DESCRIPTIVE NOTES

INTRODUCTION

The Red Lake greenstone belt is one of Canada's top gold-producing districts, with over 20 million ounces of gold produced since mining commenced there in 1930. The belt preserves an extensive record of magmatic and sedimentary activity from 3.0 to 2.7 Ga, with evidence of multiple episodes of intense hydrothermal alteration, deformation, metamorphism and gold mineralization. The belt is interpreted to have evolved on the southern flank of an ancient continental block, the ca. 3 Ga North Caribou terrane (Figure 1; Stott and Corfu, 1991), by eruption and deposition of 2.99–2.85 Ga volcano-sedimentary sequences in a continental margin setting, followed by 2.75–2.73 Ga subduction-related arc volcanism (Corfu and Stone, 1998), which led to 2.72–2.71 Ga continental collision (Kenoran Orogeny) (Stott and Corfu, 1991; Sanborn-Barrie et al., 2000, 2001).

The Red Lake greenstone belt has long been a focus of geological mapping (Figure 2), which collectively has elucidated its protracted volcano-magmatic, sedimentary, structural and hydrothermal history (Figure 3,4,5). There are currently two producing gold mines in the Red Lake camp: the Campbell Mine (Placer Dome Ltd.), in operation since 1949, and the Red Lake (formerly A.W. White\Dickenson) Mine (Goldcorp Inc.), which has also operated some 50 years (Lichtblau et al., 2003). The district supports a high level of mineral exploration activity by prospectors, and junior and major mineral exploration companies.

The prefix "meta-" has been omitted from the following descriptions of metamorphosed rocks for brevity.

BALMER ASSEMBLAGE

The oldest volcanic rocks are tholeiitic and komatiitic basalt of the Balmer assemblage, host to Red Lake's major lode gold deposits. This extensive mafic-dominated volcanic assemblage underlies the eastern and central parts of the belt. Lithological and lithogeochemical variations, supported by facing information indicate the Balmer assemblage consists of lower, middle and upper massive to pillowed tholeiitic basalt sequences, that are separated by distinctive marker horizons, including felsic and ultramafic volcanic rocks. The lowermost massive and pillowed tholeiitic basalt sequence (unit 1a) is characterized by high TiO$_2$ contents (> 1.5%), light rare-earth element (LREE-) enrichment and is associated locally with pillowed komatiite (unit 1b) and komatiitic basalt (unit 1c) (i.e. Russet Lake-Starratt-Olsen (Inset A) and Nungesser Road areas). Discontinuous occurrences of andesitic flows (unit 1d) appear to mark the transition to the middle tholeiitic basalt sequence (unit 1e), which is typically pillowed and variolitic. The middle basalt sequence has lower TiO$_2$ contents (< 1.5%) and flat to LREE-depleted trace element profiles. Metasedimentary rocks of the Balmer assemblage are dominated by thinly bedded magnetite-chert ironstone (unit 1f) which occurs at several stratigraphic levels, but appears most closely associated with the middle basalt sequence. Intermediate to felsic flows and pyroclastic units (units 1g, 1h), dated at 2989 ± 3 Ma and 2992 + 20/-9 Ma in the east (U-Pb #34, #40; Table 1), and 2988 ± 3 Ma (U-Pb #20; Table 1) in the south-central belt, occur with subordinate epiclastic to clastic metasedimentary units (unit 1i) toward the top of the middle tholeiitic basalt sequence. Balmer felsic volcanics have flat heavy rare-earth element (HREE) profiles and Zr/Y values and Zr, Y abundances that indicate FII-type affinity (cf. Lesher et al., 1986). Stratigraphically overlying ca. 2988 Ma felsic volcanic rocks, are middle komatiite (unit 1j) and komatiitic basalt (unit 1k) flows that form thin, northwest-facing horizons from Post Narrows, in the northeast, through Middle Narrows, to the southeast shore of Golden Arm in the west. These preserve cumulate and quench textures (spinifex) at Post Narrows, Golden Arm and on surface at the Campbell Mine and are locally pillowed (entrance to Martin Bay). Overlying tholeiitic basalt (unit 1m) contains the lowest TiO$_2$ (< 1.3%) and LREE contents, typically having LREE-depleted profiles. This upper tholeiitic sequence commonly shows extensive alteration and brecciation, particularly proximal to the unconformable contact with the ca. 2.74 Ga Confederation assemblage. Minor intermediate to felsic volcanic rocks (unit 1o, 1p) are locally observed in the highest parts of the stratigraphy.

