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THE STYLE AND SETTING OF SELECT VMS OCCURRENCES, CENTRAL BUCHANS–ROBERTS ARM BELT, NEWFOUNDLAND

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ABSTRACT

Volcanogenic massive sulphide (VMS) mineralization, within the central Buchans–Roberts Arm belt, is primarily hosted within a bimodal volcanic sequence dominated by tholeiitic to back-arc basin basalts, interbedded with lesser calc-alkalic felsic to intermediate tuffaceous volcanic rocks. Detailed examination and geochemical analyses of drillcore, related to select VMS occurrences within the region, highlight local shifts within the tectonic environment during the deposition of these units, which transitions from a felsic-dominated arc, to a mafic-dominated back-arc type setting. The extensional environment related to these transitions is associated with the development of VMS-style mineralization. Select occurrences have been examined, in detail, to evaluate their characteristics and classify them on the basis of a modern lithological classification system. Results from these studies highlight the predominance of bimodal-mafic mineralization preserved within the tectonostratigraphy of the region.

INTRODUCTION

Investigations into the style and setting of select volcanogenic massive sulphide (VMS) occurrences, within the central Buchans–Roberts Arm belt, have outlined several important characteristics related to the development of mineralization in the area. These studies focused on the distribution of rock types, variations in alteration and lithogeochemistry, and the general stratigraphic position of units within drillholes; sampling was undertaken from select VMS occurrences. Previous work related to mineral exploration and academic studies within this area have been summarized by Sparkes (2018, 2019).

The systematic evaluation of the lithogeochemistry collected from drillcore, coupled with short wavelength infrared data outlining the distribution of hydrothermal alteration minerals, highlight important features of the footwall, mineralized and hanging-wall sequences. The resulting dataset highlights localized transitional periods in the tectonic environment during mineralizing events, whereby arc-related volcanism transitions to back-arc dominated environments, marking extensional periods within the central Buchans–Roberts Arm belt. These transitional periods are highlighted by shifts from felsic-dominated volcanic-arc environments, through to episodic mafic-dominated bimodal volcanism interbedded with exhalites and locally developed VMS-style mineralization, and finally to a mafic-dominated back-arc-type setting.

Elsewhere within the Buchans–Roberts Arm belt, lithogeochemistry has been utilized to outline similar transitional tectonic environments accompanied by VMS mineralization, analogous to those observed within the current study area (*e.g.*, Zagorevski and Rogers, 2009). Data from regional studies have outlined a 473–462 Ma belt of arc and back-arc rocks that are host to several notable VMS deposits (Dunning *et al.*, 1987; Dunning and Krogh, 1991; Lissenberg *et al.*, 2005; Zagorevski *et al.*, 2006). Such data highlight the regional extent of these extensional episodes and their overall importance with respect to the development of VMS mineralization in the region.

REGIONAL GEOLOGY

The geology of the central Buchans–Roberts Arm belt has been discussed by Swinden (1991), Dickson (2000) and O'Brien (2007). The Buchans–Roberts Arm belt 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). Early interpretations of stratigraphic relationships within the central Buchans–Roberts Arm belt inferred a westward younging of the overall succession (*cf.* Kalliokoski, 1955; Swinden and Sacks, 1986). However, re-interpretations of this region now recognize the complex structural nature of the tectonostratigraphy, within which stratigraphic units are locally repeated (*cf.* Pope *et al.*, 1991; Pope and Calon, 1993; O'Brien, 2007). The structural re-interpretation of the region by Pope and Calon (1993) noted that, although the stratigraphy within individual structural panels is westward younging, the overall stacking of these structural panels of older, on top of younger, results in an eastward younging of units within the region.

O'Brien (2007) subdivided the rocks occurring in the central Buchans–Roberts Arm belt into four main fault-bounded structural tracts, namely the Gullbridge, Baker Brook, Burnt Pond and the Powderhorn Lake (structural) tracts. This tectonic subdivision was further expanded to include the South Brook and Catamaran Brook structural tracts (O'Brien, 2008). The Gullbridge tract is composed of altered greenschists, mineralized mafic flows and/or felsic pyroclastic rocks, iron formation, and volcaniclastic turbidities. Rocks contained within the South Brook tract include pillowed tholeiitic basalt and gabbro sills along with lesser clastic limestone and red siltstone. Volcanosedimentary rocks of the Baker Brook tract are characterized by thinning-upward and fining-upward epiclastic turbidities that structurally overlie and underlie gossanous basalt and associated felsic pyroclastic rocks. The Catamaran Brook tract consists of calc-alkalic and tholeiitic basalt and related volcaniclastic rocks, gabbro, wacke and pyritic black shale and chert. Rocks of the Burnt Pond tract are characterized by regionally metamorphosed metasedimentary schist along with higher grade migmatite and gneissic intrusive rocks. Finally, the metamorphic rocks of the Powderhorn Lake tract are composed of variably altered metavolcanic and overlying metasedimentary rocks that are regionally metamorphosed to upper-amphibolite facies.

Most of the VMS-related occurrences in the region are hosted within rocks associated with the Gullbridge (structural) tract, which largely consist of the Starkes Pond, West Lake Brook, Dawes Pond Brook, Gull Brook Bridge and Powderhouse subdivisions (Figure 1). These and other units within the region have been further refined by O'Brien (2009, 2016a, b) and the unit terminology used in the following discussion is taken from these sources.

GULLBRIDGE DEPOSIT

Local Geology

The Gullbridge deposit represents a zone of copper-dominated, VMS-style stockwork mineralization, consisting of veined and disseminated sulphides. The area is structurally complex, consisting of several westward-dipping structural panels. Individual units within these panels are inferred to be westward younging; however, the structural stacking results in the overall eastward younging of the panels (Pope and Calon, 1993). The inferred oldest rocks within the deposit stratigraphy occur within the structural hanging wall and comprise felsic volcanic rocks of the Starkes Pond division (O'Brien, 2016a; Figure 2). These rocks are composed of variably foliated, non-magnetic, calc-alkalic, LREE-enriched, arc-related rhyolite that are inferred to represent the footwall rocks to the VMS mineralization (Pope and Calon, 1993; Figure 3A, B). These rocks are devoid of any significant sulphide mineralization in the immediate area of the deposit, and are dominated by phengite alteration based on spectral analyses (Sparkes, 2019).

The mineralized sequence hosting the Gullbridge deposit is bound to the west by the Gullbridge thrust fault, and to the east by the Hidden thrust fault (Figure 2); this sequence forms the Gullbridge Imbricate System of Pope and Calon (1993). Below the Gullbridge thrust fault, the mineralized sequence is dominated by mafic volcanic rocks, interbedded with felsic to intermediate tuff, along with lesser volcaniclastic rocks and exhalites. Based on lithogeochemical signatures, these volcanic rocks are interpreted to represent a transition from an arc to a back-arc environment. The felsic to intermediate rocks typically display strong arc signatures, whereas the mafic volcanic rocks are transitional, ranging from island-arc tholeiites to back-arc basin basalts (Figure 3A). Mineralization within the deposit is predominantly hosted by mafic volcanic rocks interbedded with lesser felsic to intermediate tuff. These felsic to intermediate tuffaceous units display a distinct spatial association with the upper stratigraphic limits of the sulphide mineralization and accompanying alteration. Given the structural complexity of the area, such relationships are likely tectonic as the internal structural complexities within individual panels are more complex than that shown in Figure 2. Stratigraphically above the mineralized zone, volcaniclastic rocks locally contain interbedded exhalites, in the form of red chert and lesser iron formation and rare examples of exhalative sulphides (Plate 1A; Figure 2). These volcaniclastic rocks display variable Fe–Mg-chlorite, Mg-chlorite, biotite and lesser phlogopite alteration (Sparkes, 2019). The exhalative-style mineralization is locally capped by 1–2 m beds of red chert/iron formation interbedded with felsic tuff (Plate 1B). To the immediate north of the deposit, local intersections of similar chert are considerably thicker, measuring up to 5 m thick in drillcore (Plate 1C).

The structural footwall of the deposit is dominated by mafic volcanic rocks that display MORB-like geochemical signatures, and commonly have Nb values below the detection limit of the Geological Survey's laboratory (1 ppm). These rocks are locally interbedded with intermediate to mafic tuff, similar to that observed within the mineralized sequence, but are devoid of any significant sulphide mineralization or related alteration. The structural footwall rocks

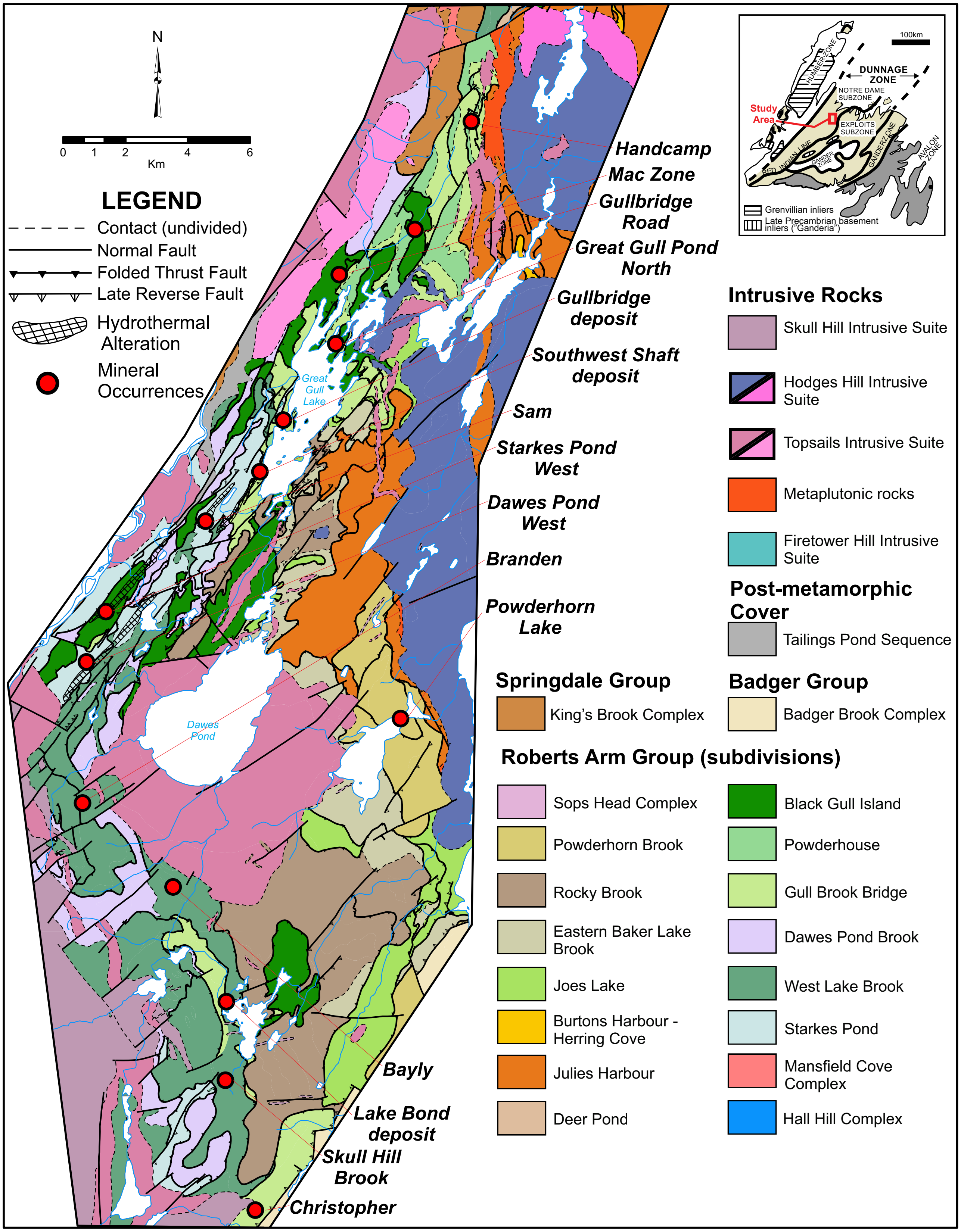


Figure 1. *Simplified geology map of the central Buchans–Roberts Arm belt, outlining select sulphide occurrences within the study area, along with the distribution of related alteration zones; modified from O'Brien (2009, 2016a, b).*

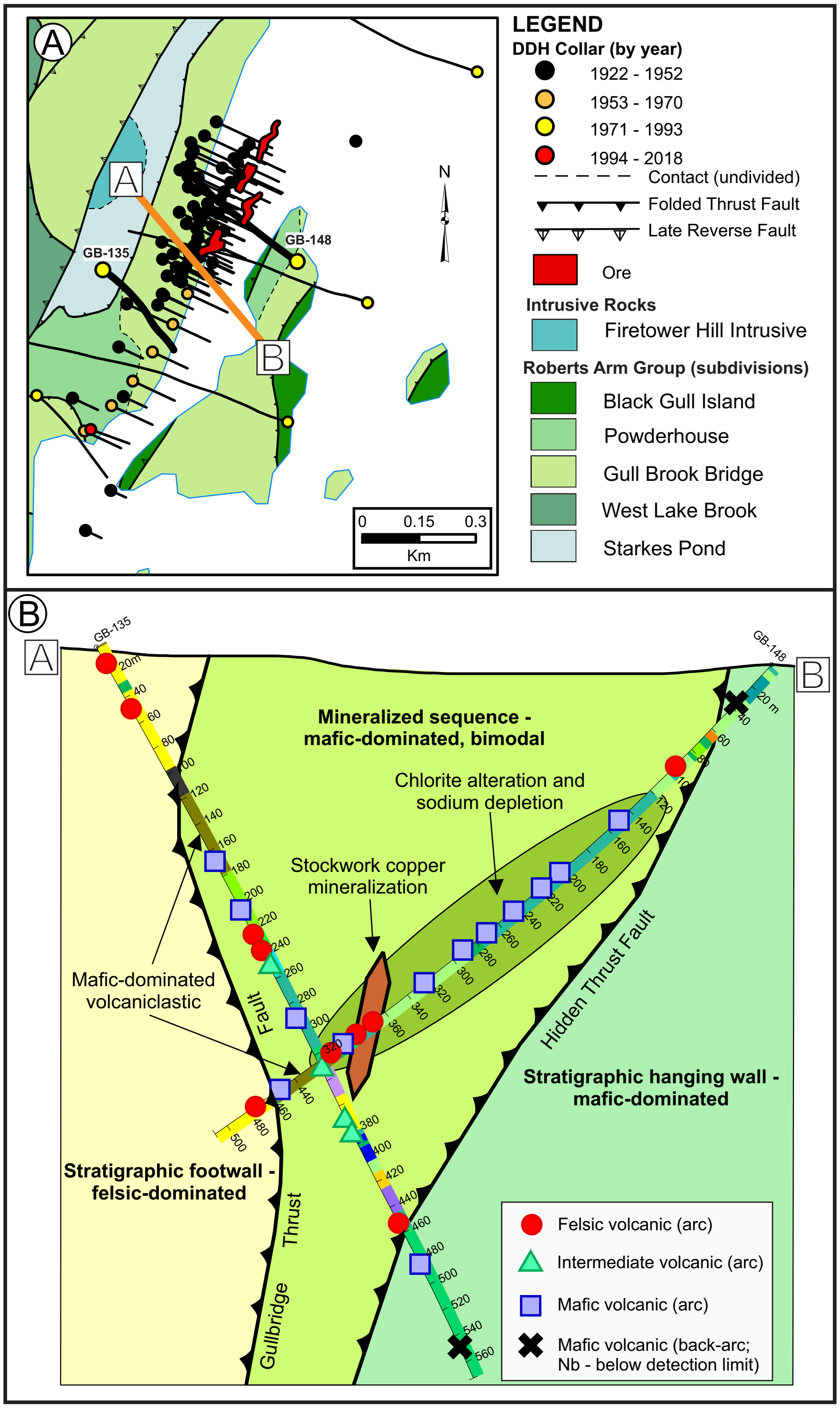


Figure 2. *A) Simplified geology map of the Gullbridge deposit outlining the distribution of diamond-drill holes (coloured by the year completed), and surface projection of the ore zone; modified from O'Brien (2016a). Note the location of the cross-section shown in (B) is outlined by the orange line; B) Schematic cross-section for drillholes GB-135 and GB-148, projected onto a common plane, illustrating the distribution of the main lithological units, location of geochemical samples* (see *Figure 3), mineralization and select alteration, and major fault structures. Note that units within individual structural panels young toward the west.*

are inferred to represent the stratigraphic hanging wall to the Gullbridge deposit (Pope and Calon, 1993; Figure 2) and are grouped with the Black Gull Island division (O'Brien, 2016a). Based on spectral analyses, alteration within the mafic volcanic rocks of the structural footwall are dominated by hornblende and epidote, with the latter commonly developed as network-style veining. The structural footwall mafic volcanic rocks display elevated magnetic susceptibility values relative to other units within the area, aside from localized iron formation or those rocks affected by magnetite alteration in the immediate vicinity of the deposit (*see* below).

