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AGE CONSTRAINTS ON THE FORMATION OF IRON OXIDE-RICH HYDROTHERMAL BRECCIAS OF THE MORAN LAKE AREA: EVIDENCE FOR POTENTIAL IOCG-STYLE MINERALIZATION WITHIN THE CENTRAL MINERAL BELT OF LABRADOR

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ABSTRACT

The development of hematite-dominated, iron oxide-rich hydrothermal breccias, amidst the Central Mineral Belt (CMB) of Labrador, represents a unique style of uranium mineralization. The combination of breccia texture, alkali-iron metasomatism, and enrichment in V, U, Cu and Ag represent characteristics that are interpreted to be analogous to those associated with Iron Oxide-Copper-Gold (IOCG) systems. New geochronological data provide the first absolute age constraints on the development of the iron oxide-rich hydrothermal brecciation developed within the Moran Lake area. In addition, these new data highlight the existence of a significant unconformity within the siliciclastic sedimentary rocks of the Bruce River Group. Two new U–Pb ages indicate the presence of an older assemblage that was previously grouped with younger units; these include an age of 1847 +12/-9 Ma from a tuff within the Heggart Lake Formation, and a granitic phase related to the intrusion of the Henri Lake gabbro, dated at 1772 ± 10 Ma. A further two new ages from the Bruce River Group are: 1665 ± 3.5 Ma from a tuff near the base of the Brown Lake Formation and 1645 ± 4 Ma from felsic volcanic rocks of the Sylvia Lake Formation.

INTRODUCTION

The Central Mineral Belt (CMB) of Labrador has been the focus of significant exploration, in part, due to the abundance of copper and uranium occurrences that are present throughout the region. Most of the copper occurrences amidst the central portion of the CMB are hosted within the Bruce River Group, whereas the most significant uranium mineralization in that area is primarily hosted within the underlying, older, Moran Lake Group (*e.g.*, Moran Lake Upper C Zone; Figure 1). Locally, however, uranium and lesser copper mineralization occur together in association with the development of iron oxide-rich hydrothermal breccias. This style of mineralization is primarily hosted within the mafic volcanic rocks of the Moran Lake Group, but is also locally developed within the unconformably overlying Heggart Lake Formation of the Bruce River Group. The occurrence of these breccias, in association with the related mineralization and alteration is interpreted to represent evidence for the development of Iron Oxide-Copper-Gold (IOCG)-style mineralization within the region (*e.g.*, Froude, 2005; Sparkes and Kerr, 2008).

In the Moran Lake area of the CMB, occurrences of hematite-dominated, iron oxide-rich breccias, in association with alkali-iron metasomatism can be traced intermittently, along strike, for upwards of 10 km (Figure 2). Within this zone, several occurrences hosting anomalous uranium and lesser copper mineralization in association with breccia development, have been identified; including the Upper C Zone, Trout Pond and Armstrong deposits, and the B Zone, Poz Pond, Anomaly No. 16 and Anomaly No. 15 prospects (Figure 2). The iron oxide-rich breccias hosted within mafic volcanic rocks of the Moran Lake Group are consistently enriched in vanadium, but also contain local enrichment in uranium, copper and silver. In the area of the B Zone prospect, similar styles of brecciation and related metasomatism occur within siliciclastic sedimentary rocks of the Bruce River Group and are noted to contain elevated uranium, copper, silver and, locally, gold (Froude, 2005).

Ongoing research into the nature and timing of breccia development, have provided geochronological data, which support the presence of a significant unconformity between the Heggart Lake and Brown Lake formations of the Bruce

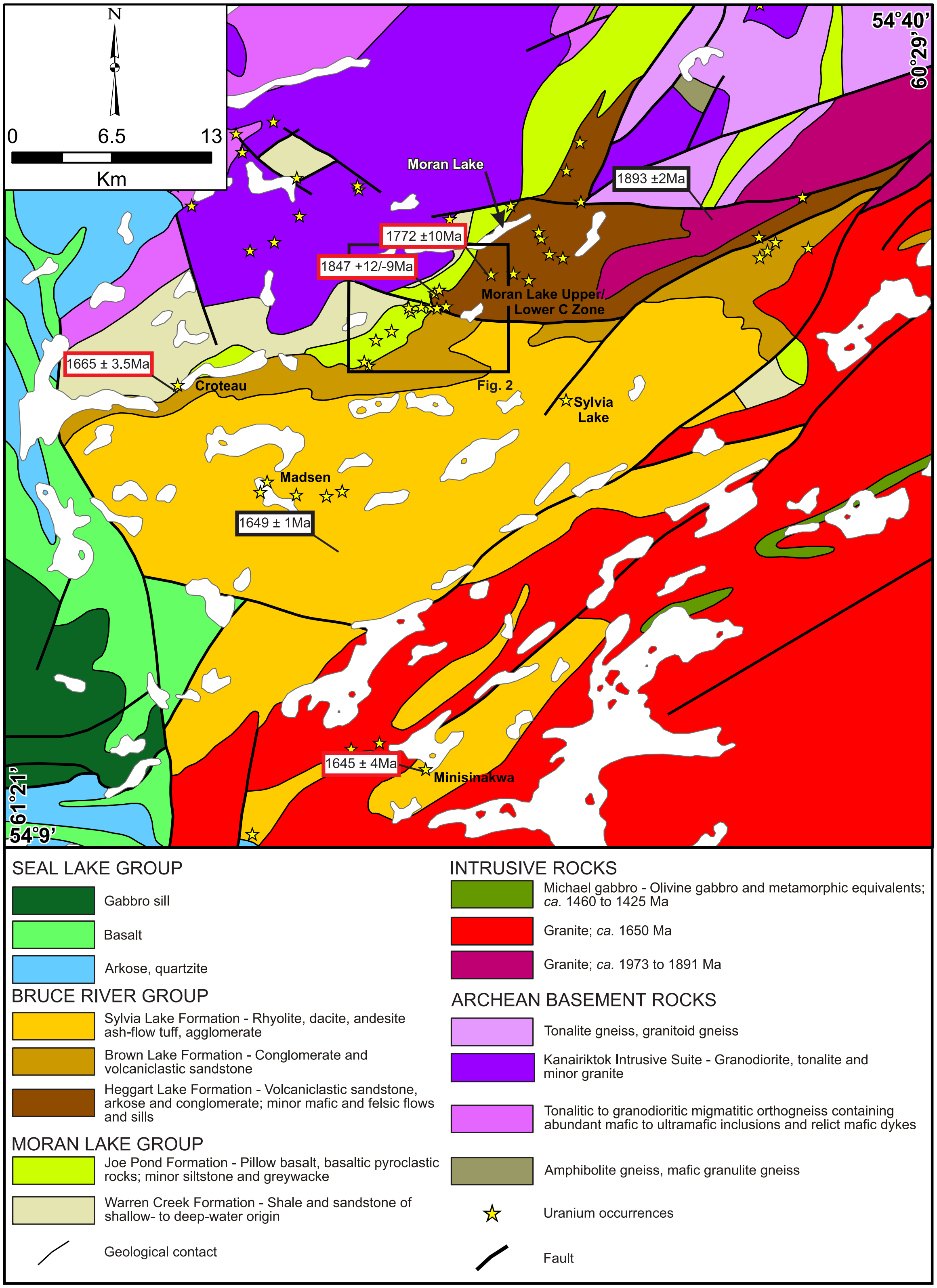

Figure 1. *Regional geology map outlining the distribution of the Bruce River Group and select uranium occurrences within the central portion of the CMB; geological base map modified from Wardle* et al. *(1997). Note the location and corresponding U–Pb age determinations for available data are also shown; these include compiled ages (black boxes) and those from this study (red boxes).*