The high proportion of pillowed mafic to ultramafic flows that constitute the Balmer assemblage, and paucity of clastic rocks relative to chemical metasedimentary rocks, indicate subaqueous eruption of the Balmer assemblage in a sediment-starved marine basinal setting from ca. 3.0 Ga to ca. 2.98 Ga. Analyzed basalts from eastern Red Lake have initial ε_{Nd} values (Tomlinson et al., 1998; R. Stevenson pers. comm., 2000; T. Skulski, unpublished data) that range from + 3.3, somewhat higher than depleted mantle at 3 Ga (~ 2), to + 0.3, typical of sources with a longer-lived history of LREE-enrichment (e.g. differentiated continental crust), while ultramafic samples encompass a wide range of initial ε_{Nd} values from -2.2 to + 1.5. Although these isotopic values may reflect interaction/contamination of Balmer magma with an older sialic substrate, differentiated continental basement rocks have not yet been identified in the Red Lake belt.

Balmer Plutonic Suite

Plutonic rocks of Mesoarchean age are typically mafic to ultramafic in composition. They include extensive, variably altered, serpentinized peridotite ± pyroxenite (unit 2a) and gabbroic to dioritic intrusions (unit 2b) that mainly cut the lower to middle Balmer assemblage. The flat- to LREE-depleted profiles for intrusions of ultramafic and mafic composition suggest affinity to upper Balmer komatiite, komatiitic basalt, and basalt.

BALL ASSEMBLAGE

A thick sequence of intermediate to felsic calc-alkaline flows and pyroclastic rocks of the Ball assemblage underlie the northwestern part of the Red Lake greenstone belt. Crystallization (Corfu and Wallace, 1986) and detrital U-Pb zircon ages reveal that two eruption events contributed to the Ball assemblage. A lower, 2940.1 + 2.4/-1.7 Ma volcanic sequence (U-Pb #5; Table 1) is dominated by dacite (unit 3c) and rhyodacite pyroclastic units with lesser rhyolite flows (unit 3d). This thick intermediate sequence appears to be underlain by massive to pillowed calc-alkaline basalt (unit 3a) and lesser spinifex-textured komatiitic basalt (unit 3b), exposed in two anticlinal hinge zones. An extensive massive to planar-bedded carbonate-chert unit, locally preserving stromatolitic mounds (unit 3g) and locally overlain by a chert-magnetite sulphidic horizon (unit 3h) overlies the ca. 2940 Ma sequence, and reflects shallow-water conditions during a wane in volcanic activity. A resurgence of calc-alkaline volcanism after some 15 millions of years is recorded by 2925.4 + 3.4/-2.9 Ma dacite (U-Pb #6; Table 1) and quartz-phyric, rhyolite flows (units 3i, 3j) that overlie stromatolitic carbonate. These younger intermediate to felsic volcanic rocks appear to be intercalated with, and overlain by, an upper tholeiitic basaltic to andesitic sequence (unit 3k) that shows flat to LREE-depleted profiles and primitive mantle (PRIM)-normalized Th/Nb > 1. The uppermost unit of the Ball assemblage consists of mantle-derived, pillowed ultramafic flows (unit 3m) that are characterized by LREE-depletion.

Ball volcanic rocks show trace element variations (e.g. Th/Nb) in mafic to felsic volcanic rocks that are consistent with contamination by differentiated crust. Relatively juvenile ε_{Nd} values of + 0.8 to + 1 in these felsic rocks suggest that the contaminant was relatively young (~ 3 Ga) crust. Ball ultramafic rocks have depleted ε_{Nd} values of + 2.2 and may reflect intra-arc extension and upwelling of depleted mantle-derived magma.

Ball Plutonic Suite

Peridotite (unit 4a) and gabbro (unit 4b) cut the ca. 2.94 Ga and ca. 2.92 Ga Ball assemblage and have chemical affinities with Ball ultramafic and mafic volcanic rocks. They are distinguished from the mafic to ultramafic Balmer plutonic suite by their flat to LREE-enriched profiles and primitive mantle-normalized Th/Nb values > 2.

SLATE BAY ASSEMBLAGE

Clastic rocks of the Slate Bay assemblage extend the length of the Red Lake greenstone belt, from the head of Trout Bay to northeast of the Chukuni River (Pineridge Road exposure). They consist of three main lithofacies. A thin lowermost polymictic conglomerate (unit 5a) is discontinuously exposed near Tomato Lake and Goldseekers Beach. Coarse, compositionally mature (quartz-rich) conglomerate, grit and crossbedded quartzose arenite (unit 5c) are extensively exposed throughout the length of the belt, and contain clasts of vein quartz, aphanitic and quartz-phyric felsic volcanic rocks and fuchsitic material, indicating derivation from both felsic and ultramafic sources, respectively. Fine, compositionally immature feldspathic wacke, lithic wacke and mudstone (unit 5d), the latter containing porphyroblasts of andalusite, are exposed near the the entrance to Slate Bay. Isolated chemical sedimentary rocks north of Martin Bay (unit 5b) may form a minor part of this assemblage.