Characteristics of the Mineralized Sequence

The main sulphide and oxide minerals occurring at the Gullbridge deposit consist of pyrite, pyrrhotite, chalcopyrite and magnetite, and are developed within two overlapping, steeply westward-dipping, tabular lenses, extending 430 m along strike (Upadhyay and Smitheringale, 1972; Pope and Calon, 1993). The mineralized zone extends to approximately 210 m depth, varies in thickness from 30 to 75 m, and is contained within a zone of cordierite–andalusite–chlorite schist that is, in turn, enveloped by a zone of cordierite–anthophyllite alteration, all of which are related to the development of contact metamorphism (Upadhyay and Smitheringale, 1972). Spectral analysis of this zone highlights the development of Fe-chlorite alteration, which is largely developed beneath the main zone of sulphide mineralization (Sparkes, 2019; Figure 2B); note that in Figure 2B, units within the mineralized sequence in drillhole GB-148 are assumed to young downhole as the drillhole is oriented to the northwest and is collared in a westward dipping stratigraphic sequence. Detailed examination of this alteration in drillcore indicates that the Fe-chlorite results from the alteration of cordierite. The

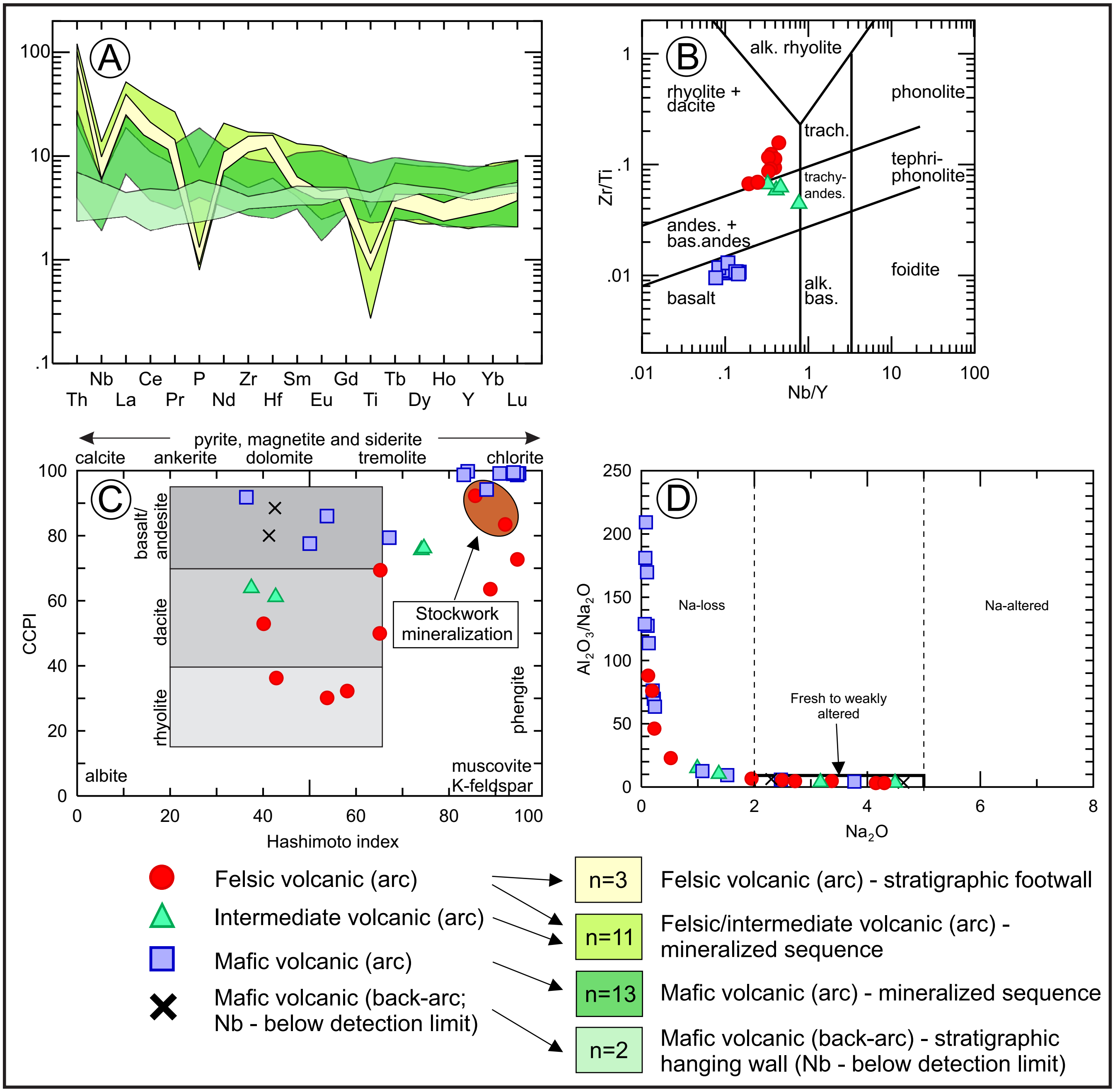


Figure 3. *A) Primitive-mantle-normalized multi-element plot for samples outlined in Figure 2; primitive-mantle values from Sun and McDonough (1989). Note "n" in the legend denotes the number of samples defining each group; B) Zr/Ti* vs. *Nb/Y discrimination diagram after Pearce (1996); C) Alteration box plot of Large* et al. *(2001), illustrating alteration* vs. *diagenetic fields. CCPI=chlorite–carbonate–pyrite index (CCPI = 100*[(MgO+FeO)/(MgO+FeO+K_2O+Na_2O)], Large* et al. *(2001); Hashimoto index = 100*[(MgO+K_2O)/(MgO+K_2O+Na_2O+CaO)], Ishikawa* et al. *(1976)); D) Al_2O_3/Na_2O* vs. *Na_2O plot illustrating the degree of sodium depletion within altered samples; Al_2O_3/Na_2O index from Spitz and Darling (1978).*

development of cordierite is inferred to represent the prograde phase of the contact metamorphism (Upadhyay, 1970), whereas the Fe-chlorite is inferred to represent a retrograde reaction related to this event (Plate 1D). This zone of Fe-chlorite alteration displays a spatial association with the development of magnetite alteration, which is also largely confined to the area beneath the mineralized zone (Figure 4). In thin section, these two phases are commonly intergrown, along with other recrystallized sulphide phases (Plate 1E, F).

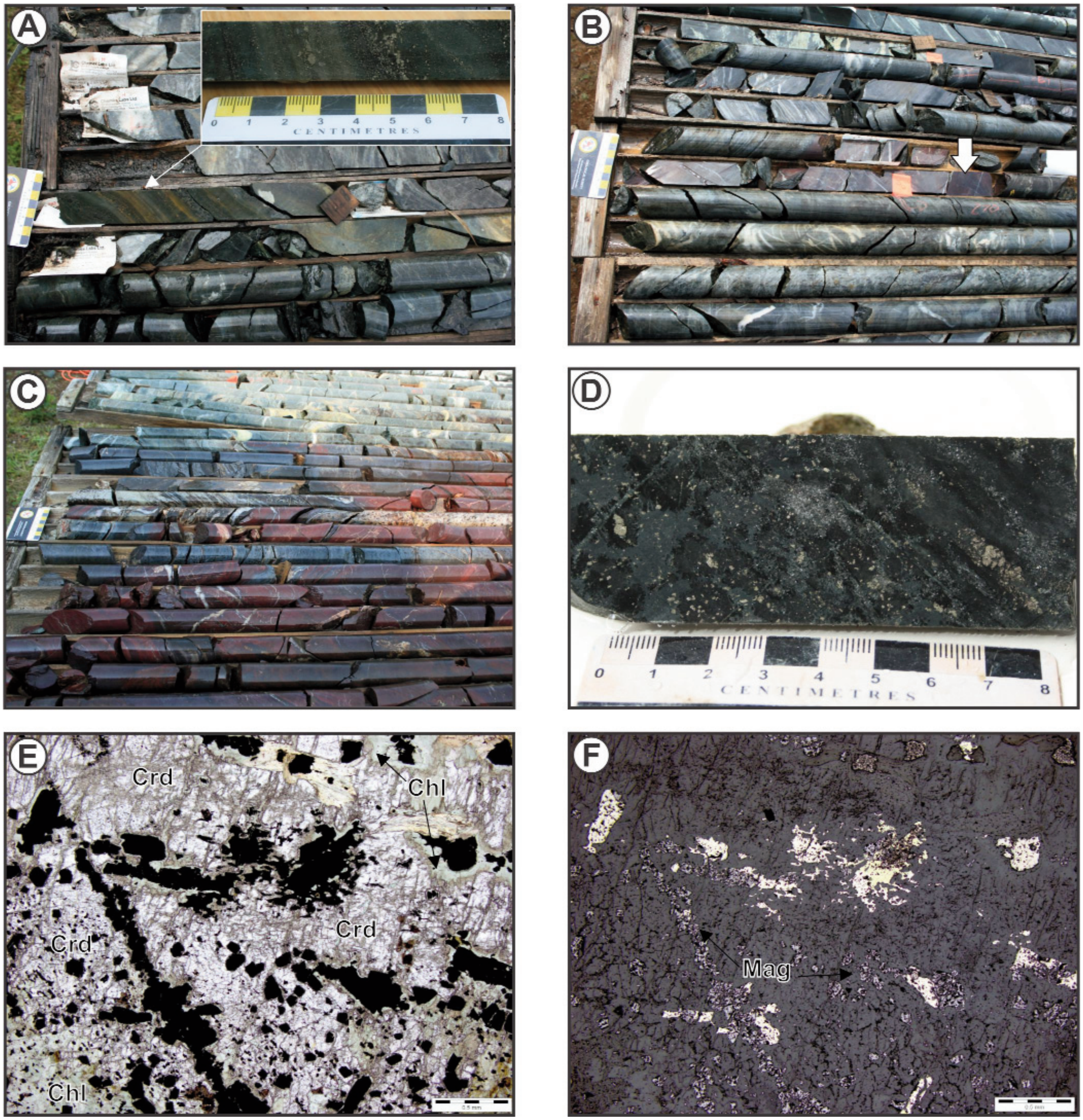


Plate 1. *Representative photos of the Gullbridge deposit. A) Exhalative-style, bedding-parallel sulphides developed in volcaniclastic rocks near the projected location of the mineralized zone (DDH-135; 315 m); B) Red chert (white arrow) capping muscovite-altered felsic volcanic rocks developed distal to (~400 m south), and stratigraphically above, the mineralized zone (DDH-135; 232 m); C) A thick intersection of red chert situated stratigraphically above the mineralized zone and approximately 500 m north of the Gullbridge deposit (DDH-144; 100 m); D) Cordierite (darker areas) altered to Fe-chlorite (lighter areas), highlighting the retrograde reaction leading to the formation of the Fe-chlorite alteration (DDH-148; 222 m); E) Plane-polarized light photomicrograph outlining the distribution of cordierite, Fe-chlorite and sulphide mineralization within the larger scale Fe-chlorite–magnetite alteration zone (DDH-148; 175 m; Chl–Fe-chlorite; Crd–cordierite); F) Reflected light photomicrograph of Plate E, illustrating the distribution of sulphides; note the abundant fine-grained magnetite intergrown with the Fe-chlorite (Mag–magnetite).*