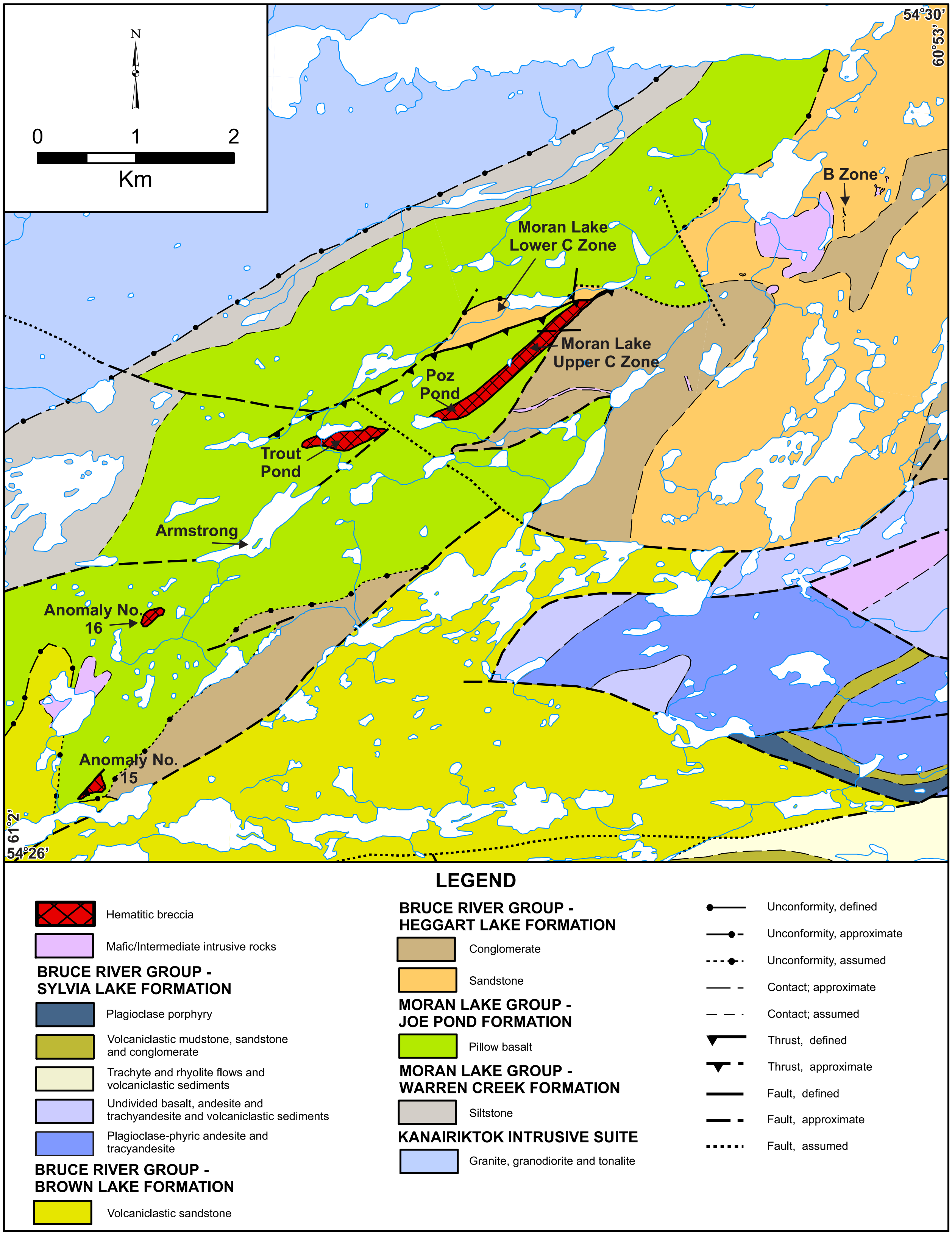

Figure 2. *Local geology map outlining the distribution of iron oxide-rich breccias and related alkali-iron metasomatism as well as the distribution of geological units in the area surrounding the Moran Lake C Zone; geology base map modified from Ryan (1984) and Gillies* et al. *(2009).*

River Group. These new data indicate that the Heggart Lake Formation is some 200 Ma older (*ca.* 1850 Ma) than previously envisaged, and thus allows the IOCG-style mineralization that is locally hosted within it to potentially be older than the previously inferred age limit of *ca.* 1650 Ma (*cf.* Sparkes and Kerr, 2008).

The potential older age for the breccia-related mineralization within the CMB highlights a possible link with other metallogenic events in the region; notably the Michelin deposit (1860–1800 Ma; Sparkes and Dunning, 2015) and analogues to the east. However, whereas the Michelin deposit is spatially and temporally associated with albitite-type alteration, a common feature of IOCG and iron oxide alkali-altered (IOAA) systems worldwide (*e.g.*, the Great Bear magmatic zone in Canada and the Mount Isa region of Australia; Oliver *et al.*, 2004; Wilde, 2013; Potter *et al.*, *in press*), the formation of breccias that have a potential IOCG affinity in the Moran Lake area, has no obvious spatial association with the albitite-type mineralization developed farther to the east. However, the new geochronological data, combined with that of earlier studies, highlight the potential for a temporal association between these two styles of mineralization.

PREVIOUS WORK

The occurrence of iron oxide-rich breccias within the Moran Lake area of the CMB has been the focus of several academic studies and episodic mineral exploration. Uranium mineralization was first identified in the Moran Lake area in 1957 with the discovery of the Moran Lake B and C zones (Figure 2), originally termed the Montague No. 1 and 2 showings, respectively (Mann, 1957). Initial work in the area of the C Zone produced values up to 0.13% U_3O_8 over 0.60 m (Corriveau, 1958), but work was discontinued in 1958 due to the relatively low grade of the mineralization. In 1964, Mokta Canada Ltd. acquired the licences for the area around the C Zone and carried out geological mapping and scintillometer surveys, identifying some 64 radiometric anomalies. The company conducted extensive trenching in the area (Bernazeud, 1965), but allowed the licenses to expire in 1969.

In 1976, Commodore Mining Ltd. acquired the ground and optioned it to Shell Canada Resources. Shell conducted additional trenching, geological mapping and scintillometer surveys at both the B and C zones, which produced positive results, *e.g.,* 0.12% U_3O_8, 0.15% Cu and 7.76 g/t Ag over 24.8 m from the B Zone prospect (McKenzie, 1976). Follow-up drilling failed to intersect any significant uranium mineralization, but drill results from the C Zone yielded assays of up to 0.20% U_3O_8 over 3.34 m, which sparked an intense exploration program on the property (McKenzie, 1977). Additional drilling demonstrated that the high-grade mineralization at the C Zone was of a limited extent, but also identified several zones of what was termed 'quartzite-hosted' uranium mineralization (McKenzie, 1978). Follow-up drilling resulted in the discovery of low-grade sandstone-hosted uranium mineralization, proximal to the unconformity between the Moran Lake Group and the overlying Bruce River Group (Gordanier, 1979; now known as the Lower C Zone deposit). A re-evaluation of the geology and uranium mineralization at the C Zone was conducted by Shell Canada Resources in 1980. As part of this work, a subdivision of the alteration assemblages within the deposit was developed and seven different styles of uranium mineralization were noted (Cook, 1980), only two of which were deemed to be of economic interest. Cook (1980) suggested that the original host rock to the iron oxide-rich breccias was a synvolcanic intrusive rock, that was affected by a complex alteration system of multiple episodes of both hematite and carbonate alteration. In the early 1980s, poor uranium market conditions contributed to a slowdown in activity in the area and the extended licence on the property expired in 1982.

In the late 1970s, Brinex and Canico explored parts of the CMB, which resulted in the discovery of the Canico Anomalies Nos. 15 and 16 prospects (Figure 2) through the follow-up of airborne radiometric anomalies. Limited drilling was conducted at Anomaly No. 15, which produced assays of up to 0.16% U_3O_8 over 3.72 m (Perry, 1979). Follow-up investigations, including geological and geophysical surveys and trenching of mineralized occurrences, indicated the mineralization was of limited extent and the concessions were allowed to lapse in 1980.

Smyth and Ryan (1977) conducted regional mapping in the area of the Moran Lake C Zone and highlighted the structural complexity in the vicinity of the deposit, noting the presence of a reverse fault that resulted in the structural repetition of the stratigraphic sequence. They interpreted the mineralization to be hosted within an explosive breccia, related to the emplacement of a gabbroic intrusion into the sedimentary rocks of the Bruce River Group. Kontak (1980) conducted work on the C Zone as part of a M. Sc. thesis and concluded that the mineralization was hosted within extrusive volcanic rocks, which he assigned to the Heggart Lake Formation of the Bruce River Group. He interpreted the breccia formation to be synvolcanic, and proposed that the accompanying uranium mineralization was the result of later fluids ascending along localized fault zones. Ryan (1984) attributed the brecciation associated with the uranium mineralization to the multi-stage emplacement of CO_2-rich fluids within a mafic igneous rock, which resulted in the formation of the 'C Zone' breccia. This process, as also noted by Cook (1980), was part of a multi-stage process that included the introduction of fracture-hosted pitchblende, chlorite, specularite and pyrite subsequent to the breccia development (Ryan, 1984). As part of regional sampling by Wilton (1996), several samples of uranium mineralization hosted by mafic volcanic rocks of the Moran Lake Group were collected within the area of the C Zone. These samples were noted to contain lower titanium contents than unaltered samples, which are inferred to represent the breakdown of modal magnetite by oxidizing, uranium-bearing hydrothermal fluids, thus liberating the titanium (Wilton, 1996).

In the early 2000s, revived uranium exploration in the Moran Lake area included the expansion and development of previously known occurrences, as well as the discovery of several new zones of mineralization. Crosshair Exploration identified intermittent uranium mineralization along a strike length of approximately 2.5 km extending southwest from the C Zone deposit. Subsequent work by the company defined the Trout Pond and Armstrong deposits (Figure 2), which have NI 43-101 compliant resource estimates of 480 000 and 900 000 lbs of U_3O_8, respectively (Morgan and Giroux, 2008). Renewed drilling by Crosshair at the Moran Lake C Zone outlined uranium mineralization over a strike length of 1.3 km, which remains open along strike to the southwest as well as down-dip (Morgan and Giroux, 2008). From this work, a NI 43-101 compliant resource estimate was generated, which consists of 7.97 million lbs U_3O_8 at a cut-off grade of 0.015% for the Upper C Zone and 1.60 million lbs at a cut-off grade of 0.035% for the Lower C Zone (Morgan and Giroux, 2008). In addition, the company also outlined a significant vanadium resource of approximately 134 million lbs of V_2O_5 within the Upper C Zone portion of the deposit (Wallis *et al.,* 2011). As part of its investigation into the vanadium mineralization the company commissioned contract work to examine select samples from the vanadium-enriched portions of the deposit. Results from this work noted that hematite (specularite) was the predominant host to elevated vanadium within the mineralized breccia (Sparkes *et al*., 2010).

REGIONAL GEOLOGY

The regional geology of the area encompassing the central portion of the CMB has been summarized by Ryan (1984), Ermanovics (1993) and Wilton (1996); the following summary is largely derived from these sources. Archean orthogneiss, amphibolite, and intrusive rocks of the Kanairiktok Intrusive Suite, which consist of massive to strongly foliated tonalite, granodiorite and granite, form the basement rocks to the Proterozoic supracrustal sequences of the CMB (Ryan, 1984; Ermanovics, 1993; Kerr *et al*., 1996). The Archean basement rocks are crosscut by a sequence of mafic dykes, known as the Kikkertavak dykes, which have been dated at 2235 ± 2 Ma (Cadman *et al*., 1993). These dykes do not crosscut the overlying supracrustal sequences of the CMB (*e.g.*, Moran Lake Group) and therefore provide a maximum age constraint on their deposition (*cf.* Ermanovics, 1993; Wilton, 1996).

In the central portion of the CMB, the Archean basement rocks are unconformably overlain by siliciclastic sedimentary rocks of the Moran Lake Group (Smyth *et al.,* 1978; Wardle and Bailey, 1981; Ryan, 1984). This group is divided into two units, the Warren Creek Formation and the overlying Joe Pond Formation, both of which have undergone polyphase deformation and greenschist-facies metamorphism (Smyth *et al.,* 1978; Ryan, 1984). Siliciclastic sedimentary rocks of the Warren Creek Formation represent a shallow nearshore to shallow marine shelf depositional environment and primarily consist of shale (slate), arkosic siltstone, greywacke and lesser iron formation, dolostone and feldspathic quartz arenite (Ryan, 1984). The Joe Pond Formation consists of an extensive sequence of tholeiitic pillow basalt and lesser interbedded shale, dolostone, chert and mafic tuff (Ryan, 1984). The mafic volcanic rocks host most of the uranium prospects within the Moran Lake Group, including the most significant deposit, the Moran Lake Upper C Zone.