Detrital zircon profiles from three widely separated samples (U-Pb #7, #25 and #33; Table 1) indicate derivation from predominantly Ball assemblage rocks, with a minor component of Balmer-age detritus. The youngest detrital zircon currently dated is 2903 ± 7 Ma (GSC SHRIMP; this study) and 2916 ± 4 Ma (TIMS; Corfu et al., 1998) providing a maximum age of ca. 2.91 Ga for deposition of the Slate Bay assemblage. A minimum age of deposition is provided by overlying ca. 2850 Ma intermediate tuff and lapilli tuff of the Trout Bay assemblage in Slate Bay and Hoyles Bay, respectively. The linear map pattern and coarse, quartz-rich, crossbedded character of much of the Slate Bay assemblage suggest these rocks represent fluviatile deposits derived from denudation of the topographically high Ball volcanic edifice(s) between ca. 2.9 and ca. 2.85 Ga. Finer, mud-rich rocks may represent distal overbank (flood-plain) deposits associated with this fluvial system. Slate Bay clastic rocks appear to overlap the Ball/Balmer contact northeast of Rowan Lake, consistent with re-deposition of Ball detritus on Balmer substrate, at a significant break in slope marked by the assemblage contact.

BRUCE CHANNEL ASSEMBLAGE

Ball volcanism was followed by the deposition on Balmer substrate of the 2.894 Ga Bruce Channel assemblage (U-Pb #29 and #45; Table 1). This assemblage consists of calc-alkaline dacitic to rhyodacitic pyroclastic rocks (unit 6a) overlain by an upward-fining sequence of clastic sediments (units 6b,c) and chert-magnetite iron-formation (unit 6d). 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-alkaline volcanic rocks of the Bruce Channel assemblage are characterized by LREE- and large ion lithophile element (LILE) -enriched trace element profiles, with negative Nb anomalies (Sanborn-Barrie et al., 2001; Fig. 5). Intermediate tuff has depleted ε_{Nd} values of + 2 (Henry et al., 1999), similar to estimated depleted mantle at this time. The change toward more isotopically depleted magmatism from 2.99 Ga (Balmer) to 2.89 Ga (Bruce Channel) is interpreted to reflect crustal growth at a juvenile continental margin (cf. Henry et al., 2000).

TROUT BAY ASSEMBLAGE

A distinct volcano-sedimentary sequence, the Trout Bay assemblage, is exposed in the southwest part of the Red Lake belt. This assemblage consists of a lower sequence of northeast-facing tholeiitic basalt (unit 7a), overlain by clastic rocks with interbedded 2853 ± 1 Ma intermediate tuff (U-Pb #4; Table 1; unit 7b) and chert-magnetite iron-formation (unit 7d). A fragmental unit consisting of mafic volcanic fragments and chemical sedimentary clasts (unit 7e) separates the lower strata from an upper northeast-facing basaltic sequence, and may represent an explosive eruptive unit at the base of the upper Trout Bay basalt sequence. The upper pillowed, tholeiitic basalt sequence (unit 7f), is notable in the Red Lake belt for its very low overall trace element abundances and depletion in light ion lithophile elements (LILE) and LREE (Fig. 7 *in* Sanborn-Barrie et al., 2001). Two samples of depleted basalt have initial ε_{Nd} values of + 2 and + 1.8, consistent with derivation from a depleted mantle source and negligible crustal contamination. The assemblage is capped by thinly bedded oxide-facies iron-formation and interbedded siltstone (unit 7g), similar to that which caps uppermost, pillowed volcanic rocks of the adjacent Ball assemblage. The homoclinal northeast-facing Trout Bay and folded Ball assemblages face toward each other across Trout Bay, which may mask a tectonic contact apparently coinciding with a telescoped continental-margin oceanic transition.

Intermediate tuff ± chert-magnetite iron-formation are also exposed throughout northeastern Red Lake belt at the entrance to Slate Bay (U-Pb #24; Table 1) and Hoyles Bay (U-Pb #33; Table 1). These ca. 2850 Ma tuffaceous rocks (unit 7c) have calc-alkaline geochemical affinity, are enriched in LREE and LILE (type FI of Lesher et al., 1986), and have negative Nb anomalies. They appear to be contemporaneous with plutonic activity recorded by the ca. 2860–2806 Ma Trout Lake batholith to the east (Sanborn-Barrie et al., 2004), and may have formed in a proximal, yet fundamentally different tectonic setting than depleted tholeiitic basalts that characterizes the Trout Bay assemblage.

