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# TECTONOSTRATIGRAPHIC ARCHITECTURE AT THE KATIE VMS PROSPECT, EASTERN BURNT HILL (NTS 2D/05) MAP AREA, CENTRAL NEWFOUNDLAND; FIELD, PETROGRAPHIC, GEOCHRONOLOGICAL AND LITHOGEOCHEMICAL CONSTRAINTS: IMPLICATIONS FOR VMS EXPLORATION

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## ABSTRACT

*Felsic to intermediate volcanic rocks of Floian to Dapingian age occur in parts of the Great Burnt Lake (NTS 12A/08) and Burnt Hill (NTS 2D/05) map areas, central Newfoundland, and have been collectively termed the North Steady Pond Formation (NSPF) of the Baie D'Espoir Group. In the eastern Burnt Hill sheet, the volcanic rocks have been the focus of intermittent exploration since the late 1970s and recent exploration in the area has outlined the Katie volcanogenic massive sulphide (VMS) prospect through mechanical trenching and diamond-drilling campaigns. The exploration programs provide new data on the lithological variability and stratigraphic and tectonic settings of the rocks of the NSPF and provide further geological insight in an area of extremely limited outcrop. Historically, two main rock types were identified in the immediate area of the Katie VMS prospect; felsic to intermediate volcanic rocks (predominantly rhyolite to rhyodacite) and felsic to intermediate intrusive rocks (dominantly quartz-feldspar porphyry and leucogranite). Based on detailed studies of contact relationships, as well as chemical variations between the main rock types, these have been the focus of further detailed chemical and geochronological studies.*

*Detailed examination of diamond-drill core lithologies, combined with new lithogeochemical, isotopic and geochronological data, demonstrate that the stratigraphic section hosting the Katie VMS prospect is more complex than previously recognized, and is composed of a repeated series of metre- to decametre-scale, tectonically imbricated thrust panels, comprising either* ca. *471 Ma felsic to intermediate, mature-arc volcanic rocks of the NSPF or,* ca. *496 Ma intra-oceanic trondhjemite of the Coy Pond Complex (CPC). The contact zones between these two rock types lack primary relationships, and are everywhere structural, with thrust slices of the trondhjemite occurring well east of the presently mapped boundary between the NSPF and the CPC.*

*The revised stratigraphic interpretation has direct implications on exploration criteria for base-metal, VMS-style mineralization. Previous exploration models and associated research interpreted brecciated white-rhyolite and leucogranite as part of the NSPF, representing vent-proximal deposits and their subvolcanic feeder intrusions, respectively; however, both units are now known to represent CPC trondhjemite. Given the strong flattening associated with the emplacement of the multiple tectonic panels, and the significant rheological contrasts between massive sulphide, felsic to intermediate volcanic rocks and trondhjemite, VMS mineral exploration in the area should be cognizant that primary sulphide mounds, or any sub-seafloor accumulations of massive sulphide, are likely to have been dismembered* via *tectonism. The lithological, compositional and structural relationships are comparable to those at the Mosquito Hill and Reid (gold) prospects ~14 km to the north, perhaps indicating, as suggested by the numerous auriferous showings, an enhanced gold prospectivity in the Katie area.*

## INTRODUCTION

Central Newfoundland contains numerous examples of volcanogenic massive sulphide (VMS) deposits hosted within Cambrian–Ordovician volcanic arc and back-arc basin remnants of the Dunnage Zone. Although the Middle Ordovician North Steady Pond Formation (NSPF) of the Baie D'Espoir Group has long been recognized to have favourable geological characteristics to host base-metal, VMS-style mineralization, the only significant base-metal mineralization discovered is the Katie VMS prospect. The prospect is hosted by felsic to intermediate volcanic rocks of the NSPF and is located within the Burnt Hill map area (NTS 2D/05, Figure 1). Other prospective portions of the NSPF outcrop in the southeastern portion of the adjacent map area to the west (NTS 12A/08).

Exploration in this part of central Newfoundland is hampered by flat topography and thick blankets of glacial till resulting in very few outcrop exposures. Early exploration focused on chromite potential of the Pipestone Pond and Coy Pond ultramafic complexes (*e.g.*, Willis, 1901; Moore, 1930), and it was not until the late 1970s and the 1980s that the area became the focus of mineral exploration work targeting base metals, akin to the VMS-style of deposit. Regional lake-sediment geochemical studies (Butler and Davenport, 1978) and regional mapping programs (1:50 000 scale, *e.g.*, Colman-Sadd, 1985) resulted in identifying prospective felsic volcanic rocks in the region, providing the impetus for the subsequent focused mineral exploration activity.

This report presents the results of detailed field observations and stratigraphic analysis of exploration trenches and of diamond-drill holes (DDHs) in the area of the Katie VMS prospect. New interpretations of the local tectonostratigraphic architecture are presented, utilizing new lithogeochemical, Sm–Nd isotopic, and U–Pb geochronological data. The data advance our understanding of the tectonic evolution of the area, and have important implications on mineral exploration models and exploration techniques used in the region. All ages referred to use the International Chronostratigraphic chart v2021/10 of Cohen *et al.* (2013).

## PREVIOUS WORK

Following very early geological investigations (*e.g.*, Cormack, 1823; Jukes, 1842), the study area did not see much systematic geological investigation until the 1960s and 1970s, when the Geological Survey of Canada conducted regional aeromagnetic surveys and 1:250 000-scale mapping in the area (Anderson and Williams, 1970). These surveys were followed by systematic and detailed lake-sediment geochemical surveys (Butler and Davenport, 1978) as well as 1:50 000-scale regional mapping programs by the Geological Survey of Newfoundland and Labrador (GSNL; Colman-Sadd, 1980a, 1985; Blackwood, 1982; Colman-Sadd and Swinden 1984a, 1989; Swinden, 1988; Colman-Sadd and Russell, 1988). In the early 2000s, a M.Sc. thesis project was initiated to explore the VMS potential of the Katie property and the Baie D'Espoir Group; however, the project was never finished and the only report of work completed is found in Dean and Wilton (2002). In more recent years, geological investigations by the GSNL have involved a systematic till-geochemical survey of the area (Campbell, 2019), and a project examining the relative ages and controls on gold mineralization (*e.g.*, Sandeman *et al.*, 2012, 2013). The GSNL has also conducted detailed, regional geophysical surveys over the study area (G. Kilfoil, unpublished data, 2022). Results and reports from these programs (*e.g.*, Colman-Sadd, 1980b; Colman-Sadd and Swinden 1981, 1984b; Colman-Sadd *et al.*, 1992; Sandeman *et al.*, 2012, 2013) have advanced our understanding of the tectonic architecture in the area.

Early mineral exploration activities focused on the chromite potential of the ultramafic lithologies of the Pipestone Pond Complex (*e.g.*, Willis, 1901; Moore, 1930). It was not until regional mapping programs (*e.g.*, Colman-Sadd 1980a, 1981, 1985) identified sequences of felsic to intermediate volcanic rocks of the NSPF, Baie D'Espoir Group, that the mineral potential for base-metal, VMS-style, mineralization was recognized. Colman-Sadd and Swinden (1981) highlighted this potential: *"The Huxter Pond Volcanic belt has only recently been mapped and little is known of its economic potential. Sericitic alteration and minor pyrite mineralization have been noted at several localities and samples from some of these localities have yielded slightly anomalous amounts of base metals and silver (Colman-Sadd, 1981). The abundance of rhyolitic pyroclastic rocks and flows interbedded with water-laid sedimentary rocks strongly suggests an environment favourable for the deposition of massive sulphides"*.

In 1981 and 1982, St. Joe Canada Inc. carried out an airborne electromagnetic–magnetic (AEM) survey over these newly identified felsic to intermediate volcanic to volcanosedimentary rocks in the Bruce Pond area with the goal of identifying base-metal sulphide deposits. The survey identified 85 discrete AEM conductors, some of which were coincident with Cu–Pb–Zn soil anomalies (Huxhold, 1982). Despite favourable results, there is no further record of additional exploration work by St. Joe Canada Inc. in the area.

Rio Algom Exploration Inc. conducted exploration programs targeting base and precious metals in the area from 1985 through to 1989 (MacGillivray, 1986; Robertson, 1986; Bonham, 1988a, b). The company targeted and drilled 14 DDHs throughout the NSPF. Results of this exploration effort identified a number of sulphide showings (pyrite–pyrrhotite), soil- and lake-sediment anomalies, as well as a number of ground electromagnetic (EM) conductors. Most drillhole intercepts indicated that the EM anomalies were related to graphitic or pyrrhotite-bearing argillite within the volcanic successions; however, some of the EM anomalies were attributed to sulphide mineralization within volcanic rocks. The best result reported from the drilling campaign was from hole 2801-87-13 where a 22-cm interval (16.72–16.94 m) of massive pyrrhotite, within silicified andesite, returned 0.6% Zn, 1.0% Pb, 0.24% Cu and 110g/t Ag