The Moran Lake Group is unconformably overlain by rocks of the Bruce River Group (Ryan, 1984). This sequence includes siliciclastic sedimentary rocks at its base (Heggart Lake and Brown Lake formations), grading upward into a thick sequence of predominantly subaerial bimodal volcanic rocks (Sylvia Lake Formation; Smyth *et al*., 1978), the latter of which is locally dated at 1649 ± 1 Ma (Schärer *et al*., 1988). The Heggart Lake Formation forms the lowest stratigraphic unit of the Bruce River Group (Smyth *et al*., 1978) and unconformably overlies rocks of the Moran Lake Group as well as local leucocratic granite dated at 1893 ± 2 Ma (Kerr *et al*., 1992); the latter provides a maximum age limit for the base of the sequence. The Heggart Lake Formation is dominated by grey to red conglomerate, sandstone and lesser mafic and felsic flows. Overall, it forms a coarsening-upward sedimentary succession interpreted to have formed within an alluvial fan–flood plain type environment (Ryan, 1984). The Heggart Lake Formation is locally host to uranium mineralization (*e.g.*, Moran Lake Lower C Zone deposit) and is also locally intruded by mafic to intermediate dykes, which are linked with the formation of localized uranium mineralization (*e.g.*, B Zone prospect; Ryan, 1984 and references therein).

The Heggart Lake Formation is overlain by the Brown Lake Formation, which is composed of a discontinuous basal conglomerate passing upward into a thick sequence of volcaniclastic sandstone containing minor interbedded conglomerate. This unit forms an overall fining-upward sedimentary sequence inferred to have formed within a shallow lacustrine environment (Ryan, 1984). The contact between the Heggart Lake and Brown Lake formations is largely structural. However, local examples of basal conglomerate of the Brown Lake Formation are observed to lie disconformably upon the Heggart Lake Formation (Ryan, 1984), whereas in other areas the contact between the two formations has been described as conformable and gradational (Collins, 1958). The Brown Lake Formation locally oversteps the Heggart Lake Formation to lie directly upon rocks of the Moran Lake Group (Ryan, 1984). The local preservation of clasts (that contain pre-existing fabrics), derived from the Moran Lake Group, within the Brown Lake Formation, provide additional evidence for deformational events prior to the deposition of the Brown Lake Formation (Smyth *et al*., 1978).

The Sylvia Lake Formation represents the uppermost unit of the Bruce River Group. It consists of mafic to felsic flows along with related pyroclastic deposits and lesser intercalated sedimentary and intrusive rocks. Lower parts of the formation are dominated by volcanic rocks of mafic to intermediate composition, whereas the upper parts of the formation are dominated by felsic rocks. The formation is primarily calc-alkaline and is inferred to represent volcanism within a regional subsiding depression (Ryan, 1984). The volcanic rocks of the Sylvia Lake Formation locally contain minor occurrences of fracture-hosted uranium mineralization (*e.g.*, Madsen and Sylvia Lake prospects), which commonly display a close spatial association with the intrusion of mafic dykes within the volcanic sequence. Uranium mineralization is also found within deformed equivalents of the Bruce River Group along the southeastern margin of the unit (*e.g.*, Minisinakwa prospect; Figure 1), where the rocks have undergone more intense deformation and recrystallization due to the emplacement of younger granites and subsequent Grenvillian deformation (Ryan and Harris, 1978).

LOCAL GEOLOGY OF THE MORAN LAKE C ZONE AREA

The Moran Lake C Zone deposit is composed of the Upper and Lower C Zones that contain distinctly different styles of uranium mineralization (*cf.* Sparkes and Kerr, 2008). Uranium mineralization within the Upper C Zone deposit is hosted by mafic volcanic rocks of the Joe Pond Formation, which display variable degrees of hydrothermal alteration and related brecciation (Morgan and Giroux, 2008; Sparkes and Kerr, 2008). These altered volcanic rocks occur in the hanging wall of the C Zone thrust fault (Gillies *et al.*, 2009), which is a high-angle reverse fault that thrusts mafic volcanic rocks of the Moran Lake Group over sandstone and interbedded conglomerate of the Heggart Lake Formation (Figure 3). The C Zone thrust fault, which is the same reverse structure identified by Smyth and Ryan (1977), is presumed to be synchronous with Grenvillian deformation, and is, in turn, transected by northwest southeast-trending normal faults; the latter locally displace the mineralized breccias of the Upper C Zone.

Within the hanging wall of the C Zone thrust fault, the distribution of the iron oxide-rich breccias is predominantly bound by two subparallel structures termed the Upper and Lower shear zones (Figure 3; Gillies *et al.*, 2009). The variably altered volcanic rocks within the Upper C Zone are, in turn, structurally overlain by poorly sorted pebble to cobble conglomerate of the Heggart Lake Formation. The extensive alteration and brecciation developed within the Upper C Zone decreases significantly at the faulted contact with the overlying siliciclastic sedimentary rocks (Plate 1); however, similar styles of brecciation are locally observed within these sedimentary rocks indicating that they are, at least, locally affected by the hydrothermal system.

The Moran Lake Lower C Zone deposit is located within the footwall of the C Zone thrust fault. Here, fine- to medium-grained sandstone and lesser interbedded pebble conglomerate, and rare metre-scale beds of felsic tuff, unconformably overlie mafic volcanic rocks of the Moran Lake Group (Figure 3). Within the Lower C Zone deposit, uranium mineralization is sandstone-hosted (*cf.* Sparkes and Kerr, 2008). Most of the sandstone sequence above the unconformity is oxidized and red, but it is locally reduced for several metres immediately above the unconformable contact. This zone of reduced sandstone is the site of uranium deposition within the Lower C Zone deposit; however, the reduced grey-green sandstone is not everywhere mineralized.

At the northeastern end of the alteration trend within the Moran Lake area, hematitic breccias and associated alkali metasomatism are also locally developed, in association with the emplacement of intermediate intrusions within siliciclastic sedimentary rocks of the Heggart Lake Formation. The most significant of these occurrences, the B Zone prospect (Figure 2), is situated along the eastern margin of a large gabbroic intrusion, informally referred to as the Henri Lake gabbro (*e.g.,* Morgan *et al*., 2007). This intrusion consists of olivine gabbro, biotite gabbro, anorthosite and lesser granite; all of which comprise a large magnetic high on airborne surveys.

To the southwest of the C Zone deposit, hematitic breccias and related alkali-iron metasomatism can be traced intermittently for approximately 8 km along strike (Figure 2). At the southwestern terminus of the alteration trend in

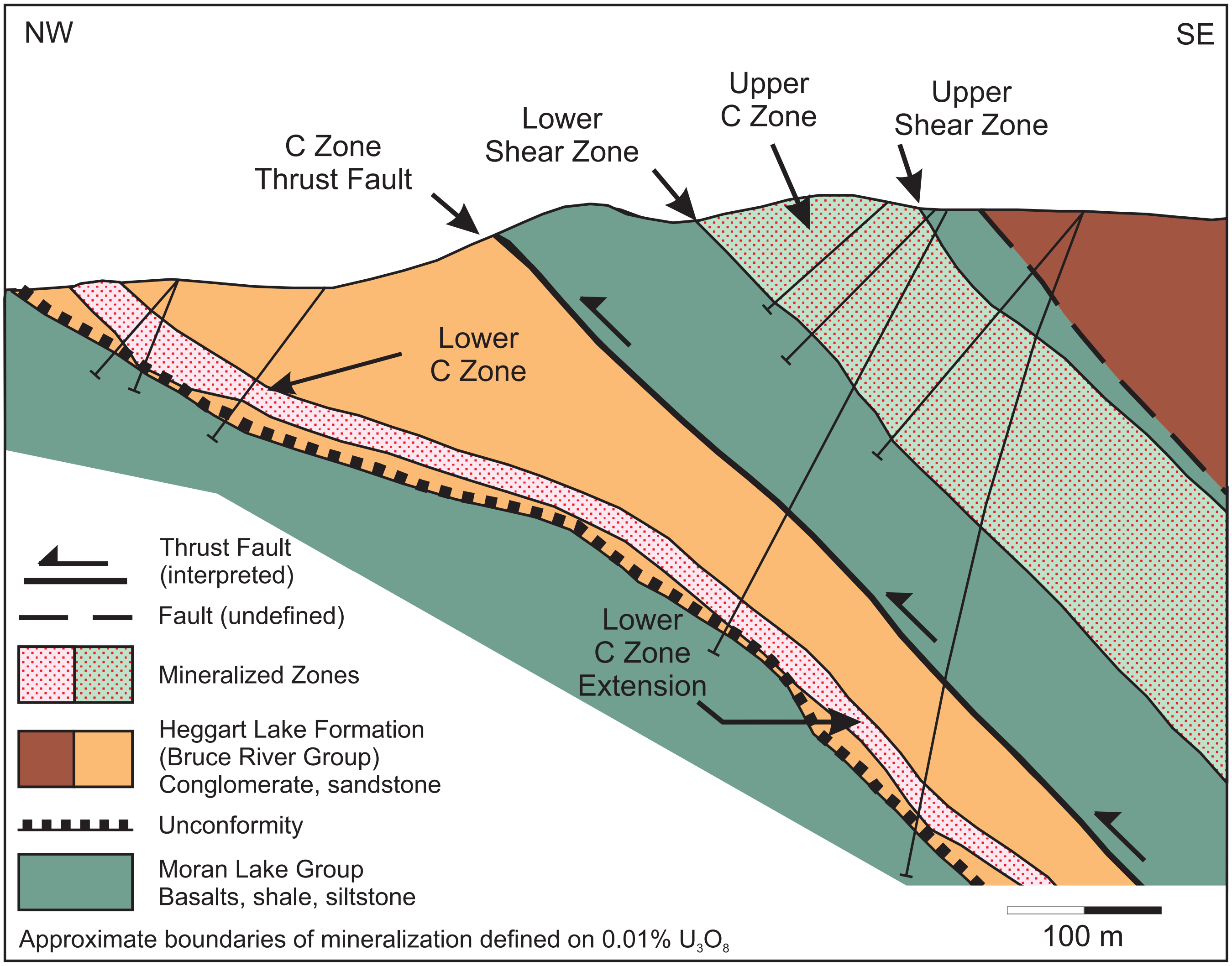

Figure 3. *Schematic cross-section through the Moran Lake C Zone deposit showing the location of the Upper and Lower C zones, along with the intervening C Zone thrust fault; modified after diagrams released on the Crosshair Exploration and Mining website.*

the area of the Anomalies Nos. 15 and 16 prospects, altered, and locally brecciated, mafic volcanic rocks of the Moran Lake Group are unconformably overlain by basal conglomerate of the Brown Lake Formation; the latter do not appear to be affected by the alkali-iron metasomatism.

