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AGE CONSTRAINTS ON VMS MINERALIZATION, CENTRAL BUCHANS–ROBERTS ARM BELT, NEWFOUNDLAND

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ABSTRACT

New U–Pb ages from the central portion of the Buchans–Roberts Arm Belt (BRAB) provide the first age constraints directly related to the development of volcanogenic massive sulphide (VMS) mineralization for this area. Samples of felsic tuff collected from the area of the Gullbridge and Lake Bond deposits have returned ages of 469.63 ± 0.41, 470.56 ± 0.50 and 470 ± 5 Ma. In addition, re-analysis of archived material from a felsic volcanic unit underlying mineralization at the MacLean deposit (Buchans area) provides a new age of 471 ± 1.6 Ma. These new ages, when combined with existing geochronological data for the BRAB, further support the composite nature of both the volcanic host rocks and the associated hydrothermal systems. Compilation of existing geochronological data for the region highlights the presence of two main periods of volcanism at ca. *470 and* ca. *465 Ma, which are both associated with the development of hydrothermal activity and related VMS mineralization.*

INTRODUCTION

Various studies have focused on mapping segments of the Buchans–Roberts Arm Belt (BRAB) over the last number of decades (*e.g.*, Kean, 1979; Thurlow and Swanson, 1981; Bostock, 1988; Coyle, 1991; Thurlow *et al.*, 1992; Evans *et al.*, 1994; Kerr, 1996; Swinden and Sacks, 1996; Thurlow, 1996; Rogers *et al.*, 2005a, b; O'Brien, 2009, 2016a, b, c; Zagorevski and Rogers, 2008, 2009; Zagorevski and McNicoll, 2012; Zagorevski *et al.*, 2007a, 2015, 2016), resulting in numerous proposed subdivisions for the rocks contained within this belt. This report deals with that portion of the BRAB extending from Pilley's Island in the northeast to Buchans in the southwest; an area host to several notable VMS deposits (*e.g.*, Pilley's Island, Gullbridge, Lake Bond, and those in the Buchans area; Figure 1A, B).

Previous work has demonstrated that rocks within the belt represent a collage of Lower to Middle Ordovician arc and back-arc environments, which, regionally, are collectively termed the Annieopsquotch accretionary tract (van Staal *et al.*, 1998; Lissenberg *et al.*, 2005; Zagorevski *et al.*, 2009, 2015). The BRAB is bound to the north by the Lobster Cove Fault, to the west by the Mansfield Cove Fault, Hungry Mountain Thrust, Lloyds River Fault and related structures, and to the east by the Red Indian Line (Thurlow and Swanson, 1981; Bostock, 1988; Zagorevski *et al.*, 2008 and references therein; O'Brien, 2009, 2016a, b, c). A regional compilation of the geology and geochronological data is outlined in Figure 1A, B.

This report provides a summary of the characteristics and distribution of relevant assemblages within the belt, focusing on those units hosting VMS-style mineralization. The report also contains three new U–Pb ages for the central portion of the belt, which provide the first age constraints on the development of VMS-style mineralization for this area. In addition, re-analysis of archived material from a sample collected in the Buchans area is also included. These data are combined with available U–Pb ages from the region to constrain the main periods of hydrothermal activity and related mineralization developed within the rocks of the BRAB.

REGIONAL GEOLOGY

The BRAB forms part of the larger Notre Dame Arc (*cf.* Swinden *et al.*, 1997; van Staal *et al.*, 1998), and is inferred to have accreted to older oceanic rocks of the Dunnage Zone along the Laurentian continental margin during the Taconic Orogeny (Cawood *et al.*, 1995; Kusky *et al.*, 1997; Draut and Clift, 2002; Lissenberg *et al.*, 2005). Within the belt, two main periods of volcanism have been outlined by Zagorevski *et al.* (2015), both of which are associated with development of VMS mineralization. This episodic volcanic