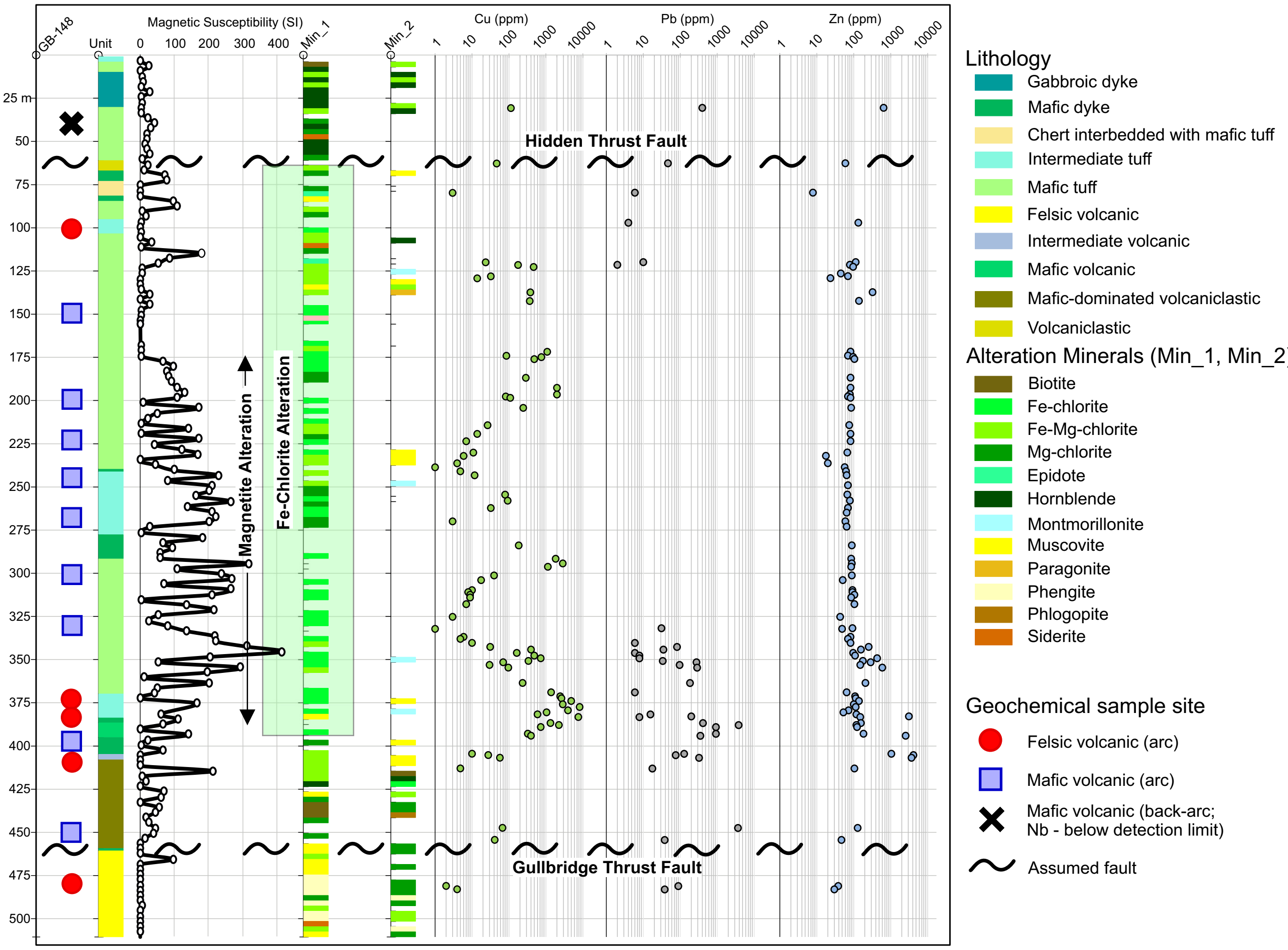


Figure 4. *Strip log for DDH GB-148, shown in Figure 2, highlighting the location of geochemical sample sites and significant fault structures, lithology, magnetic susceptibility values, mineralogy as determined from spectral data (Min_1, Min_2), and select company assay data from Pudifin* et al. *(1991). Note, the stratigraphy bound by the Hidden and Gullbridge thrust faults youngs downhole.*

Along the projected strike (~400 m southwest) and immediately above the mineralization, the related alteration signature is characterized by muscovite and Fe–Mg-chlorite (Sparkes, 2019). The upper stratigraphic limits of this muscovite alteration is accompanied by elevated barium and locally developed exhalative sulphides containing anomalous zinc (1830 ppm over 2 m; Lenters and Sears, 1990; Figure 4).

Alteration indices calculated for the lithogeochemistry from drillcore samples highlight the variable chlorite alteration developed within the mineralized sequence (Figure 3C). The most significant chlorite alteration immediately underlies the main zone of copper mineralization and extends beneath the zone for upward of 250 m (Figure 2B). This zone of chlorite alteration outlined by the lithogeochemistry results coincides with the zone of Fe-chlorite alteration highlighted by the spectral data (*cf.* DDH GB-148; Sparkes, 2019). The chlorite alteration affects both the mafic and felsic volcanic rocks within the sequence, which are also affected by variable sodium depletion as illustrated in Figure 3D. The degree of sodium depletion displayed by samples from drillhole GB-148 increases with depth up to approximately 330 m, which directly underlies the mineralized zone, and then decreases with increasing depth for those samples located above the mineralized zone.

The strip log for drillhole GB-148, shown in Figure 4, outlines the main rock types, magnetic susceptibility values, spectral data, and select element concentrations from company assay data (Pudifin *et al.*, 1991). Rock units within the drillhole are inferred to young downhole within individual structural panels, which are defined by the bounding assumed faults, as this drillhole is oriented to the west, and stratigraphic units are inferred to dip steeply to the west (Figure 2A). Industry assay data from Pudifin *et al.* (1991)

for the drillhole indicate an apparent zonation within the mineralized zone, from a copper-dominated base to a zinc-enriched top, extending downhole from approximately 375 m, which is inferred to represent a primary zonation within the sulphide mineralization (Figure 4). Below the zone of copper mineralization (*i.e.*, up hole from ~375 m), the host mafic volcanic rocks display Fe-chlorite and magnetite alteration that continues up to the Hidden thrust fault, which defines the eastern limits to the mineralization and related alteration within the Gullbridge deposit (Figure 2B).

SOUTHWEST SHAFT DEPOSIT

Local Geology

The Southwest Shaft deposit, located approximately 2 km along strike to the southwest of Gullbridge, occurs within a similar structural setting and displays many of the same features relative to the development of mineralization and associated alteration. The geology of the area is subdivided into a number of steep, west-dipping structural panels, which results in the overall eastward younging of stratigraphic units across the deposit (Figure 5). Rocks within the structural hanging wall comprise felsic volcanic rocks of the Starkes Pond division, and are inferred to form the stratigraphic footwall to the deposit, similar to that described for the Gullbridge area (Pope and Calon, 1993; O'Brien, 2016a). These rocks consist of variably foliated, non-magnetic, calc-alkalic rhyolite dominated by phengite alteration, and display arc-related geochemical signatures (Figure 6A, B). One notable difference between the Gullbridge and Southwest Shaft deposits is the development of sulphide mineralization, accompanied by muscovite alteration, within the felsic volcanic rocks of the hanging-wall sequence at the Southwest Shaft deposit (Figure 5B). Here, the felsic volcanic rocks are locally interbedded with mafic volcanic rocks similar to those developed within the mineralized sequence.

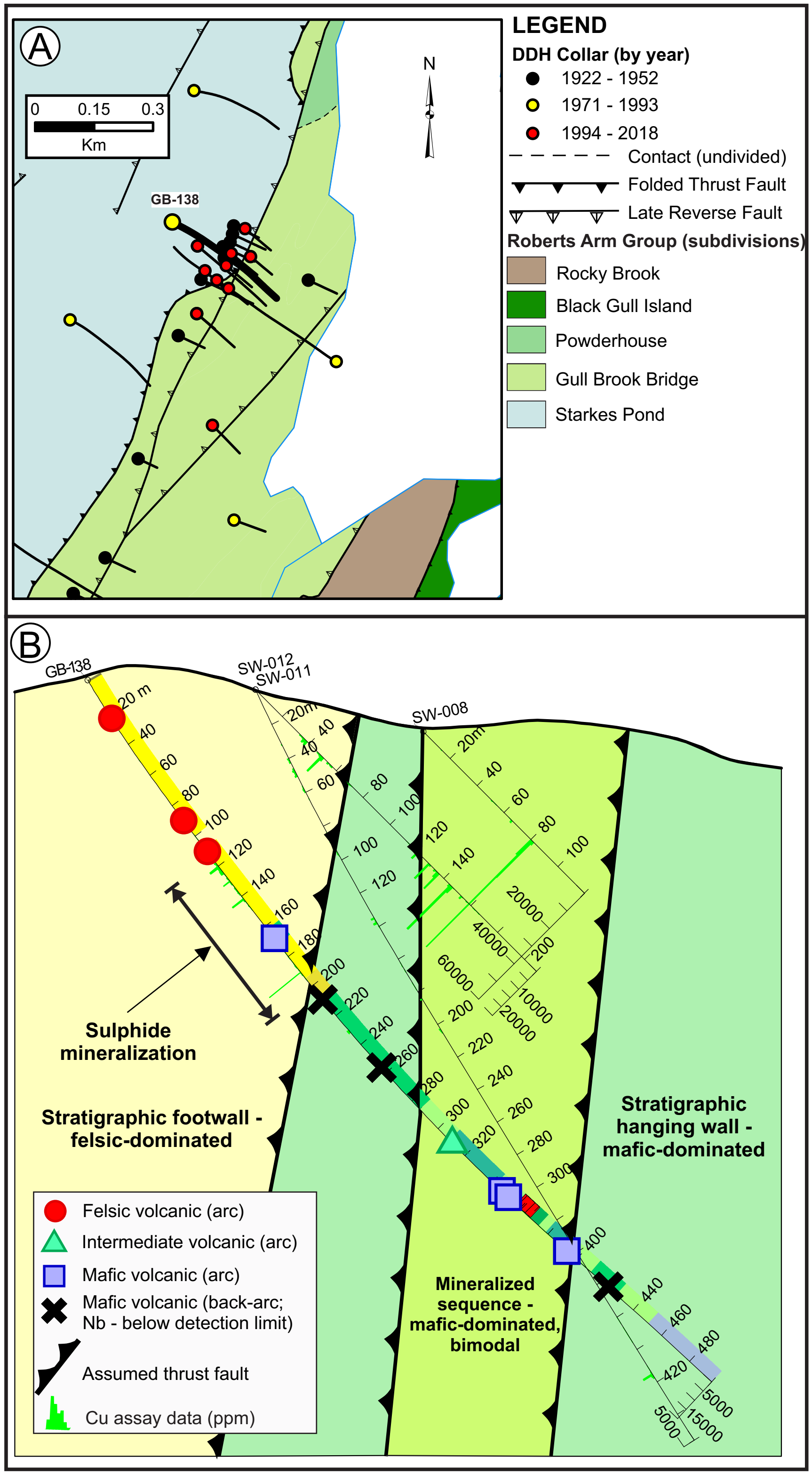


Figure 5. *A) Simplified geology map of the Southwest Shaft deposit outlining the distribution of diamond-drill holes (coloured by the year completed); modified from O'Brien (2016b); B) Schematic cross-section for drillhole GB-138, illustrating the distribution of the main lithological units, location of geochemical samples* (see *Figure 6*)*, mineralization and major fault structures.*

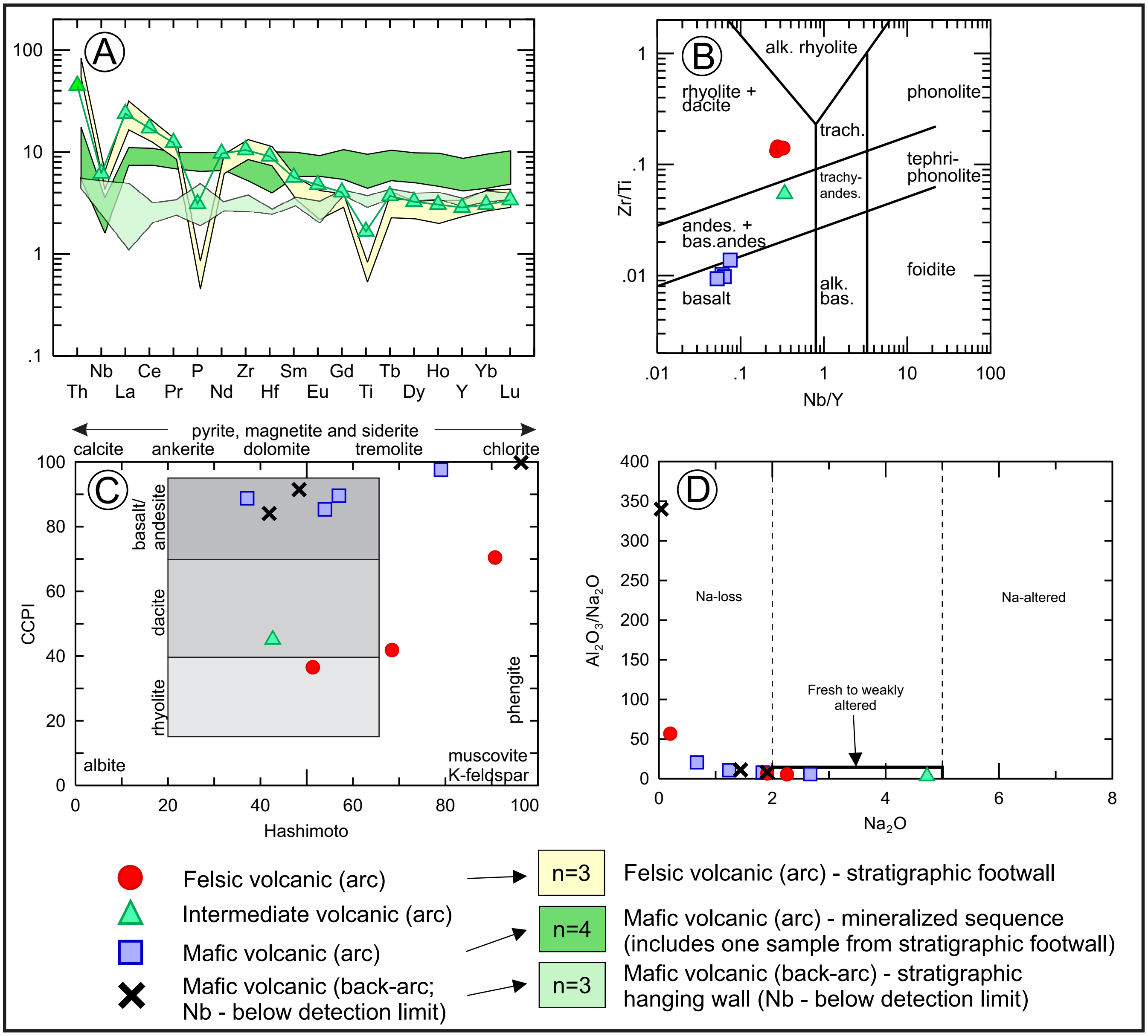


Figure 6. *A) Primitive-mantle-normalized multi-element plot for samples outlined in Figure 5; primitive-mantle values from Sun and McDonough (1989). Note "n" in the legend denotes the number of samples defining each group; B) Zr/Ti vs. Nb/Y discrimination diagram after Pearce (1996); C) Alteration box plot of Large* et al. *(2001), illustrating alteration* vs. *diagenetic fields. For a description of axis values refer to Figure 3C; D) Al_2O_3/Na_2O* vs. *Na_2O outlining sodium depletion within altered samples as in Figure 3D.*

The structural hanging-wall rocks are separated from the mineralized sequence by an inferred structural panel, dominated by mafic volcanic rocks containing weakly disseminated pyritic alteration and localized Fe-chlorite alteration (Figure 5B). The exact affinity of these rocks remains uncertain, but based on the similarities of their lithogeochemistry with those of the structural footwall, they are tentatively grouped with that sequence. The mineralized sequence at the Southwest Shaft deposit is dominated by mafic tuff and related volcaniclastic rocks, interbedded with lesser intermediate crystal tuff; the latter display similar geochemical characteristics to the felsic volcanic rocks within the structural hanging wall (Figure 6A). The mafic volcanic rocks, however, display geochemical characteristics analogous to back-arc basin basalts. The sequence is dominated by Fe–Mg-chlorite alteration, but also contains irregularly distributed zones of phengite, Mg-chlorite, hornblende, biotite and epidote (Sparkes, 2019). Although the examined drillhole (GB-138) did not contain significant sulphide mineralization within the mafic volcanic rocks, drillholes at shallower depths display higher grade mineralization (*e.g.*, DDH SW-008; Figure 5B). Although weak to moderate sulphide mineralization occurring as fine-grained disseminations and stringers were locally observed, this is not associated with any significant base-metal enrichment.