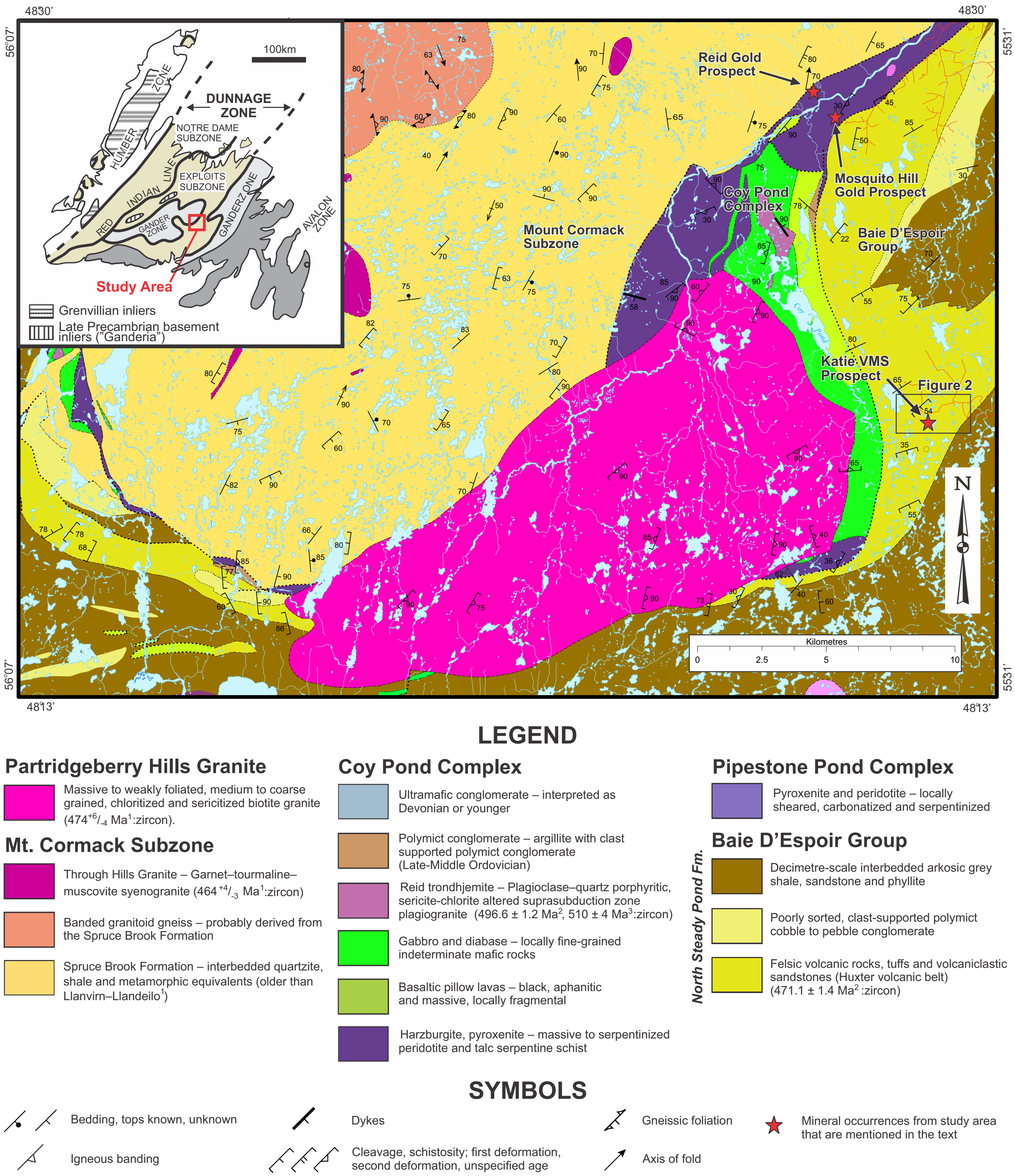

**Figure 1.** *Simplified geological map of the study area (adapted after Colman-Sadd, 1985 and Swinden, 1988). Ages quoted in legend are from: 1) Colman-Sadd* et al. *(1992); 2) this study; 3) Sandeman* et al. *(2012).*

(Bonham, 1988a). Unfortunately, the assay results were not overly favourable and the company halted work in the area (Bonham, 1988b).

Based upon the presence of a number of untested AEM conductors, combined with the presence of pyrite and pyrrhotite mineralization and anomalous zinc in lake-sediment samples, BHP Minerals acquired the property and conducted mineral exploration work in 1993 and 1994 (Williamson, 1993, 1995). Initial work consisted of geochemical sampling as well as an IP/resistivity geophysical survey that resulted in the identification of some geochemical (Zn–Cu–Au), as well as chargeability and resistivity anomalies. Follow up studies of trenching (13 trenches) and drilling of eight DDHs (Williamson, 1995) were completed. Some of the DDHs were collared in the area currently known to host the Katie VMS prospect. Trenching resulted in the discovery of several large boulders with mineralized quartz veins having sphalerite ± pyrite, galena, chalcopyrite and arsenopyrite. Drilling targeting IP/resistivity anomalies intersected sulphide-bearing quartz veins, whereas holes targeting AEM conductors invariably intersected graphite-bearing shales. Diamond-drill hole number 7 (LG-93-07) intersected a small section of dacitic tuff with minor quartz veining and sericite and quartz alteration (Williamson, 1995). BHP geologists interpreted the sulphide mineralization, combined with the sericite and quartz alteration, as being a contact alteration *via* quartz veins related to the intrusion of granitic bodies (Williamson, 1995).

Following a hiatus in exploration, the ground was staked by Black Bart Prospecting Group in the late 1990s and early 2000s, who conducted soil- and till-geochemical surveys and prospecting. Black Bart discovered a number of high-grade sulphide-rich boulders in the vicinity of what is now known as the Katie VMS prospect. This discovery led to renewed interest in the area resulting in Gallery Resources Ltd. optioning the property in 2000. Following up on the discovery of the high-grade boulders (*e.g.*, up to 25% Zn, 3.5% Pb, 1.66 % Cu; *see* French and Janes, 2004), Gallery conducted geochemical (lake-sediment and soil), MMI and geophysical surveys (IP, Gravity, VLF-EM), as well as diamond drilling focusing on four areas (Black Bart/Katie, Bruce Pond Epithermal Zone, Macdonald Zone and the Tall Tree Zone). In total, Galley completed 63 DDHs in the area.

Alterra Resources Inc. conducted exploration in the area in 2009 and 2010 (Jacobs and Delaney, 2009; Delaney, 2010) consisting of trenching (800 m), soil sampling and geological mapping. The trenching program extended an earlier trench by BHP and resulted in the discovery of significant mineralization in the newly trenched area (this discovery is the current location of the Katie VMS prospect). Subsequently, the company conducted a four DDH program, three holes of which directly targeted extensions of the mineralization discovered in the trenching. Unfortunately, the DDHs failed to intersect any significant massive-sulphide mineralization, although one zone of sericite–silica alteration with minor mineralization was intersected in DDH SM-09-04, located to the southeast of the main Katie Zone (Figure 2; Delaney, 2010).

Altius Resources Inc. conducted exploration in the area during 2014 and 2015 (Patey, 2016). Following up on compilations of previous mineral-exploration activities, Altius conducted prospecting and trenching in the general vicinity of the Katie VMS prospect. As with previous exploration efforts, trenching was hampered due to thick till cover; hence some of the attempted trenches did not reach bedrock. Trenches excavated in close proximity to the original Katie trench confirmed the presence of quartz–sericite alteration and identified some new base-metal mineralized zones (*e.g.*, trenches N3, 15A and S5; Patey, 2016).

## REGIONAL SETTING

The study area is in close proximity to one of the boundaries of the Exploits Subzone of the Dunnage Zone with the Gander Zone, and lies near the structural base of the Exploits Subzone, where it occurs on top of an oval dome of the Gander Zone basement, the latter of which is represented in the area by the Early Ordovician Mt. Cormack Subzone (Colman-Sadd *et al.*, 1992; Figure 1). In the eastern Burnt Hill map area (NTS 2D/05), the major geological units include, from west to east: the Mt. Cormack Subzone; the Ordovician Partridgeberry Hills Granite (PHG); the Late Cambrian Coy Pond Complex ophiolitic rocks and; the Ordovician felsic to intermediate volcanic, volcaniclastic and sedimentary rocks of the Baie D'Espoir Group. These are all intruded by massive, Silurian–Devonian granitic intrusions (Figure 1; *e.g.*, Colman-Sadd, 1985). Late Silurian (Ludlow–Pridoli) calcareous muscovitic sandstone and siltstone have been identified ~1 km northeast of the Burnt Hill map area (Donovan *et al.*, 1997); however, their relationship with the Cambrian–Ordovician rocks are not known. Each of these units are briefly discussed below; for more details on the regional geology the reader is referred to Colman-Sadd and Swinden (1984a, b), Colman-Sadd (1985), Colman-Sadd *et al.* (1992), Valverde-Vaquero *et al.* (2006) and Sandeman *et al.* (2012, 2013).

The Mt. Cormack Subzone, an oval-shaped, Ganderian basement dome, is predominantly composed of the Spruce Brook Formation; a unit dominated by chlorite to biotite metamorphic zone, bedded psammite and pelite, which are concentrically arrayed around a higher metamorphic-grade core consisting of sillimanite and K-feldspar-bearing gneiss

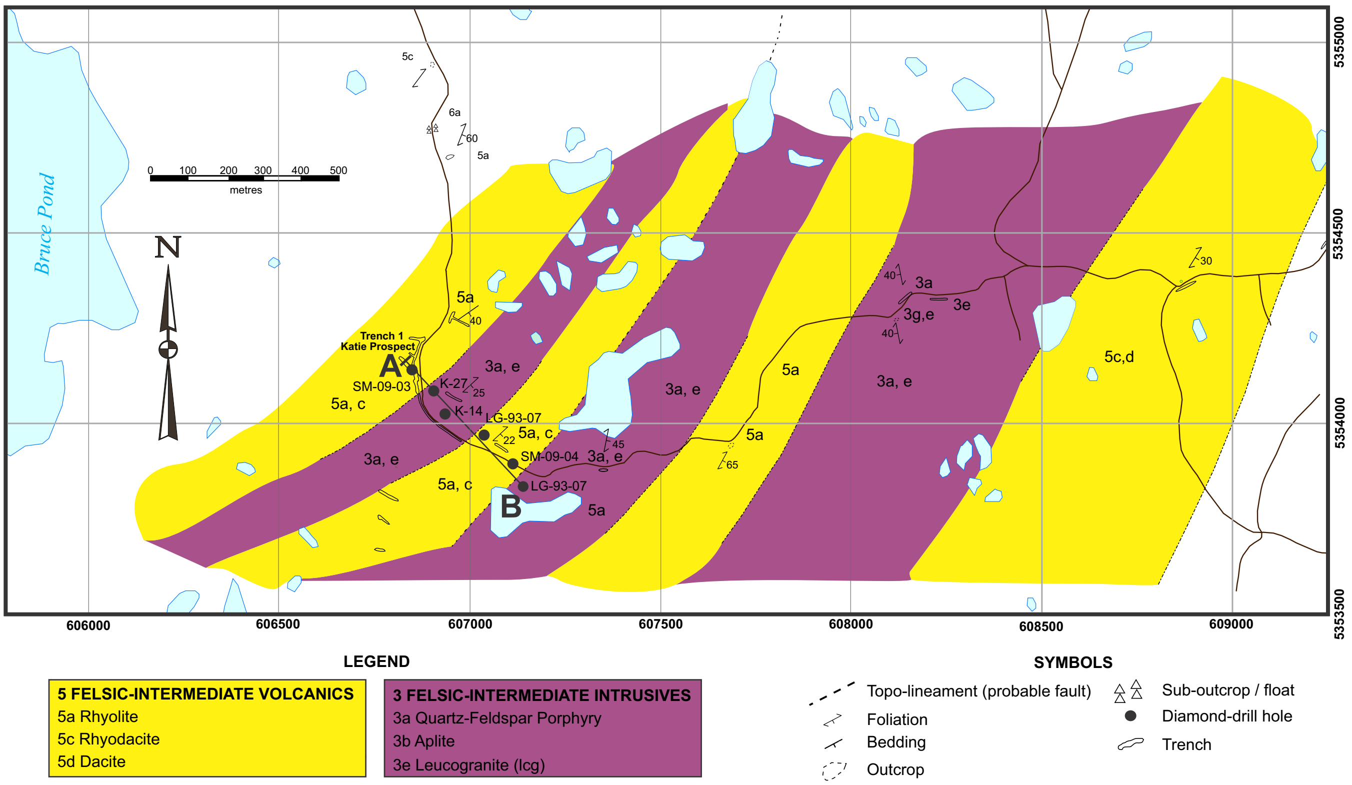

**Figure 2.** *Geological map from Alterra Resources showing identification of the distinct rock types (felsic to intermediate volcanic rocks* vs. *felsic to intermediate intrusive rocks). Modified from Jacobs and Delaney (2009).*

and migmatite, in which sedimentary structures have been largely obliterated (Colman-Sadd, 1985; Colman-Sadd *et al.*, 1992). In addition to the gneiss, the core is intruded by anatectic, quartz-feldspar–muscovite ± garnet–tourmaline-bearing granitoid rocks of the Middle Ordovician (464 +4/-3 Ma) Through Hills Granite (Colman-Sadd, 1985; Colman-Sadd *et al.*, 1992; Valverde-Vaquero *et al.*, 2006).