BRECCIA DEVELOPMENT AND ASSOCIATED MINERALIZATION

The development of the iron oxide-rich hydrothermal breccias within the Moran Lake Upper C Zone and surrounding areas is defined as an epigenetic, polymetallic style of mineralization associated with widespread alkali-iron metasomatism. The main alteration assemblages related to mineralization include carbonate (ankerite), albite and hematite, which occur with lesser amounts of chlorite, biotite, quartz, pyrite and rutile. Preliminary investigations into the paragenesis of the various alteration assemblages indicate that early stage albitic alteration is subsequently overprinted by intense carbonate alteration (Eaton *et al*., 2008). The initial phase of alteration within the mafic volcanic rock results in a pale pink, to orange, to maroon colouration as a result of hematization and albitization (Plate 2). This alteration is, in turn, crosscut by white carbonate–quartz ± albite alteration, and is subsequently overprinted by extensive brittle, network-style fracturing and associated hematite-rich brecciation. The breccias are predominantly chaotic, containing angular to subrounded, mm- to cm-scale fragments of earlier alteration assemblages supported in a dark-purple hematitic matrix that also contains abundant carbonate (Plate 3). Based on these characteristics,

Plate 1. *Hematite–carbonate–albite alteration (yellow arrow) developed in the Moran Lake Group within metres of the overlying conglomerate of the Heggart Lake Formation. Note the sharp structural contact separating the two units (*see *inset). Moran Lake C Zone, DDH ML-56, ~ 50 m depth.*

Plate 3. *Hematite-rich breccia containing fragments of the preceding hematite–carbonate–albite alteration. This breccia is barren with respect to uranium mineralization, but is enriched in vanadium (0.193% V_2O_5 over 0.5 m; Morgan* et al.*, 2007). Moran Lake C Zone, DDH ML-3, ~ 105 m depth.*

Plate 2. *Early, pinkish orange hematite–albite alteration (1), overprinted by white carbonate–quartz–albite alteration (2), which is, in turn, crosscut by dark-purple hematite-rich fracturing (3) and associated brecciation. Note pale-green patches of relatively unaltered mafic volcanic rock are still locally preserved. Moran Lake C Zone, DDH ML-3, ~ 55 m depth.*

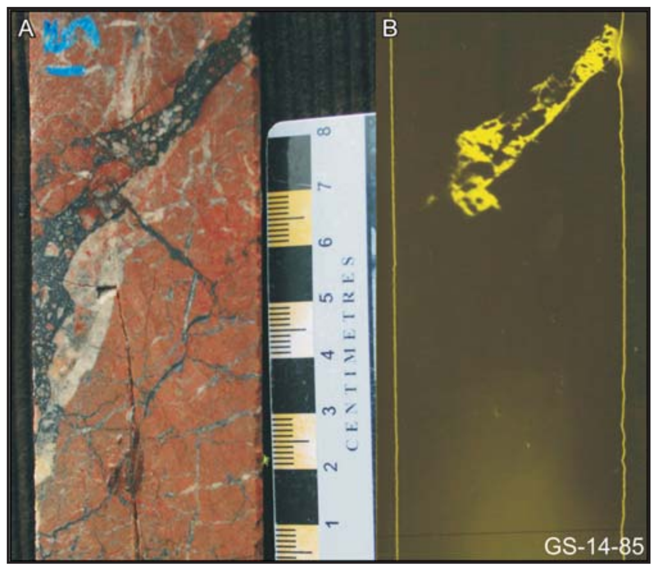

Plate 4. *A) Uranium-bearing, dark-purple, hematite-rich breccia vein crosscutting earlier hematite–albite–carbonate alteration. B) Autoradiograph of (A) outlining the distribution of radioactivity (shown in yellow, minus the outline of the sample) within the sample; note the uneven distribution of the radioactivity within the hematite-rich breccia.*

the breccias are interpreted to be hydrothermal in origin (*cf.* Cook, 1980; Ryan, 1984).

Although the alteration and brecciation form the most characteristic features associated with uranium mineralization, the hematitic breccias are not always mineralized with respect to uranium. Geochemical data indicate that the breccias are regularly associated with elevated vanadium, but elevated uranium values are less consistent. Detailed examination of uraniferous zones indicate that elevated uranium values are commonly associated with the development of dark-purple hematitic breccias and related crosscutting fractures (Plate 4). In addition, as illustrated in Plate 4, the uranium mineralization is not uniformly distributed within such breccias. Whether or not the uranium and vanadium are linked to a common mineralizing event has yet to be determined, but as shown by the geochemical data in Table 1, there is no apparent correlation regarding the enrichment of these two elements. However, there is a local association between elevated vanadium and enrichment in copper and silver (*e.g.*, GS-14-118; Table 1).

Table 1. Select elements from industry assay data covering the intervals from which select samples were collected for detailed petrographic study; Crosshair Exploration unpublished data

Sample #	Company #	Interval (m)	Ag (ppm)	Ca (%)	Cu (ppm)	Fe (%)	U (ppm)	V (ppm)
GS-14-113	66622	2	0.65	7.59	186	7.49	19.8	303
GS-14-114	66642	2	0.29	8.04	41.6	7.92	8.6	457
GS-14-118	66661	2	1.46	8.92	1280	5.78	2.8	1538
GS-14-119	66679	0.5	2.23	8.04	13	6.18	38.9	508
GS-14-120	66685	0.5	0.46	7.95	13.6	7.83	80.5	308

Distal to the main zone of mineralization, in the region separating the Upper and Lower C Zone deposits, the mafic volcanic rocks of the Joe Pond Formation are relatively unaltered. Similar, relatively unaltered, mafic volcanic rocks are also locally preserved as relict zones within the Upper C Zone alteration (Plate 2), which allow for the identification of the primary protolith to the iron oxide-rich breccias. These rocks typically contain background vanadium values of between 250−500 ppm, and represent a potential source rock for the vanadium enrichment developed in association with the hydrothermal breccias. As indicated above, the mineralized hematitic breccias are also locally developed within the poorly sorted pebble to cobble conglomerate that structurally overlies the Upper C Zone (Plates 5 and 6). This relationship demonstrates that the development of the brecciation postdates the deposition of the Heggart Lake Formation, which has implications with respect to the overall timing of mineralization (*see* below).

Detailed petrography and scanning electron microscope energy dispersive X-ray spectroscopy (SEM-EDX) of select mineralized samples (Plate 7; Table 1) investigated the mineralogy of the vanadium-bearing and locally uraniferous iron oxide-rich breccias (*cf.* Fonkwe, 2015). These analyses indicate that carbonate and hematite form the main components of the breccia matrix, with hematite occurring as both irregularly shaped patchy grains and compressed microplates (Plate 8A). Hematite is commonly intergrown with carbonate (ankerite) and lesser rutile, and where magnetite is present the hematite commonly forms rims and/or inclusions within the magnetite (Plate 8B). SEM-EDX analysis indicates that the hematite in the breccia matrix is host to variable vanadium contents, with both vanadium-rich and vanadium-poor hematite present in complex intergrowths (Plate 8C). Chalcopyrite is also locally present as fine-grained disseminations within the breccia matrix, but more commonly occurs as fracture filling material locally associated with the carbonate–quartz–albite alteration (Plate 9).

One sample included in the investigation (GS-14-119) contained elevated radioactivity, and as illustrated by the autoradiograph in Plate 7E, this radioactivity is confined to the hematite-rich breccia matrix. This sample contained a distinct mineral assemblage in comparison with the other samples included in the investigation, which included brannerite, galena and cobaltite in addition to containing more abundant pyrite (Plate 8B, D). The radioactivity within the

Plate 5. *Intensely altered and brecciated conglomerate hosting uranium mineralization. Breccia is developed marginal to a fine-grained mafic dyke that intrudes the Heggart Lake Formation; mineralization is developed approximately 10 m above the structural contact with the underlying altered Moran Lake Group. Moran Lake C Zone, DDH ML-82, ~115 m depth.*

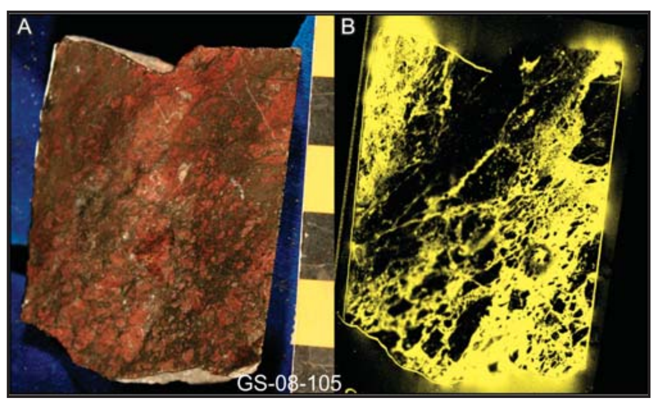

Plate 6. *A) Pervasive hematite alteration accompanied by hematite-rich brecciation within conglomerate of the Heggart Lake Formation. B) Autoradiograph of (A) outlining the distribution of radioactivity within the sample (shown in yellow; minus the outline of the sample).*