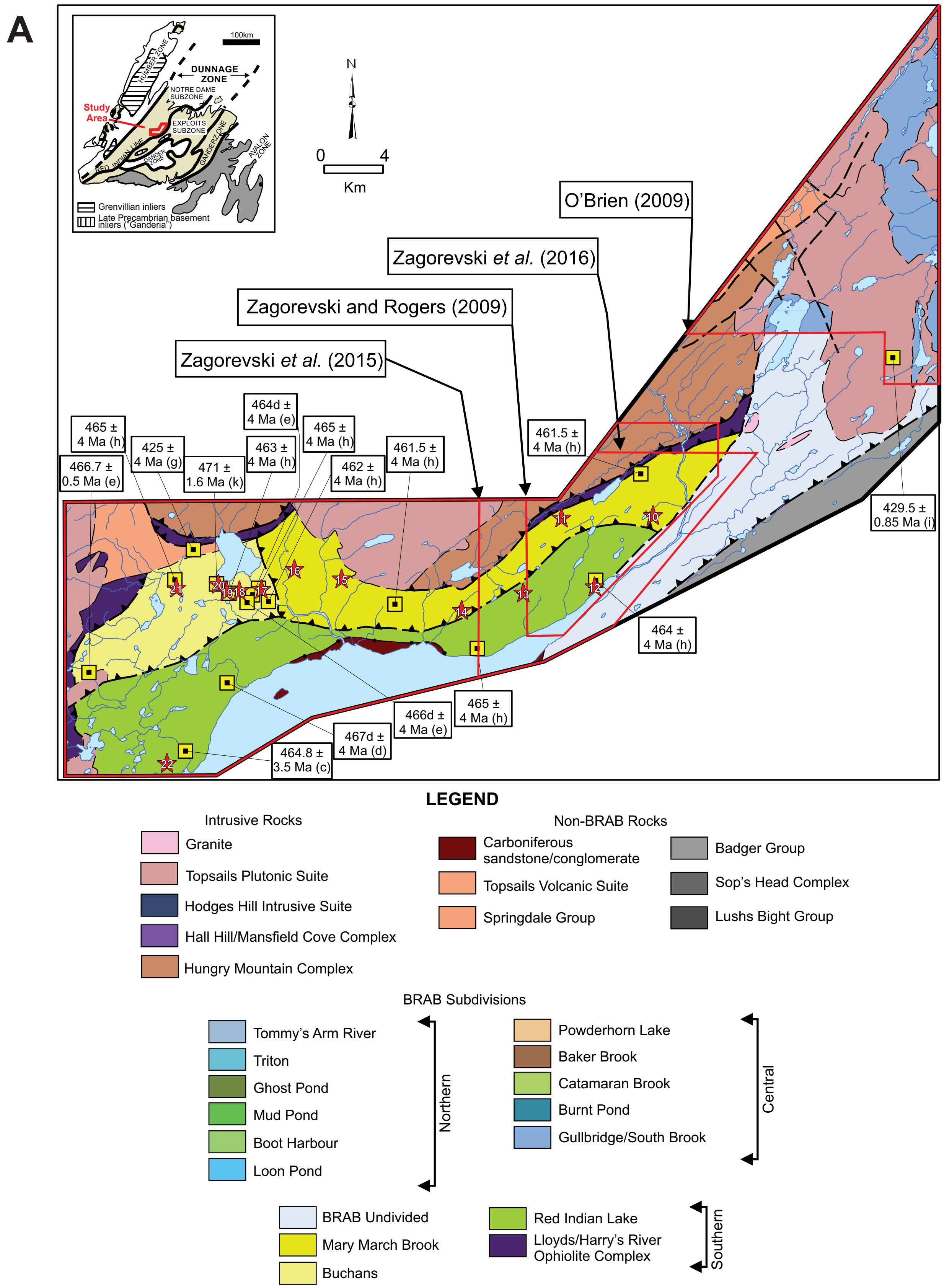

Figure 1. *Caption on page 3.*

B

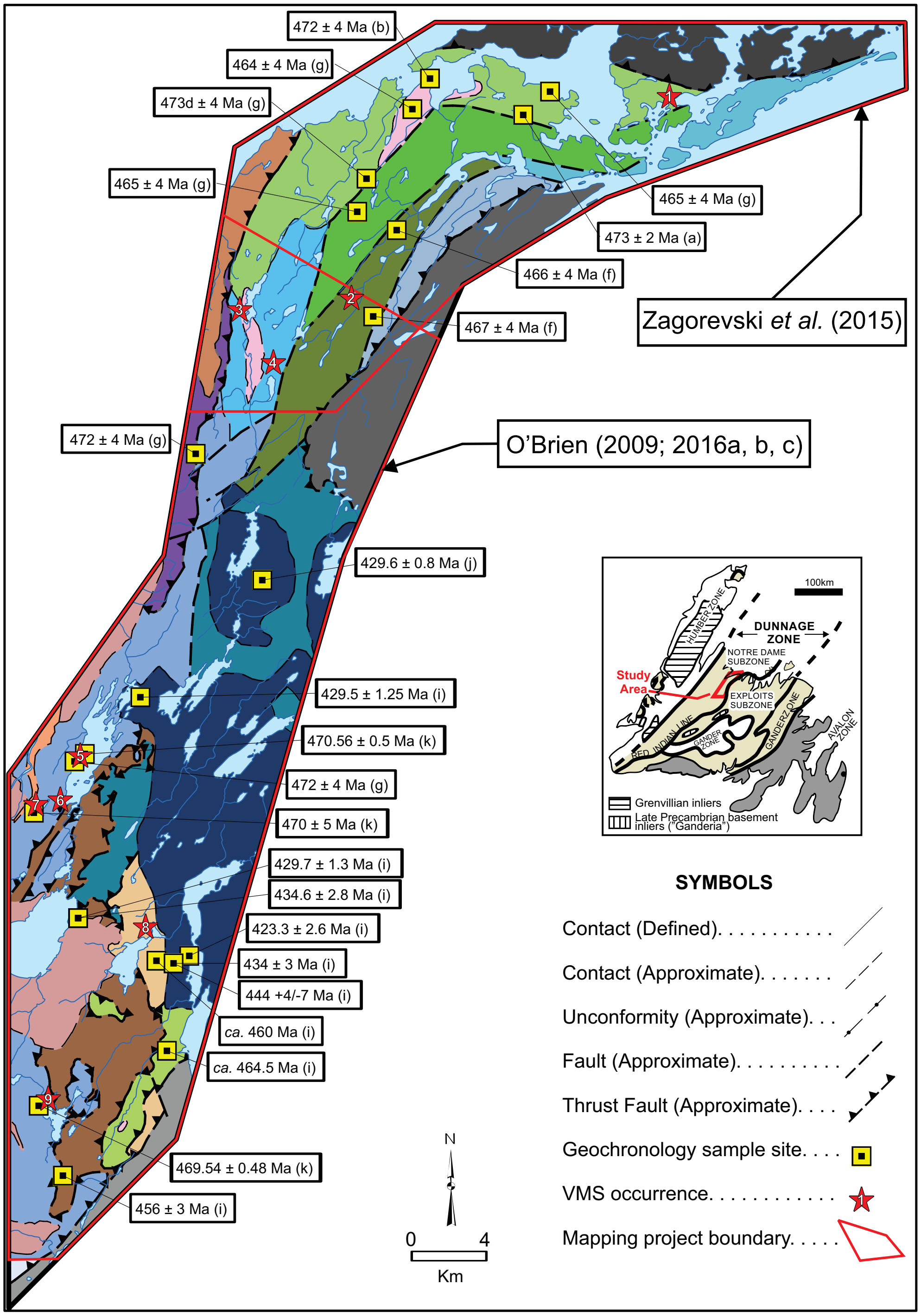

Figure 1. *Regional compilation maps outlining the distribution of unit subdivisions, locations of geochronology samples, and select VMS occurrences; geology modified from O'Brien (2009), Zagorevski* et al. *(2015) and O'Brien (2016a, b, c). A) Central and southern portions of the BRAB; B) Northern and central portions of the BRAB. Note that the South Brook tract of O'Brien (2016a, b, c) has been combined with the Gullbridge tract in this figure and is labelled Gullbridge/South Brook. Numbers corresponding to labelled VMS occurrences: 1) Pilley's Island deposits, 2) Rust Pond and Ghost Pond, 3) Loon Pond, 4) Knife Pond, 5) Gullbridge, 6) Southwest Shaft, 7) Western Alteration Zone, 8) Powderhorn, 9) Lake Bond, 10) Beaver Pond, 11) Seal Pond, 12) Mary March, 13) Connell, 14) Little Sandy, 15) Woodman's Brook, 16) Middle Branch, 17) Oriental, 18) Lucky Strike, 19) Rothermere, 20) MacLean, 21) Clementine, 22) Skidder. Geochronology compiled from: a) Dunning* et al.*, 1987; b) Kerr and Dunning, 2003; c) Zagorevski* et al.*, 2006; d) Coombs* et al.*, 2012; e) Whalen* et al.*, 2013; f) Zagorevski and McNicoll, 2012; g) Zagorevski* et al.*, 2015; h) Zagorevski* et al.*, 2016; i) O'Brien and Dunning, unpublished data; j) O'Brien and Kamo, unpublished data; k)* this study. *Note ages followed by a "d" represent the age of the youngest population of detrital zircons for that sample.*

activity consists of an early arc–back-arc environment that existed between 475–468 Ma, and a late arc–back-arc that formed between 469–458 Ma. Based on existing geochronological data, evidence for the early arc is primarily confined to the central and northern portions of the belt, while ages from the late arc sequence span the entire length of the current study area (Figure 1A, B).

NORTHERN SUBDIVISIONS

The geology of the northern portion of the belt has most recently been discussed by Bostock (1988), Kerr (1996), Zagorevski and McNicoll (2012), McKinley (2013) and Zagorevski *et al.* (2015); the geological subdivisions of Zagorevski *et al.* (2015) are utilized herein. This portion of the belt has been subdivided into eight assemblages, consisting of: the Hall Hill/Mansfield Cove Complex, the Loon Pond, Boot Harbour, Mud Pond, Ghost Pond, Triton and Tommy's Arm River assemblages, and the Sop's Head Complex (Figure 1B). Zagorevski *et al.* (2015) noted that the contacts between these largely north to northwest facing assemblages are marked by late brittle–ductile and brittle faults, and that the relationships between some of these assemblages may be stratigraphic. Only the Loon Pond, Boot Harbour, Mud Pond, and Ghost Pond assemblages are discussed in further detail, as they have relevance to the development of VMS mineralization.