To the east of the Mt. Cormack Subzone, and structurally overlying the Spruce Brook Formation, are rocks of the CPC (Colman-Sadd, 1985; Colman-Sadd *et al.*, 1992; Sandeman *et al.*, 2012, 2013). Where the contact is not truncated by the Partridgeberry Hills Granite (474 +6/-3 Ma, Colman-Sadd *et al.*, 1992), or structurally telescoped, the CPC locally preserves a relatively complete ophiolite stratigraphy with peridotite outcropping in the west and pillow lavas, dykes, gabbro and marine sedimentary rocks outcropping to the east (Colman-Sadd, 1985). An altered trondhjemite also outcrops as an irregularly shaped intrusion crosscutting gabbro, diabase and basalt to the north of Coy Pond (Figure 1, Colman-Sadd, 1985). Comparable trondhjemitic intrusions also occur in and around the Reid (gold) prospect to the north (Figure 1: Sandeman *et al.*, 2012).

To the east and south of the CPC, rocks of the NSPF, Baie D'Espoir Group, form an arcuate S-shaped belt of rocks composed of clastic sedimentary, volcaniclastic and felsic to intermediate volcanic rocks (Colman-Sadd, 1985), partially wrapping around the Mt. Cormack Subzone and occurring both to the east and west of the Partridgeberry Hills Granite. Extensive till cover precludes detailed descriptions of field relationships, but based on regional aeromagnetic patterns the stratigraphy is likely complicated by folding and faulting. More detailed descriptions of rock units and contact relationships are provided below based on detailed examination of diamond-drill core and exploration trenches.

## LOCAL GEOLOGY AND VMS-STYLE MINERALIZATION

Based upon government mapping (*e.g.*, Colman-Sadd, 1985) and recent mineral exploration activity in the region (*e.g.*, Delaney, 2010; Patey, 2016 and references therein), geological units in the vicinity of the Katie VMS prospect are assigned to the NSPF of the Baie D'Espoir Group, with mafic to ultramafic rocks of the CPC occurring to the west (Figure 1). In the immediate area surrounding the Katie VMS prospect, units are described as being predominantly composed of deformed felsic to intermediate tuffs and lapilli tuffs, quartz porphyritic rhyolite, local volcaniclastic argillite and siltstone, with medium-grained leucogranite and fine-grained, aphanitic, quartz ± feldspar porphyritic rhyolite. Minor fault-related breccia, or debris flows, were also identified. The medium-grained leucogranite was previously interpreted as either: 1) young granitic intrusions correlated with the Partridgeberry Hills Granite (*e.g.*, Williamson, 1995) or; 2) probable subvolcanic granitic feeders to the quartz ± feldspar porphyritic rhyolite and tuffs that host the Katie VMS prospect (*e.g.*, Wilton, 2001; Delaney, 2010; Patey, 2016).

The paucity of outcrop in the vicinity of the Katie VMS prospect means that the current study relied heavily on detailed trench mapping and examination of a number of diamond-drill holes. This work results in a significant reinterpretation of lithological units and their relationships and has implications for mineral potential and exploration in the area. Although field traversing in the immediate vicinity of the Katie VMS prospect was of limited value, traversing of the east–west-trending unit identified as the NSPF to the west of the Partridgeberry Hills Granite (Figure 1), further aided in classifying the rocks and their relationships.

For the focus of this paper, six main lithological units have been defined through field and drillcore observations. These include:

1) strongly foliated and deformed quartz ± feldspar crystal phyric rhyolite to rhyodacite (Unit 1A);
2) massive and homogeneous quartz ± feldspar porphyritic felsic to intermediate volcanic rocks (Unit 1B);
3) fine-grained, dark, quartz and feldspar siliceous volcanic/rhyolite to the west of PHG (Unit 1C);
4) volcaniclastic graphitic argillite to siltstone (Unit 1D);
5) a fine-grained, siliceous and locally brecciated plagiogranite/trondhjemite (Unit 2A); and,
6) a medium-grained, locally brecciated plagiogranite/trondhjemite (Unit 2B).

As Unit 1A, B are chemically identical (*see* below), and to simplify discussion, they are combined and described as 'felsic to intermediate, quartz ± feldspar porphyritic volcanic' (Unit 1 A/B). Unit 2A, B are referred to as fine-, and medium-grained trondhjemite, respectively. As detailed below, Unit 1A–D represent rocks of the NSPF, whereas Unit 2A, B represent rocks of the CPC.

## TRENCH #1 – KATIE VMS PROSPECT

The host rock is dominantly strongly foliated, variably altered, massive and homogeneous quartz ± feldspar porphyritic rhyolite (Unit 1A, B; Plate 1). Foliation is north-northeast to northeast-trending with dips ranging from 24–78° to the southeast (defined by white mica (sericite; Plate 1). When unaltered, this unit is composed of dark-grey rhyolite with glassy quartz crystals (up to 5 mm diameter) distributed throughout the rock. In contrast, where altered and mineralized, the unit is light beige and contains stringers and disseminations of pyrite, sphalerite, galena and chalcopyrite (Plate 1). Moderate to strong alteration occurs as silicification, white mica (sericite) and local fuchsite with increasing intensity in proximity to mineralization (Plate 1).

In thin section, the unit is composed of quartz phenocrysts in a groundmass of fine-grained quartz and sericite, with accessory phases including zircon (Plate 2). The quartz phenocrysts commonly display embayed textures and reaction rims; both indicative of magmatic corrosion and resorption of previously stable crystals within the melt (Plate 2). The groundmass, as well as some of the quartz phenocrysts, have recrystallization textures and commonly display undulose extinction.

Mineralization is dominated by sulphide stringers and disseminations throughout the host quartz ± feldspar porphyritic rhyolite; ubiquitously associated with silicification and sericitization (Plate 2). Sulphide phases at the main showing are dominated by sphalerite, with lesser galena, chalcopyrite, pyrite and pyrrhotite (Plates 1 and 2). Selective grab samples from this study returned up to 11.1% Zn, 5.4% Pb, 0.3% Cu, 149 ppb Au and 31.8 g/t Ag, with additional enrichments in As, Sb and Bi. Trenching by Alterra Resources Inc., in 2009, returned grades up to 10.7% Zn, 0.38% Pb, 0.196 % Cu, 33.4 g/t Ag and 1.13 g/t Au over 1.26 metres (Alterra channel sample 3009; Delaney, 2010) as well as 11.4% Zn, 0.45% Pb, 0.194% Cu, 47.9 g/t Ag and 1.83 g/t Au over 1.83 m (Alterra channel sample 3014; Delaney, 2010).

Although not observed in outcrop in this study due to reclamation of many of the trenches, mineral-exploration company mapping had also identified many exposures of 'leucogranite' and 'quartz-feldspar porphyry' (herein interpreted as equivalent to Unit 2B trondhjemite) within extensions of Trench #1 and in other adjacent trenches (Figure 2). These rocks were interpreted to represent subvolcanic feeders to the rhyolitic units (*e.g.*, Wilton, 2001; Delaney, 2010; Patey, 2016); an interpretation at odds with results of the current study (*see* below).

## DIAMOND-DRILL CORE RELATIONSHIPS

Detailed analysis of one drillhole (K-14), coupled with geochemical, geochronological and isotopic analysis on the various units, helped to define units and contact relationships (Figure 3). Based on the contained rock types and their mutual relationships, the drillhole is divided into six distinct rock packages (P-1 through 6; Figure 3). In addition, a series of other diamond-drill holes in the Katie prospect area were re-logged to produce a pseudosection of the local geological architecture (Figure 4).