Trout Bay Plutonic Suite

Clastic rocks of the Trout Bay assemblage in western Red Lake are cut by an extensive system of thick gabbroic sills (unit 8a) with chemical affinities to the overlying upper Trout Bay basalt. These mafic to ultramafic sills are economically important in terms of their nickel, copper, and platinum group element potential (Parker, 2000a). A structurally higher anorthositic unit (unit 8b) along the south shore of Trout Bay cuts youngest chemical sedimentary rocks, and therefore postdates Trout Bay volcanism. Quartz gabbro intrusive into Balmer strata at the 16th level, Red Lake Mine, has an age of 2870 ± 15 Ma (U-Pb #42; Table 1), suggesting affinity with the lower Trout Bay basalt sequence. A number of gabbroic bodies that cut clastic rocks of the Slate Bay assemblage show depleted REE profiles, consistent with a Trout Bay affinity.

CONFEDERATION ASSEMBLAGE

Following a hiatus in volcanic activity of some 100 millions of years, the onset of extensive calc-alkaline volcanism is recorded by the Confederation assemblage. This event was initiated by the eruption of ca. 2.748–2.742 Ga shallow marine to subaerial calc-alkaline intermediate (unit 9b) to mafic (unit 9c) volcanic rocks of the McNeely sequence (U-Pb #9, #13, #15, #22, #27, #38; Table 1). Felsic to intermediate volcanic rocks include lapilli tuff, tuff, and lithic tuff (locally welded) and massive to pillowed andesite, with minor interbedded siltsone and mudstone. Pillow basalt contains abundant carbonate-filled amygdules. These volcanic rocks are LREE-enriched (type FI), with PRIM-normalized Th/Nb > > 1 and low TiO$_2$ contents (< 1.0%). The McNeely calc-alkaline volcanic sequence is overlain by, and interstratified with, the ca. 2.739 Ga Heyson tholeiitic volcanic sequence (U-Pb #17, #36; Table 1), which includes massive to pillowed, plagioclase-porphyritic andesitic flows (unit 9e), dacitic tuff (unit 9f), FIII-type rhyolite (unit 9g), and tholeiitic basalt (unit 9h). Heyson felsic volcanic rocks include spherulitic and lobe-hyaloclastite flows indicative of subaqueous proximal volcanic environments associated with fissure vent systems and seafloor spreading (Parker, 1999). Whereas McNeely volcanic rocks have an ε_{Nd} value of + 1 to + 0.8, Heyson volcanic rocks have more depleted ε_{Nd} values of + 2.9. These geochemical and isotopic data are consistent with establishment of a Neoarchean shallow marine to subaerial arc (McNeely) on the existing Mesoarchean continental margin sequence, with later intra-arc extension and eruption of high temperature, tholeiitic, FIII rhyolite, and submarine tholeiitic basalt (Heyson). At several stratigraphic levels, the Heyson sequence also includes a small component of calc-alkaline andesitic to dacitic flows and tuffs (unit 9i), with low TiO$_2$ (< 1) and LREE-enrichment with primitive-mantle normalized Th/Nb > > 10.

A depositional relationship between the Confederation and Mesoarchean assemblages is supported by ca. 2.75–2.74 Ga felsic rocks that cut the Balmer assemblage (U-Pb #31, #41; Table 1), and by Mesoarchean inheritance in ca. 2.74 Ga volcanic rocks (Corfu et al., 1998). An angular unconformity is indicated by opposing facing of Balmer and Confederation strata in the Madsen area, consistent with overturning of the Balmer (D$_0$) prior to Confederation volcanism. Local occurrences of coarse clastic rocks (unit 9a), such as ironstone-derived conglomerate on Wolf Bay and mafic-volcanic dominated conglomerate on the north-central shore of Red Lake, may represent basal conglomerate marking this unconformity. Typically, however, the interface between Neoarchean and Mesoarchean volcanic rocks is covered by a syn- to late-Confederation, clastic sequence, the Huston assemblage.

Confederation Plutonic Suite

A small volume of plutonic rocks are known to correlate with the Confederation volcanic assemblage in the Red Lake belt. A ca. 2.75 Ga felsic dyke (U-Pb #31; Table 1) and 2742 + 3/-2 Ma Brewis (or Balmer Lake) porphyry (U-Pb #44; Table 1) cut Balmer strata, supporting a stratigraphic, rather than tectonic, relationship between these assemblages. The tholeiitic Howey diorite (unit 9k) is interpreted to be a subvolcanic intrusion that fed overlying tholeiitic flows of the ca. 2739 Ma Heyson sequence (Lichtblau et al., 2003).