The Loon Pond assemblage is dominated by bimodal tholeiitic volcanic and plutonic rocks. The age of this assemblage remains unconstrained, but these rocks are grouped with the Gullbridge structural tract by O'Brien (2016a; *see* below), and are inferred to represent part of the older *ca.* 470 Ma arc–back-arc complex (Zagorevski *et al.*, 2015). Discordance between these rocks and basal conglomerates of the Boot Harbour assemblage was noted by Bostock (1988), and is inferred to represent an angular unconformity between these two assemblages (Zagorevski *et al.*, 2015). Minor occurrences of VMS-style mineralization are located at the Loon Pond, Loon Pond South and Knife Pond prospects, consisting of disseminated sulphides (pyrite, chalcopyrite, pyrrhotite and sphalerite) and oxides (magnetite) in chloritized mafic and felsic volcanic rocks (Figure 1B; McNamee, 1959; MacQuarrie, 1976).

The Boot Harbour and Mud Pond assemblages are composed of calc-alkalic volcanic rocks that include thick pillow basalt sequences (Bostock, 1988; Kerr, 1996; Zagorevski *et al.*, 2015). The Boot Harbour assemblage contains bimodal volcanic rocks, whereas the Mud Pond assemblage is more mafic dominated. Geochronological data from this area provide age constraints ranging from *ca.* 473–465 Ma for the Boot Harbour assemblage, and *ca.* 465 Ma and older for the Mud Pond assemblage. The youngest population of detrital zircon from a conglomerate near the base of the Boot Harbour assemblage produced an age of 473 ± 4 Ma (Zagorevski *et al.*, 2015), while a rhyolite breccia near the base of the assemblage along strike to the northeast is dated at 473 ± 2 Ma (Dunning *et al.*, 1987). Felsic volcanic rocks from near the top of the Boot Harbour assemblage have been dated at 465 ± 4 Ma, indicating these rocks are, in part, contemporaneous with felsic tuffs dated near the top of the Mud Pond assemblage, which produced an age of 465 ± 4 Ma (Zagorevski *et al.*, 2015; Figure 1B). Both the Boot Harbour and Mud Pond assemblages host VMS-style mineralization, with the most significant being the bimodal felsic Zn–Pb–Cu–Au–Ag Pilley's Island deposits (McKinley, 2013 and references therein).

The Ghost Pond assemblage of Zagorevski *et al.* (2015) represents part of the Crescent Lake terrane of Bostock (1988), and is characterized by island-arc tholeiite basalts, calc-alkalic rhyolite, red shale and jasper. Two samples of rhyolite have been dated from this assemblage, producing ages of 466 ± 4 and 467 ± 4 Ma (Zagorevski and McNicoll, 2012; Figure 1B). Localized VMS-style mineralization is developed at the Rust Pond and Ghost Pond prospects, where tholeiitic mafic volcanic rocks host sporadic sulphide mineralization in the form of stringer and disseminated pyrite and lesser chalcopyrite associated with black chlorite alteration (Evans, 1996).

CENTRAL SUBDIVISIONS

The geology of the central portion of the Buchans–Roberts Arm belt has been discussed by Swinden (1991), Dickson (2000) and O'Brien (2007) and references therein. This region comprises a number of structural panels, which internally are predominated by a westward younging stratigraphy; however, the structural stacking of these thrust sheets results in an overall eastward younging of the panels across the central portion of the belt (*cf.* Pope *et al.*, 1991; Pope and Calon, 1993; O'Brien, 2016a, b, c). The geology of the central BRAB has been subdivided by O'Brien (2016a, b, c) into fault-bounded structural tracts, namely the Gullbridge, South Brook, Burnt Pond, Catamaran Brook, Baker Brook, and the Powderhorn Lake structural tracts (Figure 1A, B). Only the Gullbridge and Powderhorn Lake tracts are discussed in further detail, as they are locally host to VMS-style mineralization.

The Gullbridge tract forms a sequence dominated by calc-alkalic, arc-related, felsic volcanic rocks at its lowest exposed stratigraphic levels, which, in turn, transition upwards into tholeiitic to calc-alkalic mafic dominated volcanic rocks and related volcaniclastic and siliciclastic sediments (O'Brien, 2016a, b, c). This tract is host to several notable occurrences of VMS-style mineralization, which include the Gullbridge, Southwest Shaft and Lake Bond deposits (Figure 1B; Sparkes, 2019, 2020). The Powderhorn Lake tract contains rocks that are regionally metamorphosed to amphibolite facies, representing the deepest exposed level of the BRAB within the central portion of the region (O'Brien, 2007). This tract consists of variably altered tholeiitic to calc-alkalic felsic volcanic rocks overlain by pelitic schist. These rocks are locally host to Zn–Cu ± Pb ± Ag ± Au mineralization at the Powderhorn Lake prospect, which is inferred to be representative of VMS-style mineralization hosted within strongly deformed felsic volcanic rocks (Sparkes, 2018; and references therein).

Very few age constraints exist for the volcanic rocks in the central portion of the BRAB. A felsic tuff sample from the Gullbridge structural tract returned an age of 472 ± 4 Ma (Zagorevski *et al.*, 2015). Additional sampling of felsic tuffs from within the Gullbridge tract has produced ages of 469.5 ± 0.5, 470.6 ± 0.5 and 470 ± 5 Ma (*see* below). Somewhat younger ages have been obtained for the Catamaran Brook, Powderhorn Lake and Baker Brook tracts, which lie farther to the east, and have been dated at *ca.* 464.5, *ca.* 460 and 456 ± 3 Ma, respectively (Figure 1B; O'Brien and Dunning, unpublished data).

SOUTHERN SUBDIVISIONS

The geology of the southern portion of the BRAB, primarily confined to the area north of Red Indian Lake, has most recently been discussed by Zagorevski and Rogers (2008, 2009) and Zagorevski *et al.* (2007a, 2015, 2016). This work has subdivided the area's geology into five units, consisting of: the Lloyds/Harry's River Ophiolite and Hungry Mountain complexes, and the Buchans, Mary March Brook, and the Red Indian Lake groups. Only the Buchans, Mary March Brook, and the Red Indian Lake groups are discussed in further detail, as they are host to VMS mineralization.

The Mary March Brook group consists of bimodal tholeiitic and calc-alkalic volcanic rocks. The formation of tholeiitic rhyolite cryptodomes and coeval island-arc tholeiitic basalts were accompanied by the deposition of polymictic debris flows and locally develop pervasive hydrothermal alteration and VMS mineralization (Zagorevski and Rogers, 2008, 2009). These rocks are conformably overlain by bimodal calc-alkalic volcanic rocks. The Mary March Brook group is interpreted to have formed within a back-arc or intra-arc rift setting and has been dated at 461.5 ± 4 Ma (Zagorevski *et al.*, 2015, 2016). This group is host to localized VMS mineralization and related alteration zones, which include the Beaver Pond, Seal Pond, Little Sandy, Woodman's Brook and Middle Branch East prospects (Figure 1A).