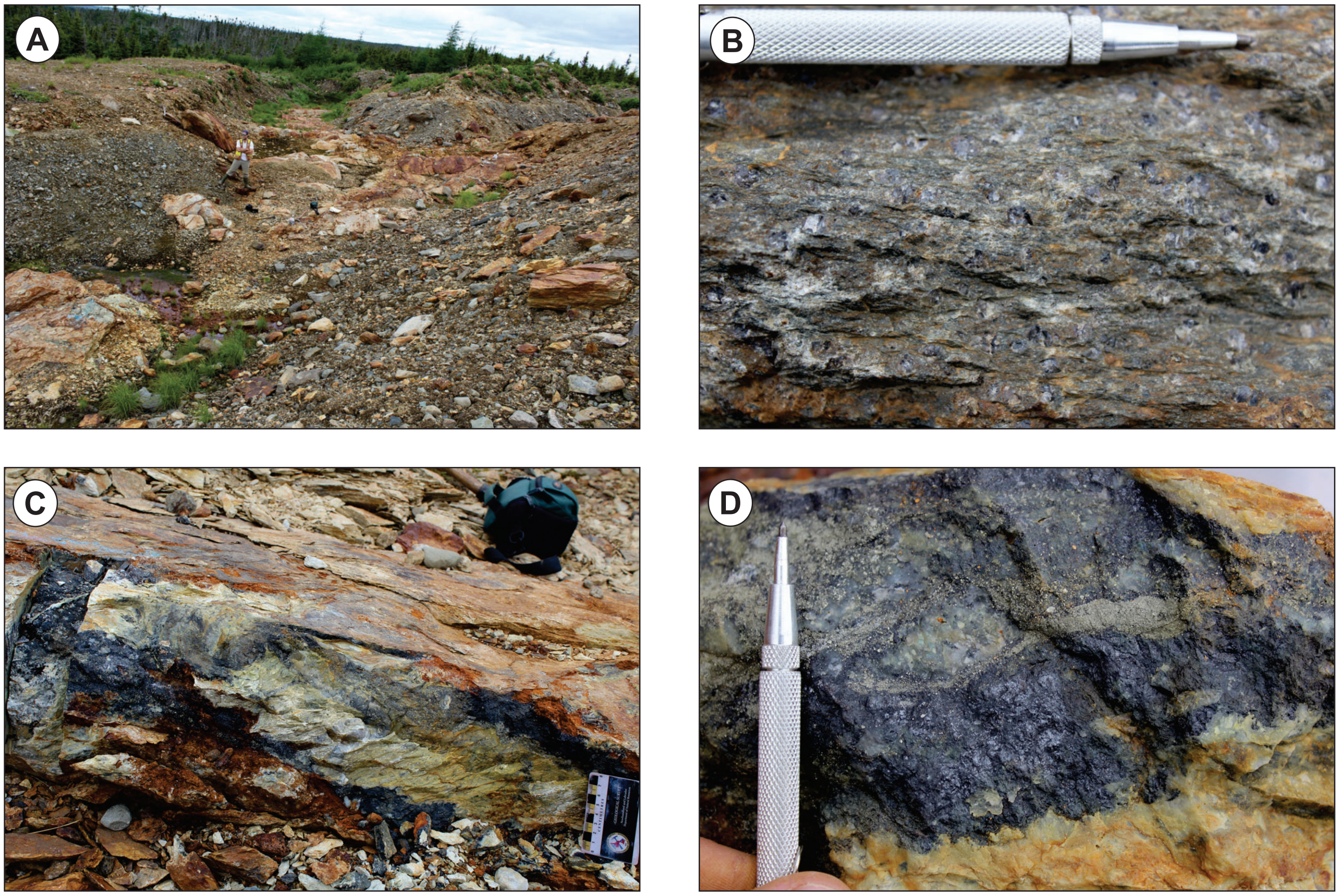

**Plate 1.** *Felsic to intermediate volcanic host (Unit 1A) to the Katie VMS prospect - Trench #1. A) Overview of trench showing bleached volcanic rocks with sulphide staining; B) Relatively unaltered, quartz-porphyritic felsic to intermediate volcanic unit; C) Silica–sericite-altered felsic to intermediate volcanic with stringers of sphalerite ± galena/chalcopyrite; D) Close-up of mineralization in C.*

### Diamond-drill Hole K-14

In diamond-drill hole K-14, thick overburden/till (~8 m) passes downhole into ~14 m of a strongly foliated, felsic to intermediate, quartz ± feldspar porphyritic volcanic rock (tuff to rhyolite/rhyodacite) of Unit 1A, B (P-1, Figure 3; Plate 3A). Disseminated and stringer sulphide occur throughout the unit and are dominantly composed of cubic pyrite with minor amounts of sphalerite. Sulphides are associated with patches of relatively coarser grained, recrystallized quartz with common undulose extinction. Sulphide stringers vary from being parallel/subparallel to discordant to the foliation. These rocks display increased silica–sericite–pyrite and locally fuchsite alteration associated with sulphide mineralization, and sulphide concentrations increase downhole, with a small interval of semi-massive, blebby pyrite where associated silicification marks the lower contact (Figure 3). The lower contact with a massive, plagioclase- and quartz-rich siliceous unit is very sharp with a 5-cm-wide intensely sheared interval.

The next lowest interval, P-2, consists of approximately 5.5 m of a massive, white, fine-grained, non-foliated silicified unit composed of interlocking quartz and feldspar crystals; herein termed a fine-grained trondhjemite (Unit 2A, Figure 3; Plate 3B). This unit contains veinlets or filled microfractures composed of sericite–silica and pyrite (Plate 3B). Feldspar crystals are commonly altered to sericite, and many of the quartz crystals display undulose extinction indicative of deformation (Plate 3). The lower contact of the fine-grained trondhjemite is gradational, passing into an approximately 14 m interval of a medium-grained, massive and homogenous trondhjemite (Unit 2B, Figure 3) easily identified because of characteristic blue-quartz crystals. As with Unit 2A, this rock is composed of interlocking quartz with undulose extinction and sericite-altered plagioclase grains (Plate 3C). Locally, mixtures of chlorite, sericite, carbonate and granular recrystallized quartz occupy fracture spaces. This interval of Unit 2B has a very sharp lower contact with an approximately 4 m interval of fine-grained, white, brecciated to fractured trondhjemite (Unit 2A, Figure

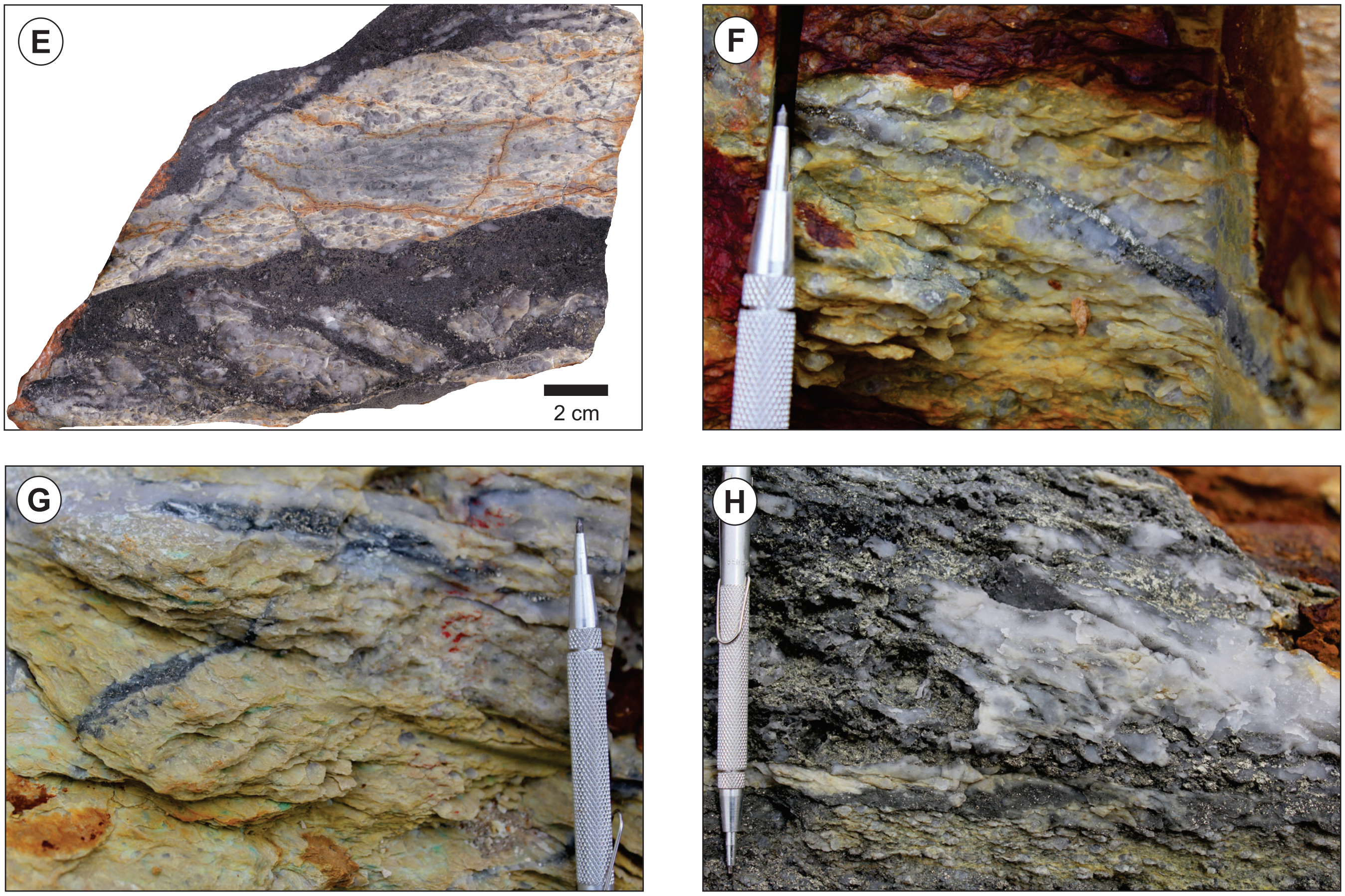

**Plate 1 (continued).** *Felsic to intermediate volcanic host (Unit 1A) to the Katie VMS prospect - Trench #1. E) Sample (15JH070) containing 11.1% Zn, 5.4% Pb, 0.3% Cu, 149 ppb Au and 31.8g/t Ag. Alteration consists of silica–sericite–pyrite; F) Bleached felsic to intermediate quartz-porphyritic volcanic rock with silica–sulphide stringer; G) Bleached felsic to intermediate quartz-porphyritic volcanic rock with silica–sulphide stringer; note fuchiste alteration; H) Intense silica–pyrite alteration of the felsic to intermediate volcanic host rock.*

3) that displays significant fracturing with chlorite, quartz and locally carbonate and pyrite infillings. The lower contact of P-2 is very sharp and abrupt, represented by broken core potentially defining a fault zone (~44 m depth, Figure 3).

Below P-2 trondhjemite (Unit 2A) is a thick (~13.5 m) interval of altered, dark-grey, homogenous quartz + feldspar porphyritic felsic to intermediate volcanic rock (Unit 1A, B from ~44–57.5 m in DDH K-14, Figure 3 and Plate 3E) of P-3. In thin section, the unit is pervasively altered with plagioclase partly replaced by sericite and a groundmass composed of fine-grained, recrystallized quartz (Plate 3E). Minor carbonate alteration occurs throughout with sparse disseminations of pyrite and magnetite. Although the interval is only weakly foliated throughout, its base close to the lower contact displays a mylonitic fabric indicative of shearing (Figure 3). In addition, the very base of the unit is marked by a mm-scale fault gouge indicative of subsequent brittle deformation along the contact.

Below P-3, is an approximately 22.5 m interval (57.7–80 m) of white, fine-grained trondhjemite (Unit 2A of P-4, Figure 3; Plate 3F). This interval is strongly fractured; with most fractures being annealed by sericite, chlorite and locally pyrite (Plate 3F). Plagioclase crystals are altered to sericite, whereas most of the quartz crystals display undulose extinction and recrystallization. Patchy chlorite alteration occurs throughout. The lower contact of P-3 is marked by a narrow interval (~1 m) of an unfoliated, massive mafic unit.