HUSTON ASSEMBLAGE

A clastic succession separating the two main stages of Neoarchean volcanic activity is designated the Huston assemblage, named after Carl Huston, a local prospector who drilled an extensive section of this succession in eastern Red Lake. The assemblage comprises coarse and fine clastic detritus (unit 10a) which unconformably to conformably overlies the McNeely sequence (Confederation assemblage) and underlies the Graves assemblage. Detrital zircon populations from basal conglomerate at two localities (U-Pb #16, #37; Table 1) show single, prominent (50–60 grains), ca. 2.74 Ga detrital age peaks indicating single-source derivation from the Confederation assemblage. Elsewhere, undated polymictic conglomerate that underlies, and is transitional with, the youngest volcanic assemblage in the belt (ca. 2.733 Ga Graves) includes sedimentary-, volcanic-, plutonic-, and hydrothermal-derived clasts that are pebble to cobble size and well rounded. Argillite, siltstone, wacke (unit 10c), and minor sedimentary carbonate (unit 10b) conformably overlie ca. 2.744 Ga McNeely volcanic rocks in central Red Lake.

Variation in lithofacies of the Huston sedimentary assemblage from a thin veneer of clastic detritus (e.g. cemetary conglomerate at Balmertown) to a thick succession (~ 0.5 km) of well-bedded argillite and turbiditic wacke conformable on McNeely tuff in central Red Lake (Parnell Islands) suggests an erosional surface of considerable topographic relief, on which deposition of sedimentary detritus under locally marine conditions took place during a hiatus in Neoarchean volcanic activity.

GRAVES ASSEMBLAGE

A younger cycle of Neoarchean calc-alkaline volcanism is represented on the north shore of Red Lake by the ca. 2733 Ma Graves assemblage (U-Pb #24; Table 1). This volcanic sequence (unit 11) is dominated by grey-weathering, biotite-bearing andesitic to dacitic pyroclastic tuff, and synvolcanic diorite and tonalite, and is interpreted to represent a shallow water to subaerial arc complex. Its calc-alkaline rocks are characterized by LREE-, LILE-enrichment, negative Nb anomalies, and depletion in HREE and HFSE. Synvolcanic plutons occur both west and north of the belt. The Graves assemblage overlies, and is locally transitional with, conglomerate of the Huston assemblage, suggesting concomitant clastic and pyroclastic activity 10 millions of years after initiation of Neoarchean volcanism in southeastern Red Lake.

Graves Plutonic Suite

Plutonic rocks coeval with Graves assemblage volcanism represent the first major intermediate to felsic plutonic activity in the Red Lake belt. These tonalitic to granodioritic rocks (unit 12) are represented by the 2734 ± 2 Ma Douglas Lake biotite tonalite pluton (U-Pb #1; Table 1), the 2731 ± 3 Ma Little Vermilion Lake hornblende tonalite-granodiorite batholith (U-Pb #26; Table 1), and the 2729 ± 1.5 Ma Red Crest diorite stock (U-Pb #11; Table 1). The Douglas Lake pluton is LREE-enriched, HREE-depleted, with normalized Th > La > Nb, interpreted to have formed by partial melting of mafic crust (Corfu and Stone, 1998). Its initial ε_{Nd} value of 0 (Henry et al., 2000), suggests significant assimilation of older continental crust. The Little Vermilion Lake batholith is also LREE-enriched, but is slightly less depleted in HREE than the Douglas Lake pluton, also possibly due to assimilated older sialic crust (Corfu and Stone, 1998).

ENGLISH RIVER ASSEMBLAGE

The youngest supracrustal rock in the belt is a pebble conglomerate (unit 15), identified at U-Pb locality #19, once thought to correlate with the “Austin tuff” ore horizon at the Madsen Mine (see also Inset A). This garnetiferous metasedimentary rock yielded a diverse detrital zircon population profile (n = 56 grains), with ages that correspond to the Balmer, Ball, Trout Bay, and Graves assemblages, and younger post-volcanic plutons. The maximum depositional age of this sample is 2700 ± 6 Ma, the upper intercept of a 5-spot regression for the youngest detrital zircon analysed (T. Skulski, unpublished data). This young supracrustal sequence provides a new maximum age for penetrative deformation and amphibolite-facies metamorphism at the southern margin of the Red Lake belt. It provides the first record in the ca. 300 millions of years history of the Red Lake belt of exposure and partial erosion of virtually all lithological units (volcanic assemblages and plutonic suites) and their redeposition, consistent with major orogeny (Uchian) at ca. 2.72–2.69 Ga. The assemblage name reflects the similarity in age and provenance between this conglomerate and marine metawacke of the English River Subprovince to the south (Corfu et al., 1995; Davis, 1996). The conglomeratic facies is interpreted to have been deposited from rivers that emptied into and beyond the south margin of the Uchi Subprovince. At present, the relationship of this conglomerate to gold mineralization is uncertain.