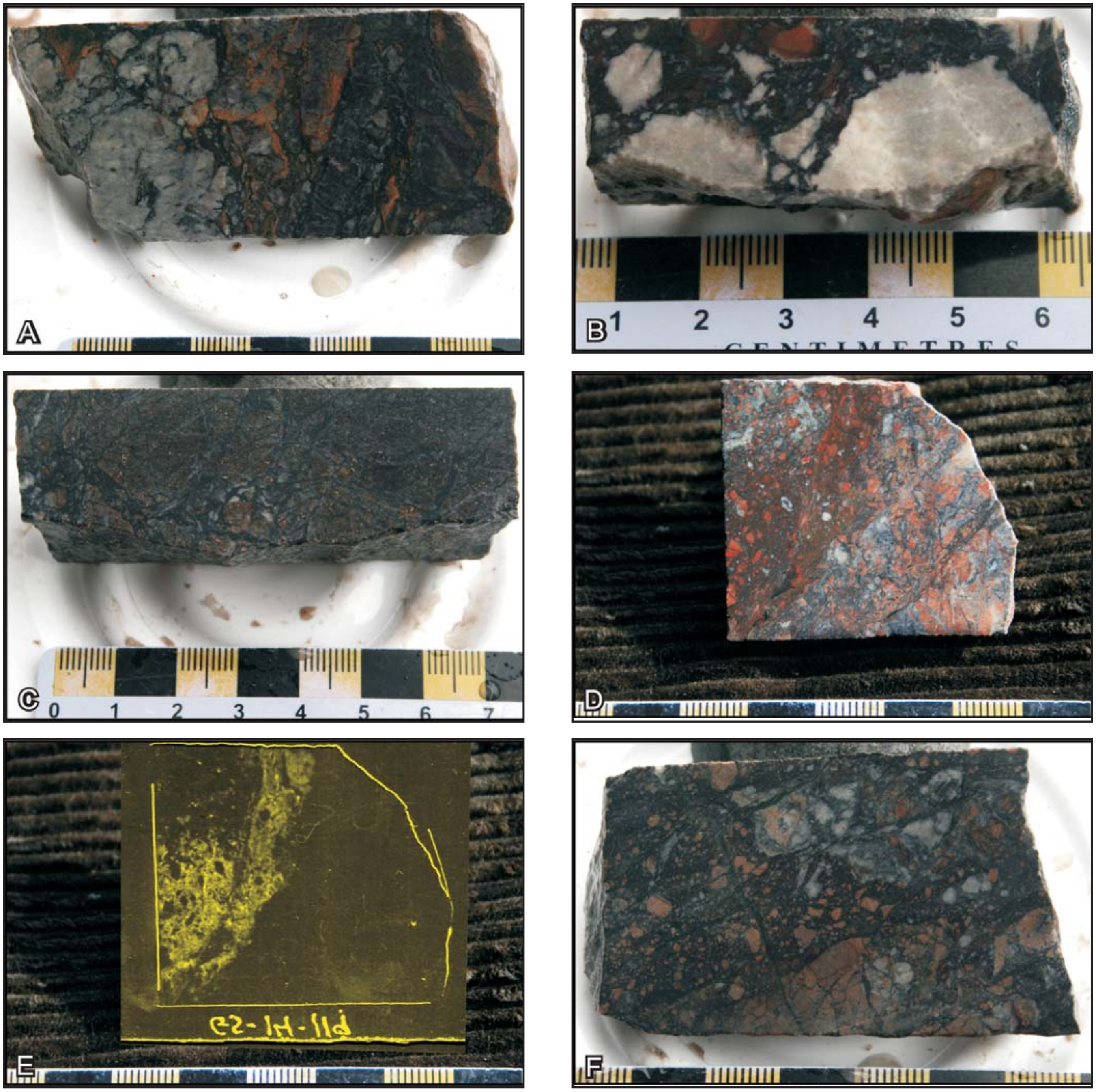

Plate 7. *Select samples from the vanadium-enriched hematitic breccia; A) GS-14-113; ML-193, 8.5 m depth. B) GS-14-114; ML-193, 34.5 m depth. C) GS-14-118; ML-193, 69.5 m depth. D) GS-14-119; ML-193, 100 m depth. E) Autoradiograph of (D) outlining the distribution of radioactivity within the sample (shown in yellow; minus the outline of the sample). F) GS-14-120; ML-193, 102.5 m depth. Note corresponding geochemical data for these samples is provided in Table 1.*

breccia matrix is attributed to the presence of brannerite, which occurs as very fine-grained disseminations and displays a close spatial association with galena and hematite. Locally fine-grained cobaltite, which has an EDX elemental signature of Co–Fe–As–S, also displays a spatial association with hematite within the breccia matrix.

U–Pb GEOCHRONOLOGY

Prior to this study, there were few age constraints on the deposition of the Bruce River Group. A maximum age of deposition was provided by the Junior Lake Granodiorite, which is unconformable overlain by the Heggart Lake For-

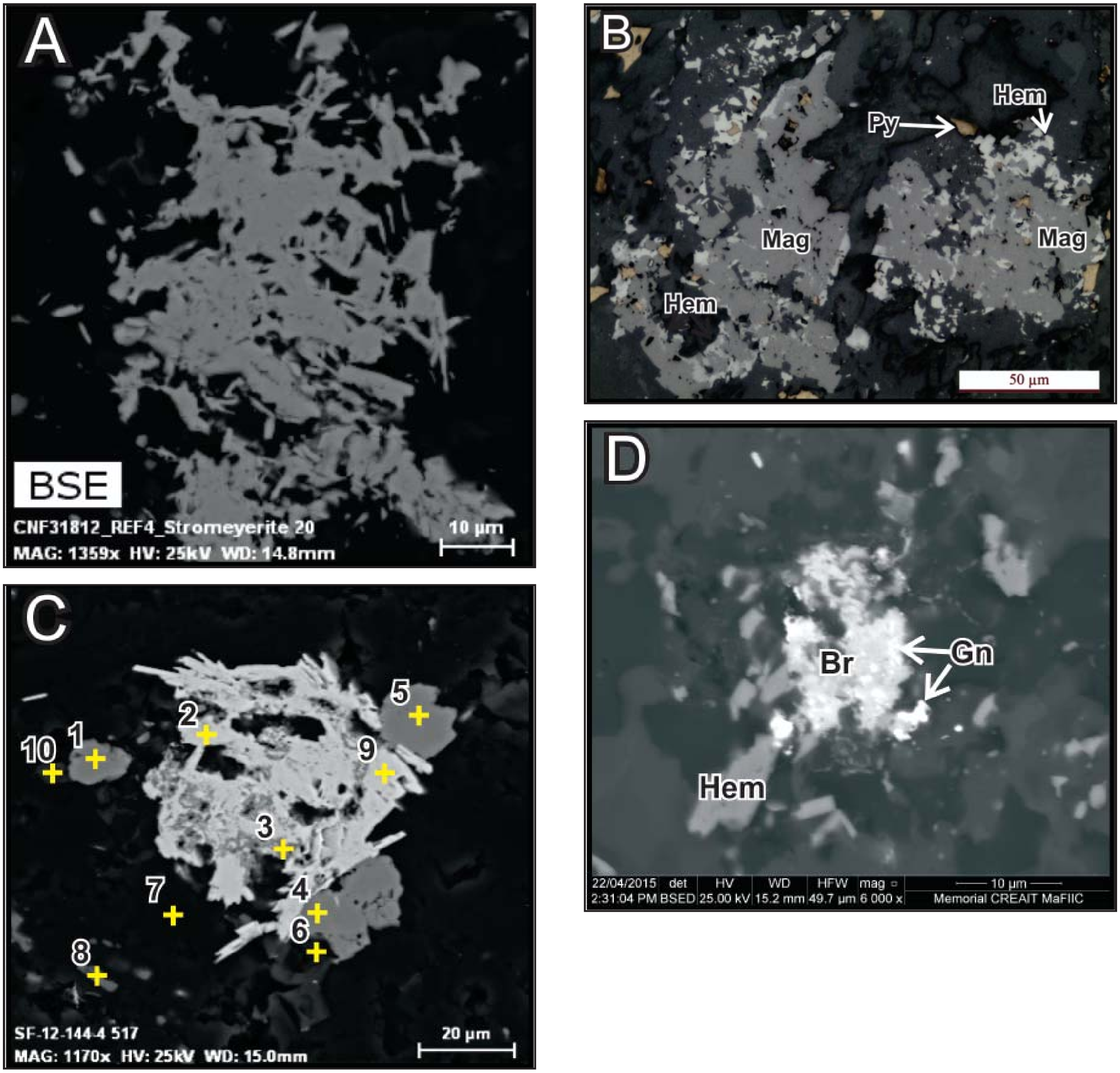

Plate 8. *A) SEM backscattered electron image (BSE) showing individual microplatey hematite and patchy hematite (light grey); sample GS-14-113. B) Reflected light image of magnetite grains rimmed by fine-grained hematite; also note hematite inclusions in magnetite crystals; sample GS-14-119. C) BSE image of a patch of hematite with EDX point analysis: points 1, 3, 4 and 5 = rutile; point 2 = vanadium-rich hematite; point 6 = Mg-rich ankerite; point 7 = albitite; point 8 = apatite; point 9 = vanadium-poor hematite; point 10 = Mg-poor ankerite; sample GS-14-118. D) BSE image of an anhedral grain of brannerite with galena and hematite. Abbreviations: Br – brannerite; Gn – galena; Hem – hematite; Mag – magnetite; Py – pyrite.*

mation (1893 ± 2 Ma; Kerr *et al*., 1992). The only direct U–Pb age for the Bruce River Group was that obtained from volcanic rocks of the Sylvia Lake Formation, located within the upper portions of the stratigraphic sequence (1649 ± 1 Ma; Schärer *et al*., 1988). As part of this study, four additional samples were collected to provide further age constraints on the deposition of the Bruce River Group. These included, a tuff from the Heggart Lake Formation, a granitic phase related to the emplacement of the Henri Lake gabbro that locally intrudes the Heggart Lake Formation, a tuff from the Brown Lake Formation, and a sample of recrystallized felsic volcanic rock from the southeastern margin of