The fine-grained trondhjemite (Unit 2A, P-4) passes downhole into another interval (22.5 m; 80–102.5 m) of a very-fine-grained, well-foliated, quartz ± feldspar porphyritic felsic to intermediate volcanic unit (Unit 1A, B) of P-5. The groundmass is composed of very fine-grained quartz and feldspar, with minor mm-scale phenocrysts of quartz. The unit is intensely altered, with sericite alteration defining the foliation (Plate 3G). Crosscutting veins of coarser grained recrystallized quartz, biotite/phlogopite, chlorite

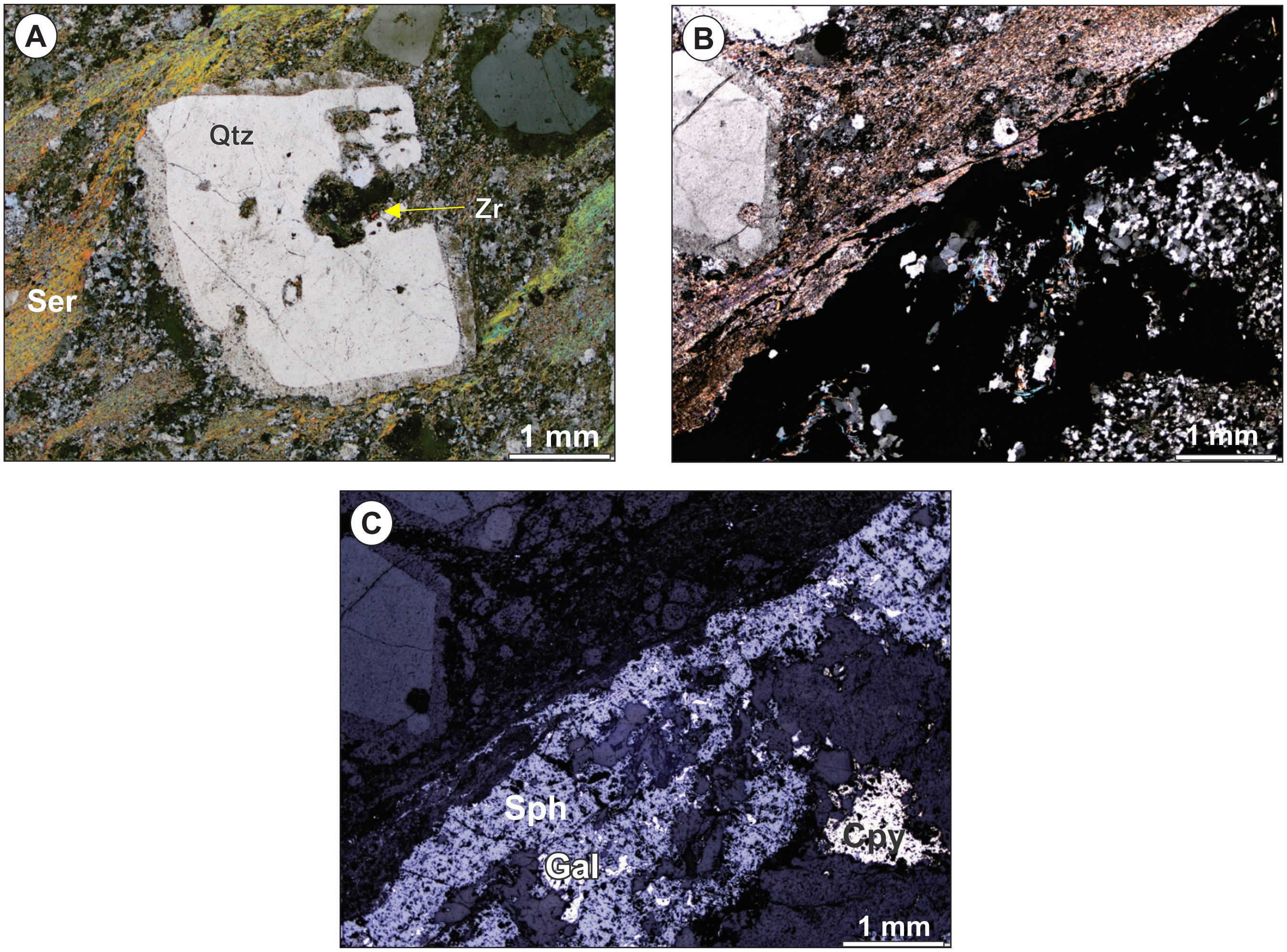

**Plate 2.** *Photomicrographs of the felsic to intermediate volcanic host (Unit 1A) to the Katie VMS prospect - Trench #1. Sample 15JH070. A) Quartz-porphyritic, sericite-altered felsic to intermediate rhyolite. Note the embayments and reaction rims on the quartz crystals indicating that they were unstable in the magma; B) Quartz-porphyritic rhyolite cut by a silica–sericite–sulphide vein; C) Same as B in reflecting light. Sulphide vein composed of sphalerite (Sph), galena (Gal) and chalcopyrite (Cpy).*

and carbonate, along with variable amounts of pyrrhotite and minor chalcopyrite are common (Plate 3G). The lower contact and base of this unit is marked by an increase in strain as illustrated by a strongly developed foliation, as well as quartz veining (Figure 3).

Below the felsic to intermediate volcanic rocks of P-5, the remainder of the DDH (through to 156 m) is composed of both brecciated and fractured, white, fine-grained trondhjemite and the fine- to medium-grained blue-quartz trondhjemite (Plate 3H). As noted in P-2 and 4, this interval varies from being very siliceous and very fine-grained, through to a blue-quartz eye porphyritic trondhjemite. Contacts between the fine- and medium-grained phases are gradational.

## SCHEMATIC CROSS-SECTION – KATIE AREA

Based upon the detailed re-examination of DDH K-14, coupled with study of other drillholes in the vicinity of the Katie VMS prospect, a schematic cross-section (northwest–southeast orientation, viewing northeast) illustrates the tectonostratigraphy of the host rocks of the Katie VMS prospect (Figure 4). The cross-section shows a repeated sequence of northeast-trending, southeast-dipping (present day orientation) packages of distinct rock units consisting of felsic to intermediate volcanic rocks (Unit 1A, B) and fine- to medium-grained (Unit 2A, B) trondhjemitic rocks. These packages of rocks are separated by discrete and thin zones consisting of fault gouge, strongly foliated felsic schist or mylonite that are interpreted to represent north-

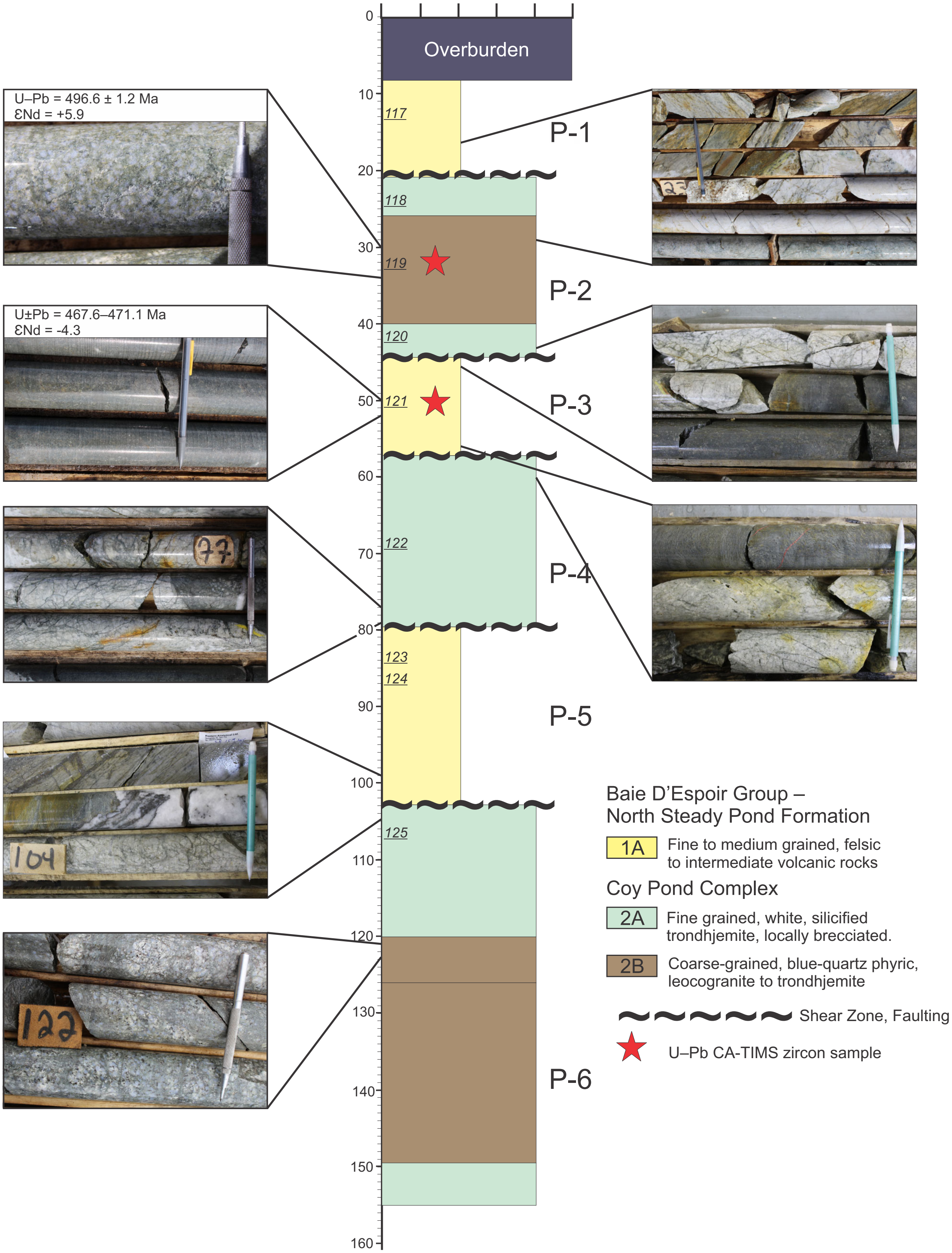

**Figure 3.** *Schematic drillhole stratigraphic column for DDH K-14 from the Katie VMS prospect. Underlined numbers (e.g., 121) represent location of samples (e.g., JHC-15-121) and are cross referenced with Plate 3.*