The structural footwall rocks consist of massive mafic volcanic rocks containing weak to moderate epidote veining throughout, along with lesser interbedded iron formation. Similar to the Gullbridge deposit, these rocks are interpreted to form the stratigraphic hanging wall to the Southwest Shaft deposit and are dominated by Fe–Mg-chlorite alteration. These mafic volcanic rocks contain Nb values below the detection limit of the Geological Survey's laboratory (Figure 6A), and are inferred to be correlative with the Black Gull Island division (O'Brien, 2016b).

Characteristics of the Mineralized Sequence

Given the lack of sulphide mineralization within the mineralized sequence of the examined drillhole, the rocks only display weakly developed hydrothermal alteration relative to that observed in the area of the Gullbridge deposit. However, in contrast to Gullbridge, sulphide mineralization in this drillhole is also developed outside of the main mineralized sequence. The felsic-hosted sulphide mineralization within the structural hanging-wall rocks is unique to the Southwest Shaft deposit, whereas mineralization observed farther downhole, within mafic-dominated bimodal volcanic and related volcaniclastic rocks (mineralized sequence), is almost analogous to that developed in the area of the Gullbridge deposit.

The sulphide mineralization occurring within the felsic volcanic rocks is associated with a distinct zone of muscovite alteration (Sparkes, 2019). This zone contains disseminated pyrite, pyrrhotite and lesser chalcopyrite within moderately to strongly foliated felsic volcanic rocks, and contains zinc-enriched (*e.g.*, 1.7% Zn and 0.6% Cu over 0.65 m), and copper-enriched (*e.g.*, 1.6% Cu over 0.35 m) zones of sulphide mineralization (Lenters and Sears, 1990; Figure 7). Samples of the pyritic felsic volcanic rock display evidence of chlorite alteration and sodium depletion (Figure 6C, D). However, the highest degree of chlorite alteration and associated sodium depletion relative to other samples from the drillhole actually occurs within the mafic volcanic sample collected from the immediate underlying structural panel, which is pyritic but are otherwise barren (Figure 5B).

Within the mineralized sequence, most of the sulphide mineralization is concentrated toward the base of the structural panel, occurring as disseminated sulphide within chloritized mafic volcanic rocks in the upper portion (~360 m) of the mineralized zone, and transitioning to stringer/stockwork-style veining at depth (375–400 m; Figure 7; Plate 2A, B). The observed sulphide mineralization within the mineralized sequence primarily consists of pyrite and lesser pyrrhotite in association with Fe–Mg-chlorite alteration, along with localized muscovite and Mg-chlorite. Development of sulphide mineralization is also accompanied by an increase in magnetic susceptibility measurements indicating potential magnetite alteration (Figure 7). Local intersections of semi-massive sulphides have been reported within the deposit at shallower depths, where the mineralization is inferred to be hosted within rocks correlative with the mineralized sequence (*e.g.*, 6.0% Cu, 0.2% Zn and 0.1% Pb over 0.5 m, DDH SW-008; French and Wells, 2001; Figure 5B)

HANDCAMP PROSPECT

Local Geology

The Handcamp prospect occurs within a sequence of pillow basalt correlated with the Gull Brook Bridge division (O'Brien, 2016a; Figure 8). The mineralized zone consists of a structurally bound, hydrothermally altered, exhalative horizon hosting Zn–Pb–Cu–Ag–Au mineralization inferred to be volcanogenic in origin (Pickett *et al.*, 2011; Sparkes, 2019). Drilling at the prospect has traced the mineralized sequence, along strike, for up to 1.2 km and to a depth of up to 150 m, and the zone remains open both along strike and at depth.

The structural hanging wall, is also assumed to represent the stratigraphic hanging wall, and consists of moderately magnetic mafic volcanic rocks characterized by weakly developed Fe–Mg- and Mg-chlorite, hornblende and epidote alteration (Sparkes, 2019). The unit is interbedded with rare, red chert/iron formation and intermediate tuff, and is locally intruded by porphyritic felsic dykes. Samples of the mafic volcanic rocks within the hanging-wall sequence display geochemical characteristics analogous to back-arc basin basalts, and are similar to those hosting VMS-related mineralization elsewhere in the region (*e.g.*, Southwest Shaft deposit; Figure 9A, B). The porphyritic felsic dykes, which intrude the sequence, display geochemical patterns indicative of an arc-related environment and have similar geochemical patterns to the felsic volcanic rocks within the structural hanging wall of the Gullbridge and Southwest Shaft deposits (Figure 9A, B). A sharp structural contact, herein termed the Handcamp thrust fault, separates the mafic volcanic rocks of the hanging wall from the underlying mineralized sequence (Figure 8B).

The mineralized sequence consists of exhalites, in the form of red chert interbedded with fine-grained, metallifer-

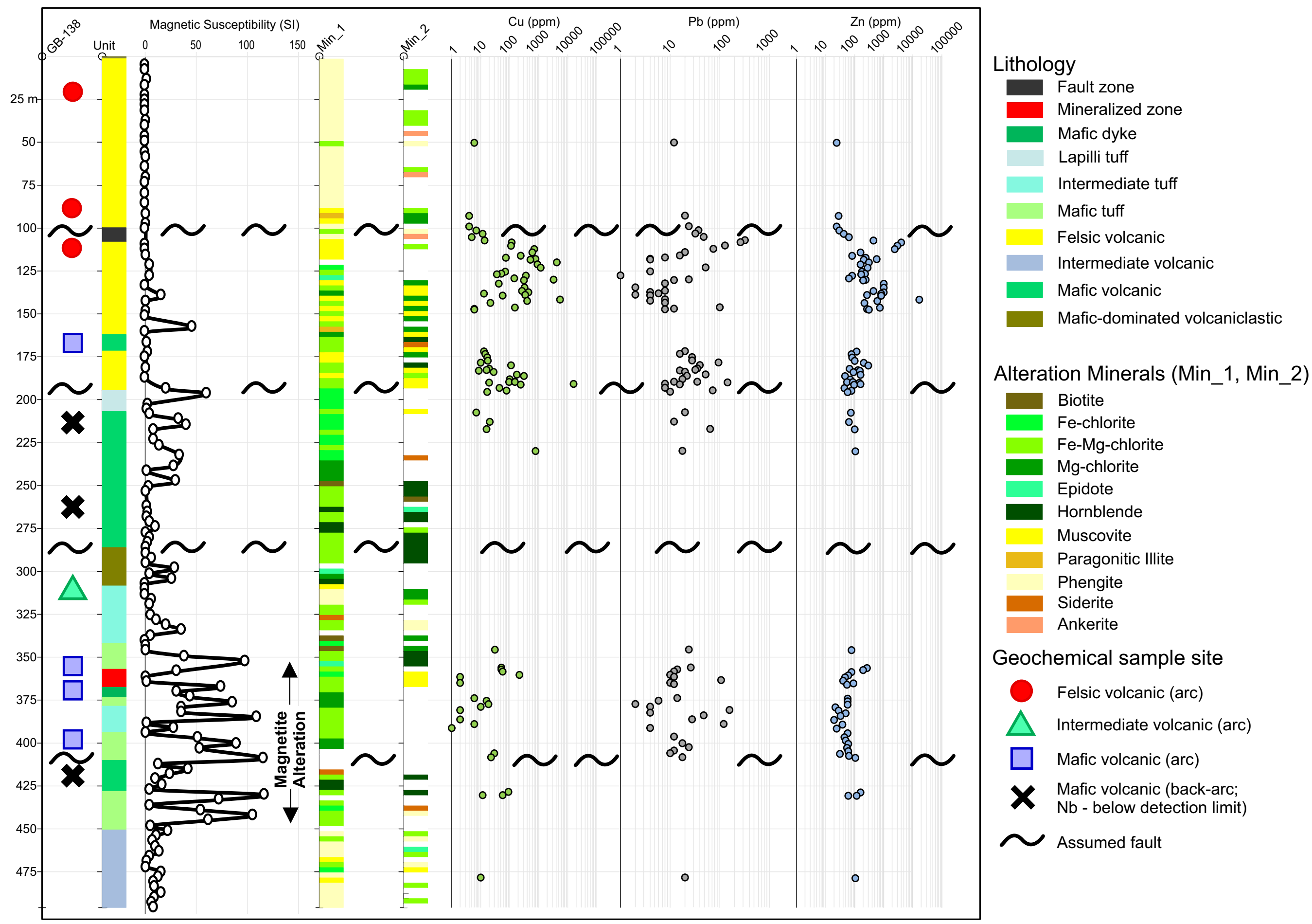


Figure 7. *Strip log for DDH GB-138, shown in Figure 5, highlighting the location of geochemical sample sites and significant fault structures, lithology, magnetic susceptibility values, mineralogy as determined from spectral data (Min_1, Min_2), and select company assay data from Lenters and Sears (1990).*

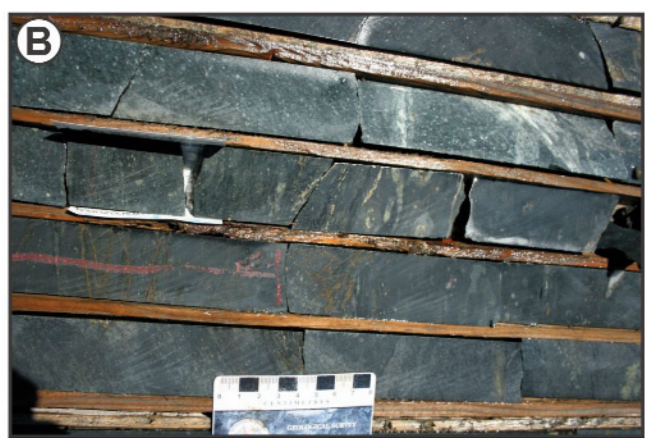


Plate 2. *Representative drillcore photographs from the Southwest Shaft deposit. A) Transition from relatively unaltered mafic volcanic rocks into a zone of disseminated pyrite accompanied by muscovite alteration and minor barium enrichment (DDH GB-138, 355 m); B) Stringer/stockwork-style sulphide mineralization developed within interbedded intermediate crystal tuff and Fe–Mg-chlorite-altered mafic volcanic rocks (DDH GB-138, 395 m).*

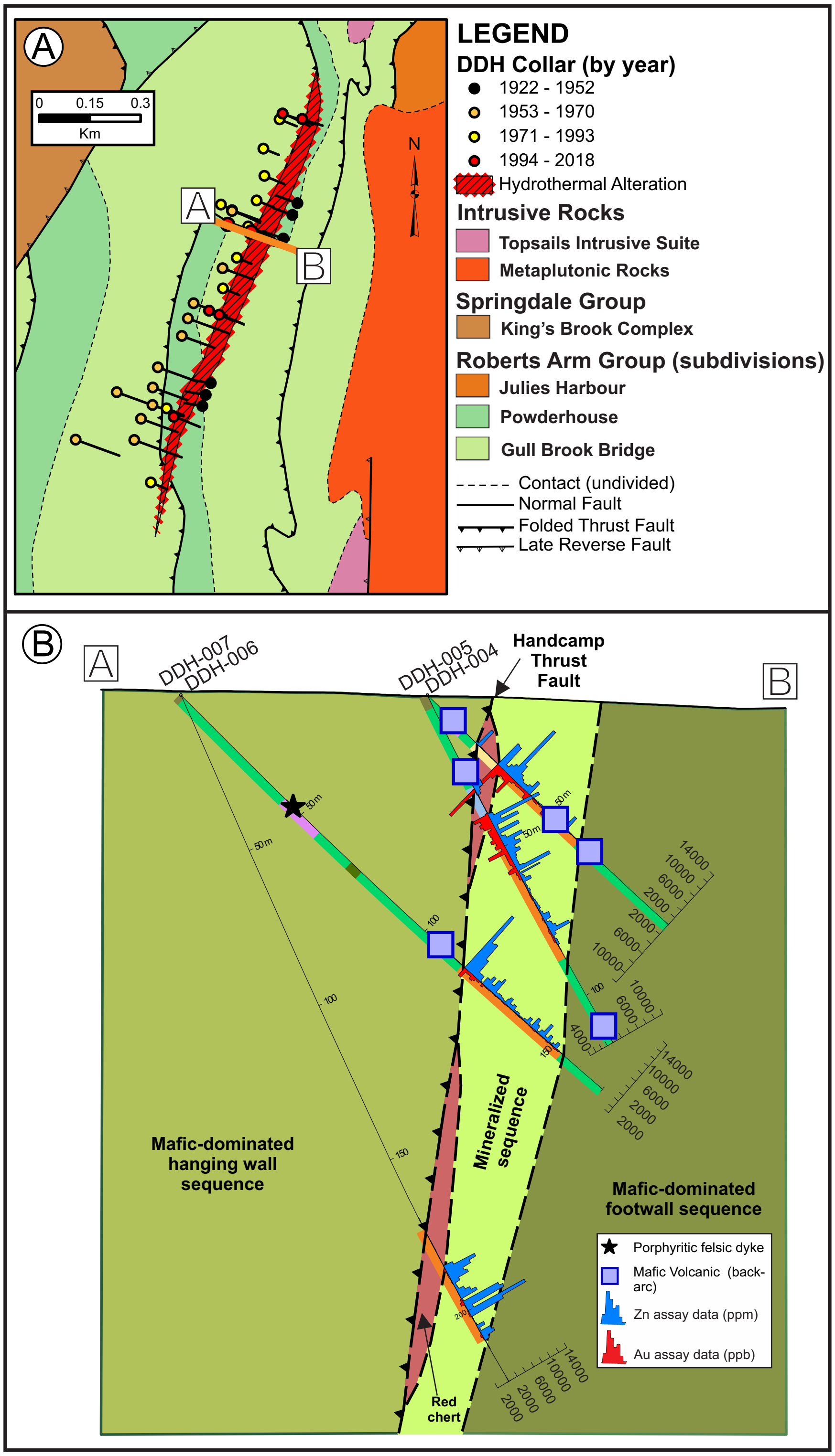


Figure 8. *A) Simplified geology map of the Handcamp prospect outlining the distribution of diamond-drill holes (coloured by the year completed); modified from O'Brien (2016a). Note the location of the cross-section shown in (B) is outlined by the orange line; B) Schematic cross-section of the main mineralized zone, illustrating the distribution of lithological units, location of geochemical samples (*see *Figure 9), mineralization and major fault structures.*

ous siliciclastic rocks and lesser mafic tuff, and grey siliceous horizons containing abundant barite. The metalliferous siliciclastic rocks locally host bedding-parallel sulphide mineralization, indicative of an exhalative environment (Plate 3A). The mineralized sequence is up to 50 m wide, dips steeply to the west, and is capped by red chert (Figure 8B). This chert is characterized by phengite alteration, along with lesser muscovite and Fe–Mg- and Mg-chlorite, and is largely barren with respect to base- and precious-metal mineralization. In contrast, the metalliferous siliciclastic rocks are commonly associated with muscovite alteration and host Zn–Pb–Cu–Ag–Au enrichment, where the highest grades of precious-metal mineralization occurs in association with the interbedded grey siliceous horizons (Plate 3B).