POST-VOLCANIC PLUTONIC ROCKS

Granitoid rocks in the Red Lake area record three main episodes of Neoarchean felsic plutonism. The first is represented by the ca. 2.73 Ga synvolcanic Graves plutonic suite, described above. A second episode of plutonic activity at ca. 2.72 Ga (unit 14) is represented by a number of plutons internal to the belt including the 2720 + 3/-2 Ma McKenzie Island stock (U-Pb #28; Table 1), 2718.2 ± 1.1 Ma Dome Stock (U-Pb #21; Table 1), and 2720 + 7/-5 Ma Abino granodiorite (U-Pb #35; Table 1) which were host to significant Au mineralization (past-producing McKenzie Red Lake, Gold Eagle, and Red Lake Gold Shore mines), and possibly the Hammell Lake pluton (U-Pb #12; Table 1). A post-ore, quartz-feldspar porphyry dyke at the Red Lake (formerly A.W. White) Mine is dated at 2714 ± 4 Ma (U-Pb #43; Table 1).

A final magmatic event (unit 16) at ca. 2.7 Ga is represented by K-feldspar megacrystic granodiorite of the late-tectonic 2704 ± 1.5 Ma Killala-Baird batholith (U-Pb #10; Table), the ca. 2699 Ma Cat Island pluton (U-Pb #46 and #47; Table 1), and 2699 ± 4 Ma post-ore dykes at Madsen (U-Pb #14 and #18; Table 1). A rapid decline in thermal and hydrothermal activity in the Red Lake belt at ca. 2.7 Ga is indicated by the small difference between zircon and titanite ages of these late- to post-tectonic plutons (Corfu and Andrews, 1987), with ongoing post-collisional tectonometamorphism (D$_3$) affecting the English River assemblage.

STRUCTURAL GEOLOGY

The Red Lake greenstone belt is an east-trending belt characterized by steeply dipping panels of volcanic and metasedimentary rocks, with shallow-dipping strata observed locally in the central and eastern parts of the belt. Although hydrothermal alteration of volcanic rocks is moderate to intense throughout the greenstone belt (see Alteration, to follow), penetrative strain is typically moderate to weak, such that primary volcanic and sedimentary structures are well-preserved across substantial parts of the belt.

The Red Lake greenstone belt displays evidence of several episodes of deformation, interpreted to be closely linked with extensive hydrothermal activity and gold mineralization. Early nonpenetrative deformation (D$_0$) appears to have involved overturning of the ca. 2.99 Ga Balmer assemblage prior to Neoarchean volcanism, as documented by opposing facing on either side of the Mesoarchean-Neoarchean unconformity in the Madsen and central Red Lake areas. Coplanar bedding orientations in oppositely facing rocks suggests that overturning of the Balmer assemblage involved recumbent folding prior to ca. 2.75 Ga.

The main stages of penetrative deformation were imposed after ca. 2.74 Ga volcanism. The first major fabric-forming event (D$_1$) resulted in the formation of northerly trending, south-plunging F$_1$ folds and associated S$_1$/L$_1$ fabrics (Fig. 4a). F$_1$ folds are recognized mainly in clastic-dominated assemblages (Bruce Channel, Slate Bay and Huston), whereas north-striking S$_1$ planar fabrics are best developed in volcanic rocks of the Balmer, Ball and Trout Bay assemblages. D$_1$ may be bracketed between 2.744 Ga, the age of Confederation volcanic rocks in central Red Lake that contain F$_1$ structures, and ca. 2.733 Ga, the age of the Graves volcanic sequence that does not appear to have been affected by D$_1$. It seems probable that deposition of the Huston assemblage took place at a late stage of, and as a response to, D$_1$ deformation. These events may have been triggered by a change in plate dynamics that took place between Confederation and Graves volcanism. For instance, shallowing of the subducted slab may have resulted in compression of the upper plate and a shift of the locus of magmatic activity to the north toward the Berens Plutonic suite (present-day co-ordinates).