The Buchans Group structurally underlies the Mary March Brook group and is composed of calc-alkalic basaltic and rhyolitic rocks of continental-arc affinity, along with abundant granitoid-bearing conglomerate and debris flows (Thurlow and Swanson, 1987; Swinden *et al.*, 1997; Zagorevski *et al.*, 2015, 2016). Geochronological data from volcanic rocks within lower stratigraphic levels of the group range from 465 ± 4 to 463 ± 4 Ma, while a felsic crystal tuff from stratigraphically higher in the sequence is dated at 462 ± 4 Ma (Zagorevski *et al.*, 2015). Granitoid clasts from within the debris flows of the Buchans mine area are dated at 464 ± 4 Ma (Whalen *et al.*, 2013), and a felsic volcanic rock located stratigraphically below one of the mineralized debris flows is dated at 471 ± 1.6 Ma (*see* below; this age replaces a previously reported age of 473 +3/-2 Ma for the same sample; Dunning *et al.*, 1987). The Buchans Group is well known for its VMS mineralization, which includes the past-producing Oriental, Lucky Strike, Rothermere and MacLean deposits. This VMS mineralization is inferred to have developed around *ca.* 465 Ma (Zagorevski *et al.*, 2007b).

The Red Indian Lake Group is composed of tholeiitic mafic, and overlying calc-alkalic bimodal, volcanic rocks, with the two sequences locally separated by polymictic conglomerate (Zagorevski *et al.*, 2006; Zagorevski and Rogers, 2008, 2009). Rocks at the base of this group are composed of island-arc tholeiities to back-arc basin basalts, along with minor felsic volcanic rocks, which are interpreted to have formed within a rifted-arc- or back-arc-type setting (Zagorevski *et al.*, 2006). Rocks included within the Red Indian Lake Group have produced ages ranging from 465 ± 4 to 462 +2/-9 Ma (Zagorevski *et al.*, 2015) and host several notable VMS occurrences, which include the Mary March, Connell and Skidder prospects (Figure 1A).

Rocks located within the eastern portion of the southern BRAB, south of the area mapped by O'Brien (2009) and east of the area mapped by Zagorevski and Rogers (2009), remain poorly constrained, in part due to poor outcrop exposure (BRAB undivided; Figure 1A). Preliminary examination of airborne geophysical data suggests the presence of a significant northeast trending fault structure within this area, which locally results in the termination of the Lloyds/Harry's River Ophiolite Complex (Figure 1A). The current lack of data for rocks occurring to the east of this structural contact impedes their incorporation with established unit subdivisions for the area.

U–Pb GEOCHRONOLOGY

The geochronological samples reported here were processed at two different laboratories; the Jack Satterly Geochronology Laboratory located at the Department of Earth Science, University of Toronto (samples GS-18-051, 088), and at the Department of Earth Sciences, Memorial University (samples GS-17-186 and 84GD13). Sample preparation and procedures for the Jack Satterly Geochronology Laboratory followed those outlined in Kamo *et al.* (2011), while the samples processed at Memorial University followed the procedures outlined in Sparkes and Dunning (2014).

As part of ongoing deposit-level studies investigating the development of VMS-style mineralization within the central portion of the BRAB, three samples were collected for geochronological study to provide age constraints on the development of mineralization in this area. These samples include two from the area of the Gullbridge deposit, and one from the Lake Bond deposit. In addition, new analyses of an archived sample from the Buchans area is also included to provide additional data for the regional comparison of mineralizing events.

GULLBRIDGE

The Gullbridge deposit is located within the Gullbridge structural tract and has produced approximately 3 million tons of ore, with an average grade of 1.1% Cu (Upadhyay and Smitheringale, 1972; Figure 1B). The deposit represents a copper-dominated stockwork zone of VMS-related mineralization hosted within a bimodal calc-alkalic to transitional tholeiitic volcanic arc sequence (Sparkes, 2020; and references therein). A sample (GS-18-088) of drillcore from this volcanic sequence was obtained for geochronological study. The sample was collected from the top of the mineralized zone, where interbedded mafic and felsic tuffaceous rocks are transitional into overlying, barren volcaniclastic sediments (Plate 1A; Figure 2; Sparkes, 2020).

The sample consisted of strongly foliated, muscovite–iron chlorite–pyrite altered, weakly mineralized felsic tuff (Plate 1B). Locally, industry assay data from within the interval sampled for geochronological study returned >1.0% Cu, and 0.3% Zn over 0.45 m (sample #27480; Pudifin *et al.*, 1991). The geochronology sample produced an abundant population of zircon dominated by very small, colourless and generally clear prismatic grains or broken prisms; locally displaying rare cloudiness and inclusions. From this population four separate fractions of both single and multi-grain analyses were completed, with three of the four analyses producing concordant points (Figure 3A). The resultant age of the weighted average of the $^{206}Pb/^{238}U$ ages for all three analyses gives 470.56 ± 0.50 Ma (MSWD = 0.62). This age is interpreted to represent the igneous crystallization age of the felsic tuff, and provides a maximum age limit for the formation of the VMS mineralization.

A second geochronological sample was also collected in the Gullbridge area, approximately 4 km southwest of the deposit, in an area known as the Western Alteration Zone (Figure 1B; Swinden, 1988; Sparkes, 2018, 2019). This area represents a zone of stratiform pyritic alteration traceable for approximately 2 km along strike; hosted within felsic volcanic rocks of the Gullbridge structural tract. Here, felsic tuff is bound by rusty-weathering, pyrite-bearing, exhalative horizons, demonstrating that volcanism was essentially coeval with hydrothermal activity (Plate 2A). A sample of the chlorite–phengite altered felsic tuff (GS-17-186; Plate 2B) produced a low zircon yield, consisting of small well-developed prisms, from which four separate multi-grain (2–4 zircon) analyses were carried out. These analyses resulted in two points overlapping concordia, and

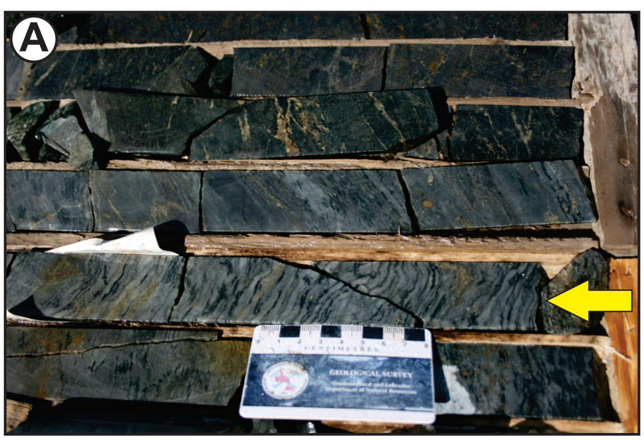

Plate 1. *Representative photographs from DDH GB-148, Gullbridge deposit. A) Gradational contact transitioning from the underlying mafic tuff to the dated felsic tuff; the location of the geochronological sample (GS-18-088) is shown by the yellow arrow (~380 m). Note that younging direction for the sequence is inferred to be toward the bottom of the photograph (*i.e.*, down hole); B) Representative sample of the material collected for geochronological study, interpreted as strongly foliated, muscovite–iron chlorite–pyrite altered felsic tuff, which is overprinted by VMS mineralization and related alteration.*