The transition into the underlying footwall rocks appears gradational in drillcore, transitioning from the siliciclastic rocks, through mafic tuff into more massive mafic volcanic rocks that are crosscut by abundant, cm-scale, network-style epidote–carbonate veining. However, at surface, the same contact is at least locally marked by a well-defined fault. The footwall sequence consists of relatively non-magnetic mafic volcanic rocks characterized by Fe–Mg- and Mg-chlorite, hornblende and epidote alteration. These rocks display similar geochemical patterns to those of the hanging-wall sequence, albeit at reduced concentrations (Figure 9B).

Characteristics of the Mineralized Sequence

The alteration and mineralization developed within the Handcamp prospect is unique for the region, given its style and distribution. As noted above, the metalliferous siliciclastic sedimentary rocks host anomalous Zn–Pb–Cu–Ag– Au values throughout the mineralized sequence (Figure 10). However, the highest grade mineraliza-

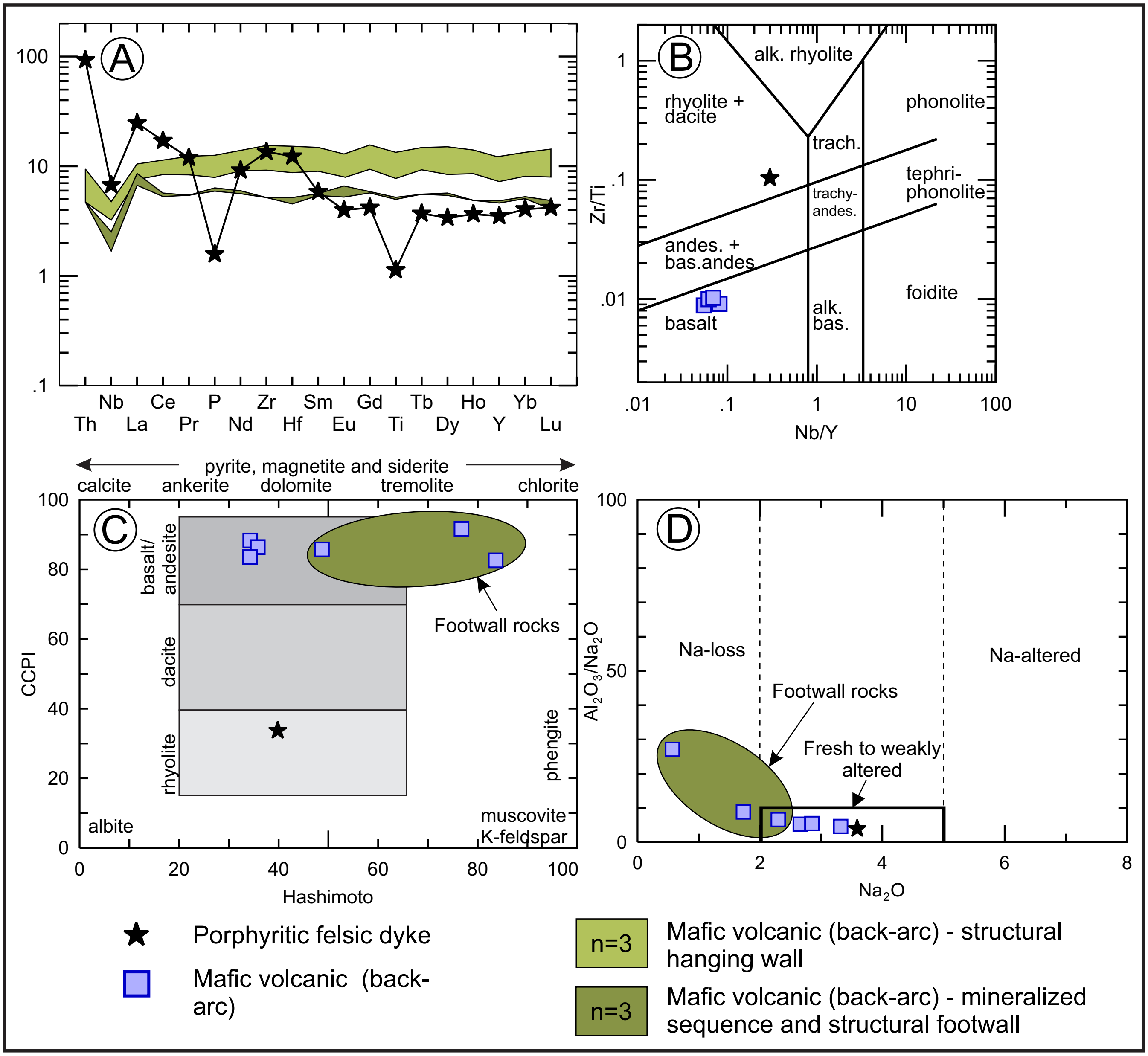


Figure 9. *A) Primitive-mantle-normalized multi-element plot for samples outlined in Figure 8; primitive-mantle values from Sun and McDonough (1989). Note "n" in the legend denotes the number of samples defining each group; B) Zr/Ti* vs. *Nb/Y discrimination diagram after Pearce (1996); C) Alteration box plot of Large* et al. *(2001), illustrating alteration* vs. *diagenetic fields. For a description of axis values refer to Figure 3C; D) Al_2O_3/Na_2O* vs. *Na_2O plot outlining sodium depletion within altered samples as in Figure 3D.*

tion is associated within interbedded grey siliceous horizons, which locally produce values of up to 8.5 g/t Au, 29.6 g/t Ag along with 0.7% Zn, 5.5% Pb, 2.4% Cu and 3.7% Ba over 0.25 m. Such horizons are host to pyrite, galena, chalcopyrite and sphalerite occurring as fine-grained disseminations within a quartz-rich groundmass, and as later remobilized crosscutting vein-hosted material. The stratiform nature of these siliceous units, coupled with their enrichment in barite, provides supporting evidence for a hydrothermal origin. Spectral data from the mineralized sequence indicate a transition from a lower, muscovite-dominated, to an upper, phengite-dominated alteration along with variable Fe–Mg and Mg-chlorite, and rare biotite and phlogopite throughout (Figure 10).

Mafic tuff interbedded with the siliciclastic sediments, within the mineralized sequence, display geochemical patterns that are inseparable from those of the footwall mafic

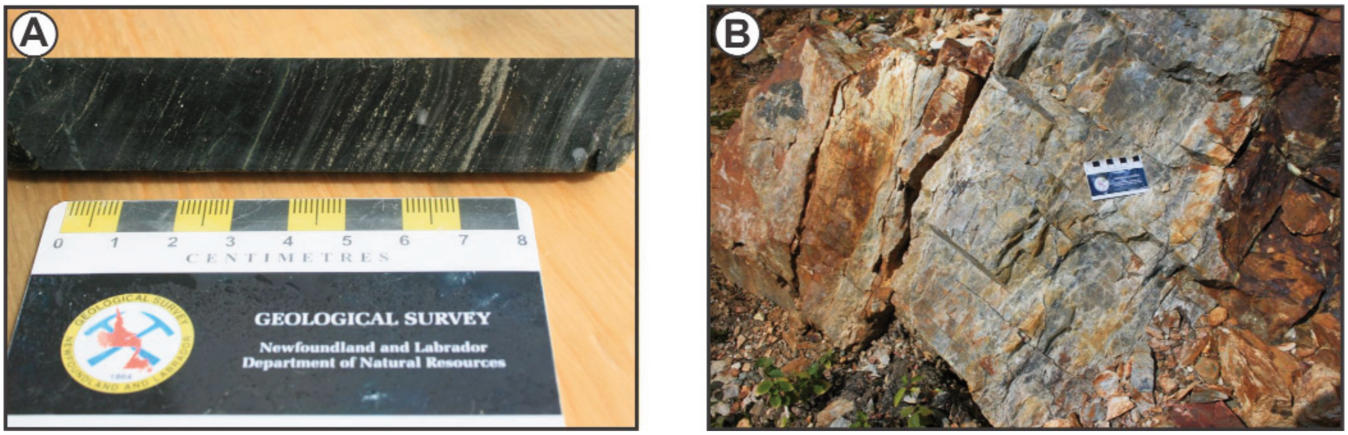


Plate 3. *Handcamp prospect. A) Exhalative-style sulphide mineralization developed within the metalliferous siliciclastic rocks of the mineralized sequence (DDH-012, ~17 m); B) Siliceous, sulphide-bearing horizon hosting Au–Ag mineralization in association with barite, interbedded with metalliferous siliciclastic rocks.*

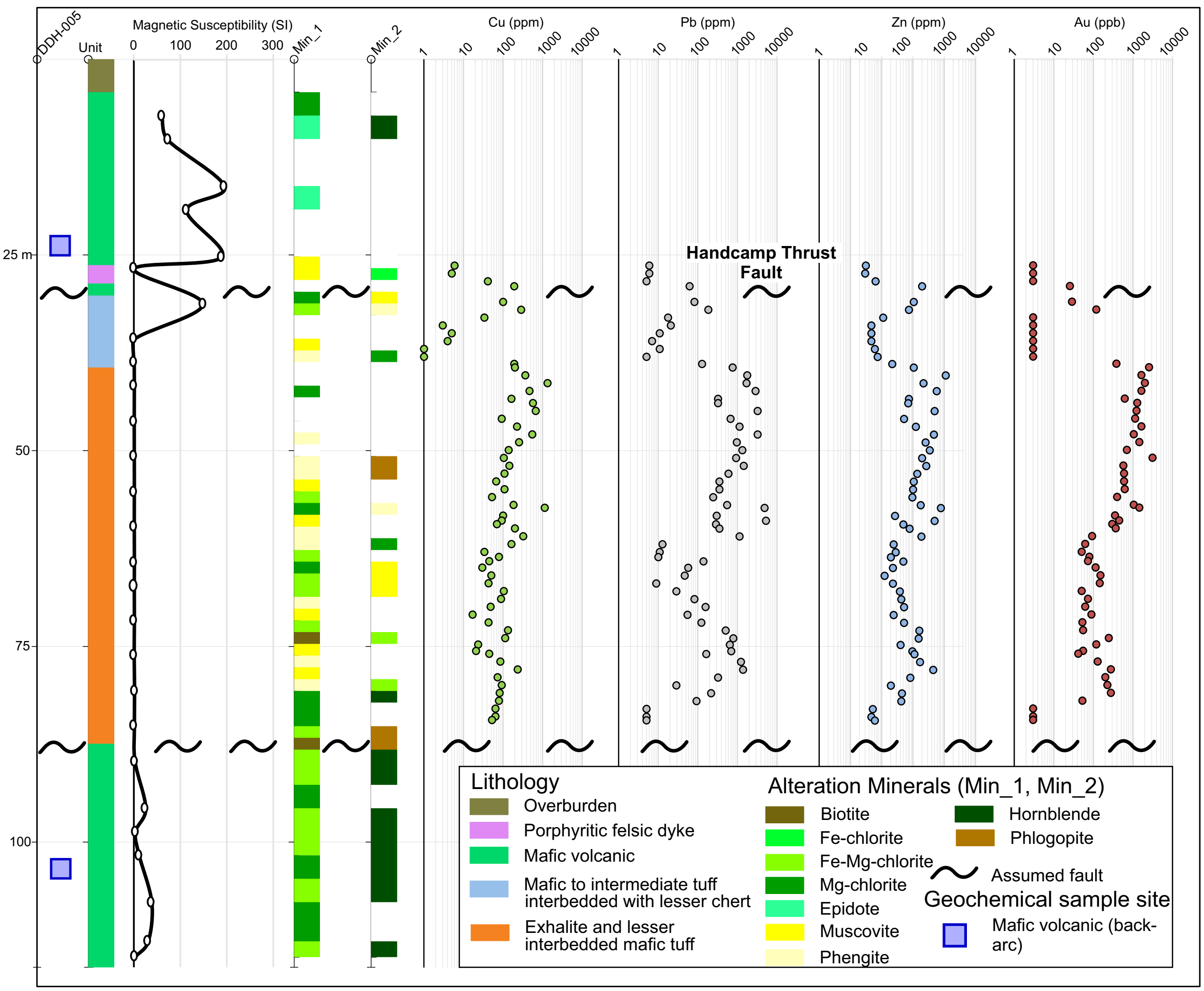


Figure 10. *Strip log for DDH-005, shown in Figure 8, highlighting the location of geochemical sample sites and significant fault structures, lithology, magnetic susceptibility values, mineralogy as determined from spectral data (Min_1, Min_2), and select company assay data from Pickett* et al. *(2011).*

volcanic rocks, and are therefore grouped with this sequence (Figure 9A). The mafic tuffaceous rocks within the mineralized sequence display the most intense chlorite alteration and accompanying sodium depletion of all samples collected within the section (Figure 9C, D). In addition, the footwall mafic volcanic rocks display similar styles of alteration to that developed within the mineralized sequence, indicating these rocks were altered by similar hydrothermal fluids. Outside of the mineralized sequence, the most significant sodium depletion observed within the lithogeochemistry from the prospect is developed within the deepest intersections of the footwall rocks (~150 m vertical depth).

STARKES POND WEST PROSPECT

Local Geology

Exhalative-style mineralization within the central Buchans–Roberts Arm belt has also been reported from the area of the Starkes Pond West prospect, where drill intersections of up to 5.6% Zn and 1.7% Cu over 0.9 m have been reported (Hudson, 1990). Diamond drilling in the area, targeting IP anomalies, has outlined anomalous base-metal mineralization extending for 800 m along strike. This mineralization occurs within mafic volcanic rocks correlated with the Black Gull Island division (O'Brien, 2016b), which is associated with a pronounced airborne magnetic anomaly extending for upwards of 2 km along strike in the immediate area of the prospect (Figure 11). This zone of VMS-related mineralization represents one of the few examples that occurs within the South Brook structural tract (O'Brien, 2008).

The geology in the immediate vicinity of the mineralization is limited by a lack of outcrop, but data gathered from drillcore indicate that a series of mafic volcanic flows, interbedded with mafic tuff and volcaniclastic and metalliferous siliciclastic rocks, are the main rock types in the area. These rocks are dominated by Fe–Mg- and Fe-chlorite alteration, along with lesser hornblende and epidote, based on spectral data. Within this sequence, the sulphide mineralization is primarily hosted within the volcaniclastic and siliciclastic rocks (Plate 4A). Similar relationships are locally observed in rare outcrops proximal to the mineralized zone, whereby volcaniclastic horizons display pyrite–magnetite alteration (Plate 4B).