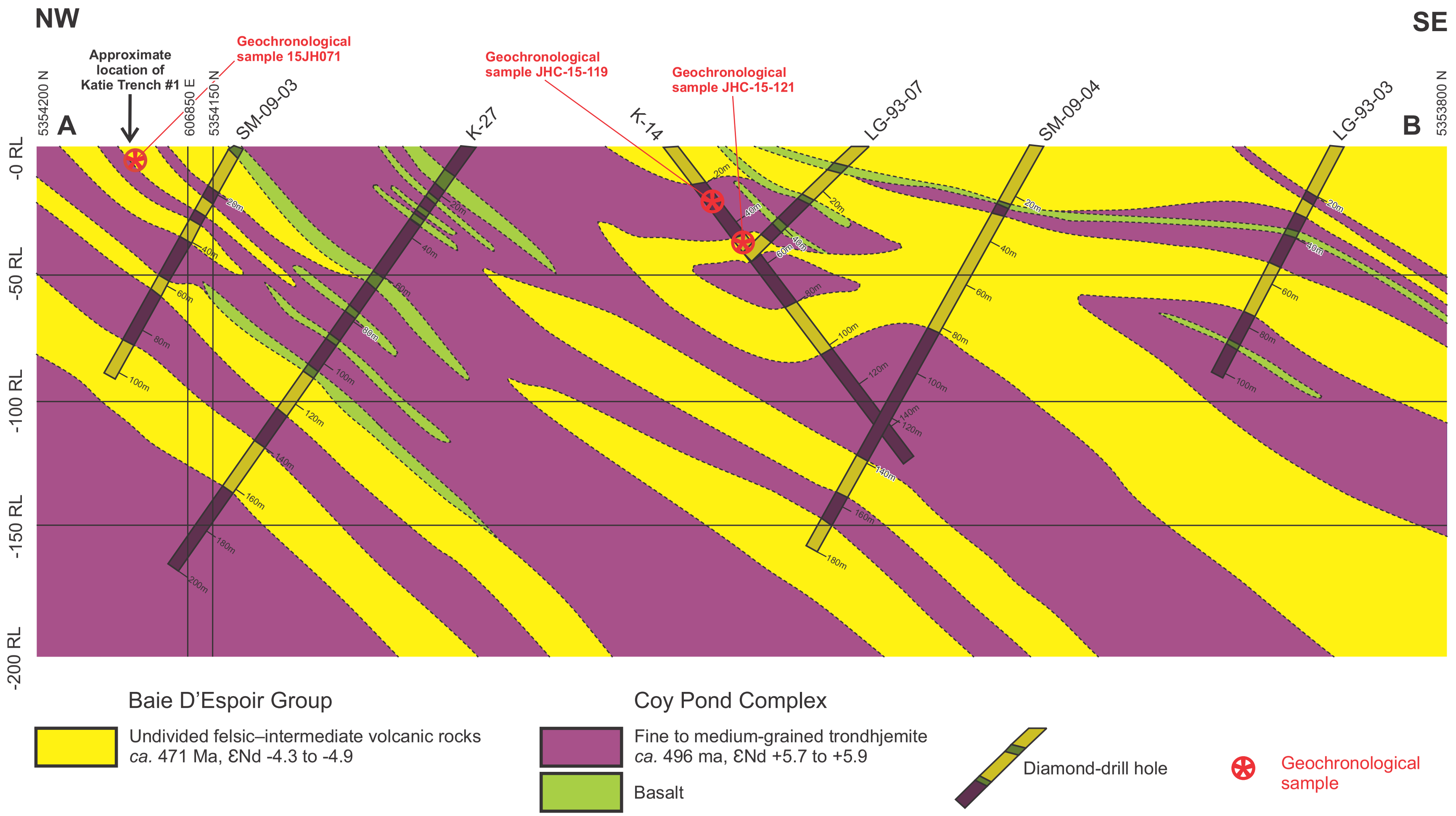

**Figure 4.** *Schematic northwest–southeast cross-section (looking northeast) through the host rocks of the Katie VMS prospect illustrating the repeated southeast-dipping imbricate thrust packages of NSPF felsic to intermediate volcanic rocks with trondhjemite of the CPC.*

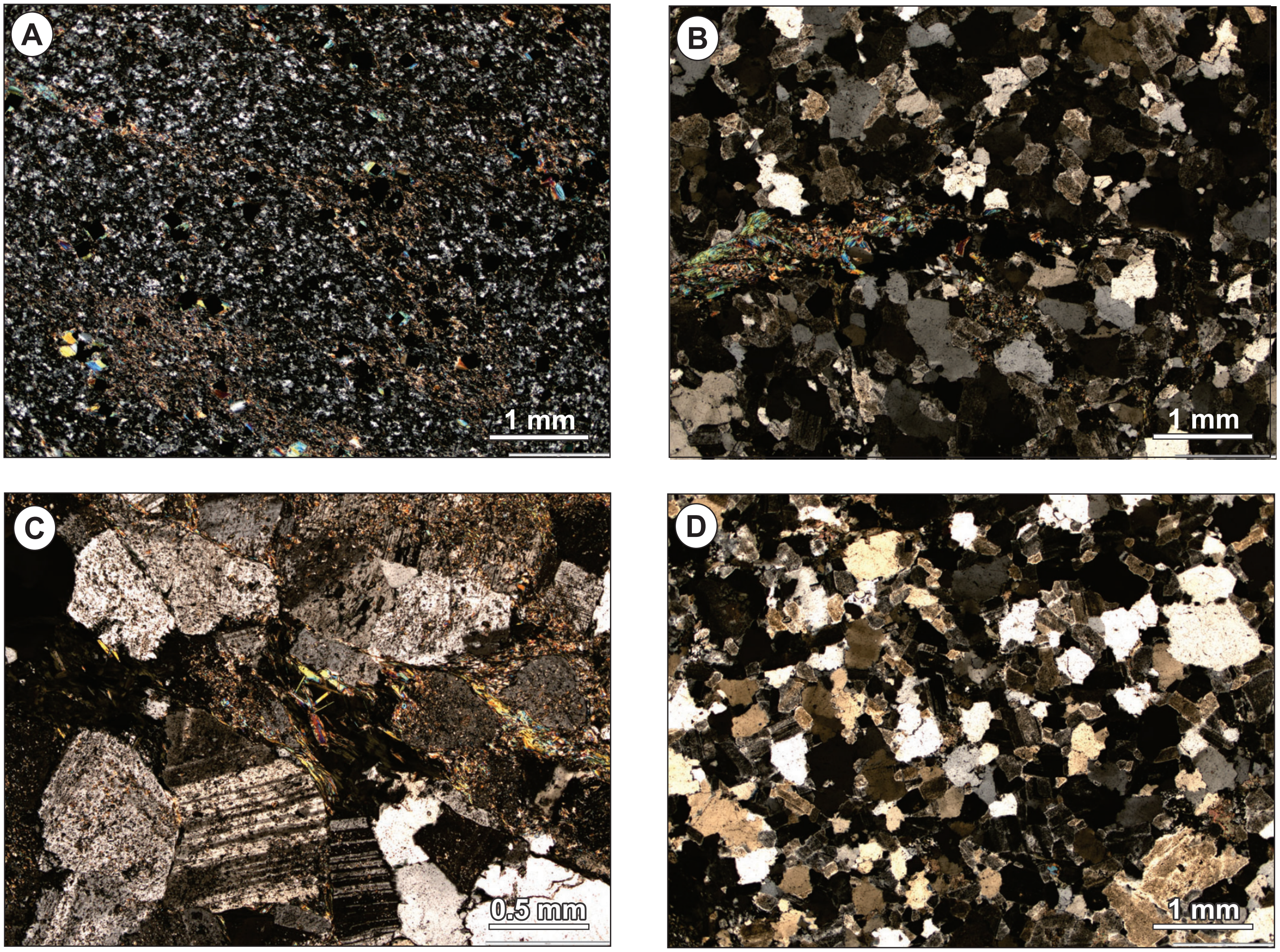

**Plate 3.** *Photomicrographs of lithologies observed in DDH K-14 (schematically illustrated in Figure 5). A) Foliated, fine-grained felsic to intermediate volcanic rock with sericite and pyrite alteration (JHC-15-117); B) Fine-grained, non-foliated silicified trondhjemite with microfractures filled with sericite and pyrite (JHC-15-118); C) Medium-grained, massive and homogeneous trondhjemite composed of interlocking quartz and plagioclase crystals. Sercite alteration after plagioclase (JHC-15-119); D) Fine-grained trondhjemite, similar to C (JHC-15-120).*

west-vergent faults and suggest thrust imbrication as portrayed in Figure 4.

## NSPF ROCKS WEST OF PARTRIDGEBERRY HILLS GRANITE (PHG)

Immediately to the west of the PHG, a package of felsic to intermediate volcanic rocks were mapped as part of the NSPF (*e.g.*, Swinden, 1988). Field observations during this survey noted that some of these rocks are similar in composition to those in the vicinity of the Katie VMS prospect (Unit 1A, B), being composed of quartz-feldspar porphyritic felsic volcanic rocks, whereas other portions of the stratigraphy to the west of the PHG appear more siliceous than the host rocks of the Katie VMS prospect; these siliceous rocks are herein termed Unit 1C. These siliceous rocks are fine grained, dark-grey to black and have small plagioclase and quartz phenocrysts within a groundmass of very fine-grained, amorphous silica and sparse fine-grained feldspar grains. Local examples display faint banding, indicative of flow-banding. Foliations to the west of the PHG are variable; rocks immediately (within approximately 3 km from contact) to the west of the PHG display foliations trending to the northwest to northeast, whereas rocks farther to the west of the PHG (>3 km from contact) mostly display a strong south-southwest to southwest-trending foliation, variably dipping 50–86°W; this is distinct from the north-northeast-trending foliations in rocks exposed east of the PHG.