Superimposed on D$_1$ structures are east- to northeast-trending D$_2$ structures (F$_2$/S$_2$/L$_2$) in western and central Red Lake, and southeast-trending folds and fabrics (the “mine trend”) in eastern Red Lake (Fig. 4b). Like F$_1$, F$_2$ folds are best developed in clastic rocks, where northeast-trending F$_2$ folds plunge moderately to steeply to the northeast and southeast-trending F$_2$ folds plunge moderately (45°–65°) to the southwest. A progressive change in orientation of S$_2$ structures across central Red Lake, with no evidence of an overprinting relationship between the northeast-striking S$_2$ and southeast-striking “mine trend” fabrics, suggests that these fabrics formed coevally during D$_2$. Given the relative absence of mylonitic rocks, or strain gradients, within these strain corridors, they are not interpreted as belt-scale conjugate shear zones, in contrast to the model of Andrews et al., (1986).

An important constraint on the timing of D$_2$ is provided by the relationship of regionally extensive D$_2$ fabrics to the ca. 2718 Ma Dome Stock. Supracrustal rocks adjacent to the stock, and occurring as xenoliths within the stock, contain a penetrative S$_2$ fabric. The stock itself contains a weak through going NE-striking foliation coplanar to S$_2$ observed elsewhere. These fabric relationships suggest that the main cleavage-forming stage of D$_2$ predated intrusion of the Dome stock at 2718 Ma, but that shortening was sustained beyond its emplacement. The onset of penetrative D$_2$ strain across the Red Lake greenstone belt from ca. 2.72 Ga is interpreted to record the collisional stage of the Uchian orogeny, involving collision between the North Caribou terrane margin, on which the Red Lake greenstone belt formed, and the Winnipeg River Subprovince, a ca. 3.5 Ga and younger continental terrane to the south. Penetrative strain appears to have been protracted, with post-collisional (D$_3$) strain locally recorded in the Red Lake belt after 2700 ± 6 Ma, the maximum age of young, unconformably overlying English River assemblage (unit 15) that displays a penetrative tectonic foliation coplanar to D$_2$ fabrics throughout central Red Lake.

ALTERATION

Hydrothermal alteration in the Red Lake greenstone belt is distributed in regional, zoned alteration envelopes that show a spatial relationship to gold deposits (Figure 5). Calcite carbonatization is most widespread, occurring distal to gold deposits and affecting much of the Balmer, Ball, Trout Bay, Bruce Channel, and Confederation assemblages. Calcite alteration is generally more intense in rocks of mafic and ultramafic composition, relative to intermediate and felsic metavolcanic, metasedimentary, and granitoid rocks. Chloritization and weak potassic alteration, mainly reflected by incipient sericitization of chlorite and plagioclase, also characterize distal alteration zones.

Alteration zones proximal to gold deposits (Figure 5) are characterized by variable degrees of ferroan-dolomite and potassic alteration. Strong to intense ferroan-dolomite alteration (iron carbonate) affects mafic and ultramafic metavolcanic and intrusive rocks in the Balmer, Ball, and Confederation assemblages. Weak to moderate ferroan-dolomite alteration affects intermediate pyroclastic rocks of the Confederation assemblage and granodiorite of the Dome and McKenzie Island stocks. Potassic alteration is typically manifested by disseminated sericite/muscovite and some biotite accompanied by the destruction of amphibole and plagioclase (Andrews et al., 1986), and by bright green mica and fuchsite in ferroan-dolomite-altered ultramafic rocks. Aluminous potassic alteration in intermediate to felsic rocks is most notable in the Bruce Channel assemblage, where intensely altered intermediate to felsic metavolcanic rocks, known locally as "Point rock" are structureless, light grey weathering, siliceous, and sericitized rocks, that may contain andalusite porphyroblasts and disseminated fuchsite.

Proximal alteration zones metamorphosed to amphibolite facies may contain variable amounts of aluminosilicate minerals such as andalusite, staurolite, and cordierite, as well as garnet, chloritoid, cummingtonite, and anthophyllite. Aluminous assemblages are particularly well-developed in the Balmer assemblage (Andrews et al., 1986; Dubé et al., 2000) near Madsen, East Bay, Balmertown, and on the Pineridge Road (near the Chukuni River), and are also evident at the Rowan and Mt. Jamie mines (Wallace, 1982; Parker, 1999a). The geochemistry of altered, aluminosilicate-bearing mafic and ultramafic metavolcanic rocks is characterized by: 1) Na$_2$O, MgO, and CaO depletion (Penczak and Mason, 1997; Durocher, 1983; Andrews et al., 1986) caused by the destruction of feldspar and amphibole by alteration reactions; 2) K$_2$O enrichment due to potassic metasomatism (Penczak and Mason 1997; Durocher 1983; Andrews et al., 1986); and 3) residual enrichment of relatively immobile Al$_2$O$_3$ due to significant losses of Na$_2$O, MgO, and CaO.