Characteristics of the Mineralized Sequence

The rocks hosting mineralization within the Starkes Pond West prospect are variably deformed, ranging from relatively undeformed to strongly foliated, in addition to hosting locally developed, metre-scale, cataclastic breccia zones. The mafic volcanic rocks within the sequence are variably magnetic, and display geochemical characteristics similar to back-arc basin basalts (Figure 12A, B). The sulphide and

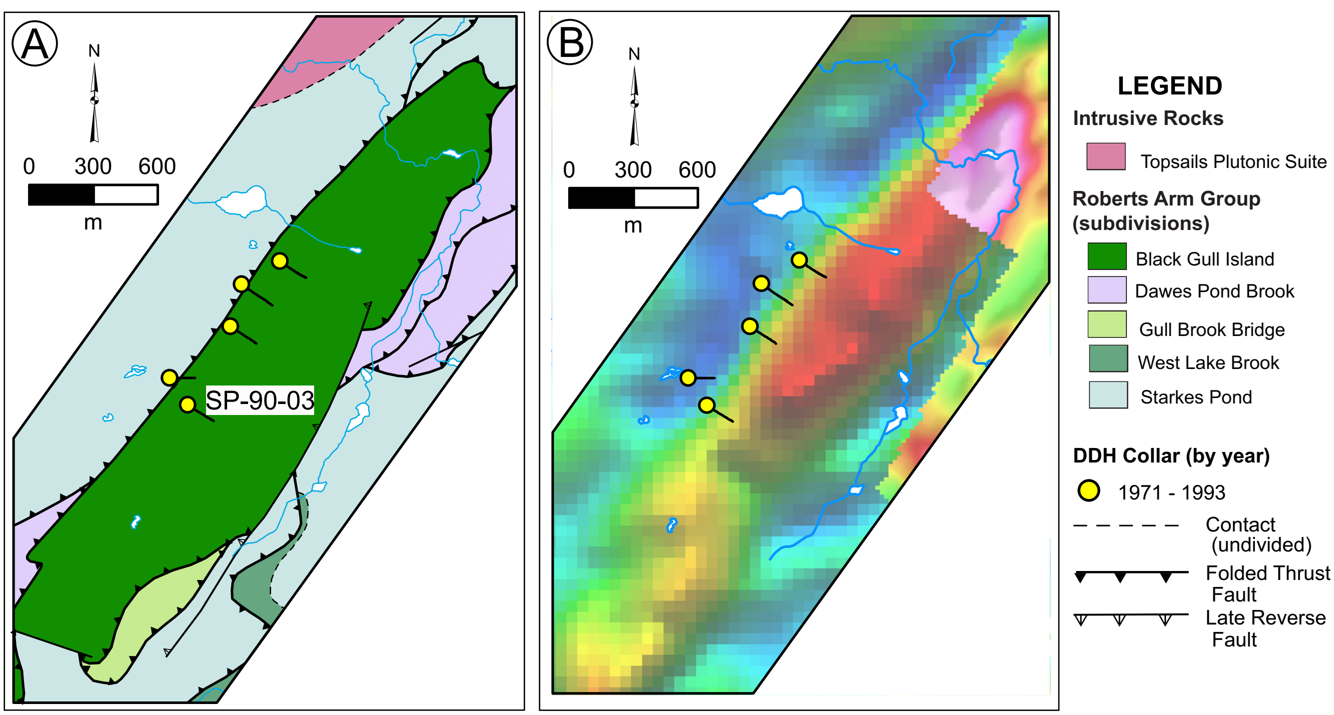


Figure 11. *A) Simplified geology map of the Starkes Pond West prospect outlining the distribution of diamond-drill holes (coloured by the year completed); modified from O'Brien (2016b); B) Regional airborne magnetic data highlighting the magnetic signature of the Black Gull Island basalts.*

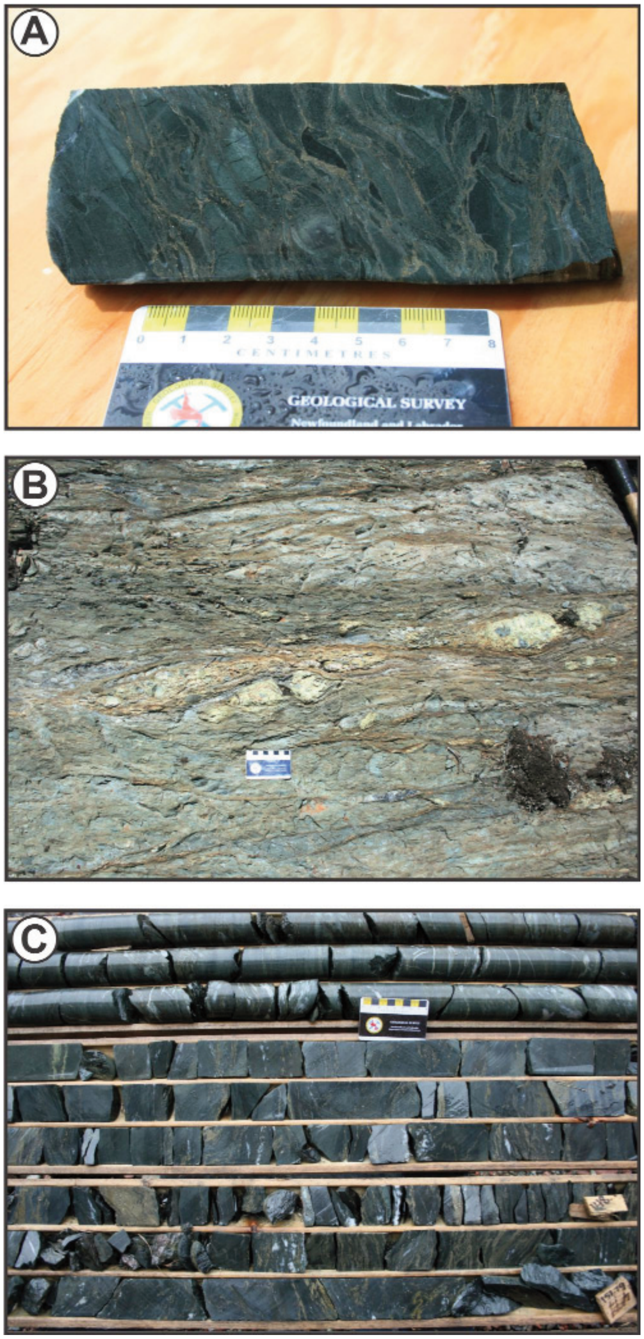


Plate 4. *Starkes Pond West prospect: A) Drillcore intersection of volcaniclastic-hosted sulphide mineralization (DDH SP-90-001, 168 m depth); B) Moderately magnetic mafic volcaniclastic rock containing sulphide mineralization, predominantly in the form of pyrite, along with accompanying magnetite alteration; Starkes Pond West prospect (UTM 556149E/ 5443395N; NAD 83, Zone 21); C) Stringer/stockwork sulphide mineralization associated with anomalous copper enrichment developed within a volcaniclastic horizon bound by mafic tuff. (DDH SP-90-003, 150 m depth).*

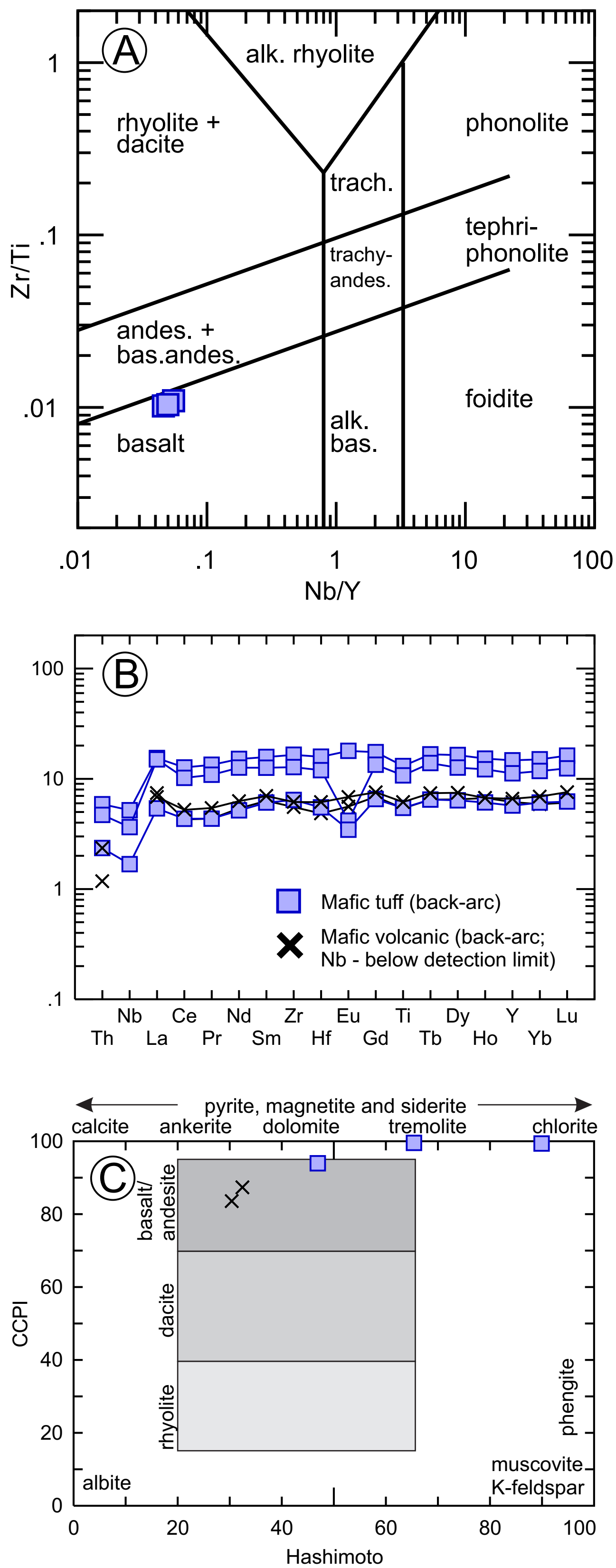
oxide minerals hosted within the tuffaceous volcaniclastic rocks interbedded with siltstone consist of pyrite along with pyrrhotite and magnetite, forming stringer and rare exhalative-style mineralization. These zones are dominated by Cu–Zn enrichment, and are associated with Fe–Mg- and Fe-chlorite alteration and weakly developed sodium depletion (*see* Figures 12C and 13). Localized zones of anomalous copper mineralization (0.3% Cu over 13 m; Butler and Hudson, 1990) are hosted within volcaniclastic horizons containing siltstone and interbedded mafic tuff (Plate 4C). The samples in Figure 12C displaying chlorite alteration represent tuffaceous horizons associated with volcaniclastic rocks containing stringer sulphides, whereas the remaining, less-altered samples represent more massive mafic volcanic rocks marginal to the mineralized zone. As illustrated in Figure 13, the volcaniclastic horizons hosting mineralization locally display slightly elevated magnetic susceptibility measurements, indicating possible stratiform magnetite alteration similar to that observed in nearby outcrops.

LAKE BOND DEPOSIT

Local Geology

The Lake Bond deposit represents a Zn-enriched zone of stockwork-style mineralization hosted by variably altered pillow basalt. From a regional scale, the host rocks are assigned to the West Lake Brook division, which, in turn, are structurally overlain, to the west, by rocks correlated with the Gull Brook Bridge division (O'Brien, 2009; Figure 14). Within the pillow basalt sequence, sulphide mineralization occurs as disseminations, stringers, veinlets and small pods of pyrite, sphalerite, lesser chalcopyrite and rare galena in association with chlorite alteration and silicification (Harris, 1976; Swinden and Sacks, 1986; Swinden, 1988; Hudson and Swinden, 1990).

The hanging-wall rocks to the mineralized sequence are primarily composed of variably hematite-altered mafic volcanic flows and interbedded hyaloclastite, both of which are crosscut by moderate to strong carbonate veining. Within the deposit, the mafic volcanic rocks, both above and below the mineralization, are geochemically similar and are therefore assumed to represent part of the same unit, which is inferred to be younging to the west. The mafic volcanic rocks are non-magnetic and characterized as island-arc tholeiites (Figure 15A, B). These rocks are interbedded with red siltstone and sandstone, red chert and lesser felsic tuff (Plate 5A), which are calc-alkalic, LREE enriched, and display arc-related geochemical signatures (Figure 15A, B). The hanging-wall sequence is dominated by Fe–Mg- and Mg-chlorite, muscovite, epidote and rare hornblende and phlogopite assemblages based on spectral data. These rocks



are separated from the underlying mineralized sequence by a sharp structural contact, highlighted by the development of a narrow zone of white mica alteration (Plate 5B). Below this contact the mineralized sequence is characterized by Fe–Mg- and Mg-chlorite alteration, in association with the development of sulphide mineralization.

Volcanic rocks within the deposit are generally non-magnetic, whereas strongly magnetic mafic to intermediate dykes crosscut the sequence, displaying as prominent east–northeast-trending linear magnetic anomalies on regional airborne geophysical surveys. These dykes display arc-related geochemical signatures and are classified as sub-alkalic tholeiitic basalts (Figure 15). Within the footwall of the deposit, a medium-grained, moderate to strongly magnetic gabbro is present and locally forms the eastern limit of the mineralized sequence (Figure 14B).

Characteristics of the Mineralized Sequence

The Lake Bond deposit has a strike length of up to 1.4 km, and has been intersected at depths of up to 350 m where the mineralization remains open down-dip (Collins, 1992). The relatively unaltered mafic volcanic rocks above the mineralized sequence display similar geochemical trends to those affected by alteration associated with the sulphide mineralization, with the most notable difference being that the altered rocks contain Nb values below the detection limit of the Geological Survey's laboratory (1 ppm). For this reason, the altered rocks are herein separated into a stand-alone group; but are inferred to be geochemically similar to those of the hanging-wall sequence (Figure 15). A sample of the structurally controlled, white mica-altered mafic volcanic rocks of the mineralized sequence displays the greatest depletion of trace elements, and represents one of the more strongly altered samples collected from the section (Figure 15). The predominance of chlorite alteration in association with the development of mineralization is illustrated in Figure 15C, which is also accompanied by significant sodium depletion (Figure 15D).