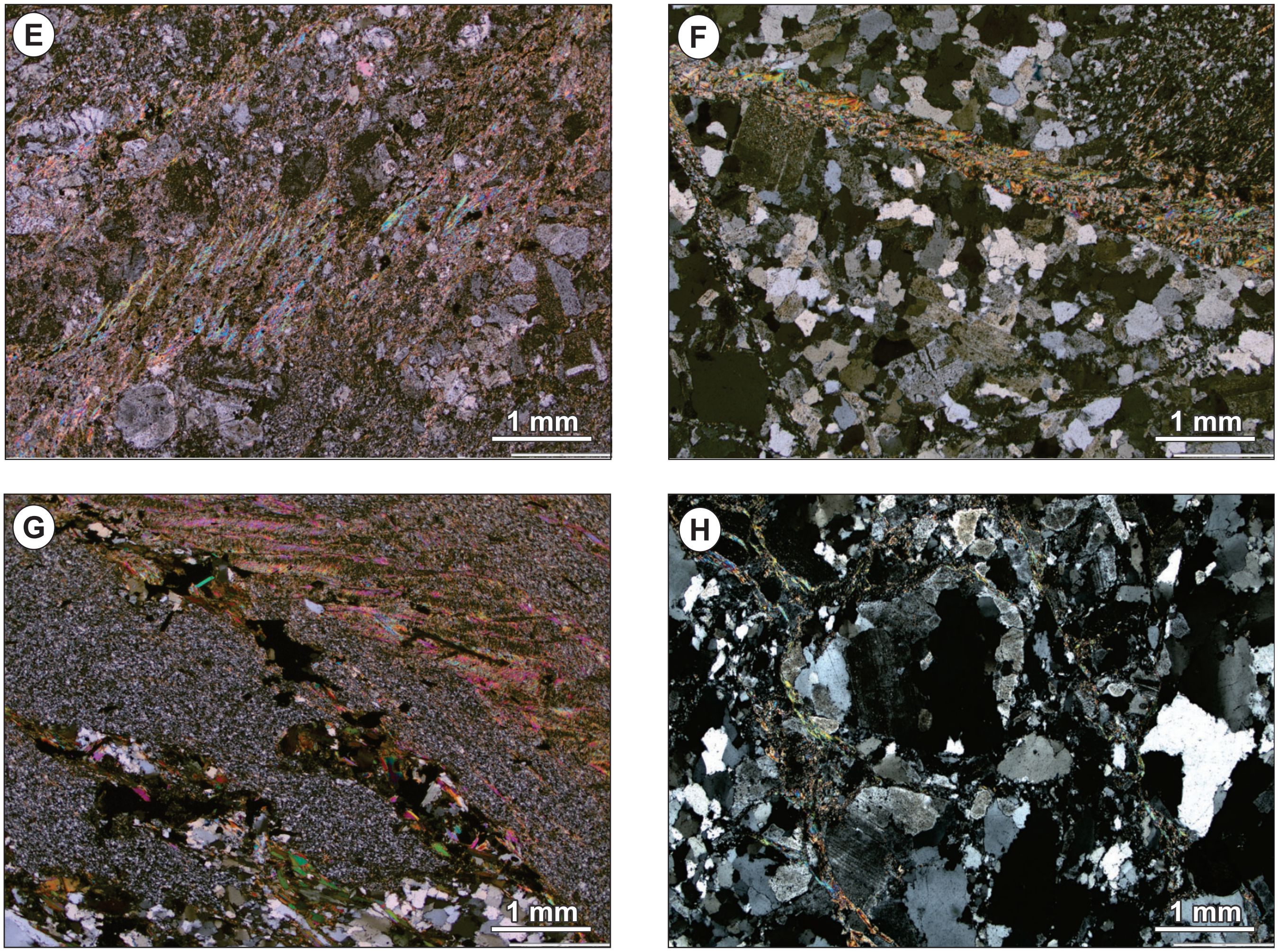

**Plate 3 (continued).** *Photomicrographs of lithologies observed in DDH K-14 (schematically illustrated in Figure 5). E) Fine-grained, intensely altered (sericite ± carbonate and pyrite) felsic to intermediate volcanic rock (JHC-15-121); F) Fine-grained trondhjemite composed of interlocking quartz and feldspar grains; note sericite annealed fracture (JHC-15-122); G) Intensely altered (sericite, pyrite, phlogopite, chlorite, carbonate), well-foliated, felsic to intermediate volcanic rock (JHC-15-123); H) Fine-grained, trondhjemite (JHC-15-125).*

Minor mineralized zones were discovered in areas to the west of the PHG, mostly associated with the quartz-feldspar porphyritic unit (Unit 1A, B) similar to the host rocks at the Katie VMS prospect (Plate 4). These mineralized zones contain disseminated sphalerite in association with silica–sericite–pyrite–chlorite alteration of the quartz-feldspar porphyritic host.

## U–Pb GEOCHRONOLOGY

Three samples were collected from the vicinity of the Katie VMS prospect for U–Pb chemical abrasion-thermal ion mass spectrometry (CA-TIMS) zircon geochronological analysis. These consisted of: 1) 15JH071, a strongly foliated and deformed quartz ± feldspar porphyritic rhyolite to rhyodacite collected from the main mineralized trench #1 (Unit 1A); 2) JHC-15-119, a sample of the medium-grained, locally brecciated trondhjemite collected from approximately 30.5–34.3 m depth in DDH K-14 (Unit 2B, P-2; Figure 3) and; 3) JHC-15-121, a sample of the quartz-feldspar porphyritic felsic to intermediate volcanic from approximately 50.4–51.9 m depth in DDH K-14 (Unit 1B, P-3; Figure 3). Samples were all processed at Memorial University of Newfoundland using standard CA-TIMS techniques (Mattinson, 2005). Further details on the zircon preparation and analytical techniques are outlined in Sparkes and Dunning (2014).

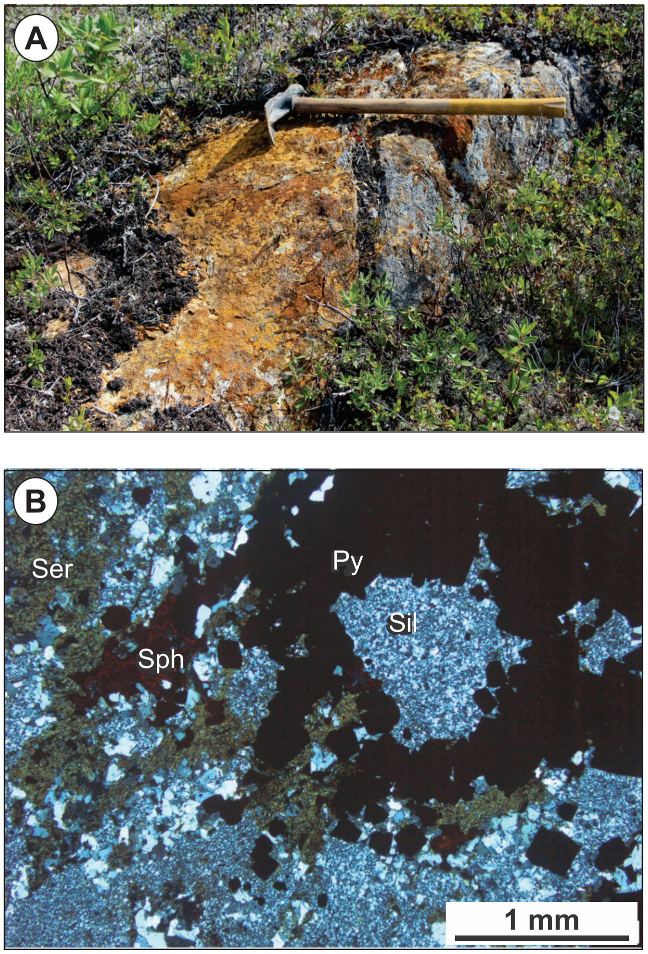

**Plate 4.** *A) Silica–sericite–pyrite ± chlorite alteration zone (15JH056) discovered within quartz-feldspar porphyritic felsic volcanic rocks of the NSPF to the west of the PHG. Alteration indices: Alteration Index of Ishikawa* et al. *(1976) AI = 84, chlorite–carbonate–pyrite index of Large* et al. *(2001) CCPI = 9; B) Photomicrograph of the quartz ± feldspar porphyritic felsic volcanic rock shown in A. Note the presence of sphalerite (Sph) in association with the silica–sericite–pyrite ± chlorite alteration.*

### 15JH071 (Unit 1A)

The sample collected from the main trench #1 at the Katie VMS prospect consists of a strongly foliated, prominent quartz-porphyritic felsic to intermediate volcanic rock with sericite alteration. The sample yielded a large amount of high-quality, mostly euhedral zircon crystals displaying fine-scale igneous growth zoning textures (Figure 5A). The zircon crystals also display evidence of corrosion with subsequent re-growth of new zircon (Figure 5A). Five zircon fractions consisting of clear, high-quality grains were analyzed. Although all five fractions are concordant, one analysis (Z2) is older and has been excluded from the age calculation (Table 1, Figure 5B). The age calculation utilized four fractions Z1, 3, 4 and 5, which together yielded a weighted average $^{206}Pb/^{238}U$ age of 471.1 ± 1.4 Ma (95% confidence interval, MSWD = 0.42).

### JHC-15-119 (Unit 2B)

A sample was collected form DDH K-14 at a depth of approximately 30.5–34.3 m (Figure 3). The rock consists of a prominent blue-quartz-bearing, medium-grained, massive and homogenous trondhjemite with interlocking quartz and variably altered plagioclase crystals. The sample yielded abundant sharp euhedral zircon prisms, from which six fractions were analyzed (five were single grains). Zircon fraction Z1, composed of two grains, overlaps the other analysis but is slightly older (~3 Myr) and is excluded from the age calculation. Analysis from zircons Z2–Z6 resulted in tightly clustered $^{206}Pb/^{238}U$ ages ranging from 497.5 ± 2.6 to 494.4 ± 4.6 Ma. The weighted average of the analyses yields a $^{206}Pb/^{238}U$ age of 496.6 ± 1.2 Ma (MSWD = 0.50; Table 1, Figure 5C).

### JHC-15-121 (Unit 1B)

A sample was collected from DDH K-14 at a depth of approximately 50.4–51.9 m (Figure 3) and consists of a strongly sericite-altered and foliated, feldspar and quartz-porphyritic felsic to intermediate volcanic rock. The sample yielded a relatively small amount of high-quality, small zircon prisms. Three single grains were analyzed resulting in two overlapping analysis (Z1 and Z2), whereas the other analysis (Z3) has a Proterozoic component (*ca.* 1269 Ma) (Table 1; Proterozoic age not plotted). The analyses yielded $^{206}Pb/^{238}U$ ages of 471.1 and 467.6 Ma (Figure 5D); overlapping with the age of sample 15JH071 discussed above. Further analyses are required to finalize an age. The inherited Proterozoic zircon suggests that there is Proterozoic inheritance in the sample, an observation supported by the Nd model ages for both samples of NSPF volcanic rocks (*see* below, Table 2).

## LITHOGEOCHEMISTRY

Representative suites of all felsic to intermediate volcanic, volcaniclastic and intrusive rocks from the study area were analyzed for major and trace elements using ICP-ES (Inductively Coupled Plasma-Emission Spectrometry) and ICP-MS (Inductively Coupled Plasma-Mass Spectrometry) methods at the Geological Survey's geochemical laboratory. Analytical methods for these elements are described in Finch (1998) and Finch *et al.* (2018). A subset of samples were analyzed *via* INAA at Becquerel Laboratories in Ontario (now Bureau Veritas Laboratories: https://www.