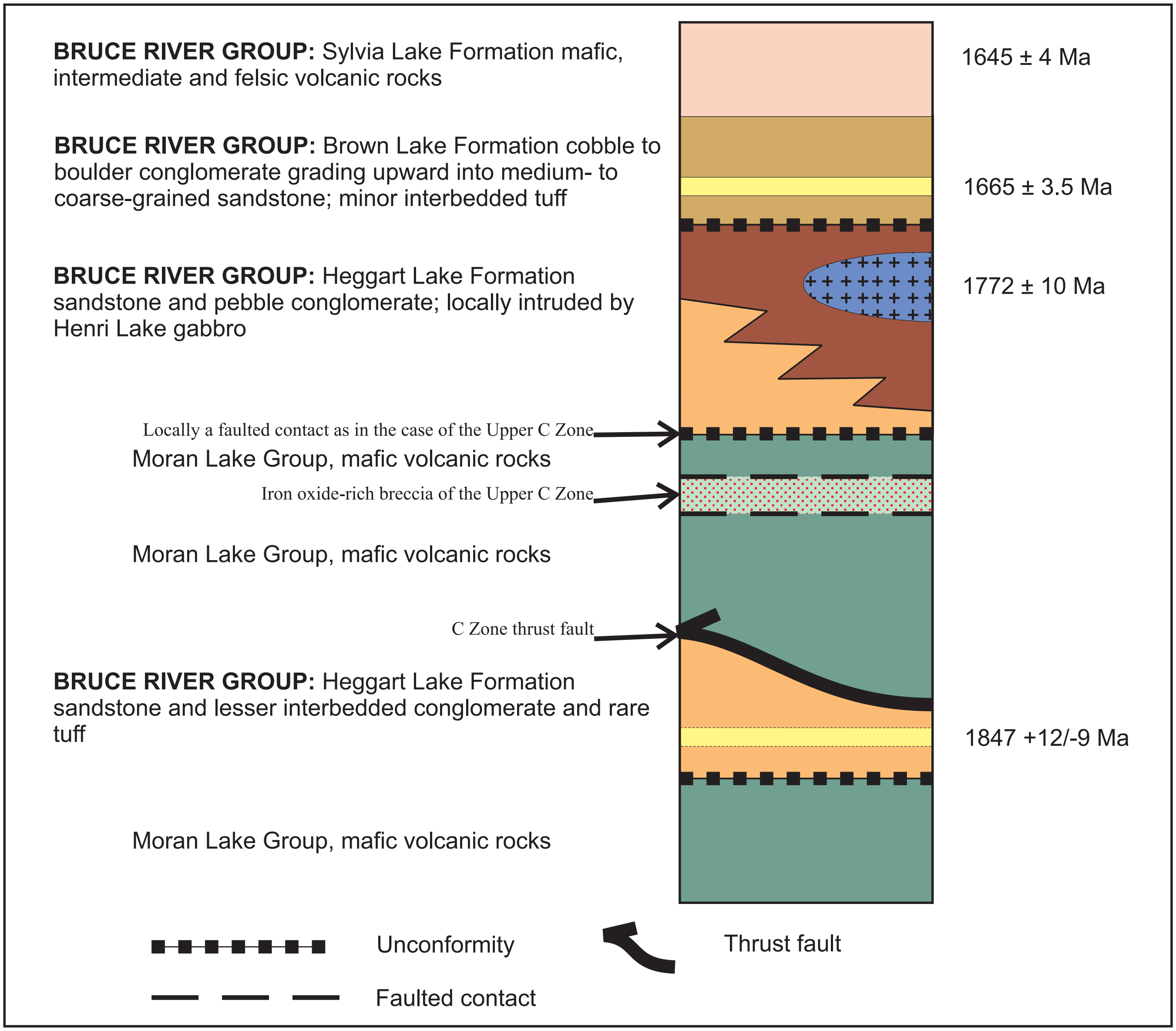

Figure 4. *Schematic stratigraphic column outlining the relative positions of the geochronological samples collected as part of this study.*

the Sylvia Lake Formation. A schematic stratigraphic column, outlining the relative stratigraphic position of each of these samples, is outlined in Figure 4, and the geographic locations are shown in Figure 1.

Samples were processed by standard techniques of crushing and concentration of a heavy mineral separate of zircon (*see* Sparkes and Dunning, 2014). All zircon grains were chemically abraded to remove altered domains prior to analysis (*cf.* Mattinson, 2005). Lead and uranium isotopic ratios were measured by thermal ionization mass spectrometry, and results calculated using ISOPLOT for weighted averages or following the procedure outlined by Davis (1982) for linear regressions. Uncertainties on all ages are reported at the 95% confidence interval. The following summary provides a brief description of each unit and its corresponding age determination.

HEGGART LAKE FORMATION TUFF

Company drill logs from the Lower C Zone noted the occurrence of fine ash deposits interbedded with the red sandstone of the Heggart Lake Formation (*e.g.,* Eaton *et al*., 2008; DDH ML-166). This unit was targeted for geochronological study to provide an age for the deposition of the basal Heggart Lake Formation, and thus provide a maximum age for the development of the iron-oxide breccias that are locally hosted within the unit. Sample GS-14-123 was

Plate 9. *Late chalcopyrite-rich vein associated with the carbonate–quartz–albite alteration crosscutting earlier hematitic alteration; Upper C Zone deposit.*

collected from drillhole ML-166, at a depth of about 250 m, approximately 66 m above the basal unconformity between mafic volcanic rocks of the Joe Pond Formation and overlying medium- to coarse-grained red to green sandstone of the Heggart Lake Formation (Plate 10A). This sample yielded abundant zircon from which nine analyses (Table 2) of the clearest euhedral zircon prisms, displaying excellent igneous growth zoning (Plate 11), yielded a discordant and non-collinear data array. A line with a poor probability of fit of 3.6% yields an upper intercept age of 1847 +12/-9 Ma (95% CI, Figure 5A). The lower intercept of this line is 491 Ma, with a large uncertainty of +/-100 Ma suggesting that the rock may have been subject to a younger thermal event. There is clearly inherited older zircon in this rock, such as the core shown in one grain in Plate 11.

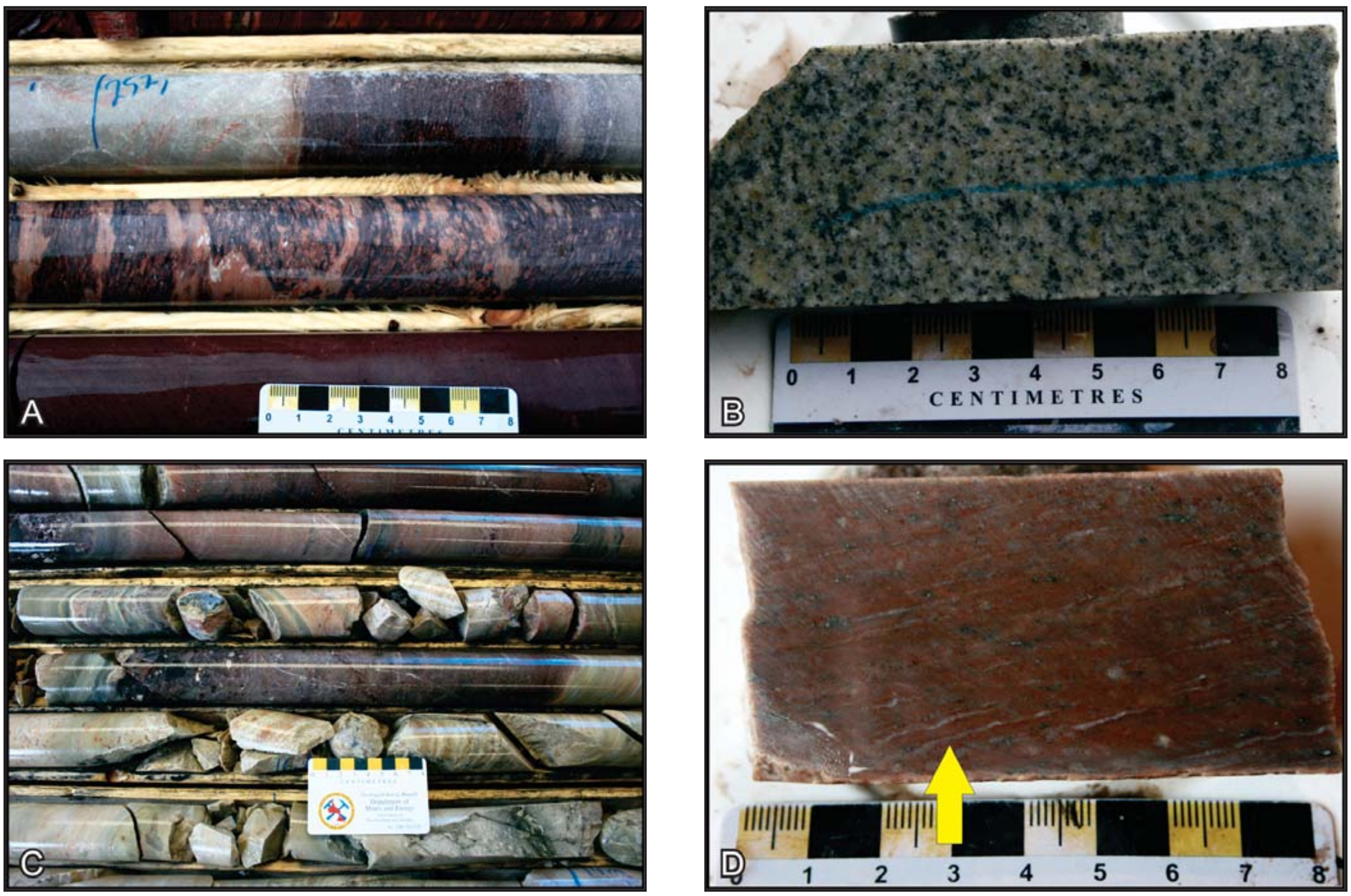

Plate 10. *Photographs of the geochronological samples collected as part of this study; A) Tuff interbedded with red coarse-grained sandstone of the Heggart Lake Formation (GS-14-123; DDH ML-166, ~255 m depth). B) Medium-grained granitic phase inferred to be comagmatic with the Henri Lake gabbro (GS-14-130; DDH ML-GV-01, ~480 m depth). C) Tuff interbedded with the basal conglomerate of the Brown Lake Formation (GS-08-137; DDH CL-06, ~15 m depth). D) Quartz–feldspar-phyric crystal tuff of the Sylvia Lake Formation displaying relic fiamme (yellow arrow; GS-14-203; DDH ML-08-02, ~85 m depth).*