The mineralized sequence primarily consists of stockwork-style veining, and lesser disseminated sulphides, with-

Figure 12. *A) Zr/Ti* vs. *Nb/Y discrimination diagram after Pearce (1996); B) Primitive-mantle-normalized multi-element plot for samples outlined in Figure 13; primitive-mantle values from Sun and McDonough (1989); C) Alteration box plot of Large* et al. *(2001), illustrating alteration versus diagenetic fields. For a description of axis values refer to Figure 3C.*

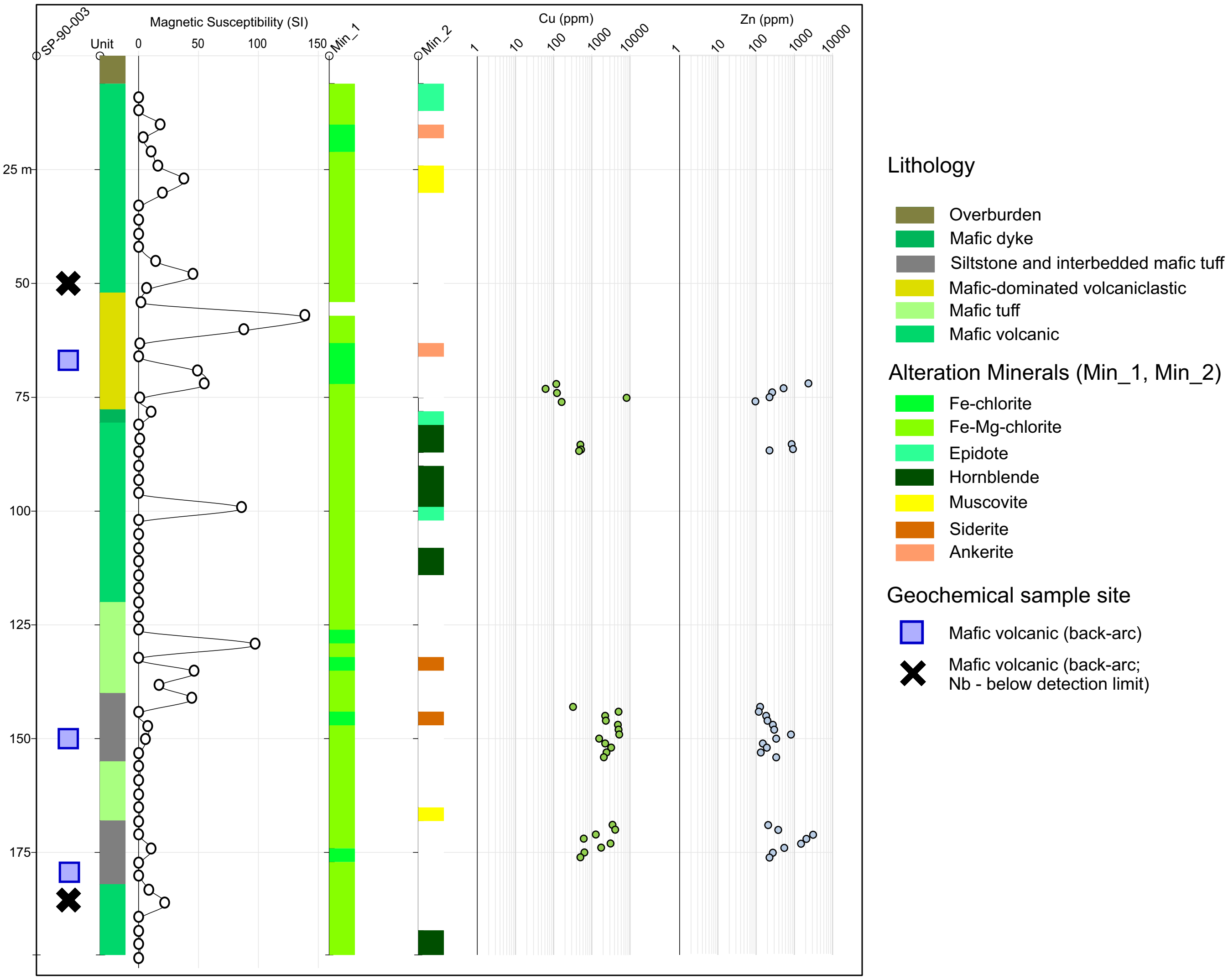


Figure 13. *Strip log for DDH SP-90-003, shown in Figure 11, highlighting the location of geochemical sample sites, lithology, magnetic susceptibility values, mineralogy as determined from spectral data (Min_1, Min_2), and select company assay data from Butler and Hudson (1990).*

in chlorite–epidote-altered mafic volcanic rocks (Plate 5C). This mineralization is largely Zn-dominated, but localized zones of Cu and Pb enrichment are also present (Figure 16). In addition, rare precious-metal mineralization is developed in association with the structurally controlled white mica alteration along the upper structural contact of the mineralized sequence; but the deposit is otherwise devoid of any significant precious-metal enrichment.

DISCUSSION

GULLBRIDGE DEPOSIT

The lithogeochemistry results from the Gullbridge deposit indicates an overall transition from arc-related felsic volcanism, to a back-arc, mafic-dominated environment. This transition is marked by a period of bimodal volcanism associated with the development of VMS mineralization. The resulting mineralization is underlain by an extensive zone of Fe-chlorite–magnetite alteration within the footwall sequence. Distal signatures of this mineralized zone are interpreted to be related to the development of muscovite alteration in association with elevated values of barium and zinc within the upper portions of the mineralized sequence, which is locally interbedded with exhalites. However, given the structural complexity of the deposit, it is difficult to directly relate such zones to the development of VMS-style mineralization. The Cu–Zn-dominated signature of the overall mineralizing system developed at the Gullbridge deposit, combined with the predominant mafic volcanic rocks hosting mineralization, suggest the deposit be classified as a bimodal-mafic-type system (*see* Galley *et al.*, 2007).

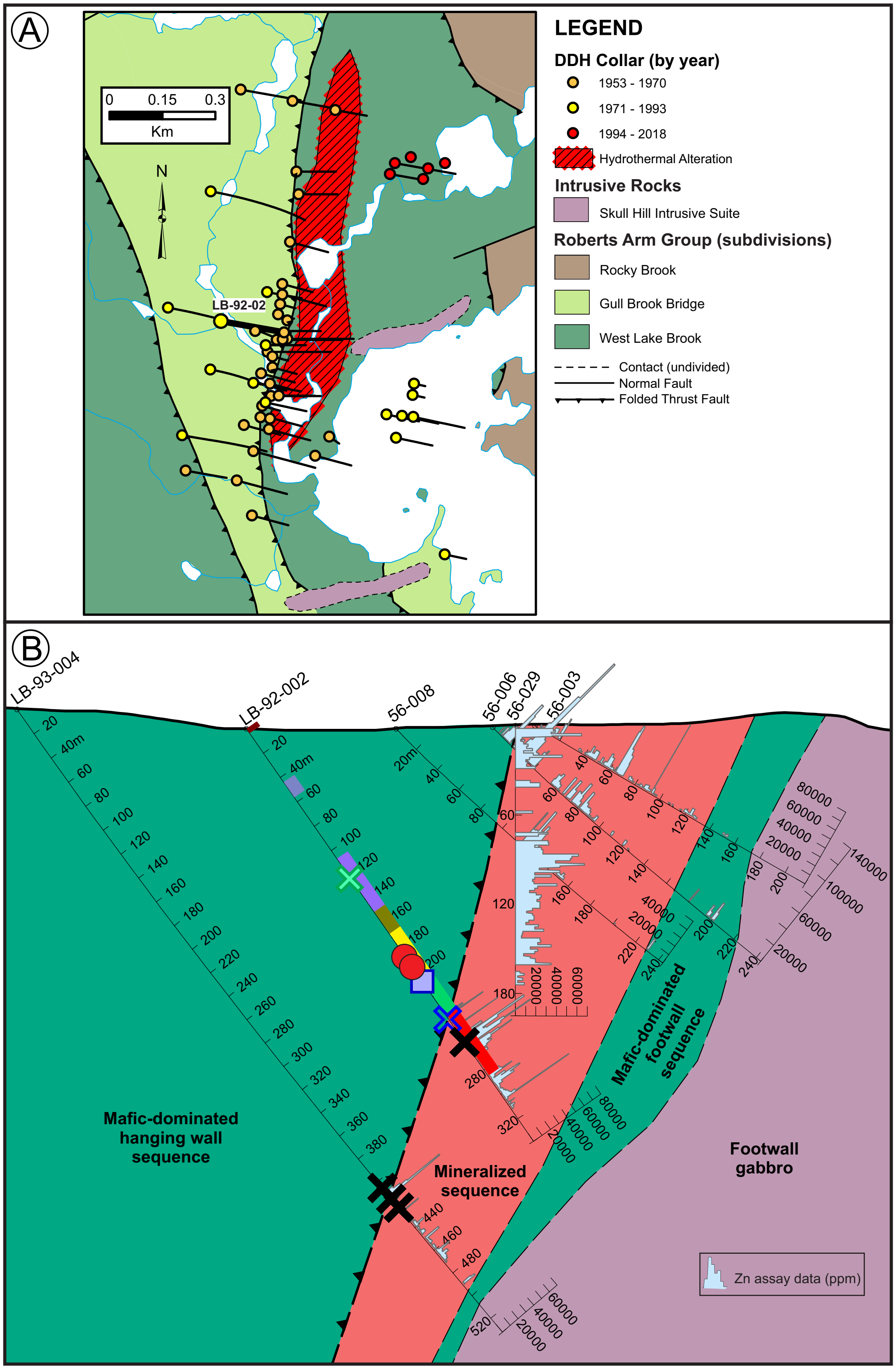


Figure 14. *A) Simplified geology map of the Lake Bond deposit outlining the distribution of diamond-drill holes (coloured by the year completed); modified from O'Brien (2009); B) Schematic cross-section for drillhole LB-92-002, illustrating the distribution of lithological units, location of geochemical samples (*see *Figure 15), mineralization and major fault structures.*

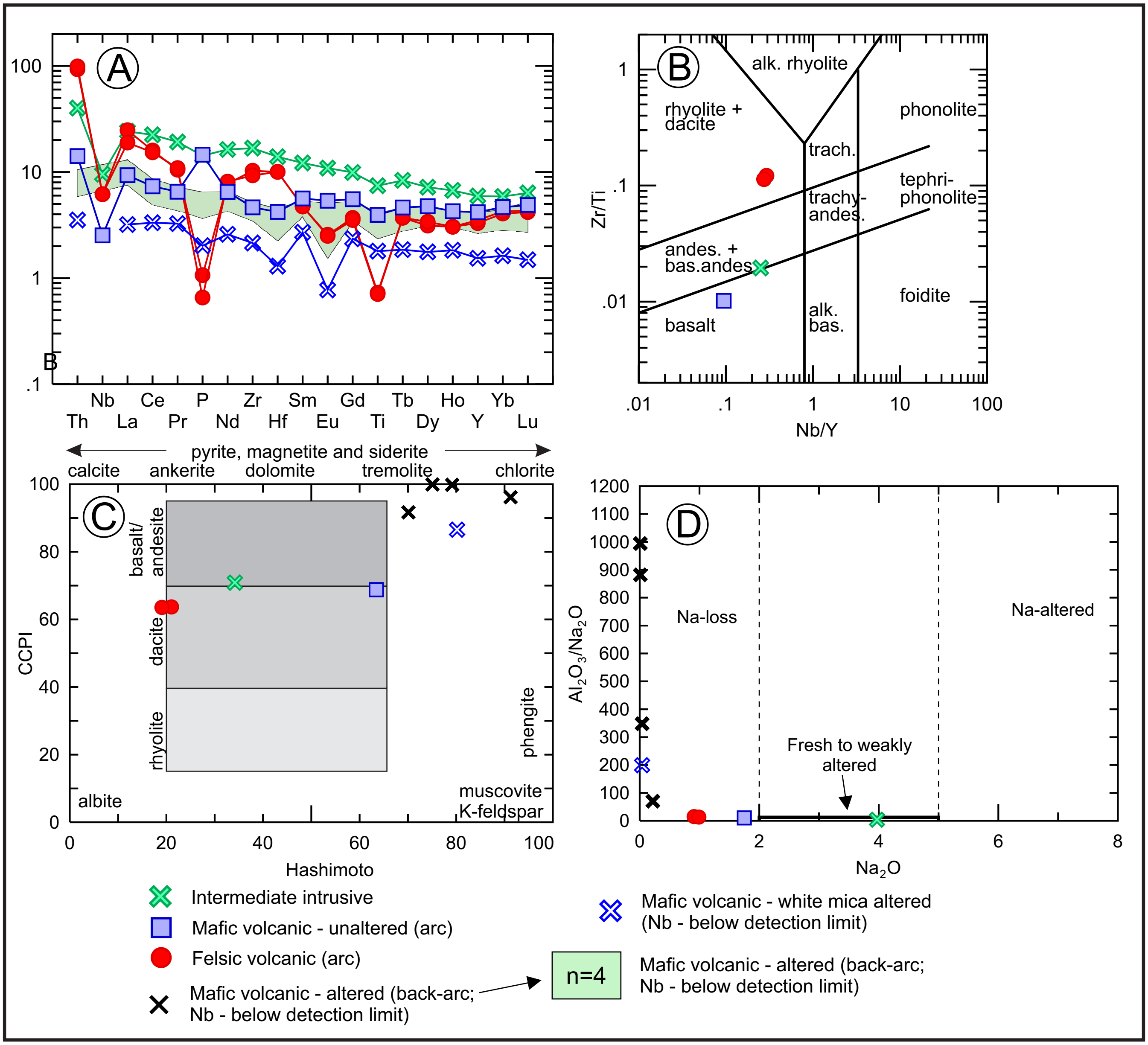


Figure 15. *A) Primitive-mantle-normalized multi-element plot for samples outlined in Figure 14; primitive-mantle values from Sun and McDonough (1989). Note "n" in the legend denotes the number of samples defining each group; B) Zr/Ti* vs. *Nb/Y discrimination diagram after Pearce (1996); C) Alteration box plot of Large* et al. *(2001), illustrating alteration versus diagenetic fields. For a description of axis values refer to Figure 3C; D)* Al_2O_3/Na_2O vs. Na_2O *plot outlining sodium depletion within altered samples as in Figure 3D.*

The main zone of stockwork-style mineralization at Gullbridge is associated with a magnesium-rich alteration that has been structurally disrupted, and thermally metamorphosed, by regional plutonic activity. This thermal metamorphism results in the development of cordierite-, andalusite- and anthophyllite-bearing alteration assemblages that overprint the pre-existing VMS-related alteration minerals (Upadhyay and Smitheringale, 1972; Pope and Calon, 1993). The cordierite alteration is commonly altered to chlorite, which is assumed to represent a retrograde reaction. The Fe-chlorite and magnetite alteration identified in association with rocks hosting sulphide mineralization is assumed to be part of this same reaction. Textural relationships displayed by these alteration minerals, such as Fe-chlorite enveloping an earlier cordierite–sulphide-bearing assemblage and magnetite occurring as fine-grained disseminations throughout the Fe-chlorite alteration (Plate 1E, F), illustrate the inferred metamorphic origin for these assem-