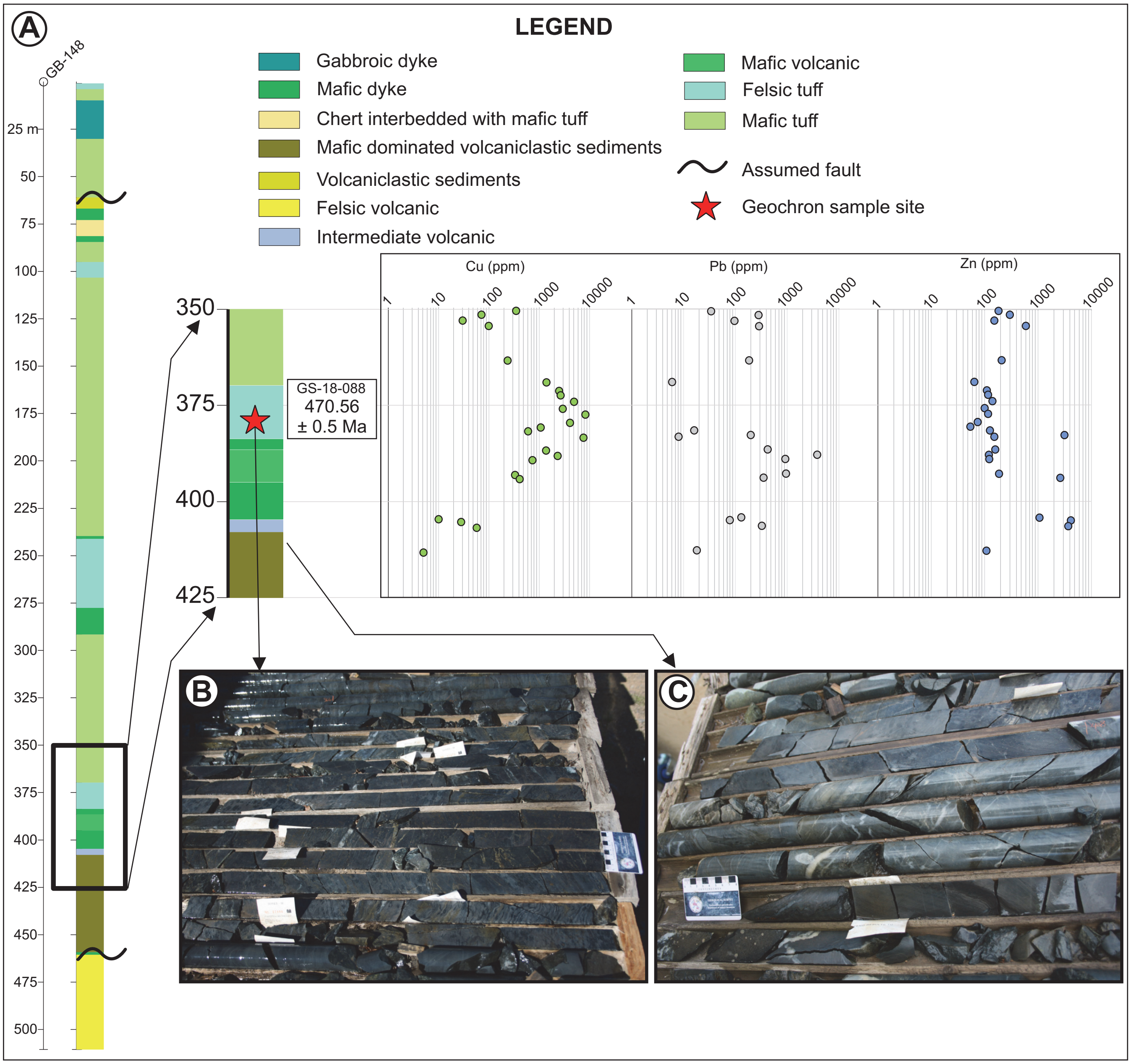

Figure 2. *A) Strip log for DDH GB-148; modified from Sparkes (2020; Figure 4). The enlarged area of this strip log outlines the location of the geochronological sample site relative to the industry Cu, Pb and Zn assay values for that interval; B) Photograph of the mineralized zone and geochronological sample site (~380 m); C) Photograph of the barren overlying volcaniclastic sediments interbedded with lesser red chert (~410 m); note the end of the split core at the top of the photograph denotes the end of the assay data outlined in Figure 2A. Note, the stratigraphy bound by the two assumed faults youngs downhole.*

two discordant points demonstrating inheritance (Figure 3B). The $^{206}Pb/^{238}U$ age for Z1 is 470 ± 5 Ma. This age is interpreted to represent the igneous crystallization age of the felsic tuff, and also provides the age of hydrothermal activity associated with the formation of the Western Alteration Zone.

LAKE BOND

The Lake Bond deposit is located approximately 19 km to the south of the Gullbridge deposit, and is also hosted within the Gullbridge structural tract (Figure 1B). The deposit represents a zone of Zn-rich stockwork-style mineralization hosted by variably altered island-arc tholeiitic pil-