Table 2. U–Pb zircon data for samples from the central portion of the CMB of Labrador; UTM's are in NAD 27, Zone 21 coordinates

		Concentration		Measured		Corrected Atomic Ratios *							Age [Ma]		
Fraction	Weight [mg]	U [ppm]	Pb rad	total common Pb [pg]	$^{206}Pb/^{204}Pb$	$^{208}Pb/^{206}Pb$	$^{206}Pb/^{238}U$	+/-	$^{207}Pb/^{235}U$	+/-	$^{207}Pb/^{206}Pb$	+/-	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$
GS14-123 Tuff – Heggart Lake Formation (244157m E, 6043818m N)															
Z1 1 prm	0.002	533	163.2	6.7	2220	0.1009	0.29319	180	4.5575	278	0.11274	20	1657	1742	1844
Z2 2 prm	0.003	1071	328.9	48	1239	0.1004	0.29466	220	4.5061	336	0.11091	18	1665	1732	1814
Z3 2 prm	0.003	801	241.6	29	1496	0.1198	0.28448	224	4.4107	352	0.11245	14	1614	1714	1839
Z4 2 prm	0.003	614	178.0	32	1010	0.0941	0.28013	158	4.2361	232	0.10967	24	1592	1681	1794
Z5 1 prm	0.002	1213	363.3	34	981	0.1031	0.28702	174	4.3365	262	0.10958	26	1627	1700	1792
Z6 1 prm	0.002	2075	646.6	35	1704	0.0926	0.30097	322	4.6041	494	0.11095	14	1696	1750	1815
Z7 1 clr euh prm	0.001	286	94.2	5.1	1131	0.1049	0.31434	344	4.8635	482	0.11221	60	1762	1796	1836
Z8 2 clr euh prm	0.002	527	159.3	13	1461	0.1018	0.28956	178	4.4400	274	0.11121	30	1639	1720	1819
Z9 1 clr euh prm	0.001	524	177.2	7.4	1417	0.1246	0.31728	580	5.0099	914	0.11452	30	1776	1821	1872
GS14-130 Granite – Henri Lake (246963m E, 6044570m N)															
Z1 1 prm	0.002	1818	497.4	58	749	0.1628	0.24956	220	3.8290	334	0.11128	24	1436	1599	1820
Z2 1 prm	0.002	529	160.0	16	945	0.0659	0.29964	376	4.4674	556	0.10813	50	1690	1725	1768
Z3 2 prm	0.003	435	90.1	18	893	0.1151	0.19689	188	2.8994	262	0.10680	46	1159	1382	1746
Z4 2 simple prm	0.003	383	56.7	15	637	0.1920	0.13284	60	1.8706	96	0.10213	42	804	1071	1663
Z5 3 prm	0.004	470	155.0	18	2220	0.1370	0.30151	210	5.6150	386	0.13506	26	1699	1918	2165
Z6 1 clr prm	0.001	267	89.8	6	834	0.1199	0.31781	162	4.8803	304	0.11137	46	1779	1799	1822
GS08-137 Tuff – Brown Lake Formation (226840m E, 6037730m N)															
Z1 1 clr med prm	0.001	643	223.6	2.6	4662	0.2714	0.29413	160	4.1451	214	0.10221	22	1662	1663	1665
Z2 1 clr euh prm	0.001	242	84.7	2.7	1697	0.2757	0.29552	184	4.1658	270	0.10224	42	1669	1667	1665
Z3 2 clr euh prm	0.002	68	30.7	1.9	1771	0.1573	0.39627	210	8.8244	526	0.16151	50	2152	2320	2472
GS14-203 Crystal Tuff – Sylvia Lake Formation (242807m E, 6012434m N)															
Z1 1 lrg euh clr prm	0.002	506	173.3	4.7	3010	0.2326	0.29782	240	4.2671	296	0.10391	44	1680	1687	1695
Z2 2 lrg clr euh prm	0.003	288	97.5	80	214	0.2534	0.29089	174	4.0541	318	0.10108	54	1646	1645	1644
Z3 4 lrg clr euh prm	0.006	333	114.0	64	583	0.2754	0.28874	262	4.0197	384	0.10097	34	1635	1638	1642
Z4 2 lrg clr euh prm	0.003	128	41.9	2.8	2510	0.2145	0.28857	124	4.0285	170	0.10125	32	1634	1640	1647

Notes: Z=zircon, 1,2 =number of grains, lrg=large, clr=clear, med=medium, prm =prism, euh=euhedral.
All zircon was chemically abraded (Mattinson, 2005). Weights were estimated so U and Pb concentrations are approximate.
* Atomic ratios corrected for fractionation, spike, laboratory blank of 1-2 picograms of common lead, and initial common lead at the age of the sample calculated from the model of Stacey and Kramers (1975), and 0.3 picogram U blank. Two sigma uncertainties are reported after the ratios and refer to the final digits.

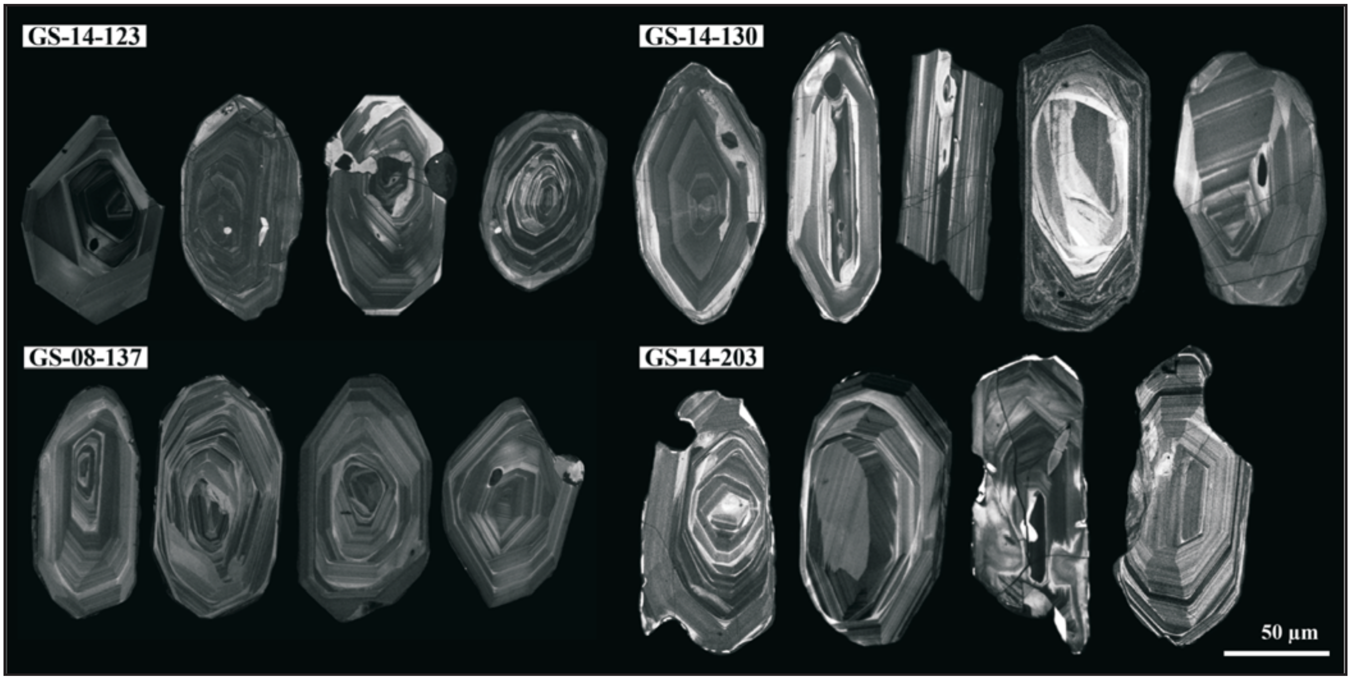

Plate 11. *Cathode luminescence images for select grains outlining the typical textures observed within zircon separates obtained from the geochronological samples discussed in the text. GS-14-123 – Tuff from Heggart Lake Formation, Bruce River Group; GS-14-130 – Granitic phase related to the Henri Lake gabbro; GS-08-137 – Tuff from the Brown Lake Formation, Bruce River Group; GS-14-203 – Crystal tuff from the Sylvia Lake Formation, Bruce River Group.*

GRANITIC PHASE OF THE HENRI LAKE GABBRO

In the area of the Moran Lake B Zone prospect, deep drilling by Crosshair targeted a gravity anomaly in the area, associated with the intrusion of the Henri Lake gabbro *(e.g.*, Gillies *et al*., 2009; DDH ML-GV-01). Examination of drillcore from hole ML-GV-01 identified the presence of a comagmatic granitic phase related to the intrusion of the more voluminous gabbro. The granite phase of the intrusion was sampled for geochronological study (GS-14-130; Plate 10B), as several attempts at dating other gabbroic intrusions in the area of the C Zone by the first author were unsuccessful. The present sample generated many coarse zircon prisms that appear to be an igneous population (Plate 11). Six analyses are discordant and non-collinear, and the three farthest to the left yield a line (Z2, Z3, Z4; 60% probability of fit after error expansion) with an upper intercept age of 1772 ± 10 Ma and a lower intercept of 115 ± 105 Ma (Figure 5B). One analysis (Z5) of 3 prisms must have an older component and gives a $^{207}Pb/^{206}Pb$ age of 2165 ± 10 Ma.