Silicification with associated with gold and sulphide mineralization (i.e. arsenopyrite, pyrite, pyrrhotite) post-dates most ferroan-dolomite and potassic alteration, and alteration zones are typically barren of gold unless they have been silicified. Silicification is manifested by extension and fault-fill quartz veins, "jigsaw-puzzle" breccia veins, open-space filling of primary features such as vesicles and interpillow spaces, or as pervasive replacement of ferroan-dolomite.

METAMORPHISM

Supracrustal rocks of the Red Lake belt are characterized by mineral assemblages typical of greenschist- and amphibolite-facies regional metamorphism. Although there is little quantitative pressure-temperature data for these rocks, hydrothermally altered volcanic rocks with kyanite-andalusite-chloritoid assemblages from several localities in the Red Lake area yield pressure estimates of 3–4 kb (Menard and Pattison, 1998). An increase in grade to amphibolite facies toward the margins of the greenstone belt, is reflected by the presence of andalusite, staurolite, cordierite, garnet, and biotite in metasedimentary rocks and potassic altered volcanics and by hornblende, orthoamphibole, and garnet in mafic rocks (Thompson, 2003). Higher grade may, in part, be attributed to contact metamorphism by bordering plutonic phases, however, the present-day metamorphic zonation of the belt represents a polyphase tectonometamorphic history with thermal events likely at ca. 2735 Ma (pre-collisional D$_1$ and extensive Graves plutonism), 2720–2715 (collisional D$_2$ event), and ca. 2690 Ma (post-collisional D$_3$ strain and peak metamorphism of flysch-like rocks of the English River). Three world-class gold deposits, the Campbell and Goldcorp mines and the past-producing Madsen mine, occur close to the transition between greenschist- and amphibolite-facies host rocks (Damer, 1997; Dubé et al., 2000; Andrews et al., 1986) highlighting the potential importance of metamorphism in understanding gold mineralization in the belt (Thompson, 2003).

A rapid decline in high-temperature thermal and hydrothermal activity in parts of the Red Lake belt at ca. 2.7 Ga is indicated by the small difference in zircon, titanite and apatite U-Pb ages of syn- to late-tectonic plutons (Corfu and Andrews, 1987; Corfu and Stone, 1998; Table 1). This decline was likely driven by orogenic uplift and tectonic exhumation, processes that led to flysch deposition in the English River Subprovince, which was derived from Uchi-age detritus and subsequently buried. Metamorphic mineral assemblages from unit 15 and surrounding rocks include staurolite-cordierite-garnet-biotite from pelitic compositions and orthoamphibole-garnet from mafic compositions, indicating that amphibolite-facies metamorphism related to post-collisional thickening, outlasted ca. 2700 ± 6 Ma in the southern Red Lake area. ^{40}Ar-^{39}Ar dates of ca. 2660 Ma for hornblende and ca. 2630 Ma for biotite from the Red Lake area (Hanes and Archibald, 1998) reflect the time of cooling to about ca. 450°C, the closure temperature for Ar in hornblende, and about 275°C, the closure temperature for Ar in biotite.

GOLD MINERALIZATION

The Red Lake greenstone belt is one of Canada's largest gold camps with historical production of more than 20 M oz Au, essentially produced from three deposits, the Campbell-Red Lake orebody (> 13 M oz Au), the Cochenour-Willans Mine (1.2 M oz Au) and the Madsen Mine (2.4 M oz Au). The camp is famous for very high-grade gold mineralization, as is currently being mined from the High Grade Zone at the Red Lake (formerly A.W. White) Mine (Dubé et al., 2001, 2002) where diamond-drill intersections of 17.46 ounces gold per ton across 16.4 feet have been reported (Hinz et al., 2000). The gold deposits at Red Lake are similar to quartz-carbonate vein deposits (Robert, 1995) associated with deformation and folding in metamorphosed volcanic, sedimentary and granitoid rocks. Virtually all gold mineralization has an epigenetic aspect and is structurally controlled in detail, occurring in veins, lenses, fractures, and hinge zones, particularly between two rheologically distinct units (Andrew et al., 1986; Dubé et al., 2002). The largest and highest-grade gold deposits are located in the Balmer assemblage, within the middle tholeiitic basalt sequence and associated serpentinized peridotite and talc schist bodies. Gold production from the McKenzie (650,000 oz), Gold Eagle (40,000 oz), and Gold Shore (21,000 oz) mines came mainly from deposits in the granodioritic Dome and McKenzie Island stocks. The past-producing Madsen gold deposit is interpreted by Dubé et al., (2000) as a high-temperature gold deposit similar to gold skarns in mafic metavolcanic rocks.

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