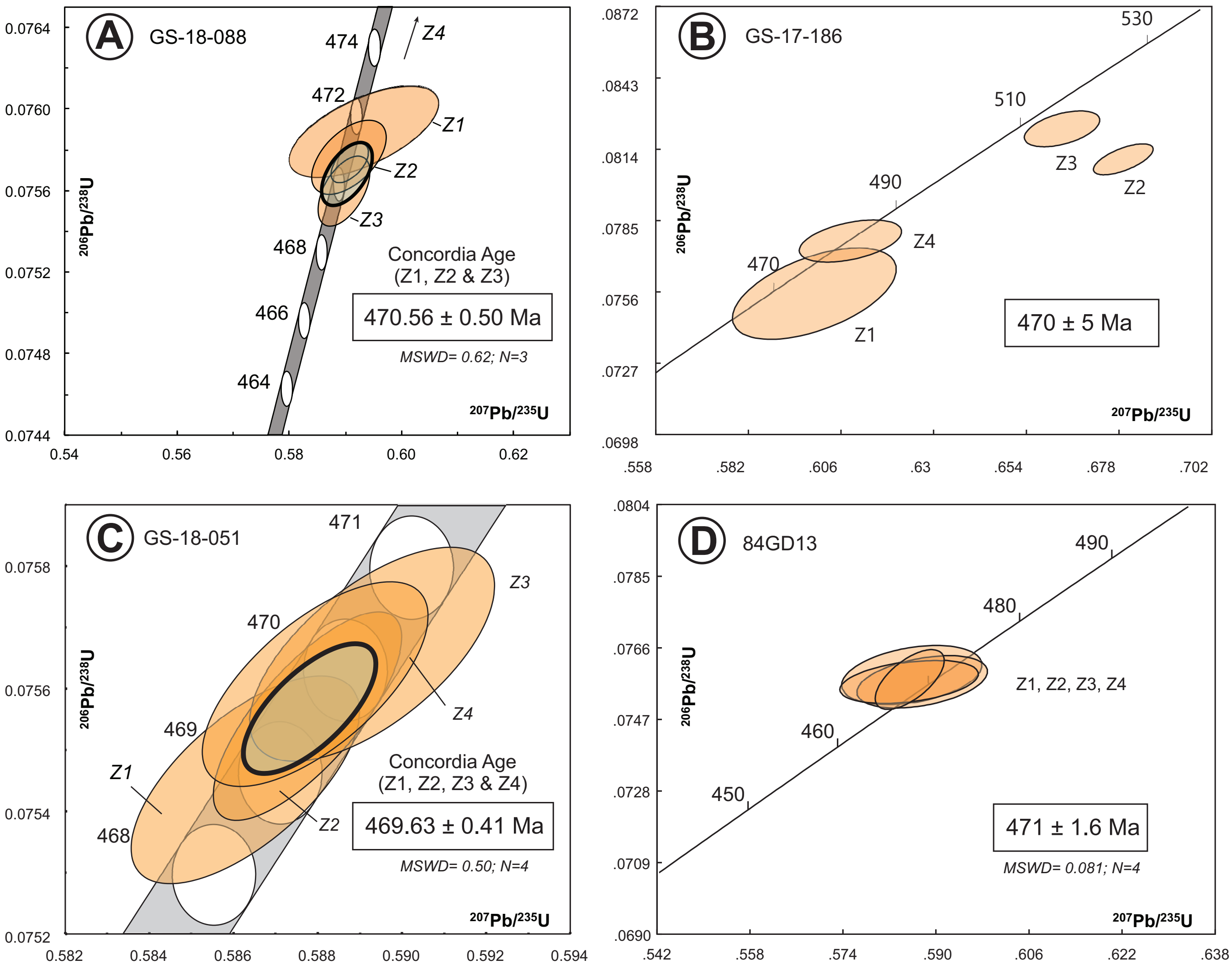

Figure 3. *Concordia diagrams of U–Pb results from the zircon analyses discussed in the text. Error ellipses are at the 2σ level. Refer to Table 1 for sample location and description data. A) GS-18-088, Gullbridge deposit; B) GS-17-186, Western Alteration Zone; C) GS-18-051, Lake Bond deposit; D) 84GD13, MacLean deposit.*

Table 1. Sample location and description data for geochronological samples discussed in text

Sample No.	UTM_E	UTM_N	Datum	Zone	Sample Type	Drillhole	Depth (m)	Rock Type
GS-17-186	559131	5446537	NAD 83	21	Outcrop	n/a	n/a	Felsic tuff
GS-18-051	559390	5430848	NAD 83	21	Drillcore	LB-92-002	196.5	Felsic tuff
GS-18-088	561859	5449683	NAD 83	21	Drillcore	GB-148	380.65	Felsic tuff
84GD13	508211	5408910	NAD 83	21	Underground mine workings	n/a	n/a	Rhyolite

low basalt. The mineralization is separated from the overlying relatively unaltered mafic volcanic rocks, interbedded felsic tuff, and red chert by an inferred thrust fault. However, the similar geochemical characteristics of the mafic rocks both above and below this structure implies the rocks are part of the same volcanic sequence (Sparkes, 2020). A sample (GS-18-051) of the felsic tuff from the hanging wall sequence was collected from drillcore (DDH LB-92-002) to constrain the age of the volcanic rocks hosting the VMS mineralization (Figure 4).

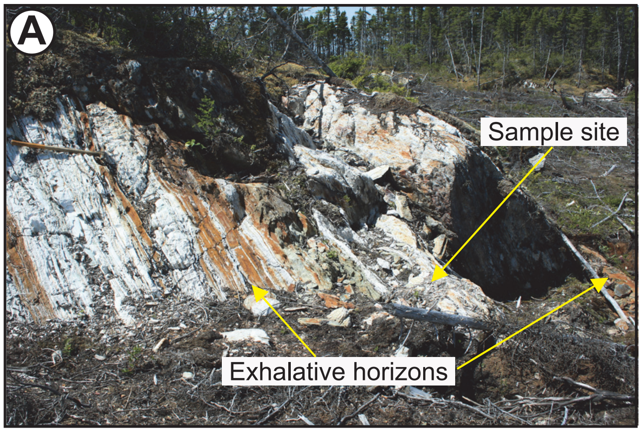

Plate 2. *A) Photograph of the geochronological sample site within the Western Alteration Zone, highlighting the interbedded nature of the felsic tuff and sulphide-bearing exhalative horizons. Note rock hammer in the upper left corner for scale; B) Representative photograph of the material collected for geochronological study (GS-17-186).*

The geochronological sample was collected approximately 35 m (core length) above the mineralized zone and consisted of thin- to medium-bedded, very fine-grained, felsic tuff (Plate 3A), which yielded a homogenous population of euhedral, primarily pale-yellow zircon prisms. From this population, four single grain analyses resulted in four concordant points, giving a weighted average $^{206}Pb/^{238}U$ age for all four analyses of 469.63 ± 0.41 Ma (MSWD = 0.50), which is interpreted to represent the igneous crystallization age of the felsic tuff. As the felsic tuff is bound by mafic volcanic rocks displaying similar characteristics to those hosting mineralization, this age is also assumed to provide a maximum age limit for the development of the VMS mineralization.

BUCHANS

New analyses of zircon from an archived sample collected in the Buchans area are presented here. The sample, previously reported by Dunning *et al.* (1987) was collected from the 21 level, drift 21-2, of the underground workings at the MacLean deposit (mine coordinates of N8940, W1000). Sampled material consisted of purplish feldspar-phyric rhyolite from a small domal body 20 m stratigraphically below the MacLean Extension orebody. Processing of the sample returned a small number of zircons from which 3 previously reported multi-grain analyses produced a $^{206}Pb/^{238}U$ age of 473 +3/-2 Ma (Dunning *et al.*, 1987). New multi-grain (2–5 zircons) analyses utilized current processing techniques, which included chemical abrasion of the zircon prior to analysis (*cf.* Sparkes and Dunning, 2014). Four new analyses resulted in overlapping concordant points giving a weighted average $^{206}Pb/^{238}U$ age of 471 ± 1.6 Ma (MSWD = 0.081; Figure 3D), which is interpreted as the crystallization age of the rhyolite unit.

DISCUSSION

The geological mapping conducted within the BRAB demonstrates the composite nature of the rocks that comprise the Lower to Middle Ordovician arc and back-arc environments of the Annieopsquotch accretionary tract (van Staal *et al.*, 1998; Zagorevski *et al.*, 2015; O'Brien, 2016a, b, c). Rare overlap between individual mapping projects locally allow for the correlation of assemblages grouped under different terminologies. One such example exists in the northern portion of the BRAB. Here, units grouped within the Gullbridge structural tract by O'Brien (2016a), broadly overlap with those units assigned to the Loon Pond assemblage (Figure 1B), supporting the proposed correlation of these two units by Zagorevski *et al.* (2015). In addition, the similar characteristics of individual groups/assemblages throughout the belt can be used to infer potential associations, such as the inferred correlation between the Ghost Pond assemblage and the Red Indian Lake Group (Zagorevski and McNicoll, 2012).