BROWN LAKE FORMATION TUFF

To test the age of the Brown Lake Formation, a sample of tuff was collected from drillcore from the Croteau Lake prospect (Figure 1), which intersects local tuffaceous layers within the basal conglomerate of the Brown Lake Formation (*e.g.,* Eaton *et al*., 2008; DDH CL-06). Sample GS-08-137 was collected from drillhole CL-06, at an approximate depth of 15 m, roughly 45 m above the basal unconformity separating grey siltstone and interbedded chert of the Moran Lake Group from the overlying pebble to cobble conglomerate of the Brown Lake Formation (Plate 10C). This sample yielded many euhedral prisms of high quality zircon (Plate 11). Two analyses of single grains yield overlapping concordant data points giving a weighted average $^{207}Pb/^{206}Pb$ age for igneous crystallization of 1665 ± 3.5 Ma (MSWD=0.016; Figure 5C). A third analysis of 2 grains, not shown on Figure 5C, is older with a $^{207}Pb/^{206}Pb$ age of 2472 Ma and is interpreted to represent a detrital component within the tuff.

SYLVIA LAKE FORMATION CRYSTAL TUFF

Finally, a sample of strongly deformed and recrystallized metavolcanic rock from the southeastern Sylvia Lake Formation was collected at the Minisinakwa prospect. Here, locally developed uranium mineralization is associated with hematite–magnetite alteration developed within the felsic volcanic host rock. The geochronological sample was collected from drillhole ML-08-02 (*cf.* Fraser *et al*., 2009), at approximately 85 m depth and consisted of weakly quartz–feldspar-phyric crystal tuff with relict fiamme (Plate 10D). This sample yielded many high-quality zircon prisms displaying spectacular igneous growth zoning (Plate 11). Some grains display evidence of multiple zircon growth –

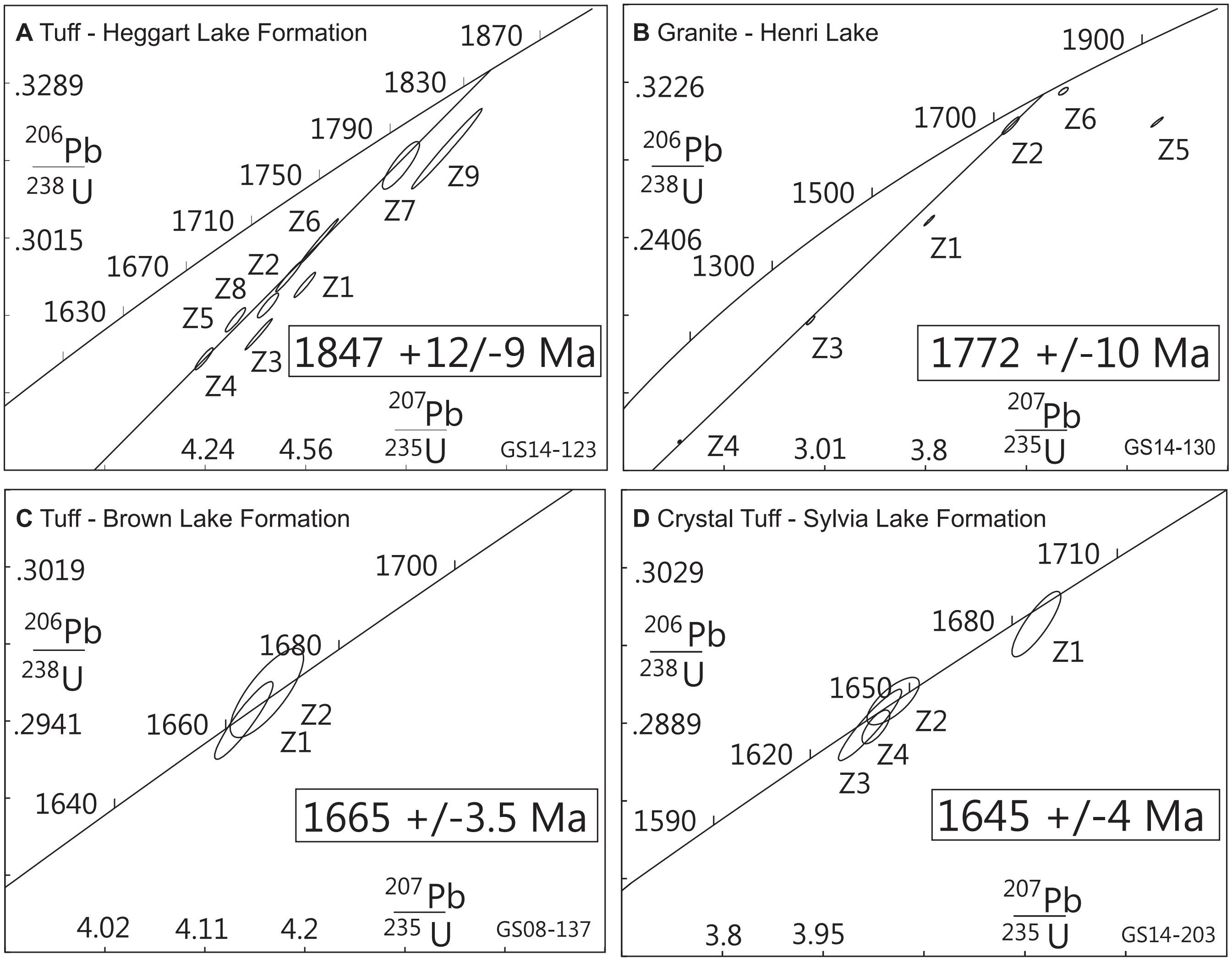

Figure 5. *Concordia diagrams of U–Pb results from zircon analyses for samples discussed in the text. Error ellipses are at the 2σ level. Refer to Table 2 for sample location and description.*

corrosion – new growth events, which is typical of zircon in rhyolite. Of the four analyses, three are overlapping and concordant and yield a weighted average $^{207}Pb/^{206}Pb$ age of 1645 ± 4 Ma (MSWD = 0.73; Figure 5D). The fourth analysis is concordant at 1695 Ma.

SUMMARY AND DISCUSSION

The occurrence of iron oxide-rich hydrothermal breccias along a *ca.* 10-km strike length, in association with the development of albite, carbonate and hematite alteration, provides supporting evidence for the local development of IOCG-style mineralization. In the Moran Lake area of the CMB, the iron oxide-rich hydrothermal breccias are primarily hosted within the mafic volcanic rocks of the Moran Lake Group, but also locally occur within the overlying siliciclastic rocks of the Heggart Lake Formation. The hematite-dominated iron oxide breccias overprint earlier albite–carbonate alteration, display evidence for multiple episodes of brecciation, and are generally associated with enrichment in V, U, Cu and Ag. The most detailed study of this brecciation has been conducted in the area of the Moran Lake Upper C Zone deposit, where breccia development is largely structurally bound as determined through detailed diamond drilling. The structures bounding the mineralized breccias are roughly subparallel to the C Zone thrust fault, and are likely linked to this larger regional structure, which is inferred to be synchronous with Grenvillian deformation.

Detailed mineralogical investigations indicate that there may be at least two different phases of hematite associated with breccia development. Patchy hematite alteration potentially results from the oxidation of magnetite, whereas microplaty hematite may represent a separate phase related to precipitation from an oxidized fluid-rock system, allowing for the mobilization of V and Ti. The host mafic volcanic rocks represent a probable source for the vanadium contained within the mineralized breccias; however the source for the uranium and copper enrichment is less apparent. One potential source is the overlying siliciclastic sedimentary rocks of the Heggart Lake Formation, which is locally host to a number of uranium occurrences containing anomalous copper and silver mineralization (*e.g.,* Moran Heights prospect; Morgan *et al*., 2007).

General models regarding IOCG deposits suggest that hematite-dominated alteration is developed at shallower depths or within peripheral halos in lower temperature, more oxidizing environments, while magnetite-dominated alteration is confined to deeper, higher temperature and/or reducing environments. Hematite forms the predominant iron oxide along the alteration trend in the Moran Lake region; however a noticeable increase in the proportion of magnetite is observed in the southwestern end of the trend, in the area of the Anomaly No. 16 prospect. This contrast may imply that deeper and/or higher temperature environments persisted within this portion of the alteration trend; however further work is required to investigate such relationships.

The new geochronological data highlights the presence of a substantial unconformity between the Heggart Lake and Brown Lake formations of the Bruce River Group. These new data suggest that the Heggart Lake Formation (1847 +12/-9 Ma) is some 170 Ma older than the Brown Lake Formation (1665 ± 3.5 Ma). The older age for the Heggart Lake Formation is further supported by the emplacement of the Henri Lake gabbro (1772 ± 10 Ma), which locally intrudes the siliciclastic sedimentary rocks of the Heggart Lake Formation. The similar ages of the Brown Lake (1665 ± 3.5 Ma) and Sylvia Lake (1645 ± 4 Ma) formations are supportive of the two units being part of the same depositional environment as outlined by Ryan (1984).

These new U–Pb ages also provide constraints for the development of the iron oxide-rich hydrothermal breccias within the region. As noted previously, these breccias are locally developed within the siliciclastic sedimentary rocks of the Heggart Lake Formation. In addition, the Brown Lake Formation appears to be unaffected by the alkali-iron metasomatism developed within the mafic volcanic rocks of the Moran Lake Group at the southwestern terminus of the alteration trend, and it is therefore inferred that the Brown Lake Formation postdates the formation of the hydrothermal breccias. On the basis of this inference, the formation of the iron oxide-rich breccias can be bracketed between 1857 and 1661.5 Ma, within analytical error. This age bracket broadly overlaps the 1860 to 1800 Ma bracket for albitite-style mineralization associated with the formation of the Michelin deposit (Sparkes and Dunning, 2015). These data support a possible temporal relationship between the development of IOCG-style and albitite-type mineralization within the CMB, and will be the focus of ongoing studies.

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