. *Geology of the Madsen Mine area.*

permeable horizon that focused hydrothermal (±mineralizing) fluids, explaining, at least in part, the physical location and stratabound nature of the deposit. It has been proposed that the deposit is localized within a sinistral shear zone formed during emplacement of the 2704 ± 1.5 Ma Killala–Baird batholith (Hugon and Schwerdtner, 1988); however, our observations show that the outer alteration (reflected by aluminosilicate porphyroblasts in metamorphosed rocks) occurred prior to, or during D_1 (Fig. 13), and may have been synvolcanic. The alteration assemblage at Madsen may be the result of two distinct hydrothermal events. Early synvolcanic, VMS-type alteration characterized by large-scale aluminum enrichment, followed by more restricted, pre- to early-D_2 gold mineralization. The minimum age of deformation and mineralization at Madsen is provided by a 2699 ± 4 Ma (U-Pb titanite) post-tectonic, post-ore, diorite dyke (Corfu and Wallace, 1986).

***Figure 13.** Andalusite porphyroblasts in dacite clast define S_1 foliation, parallel to pencil, and are crenulated by S_2, indicating hydrothermal alteration near Madsen is pre- to syn-D_1*

DISCUSSION

Contacts between assemblages

The Red Lake greenstone belt is described by Stott and Corfu (1991) as a collage of tectonometamorphic assemblages, juxtaposed along fault boundaries that lie within belt-scale deformation zones described by Andrews et al. (1986). Our preliminary results suggest that some assemblage contacts may be tectonic, but that others are demonstrably stratigraphic, with disconformities and unconformities between assemblages.

The base of the oldest, ca. 2.99–2.96 Ga, Balmer volcanic assemblage is not observed. Its trace-element signature is consistent with contamination by ≥3 Ga continental crust (Tomlinson et al., 1998; Hollings et al., 1999), suggestive of subaqueous eruption of Balmer basaltic magma through Mesoarchean continental crust. The closest known Mesoarchean continental crust is the ca. 2838 Ma phase of the Trout Lake batholith (Noble, 1989) (Fig. 1).

A tectonic contact between Mesoarchean Balmer- and Ball-age rocks is postulated based on opposed facing directions in adjacent stratigraphic panels separated by lineaments defined by Trout Bay and Golden Arm. Strain related to a tectonic break between these assemblages has not been identified. Rather, high-strain rocks at the head of Trout Bay define a deformation zone that transects both the Balmer and Ball assemblages and is parallel to the margin of the ca. 2734 Ma Douglas Lake pluton (Corfu and Stone, 1998). This shear zone is parallel to S_1 elsewhere in the area (Fig. 2, inset A), suggesting that heterogeneous D_1 strain may be related to the emplacement of the Douglas Lake pluton at ca. 2734 Ma.

Clastic rocks of the Slate Bay assemblage were deposited after ca. 2916 Ma and contain detrital zircon grains with Mesoarchean $^{207}Pb/^{206}Pb$ ages (Corfu et al., 1998) of 2989–2984 Ma (n=3), 2957 Ma (n=1) and 2926–2916 (n=4). These ages are consistent with Balmer- and Ball-age sources and deposition of the Slate Bay assemblage in response to denudation of Mesoarchean strata at ca. 2.9 Ga.

Although the distribution of the ca. 2894 Ma Bruce Channel assemblage remains to be defined, observations near Cochenour suggest that the Bruce Channel assemblage lies disconformably on the Balmer assemblage, and is, in turn, unconformably overlain by rocks of the Confederation assemblage. The Bruce Channel assemblage consistently faces away from Balmer volcanic rocks in the Cochenour and Martin Bay areas, and tectonic contacts and polymictic conglomerate (which could potentially mark an unconformity) are absent between these units. These observations refute the previous interpretation which held that Bruce Channel assemblage tectonically underlay the older Balmer assemblage, and was in fault contact with the Confederation assemblage (Stott and Corfu, 1991).