The ages determined for rocks hosting VMS mineralization represent the maximum age for the development of the related hydrothermal systems (*e.g.*, Gullbridge and Lake Bond deposits). However, in areas where exhalative-style mineralization can be demonstrated as contemporaneous with the deposition of the dated unit, the determined age then represents the absolute age of the hydrothermal activity and related mineralization. One such example occurs within the Western Alteration Zone in the Gullbridge area, where the dated tuff and contemporaneous exhalative pyritic horizons are bracketed between 475–465 Ma. The ages of volcanic rocks associated with VMS mineralization at both the Gullbridge and Lake Bond deposits overlap the age bracket of the Western Alteration Zone, which suggests that

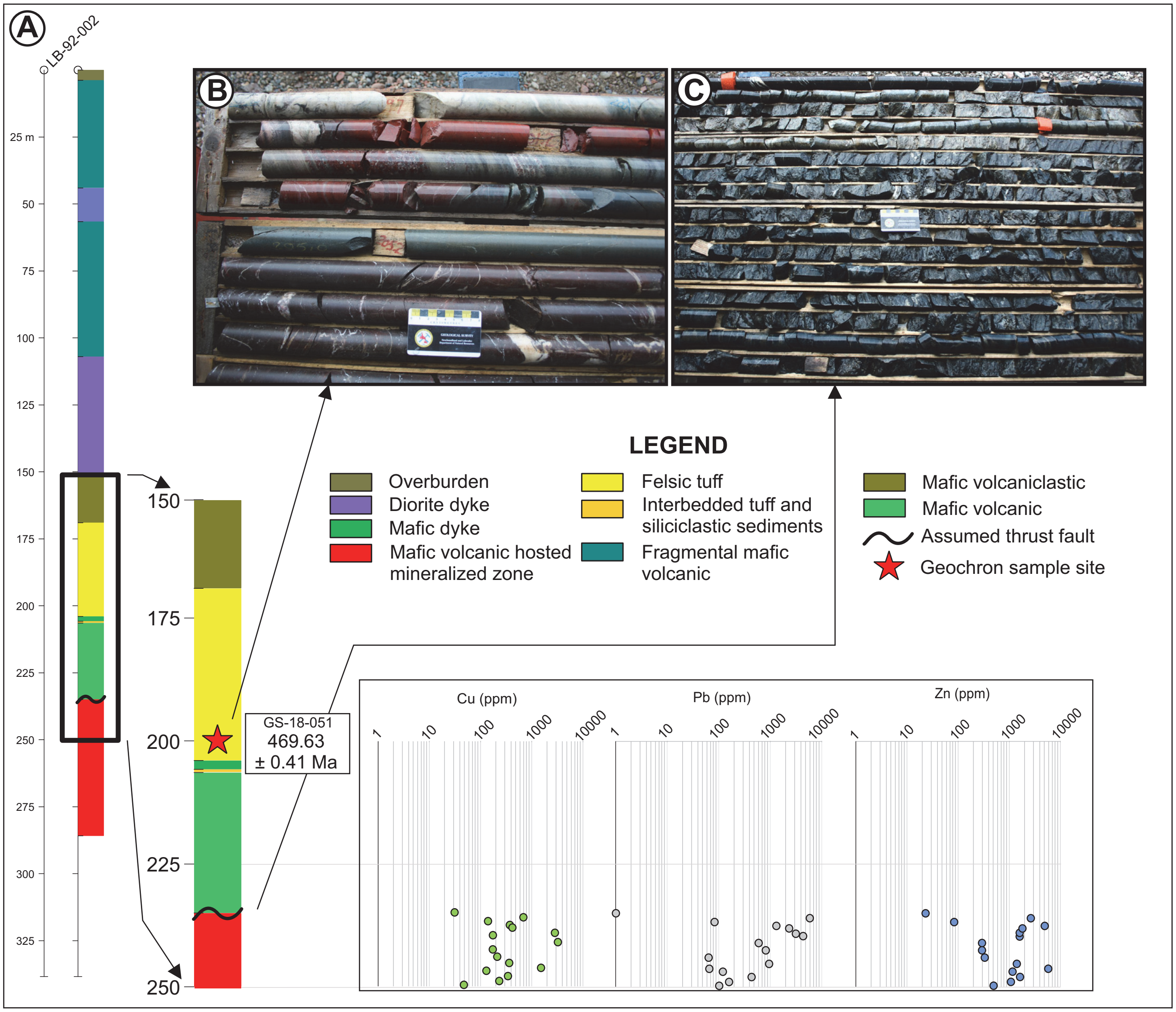

Figure 4. *A) Strip log for DDH LB-92-002; modified from Sparkes (2020; Figure 16). The enlarged area of this strip log outlines the location of the geochronological sample site relative to the start of the mineralization outlined by the industry Cu, Pb and Zn assay values; B) Photograph of the interbedded felsic tuff and lesser red chert along with underlying variably hematized mafic volcanic rocks (~205 m); C) Photograph of the mineralized zone, which is host to primarily stockwork-style, zinc-dominated, sulphide mineralization within mafic volcanic rocks (~240 m).*

these hydrothermal systems may all be of comparable age, and are likely linked to the *ca.* 470 Ma volcanic event.

Based on existing data, the mineralization developed within the Gullbridge structural tract represents a separate, older period of hydrothermal activity, relative to that developed in the area of the Buchans deposits, which are dated at *ca.* 465 Ma (Zagorevski *et al.*, 2015; Figure 5). Attempts to constrain the age of mineralization at the northern end of the belt in the Pilley's Island area have thus far proven unsuccessful (McKinley, 2013). Compilation of the existing geochronological data for the region outlines two main episodes of volcanic activity, an early 475–468 Ma event, constrained by samples from the northern and central portions of the belt, and a late 469–458 Ma event, primarily represented by those rocks occurring within the southern portion of the study area (Figure 5). Local evidence exists for the early volcanic event within the southern portion of the belt, which is represented by the *ca.* 470 Ma age reported here. This sample was inferred by Zagorevski *et al.* (2015) to provide evidence of the early volcanic sequence, representing basement rock to the development of the younger

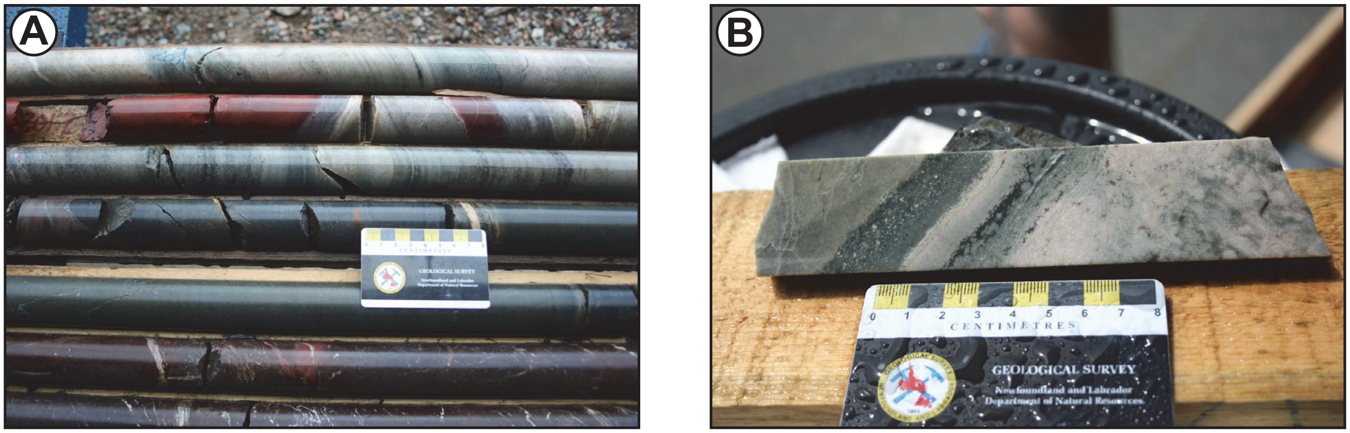

Plate 3. *Representative photographs from DDH LB-92-002, Lake Bond deposit. A) Location of the felsic tuff sample (GS-18-051); note tuff and interbedded red chert are in depositional contact with underlying variably hematized mafic volcanic rocks, both of which are crosscut by later fine-grained mafic dykes; B) Representative sample of the material collected for geochronological study, interpreted as chlorite–muscovite altered felsic tuff.*