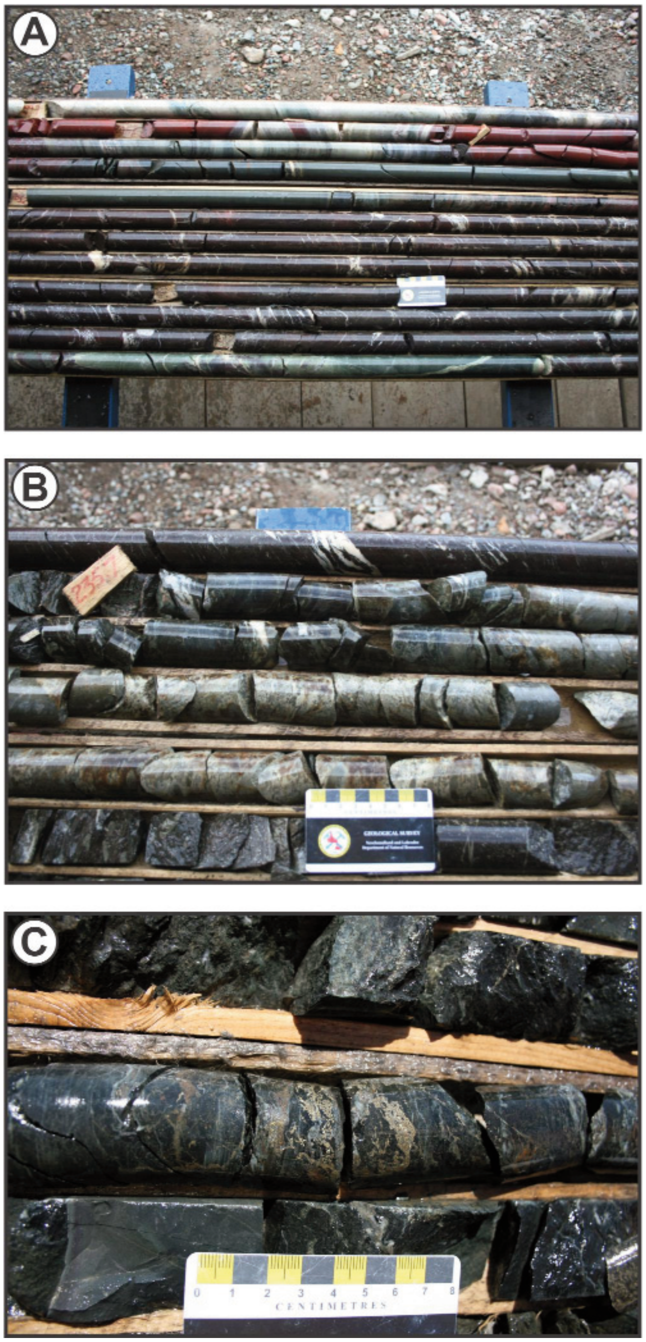


Plate 5. *Lake Bond deposit. A) Variably hematite-altered, carbonate-veined mafic volcanic rocks interbedded with felsic tuff and lesser red chert (DDH LB-92-002; ~200 m); B) White mica–pyrite alteration hosting anomalous gold mineralization developed along the upper structural contact of the mineralized sequence (DDH LB-92-002; 235 m); C) Stockwork-style, pyrite–sphalerite-dominated sulphide mineralization within strongly chloritized mafic volcanic rocks (DDH LB-92-001; 330 m).*

blages. Despite the secondary nature of the Fe-chlorite and magnetite alteration, the close spatial association of their development with zones of VMS mineralization, in addition to the distal muscovite alteration associated with barium enrichment, highlight the importance of these features as regional vectors toward mineralized zones.

SOUTHWEST SHAFT DEPOSIT

The development of localized pyritic alteration hosting anomalous copper within the stratigraphic footwall felsic volcanic rocks of the Southwest Shaft deposit highlights the potential of this unit for hosting VMS mineralization. Although the most significant mineralization observed within the examined drillhole is hosted within felsic volcanic rocks, the bulk of significant historical intersections are reported to occur within mafic volcanic rocks. The Cu–Zn-dominated mineralization at the Southwest Shaft deposit is therefore tentatively classified as a bimodal-mafic-type system (*see* Galley *et al.*, 2007), similar to that of the Gullbridge deposit. However, the lithogeochemistry of mafic volcanic rocks within the mineralized sequence displays minimal LREE-enrichment in comparison to those within the mineralized sequence of the Gullbridge deposit, and are more indicative of back-arc basin basalts (Figure 6A). As these rocks do not host significant sulphide mineralization, they may not truly be representative of the mineralized sequence, and may in fact be more comparable to the stratigraphic hanging-wall rocks; however, further work is required to investigate such relationships. In addition, the development of chlorite alteration and sodium depletion within rocks correlated with the stratigraphic hanging-wall sequence suggests that at least locally, these rocks are affected by similar hydrothermal fluids as those hosting the development of sulphide mineralization.

The presence of elevated magnetic susceptibility measurements between 350–450 m is associated with interbedded, or structurally interleaved, mafic and intermediate tuff hosting variably developed pyrite–pyrrhotite–magnetite alteration, in addition to rare red chert/iron formation (Figure 7). The extension of the magnetite and Fe–Mg-chlorite alteration across the assumed fault marking the lower limit of the mineralized sequence (the placement of which is based on lithogeochemistry), may imply that the geochemically distinct mafic volcanic rocks are actually interbedded rather than structurally juxtaposed. The proposed structure could potentially be placed at ~450 m to denote the end of the Fe–Mg-chlorite–magnetite alteration marked by the transition into intermediate volcanic rocks; however, such complexities require further detailed investigation.

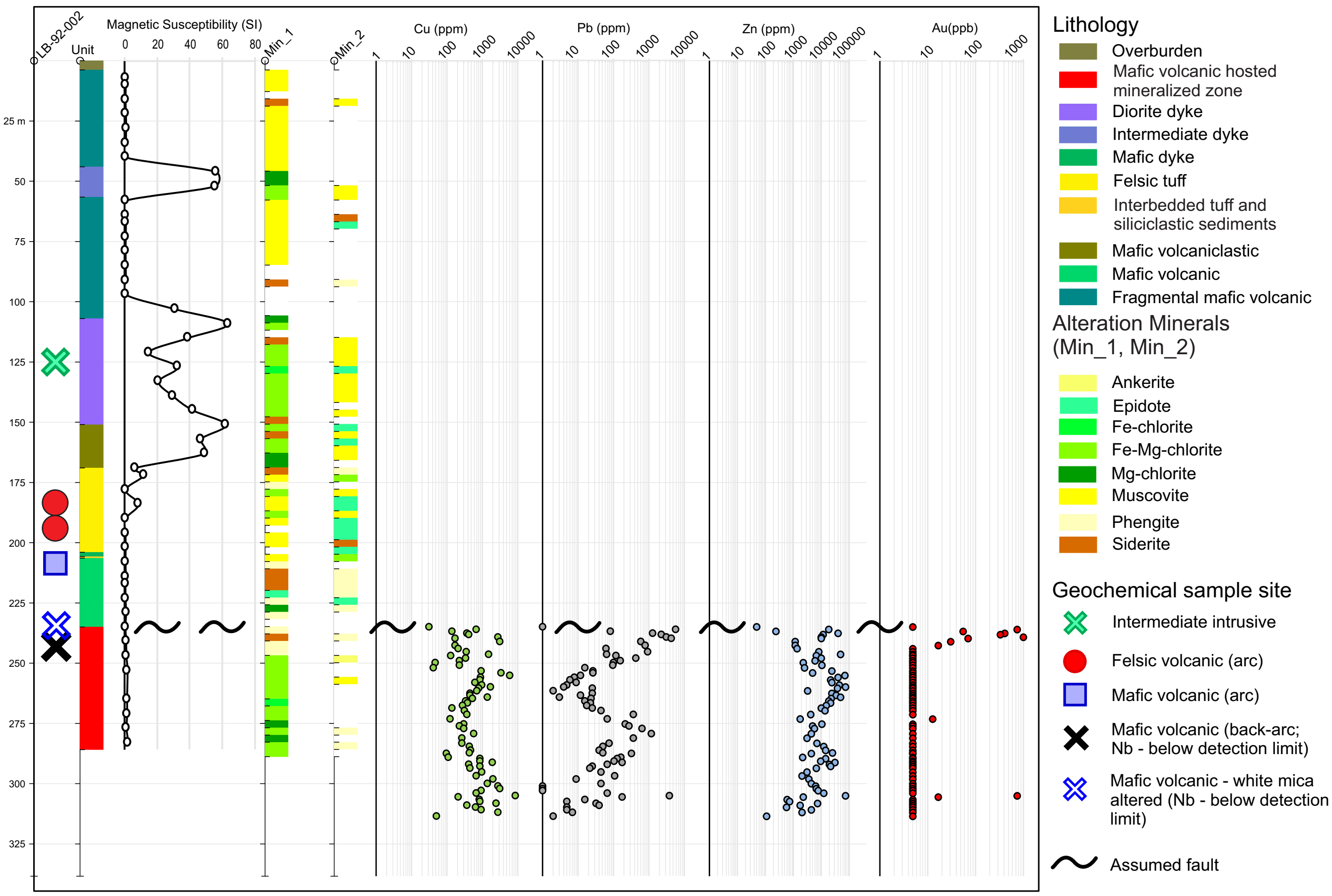


Figure 16. . *Strip log for DDH LB-92-002, shown in Figure 14, highlighting the location of geochemical sample sites and significant fault structures, lithology, magnetic susceptibility values, mineralogy as determined from spectral data (Min_1, Min_2), and select company assay data from Collins (1992).*

HANDCAMP PROSPECT

The Handcamp prospect is unique with respect to other deposits and prospects discussed herein, as it was previously classified as an example of VMS mineralization overprinted by orogenic-style gold mineralization (*e.g.*, Hudson and Swinden, 1989; Evans, 1996). However, examination of the most recent drillcore from the prospect indicates that the alteration and related mineralization are entirely related to the development of VMS mineralization, as previously suggested by Pickett *et al.* (2011).

The recent drillcore illustrates that both base- and precious-metal mineralization is associated with a structurally bound zone of exhalative-style sulphide mineralization. This zone displays a spatial association with the development of red chert, which immediately overlies, and is locally interbedded within, the mineralized sequence. The main mineralized zone is associated with phengite, muscovite, biotite and phlogopite alteration developed within metalliferous sedimentary rocks. This mineral assemblage closely resembles that developed immediately above the Gullbridge deposit farther to the south, suggesting a potential vent-proximal environment for the accompanying mineralization. Despite the predominance of back-arc mafic volcanic rocks within the prospect, minor intermediate tuff is locally noted within the hanging-wall sequence and therefore, the mineralization is classified as a bimodal-mafic-type system (*see* Galley *et al.*, 2007). With respect to the development of the precious-metal enrichment within the mineralized sequence, preliminary geochemical data indicate a correlation between barium content and gold enrichment. In addition, the highest gold values also display a spatial association with siliceous horizons containing disseminated and locally layered pyrite, suggesting a potential exhalative origin for the precious-metal mineralization. The development of exhalative mineralization, in association with muscovite alteration and barium enrichment, potentially points to the development of more significant VMS mineralization in the immediate vicinity, similar to that demonstrated in other VMS districts (*e.g.*, Peter and Goodfellow, 1996; Peter, 2003). Future exploration in the area could potentially utilize lithogeochemistry as a vectoring tool, such as the noted increase in sodium depletion with increasing depth within the rocks of the footwall sequence.

STARKES POND WEST PROSPECT

The mafic volcanic rocks hosting localized examples of exhalative-style VMS mineralization within the Starkes Pond area are correlated with the Black Gull Island division (*see* O'Brien, 2016b), and thus represent some of the youngest inferred stratigraphic volcanic rocks to host VMS mineralization in the area. Here, the host mafic volcanic rocks display geochemical signatures analogous to back-arc basin basalts, similar to that observed in the area of the Handcamp prospect. However, the alteration and associated mineralization at the Starkes Pond West prospect is distinctly different from that observed at Handcamp. The VMS mineralization is primarily hosted within tuffaceous and volcaniclastic rocks, forming stringer and rare exhalative-style mineralization. Limited data exist regarding the overall setting of the mineralization, but given the similarities with the host rocks to the Handcamp prospect, Starkes Pond West is tentatively classified as bimodal-mafic, despite the lack of evidence for felsic volcanism in the immediate area. Regardless of the lack of significant mineralization, its development within rocks correlated with the Black Gull Island division, highlights the potential of this unit for hosting VMS mineralization elsewhere in the region.

LAKE BOND DEPOSIT

The Lake Bond deposit represents an example of Zn-dominated mineralization within the study area. Here, mineralization is developed within a sequence of mafic volcanic rocks displaying geochemical similarities to those hosting the Gullbridge deposit; albeit with a lower intensity of alteration and a relative enrichment in Zn-dominated mineralization. These features may be indicative of a lower temperature, distal environment, relative to any significant vent-related hydrothermal activity. Based on the characteristics of the host rocks, and the occurrence of felsic tuff within the immediate hanging-wall sequence, the deposit is classified as a bimodal-mafic-type system (*see* Galley *et al.*, 2007). The mafic volcanic host rocks within the deposit are generally non-magnetic; however, the intrusion of a medium-grained, moderate to strongly magnetic gabbro within the footwall sequence displays a close spatial association with the development of mineralization in the area. The timing of emplacement for this unit, its relationship to the development of mineralization in the area, and its association with the strongly magnetic dykes crosscutting the deposit remain unclear. Lithogeochemistry from the latter suggests that these dykes represent possible equivalents to the Type-2 Exploits dykes (*see* Sandeman and Copeland, 2010), which are noted to form regionally extensive units farther to the east.

CONCLUSION

Detailed investigations of select VMS occurrences highlight several important features related to the development of mineralization that could assist with identification of additional prospective stratigraphic horizons within the region. Within the Gullbridge deposit, Fe-chlorite alteration displays a close spatial association with sulphide mineralization and magnetite alteration. Despite the secondary nature of these minerals, their affinity with the development of VMS mineralization highlights their potential use as vectors within these deformed hydrothermal systems.

Lithogeochemical data collected from select VMS occurrences highlight the local development of a transition from an arc to back-arc environment, which occurs in association with the development of VMS-style mineralization in the region. The development of mineralization within host rocks displaying various tectonic affinities provides supporting evidence for multiple episodes of hydrothermal activity, which likely coincides with periodic extensional events within the region. The lithogeochemical data also highlight the development of chlorite alteration and sodium depletion in the vicinity of the studied mineralization, which are characteristic features related to the development of VMS-related systems. In many instances, the chlorite alteration highlighted by the lithogeochemistry corresponds well with similar alteration identified by short wavelength infrared spectrometry, which further supports the usefulness of this technique.

Most of the mineralization identified, to date, within the region consists of stringer and stockwork-style sulphides, with little to no identified massive sulphide (*e.g.*, Gullbridge, Southwest Shaft and Lake Bond deposits). Given the tectonically disrupted nature of the host rocks to the mineralization, identifying prospective stratigraphic horizons is key in the exploration of the area. In rare instances, the development of exhalative-style mineralization provides supporting evidence for a vent proximal environment (*e.g.*, Handcamp and Starkes Pond West prospects), and highlights the potential of the associated host rocks with respect to hosting VMS mineralization.

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