A major unconformity between the Mesoarchean Balmer assemblage and Neoarchean Confederation assemblage is recognized at several localities within the belt. East of McNeely Bay, strongly altered, variolitic pillowed basalt and interbedded 2964 +5/-1 Ma rhyolite (Corfu and Wallace, 1986) of the Balmer assemblage lie within 1 km of 2748 +10/-5 Ma Confederation assemblage volcanic rocks (Corfu and Wallace, 1986). Between the two dated samples, polymictic conglomerate (Fig. 14a) lies with local angular unconformity (ca. 70°) on Balmer assemblage rocks. Near Madsen (Fig. 12), northwest- and north-facing pillowed volcanic rocks of the Balmer assemblage are adjacent to ca. 2744 Ma southeast-facing intermediate pyroclastic and minor clastic rocks of the Confederation assemblage (Fig. 15a). Surface exposures of the contact between these assemblages are marked by fragmental rocks, which, contrary to previous interpretations (Andrews et al., 1986; Hugon and Schwerdtner, 1988), show a small degree of finite strain such that primary clast shapes, grading, and obliquity between bedding and foliation are preserved (Fig. 15). We interpret these fragmental rocks to mark a profound angular unconformity between Mesoarchean and Neoarchean strata in the Red Lake camp, and to be important in localizing hydrothermal fluids and gold mineralization at Madsen, and potentially elsewhere in the belt. Lastly, massive basaltic flows on the north shore of central Red Lake, which are likely correlative with the Balmer assemblage, are in contact with a mafic volcanic-derived conglomerate (Fig. 14b) overlain by turbiditic wacke. This locality (Fig. 2, inset C) is interpreted to mark the regional unconformity between Mesoarchean and Neoarchean rocks in the Red Lake greenstone belt.

Our interpretation that the Confederation assemblage erupted (unconformably) on Mesoarchean crust is consistent with crosscutting relationships of Confederation-age plutonic rocks, such as the 2742 +3/-2 Ma Balmer Lake porphyry in the east, and the 2729 ± 1.5 Ma Red Crest quartz-diorite stock in the west, to the Balmer assemblage.

Tectonic setting

The trace-element compositions of subaqueous mafic and ultramafic volcanic rocks of the Balmer assemblage indicate that their parental magmas, which may have been derived from partial melting of an ascending mantle plume, assimilated continental crust (Tomlinson et al., 1998; Hollings et al., 1999). Ongoing geochemical and isotopic studies will address whether felsic volcanic rocks in this sequence are arc related (Hollings et al., 1999) or, alternatively, related to crustal melting and mixing accompanying high-temperature komatiitic magmatism.