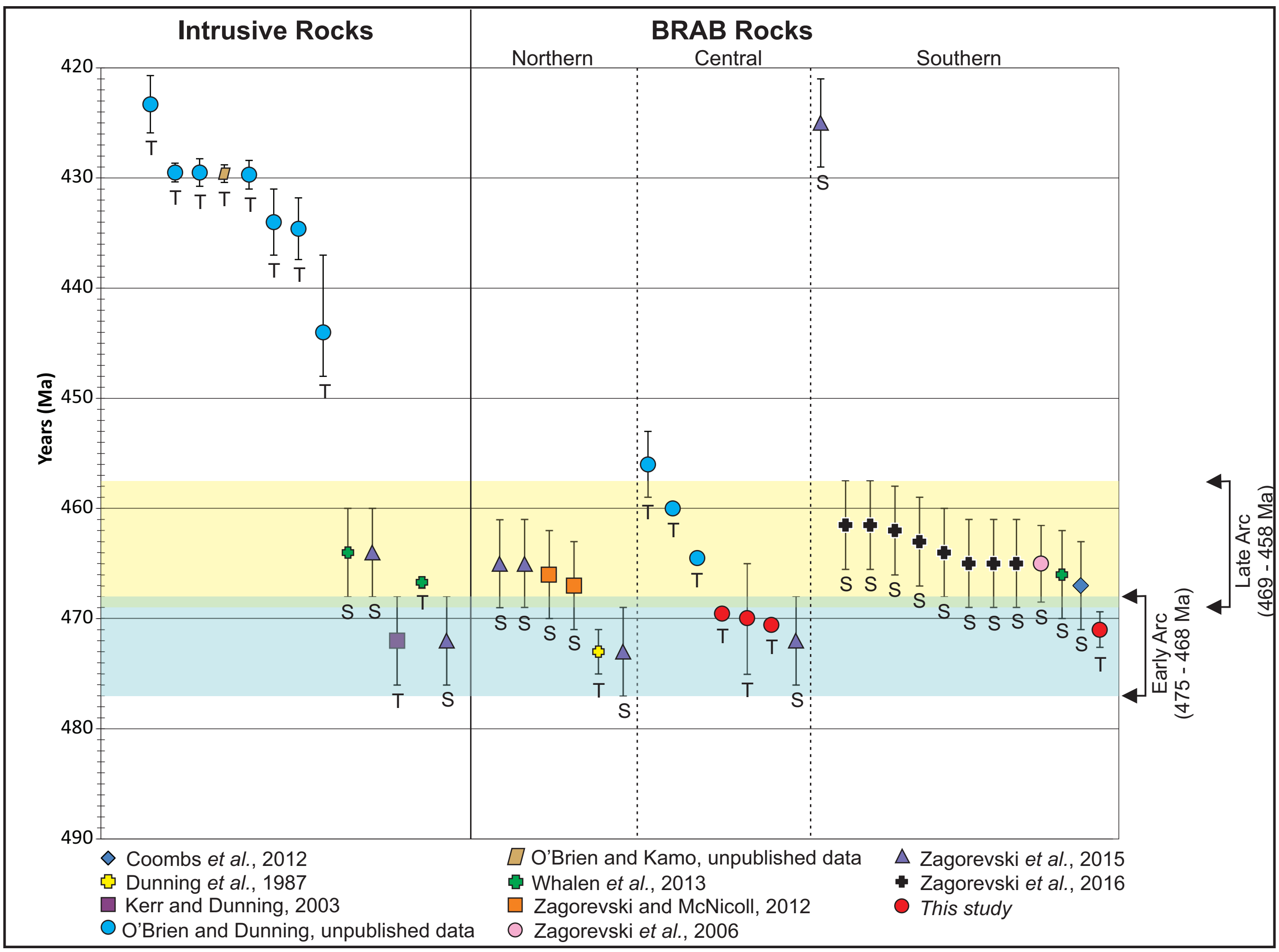

Figure 5. *Compilation of available U–Pb data for the BRAB shown in Figure 1A, B. Note that the ages have been grouped by intrusive-related and BRAB-related rocks, with those grouped under the BRAB rocks being further subdivided on the basis of their location within the study area. Note, the diagram includes ages determined by different methods, denoted by the letter below each age: T–Thermal Ionization Mass Spectrometry (TIMS); S–Sensitive High Resolution Ion Micro-probe (SHRIMP).*

Buchans Group. A similar relationship is also inferred for the *ca.* 470 Ma ages occurring near the base of the Boot Harbour assemblage in the northern portion of the belt (Zagorevski *et al.*, 2015; Figure 5).

Within the central portion of the belt, VMS mineralization is also developed within the *ca.* 460 Ma Powderhorn Lake structural tract, which represents a sequence of younger rocks relative to those hosting the Gullbridge deposit, and is inferred to represent a separate mineralizing event. This younger event overlaps the age of the 469–458 Ma late arc (Figure 5), which is associated with the formation of the Mary March Brook, Buchans and Red Indian Lake groups and is potentially correlative with these units.

CONCLUSION

New U–Pb ages from the central portion of the BRAB provide the first age constraints directly related to the development of VMS mineralization in the area. These data highlight the *ca.* 470 Ma age of the host rocks within the Gullbridge structural tract, which is also inferred to represent the age of hydrothermal activity and related mineralization responsible for the formation of the Gullbridge and Lake Bond deposits. A second mineralizing event is developed within rocks of the Powderhorn Lake tract, which represents a younger episode of mineralization based on existing geochronological data.

The compilation of regional geological subdivisions and related geochronological data for the BRAB outlines the composite nature of the various assemblages contained within the region. In addition, such an exercise also outlines areas that require further investigation, such as the undivided BRAB unit located within the southern portion of the belt (Figure 1A). Such investigations could avail of existing, modern geophysical data (which was not available during earlier mapping projects in this area), detailed geochemical sampling of existing drillholes, and additional geochronological sampling to better characterize these volcanic rocks. The expansion of existing datasets to include samples from this undivided unit will form part of future studies in the region, which will better enable the inclusion of these rocks with either the 475–468 Ma early arc, or the 469–458 Ma late arc sequences.

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