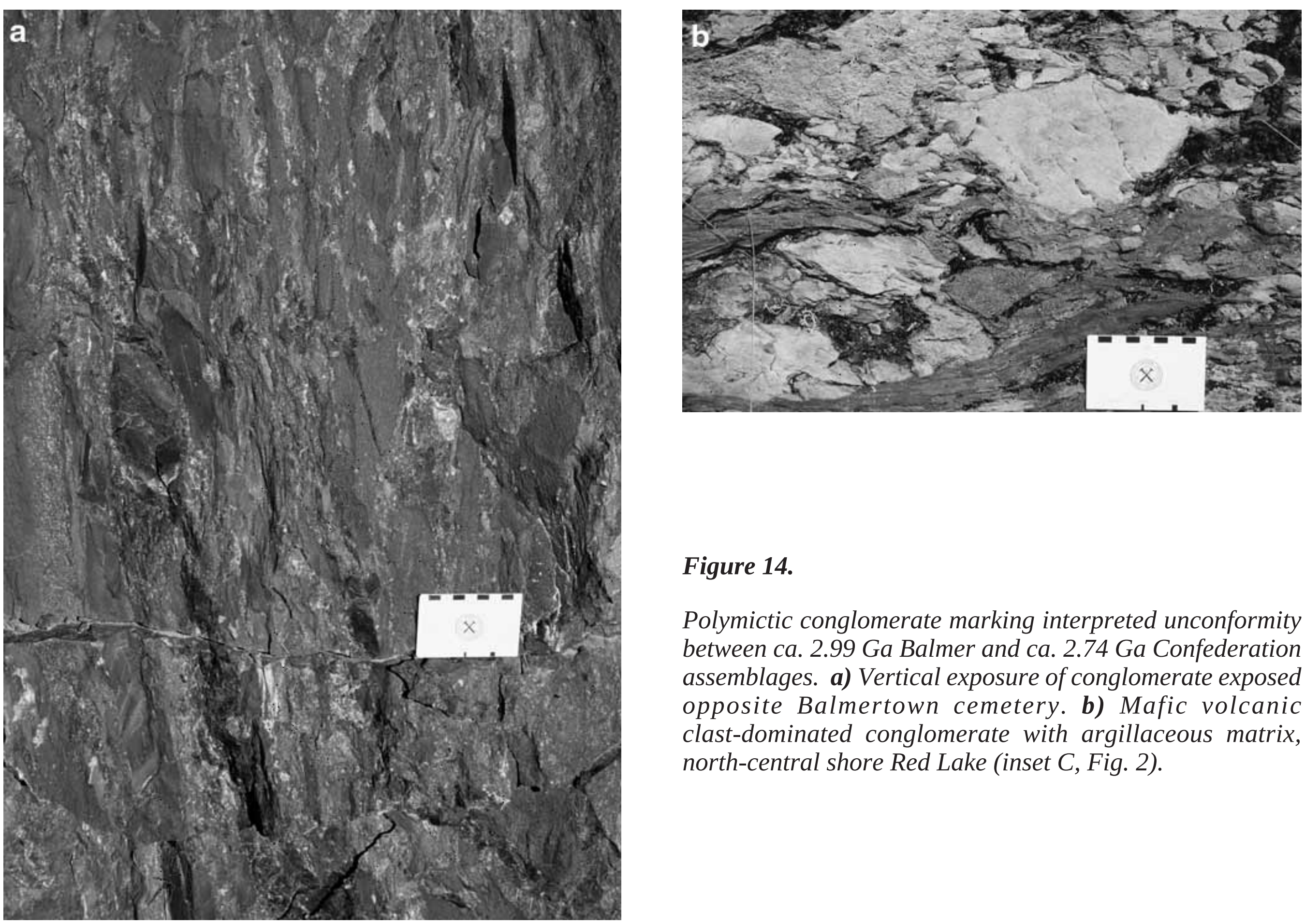


Figure 14.

Polymictic conglomerate marking interpreted unconformity between ca. 2.99 Ga Balmer and ca. 2.74 Ga Confederation assemblages. ***a)*** *Vertical exposure of conglomerate exposed opposite Balmertown cemetery.* ***b)*** *Mafic volcanic clast-dominated conglomerate with argillaceous matrix, north-central shore Red Lake (inset C, Fig. 2).*

Figure 15.

Fragmental rocks at, or close to, the interpreted angular unconformity near Madsen. ***a)*** *Graded bedding in wacke and polymictic pebble conglomerate. Pencil is parallel to S_2 and points in direction of younging, as indicated by normal grading of clasts in S_2 direction (structural facing). Note also bedding-parallel S_1 cleavage.* ***b)*** *Fragmental nature of the Austen tuff horizon. Note preservation of polymictic clasts and S_1 cleavage, which is folded and crenulated by an F_2 fold. Axial plane of F_2 is parallel to pencil. Horizontal exposure is adjacent to Madsen No. 2 headframe.*

Relative to the Balmer assemblage, the Ball assemblage comprises a greater proportion of intermediate to felsic volcanic rocks (Fig. 2), and its ultramafic and mafic rocks show higher $(Th/Nb)_n$ values (Fig. 4c). These attributes may reflect potentially larger crustal inputs. As for the Balmer assemblage, Hollings et al. (1999) postulated that ultramafic and calc-alkaline magmas of the Ball assemblage reflect plume-related magmatism in a subduction-zone setting. Ongoing detailed geochemical and isotopic studies will help constrain the nature of crust through which the Ball assemblage was erupted, and assess the relative role of mantle and crustal sources in the petrogenesis of these rocks.

Breaks in volcanic activity of the Red Lake greenstone belt are indicated by shallow-water carbonate deposition between ca. 2940 and 2925 Ma, during a hiatus in Ball volcanism, and by accumulation of iron-rich chemical sediments at the top of the ca. 2894 Ma Bruce Channel assemblage. Clastic sedimentation, represented by the Slate Bay assemblage, likely reflects denudation of local volcanic edifices, but could also have included intracratonic sources.

Analytical results indicate that the majority of felsic metavolcanic rocks in the Confederation assemblage show tholeiitic to transitional affinities and have negative Nb and Ti anomalies characteristic of volcanic rocks erupted within a subduction-zone setting. Stott and Corfu (1991) have suggested that the assemblage may have developed along the leading edge of a continental margin, an interpretation which is consistent with Nd-isotopic evidence for a minor, older, crustal component in Confederation volcanic rocks of the Birch–Uchi belt (Tomlinson and Rogers, 1999; Fig. 1). Lobe-hyaloclastite flows and coarse pyroclastic breccia near the base of the assemblage reflect eruption in a subaqueous proximal volcanic environment. The FIII-type geochemical signature of many of these rhyolitic flows, characteristic of VMS mineralized suites, suggests magmatic evolution in high-level magma chambers in an extensional (intra-arc) tectonic environment (Lesher et al., 1986; Parker, 1999).

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