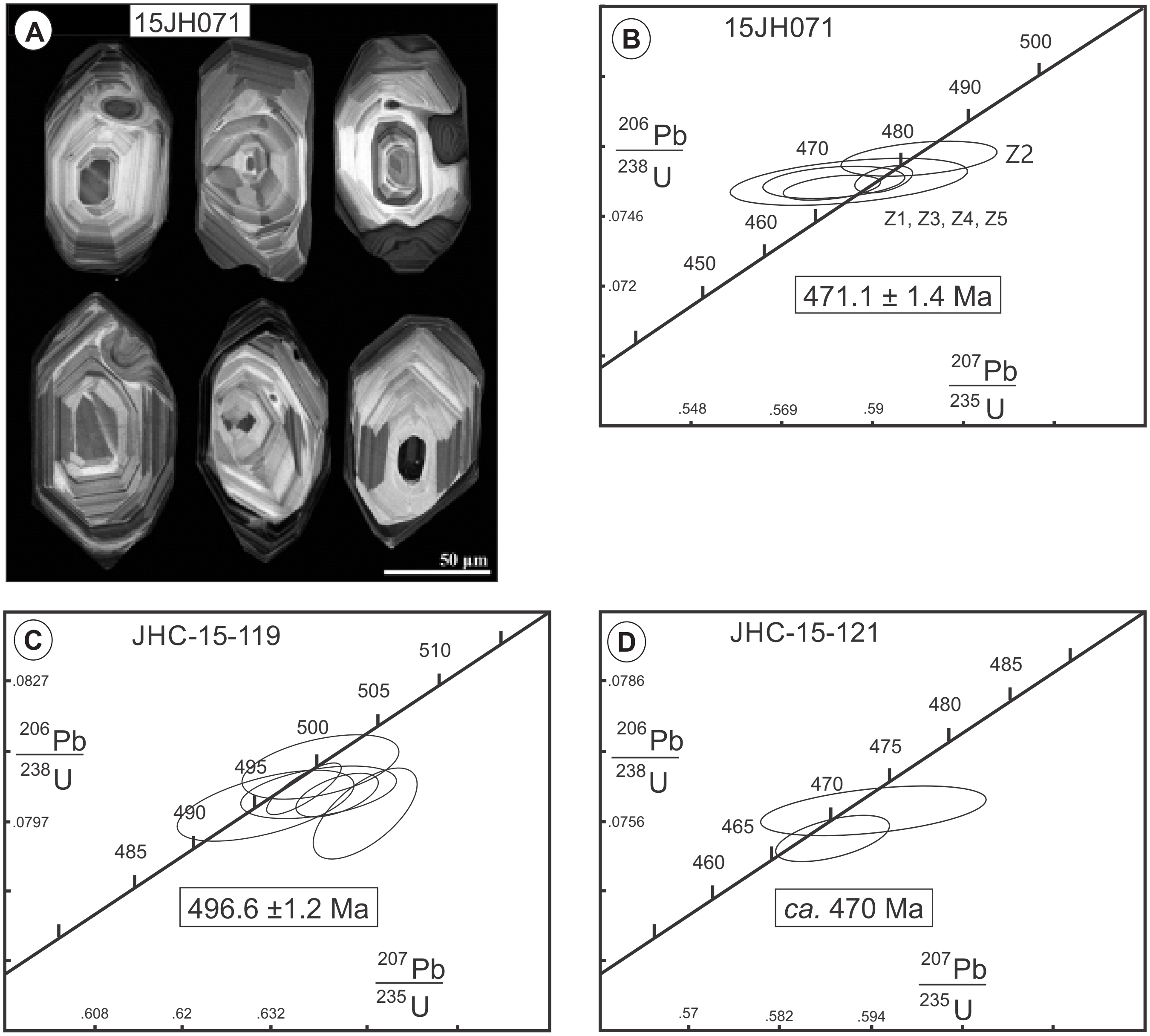

**Figure 5.** *Cathodoluminescence image of zircon crystals and concordia diagrams of U/Pb CA-TIMS zircon analyses from samples from the NSPF felsic to intermediate volcanic rocks (15JH071 and JHC-15-121) and CPC trondhjemite (JHC-15-119). Refer to Tables 1 and 2 for sample locations and U–Pb data.*

bvlabs.com). The full geochemical dataset is available from Hinchey (2022).

The samples have been separated into five main rock types; three from the felsic to intermediate volcanic and volcaniclastic rocks of the NSPF (Unit 1A–C) and two constituting what are considered trondhjemite of the CPC (Unit 2A, B). Only two samples of argillite/siltstone (Unit 1D) were analyzed, with results indicating that they are chemically indistinguishable from rocks of Unit 1A or B; hence they are not discussed in detail here. The three units from the NSPF are: 1) strongly foliated and deformed quartz ± feldspar crystal phyric rhyolite to rhyodacite (Unit 1A); 2) homogeneous quartz ± feldspar porphyritic felsic to intermediate volcanic rocks (tuff and lava: Unit 1B); and, 3) dark-grey to black, fine-grained, quartz and feldspar porphyritic siliceous tuff and rhyolite exposed to the west of PHG (Unit 1C). The units inferred to represent rocks of the CPC are composed of: 1) fine-grained, siliceous and locally brecciated trondhjemite (Unit 2A); and, 2) medium-grained, locally brecciated trondhjemite (Unit 2B); commonly in gradational contact with Unit 2A.

**Table 1.** U–Pb zircon data

| | | Concentration | | | Measured | Corrected Atomic Ratios* | | | | | | | Age (Ma) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Fraction** | **Weight (mg)** | **U** | **Pb rad (ppm)** | **Total common Pb (pg)** | **$^{206}$Pb/$^{204}$Pb** | **$^{208}$Pb/$^{206}$Pb** | **$^{206}$Pb/$^{238}$U** | **±** | **$^{207}$Pb/$^{235}$U** | **±** | **$^{207}$Pb/$^{206}$Pb** | **±** | **$^{206}$Pb/$^{238}$U** | **$^{207}$Pb/$^{235}$U** | **$^{207}$Pb/$^{206}$Pb** |
| **15JH071** | | | | | | | | | | | | | | | |
| Z1 2 clr sml euh | 0.002 | 180 | 13.2 | 2.3 | 763 | 0.0716 | 0.07597 | 42 | 0.5926 | 54 | 0.05657 | 46 | 472.0 | 473 | 475 |
| Z2 3 clr sml euh | 0.003 | 72 | 5.4 | 4.6 | 246 | 0.0804 | 0.07674 | 54 | 0.6007 | 148 | 0.05678 | 130 | 476.6 | 478 | 483 |
| Z3 2 clr sml prm | 0.002 | 92 | 6.7 | 3.5 | 268 | 0.0684 | 0.07588 | 72 | 0.5845 | 224 | 0.05587 | 196 | 471.5 | 467 | 447 |
| Z4 1 clr sml prm | 0.001 | 146 | 10.9 | 1.9 | 383 | 0.0883 | 0.07566 | 38 | 0.5806 | 92 | 0.05566 | 80 | 470.2 | 465 | 439 |
| Z5 1 clr sml prm | 0.001 | 122 | 9.0 | 2.4 | 263 | 0.0679 | 0.07586 | 48 | 0.5810 | 134 | 0.05555 | 122 | 471.4 | 465 | 434 |
| **JHC-15-119** | | | | | | | | | | | | | | | |
| Z1 2 clear prm | 0.004 | 172 | 14.1 | 11.0 | 333 | 0.1287 | 0.08069 | 56 | 0.6370 | 86 | 0.05725 | 68 | 500.2 | 500 | 501 |
| Z2 1 clr euh prm | 0.002 | 550 | 45.1 | 17.2 | 259 | 0.1359 | 0.07972 | 78 | 0.6434 | 58 | 0.05853 | 46 | 494.4 | 504 | 550 |
| Z3 1 clr euh prm | 0.002 | 258 | 21.2 | 8.2 | 256 | 0.1342 | 0.08010 | 36 | 0.6395 | 46 | 0.05790 | 34 | 496.7 | 502 | 526 |
| Z4 1 clr euh prm | 0.002 | 463 | 37.9 | 13.2 | 282 | 0.1294 | 0.08017 | 46 | 0.6369 | 86 | 0.05762 | 68 | 497.1 | 500 | 515 |
| Z5 1 clr prm | 0.002 | 254 | 20.8 | 7.8 | 262 | 0.1343 | 0.07987 | 60 | 0.6297 | 98 | 0.05718 | 72 | 495.4 | 496 | 499 |
| Z6 1 clr euh prm | 0.002 | 651 | 53.7 | 8.9 | 572 | 0.1385 | 0.08023 | 44 | 0.6347 | 40 | 0.05737 | 20 | 497.5 | 499 | 506 |
| **JHC-15-121** | | | | | | | | | | | | | | | |
| Z1 1 clr euh prm | 0.002 | 437 | 33.0 | 12.0 | 275 | 0.1087 | 0.07523 | 42 | 0.5889 | 60 | 0.05677 | 48 | 467.6 | 470 | 483 |
| Z2 1 clr euh prm | 0.002 | 301 | 23.3 | 15.3 | 159 | 0.1282 | 0.07582 | 44 | 0.5944 | 120 | 0.05686 | 106 | 471.1 | 474 | 486 |
| Z3 1 clr euh prm | 0.002 | 247 | 59.8 | 14.9 | 356 | 0.1881 | 0.21757 | 94 | 3.1826 | 184 | 0.10610 | 48 | 1269.0 | 1453 | 1733 |

**Notes:** Z=zircon, 1,2 =number of grains, clr=clear, prm =prism, euh=euhedral. All zircon was chemically abraded (Mattinson, 2005). Weights were estimated so U and Pb concentrations are approximate.

* Atomic ratios corrected for fractionation, spike, laboratory blank of 2 picograms of common lead, and initial common lead at the age of the sample calculated from the model of Stacey and Kramers (1975), and 0.3 picogram U blank. Two sigma uncertainties are reported after the ratios and refer to the final digits.

**Table 2.** Sm/Nd isotopic data

| Sample | Easting | Northing | Lithology | Sm | Nd | $^{147}$Sm/$^{144}$Nd | $^{143}$Nd/$^{144}$Nd | Age(Ma)[a] | eNd$_{(t=471 \text{ and } 496 \text{ Ma})}$[b] | f$_{(Sm/Nd)}$[c] | T$_{(DM)}$[d] | NCI[e] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 15JH017 | 566476 | 5349878 | Felsic-intermediate volcanic | 7.96 | 38.26 | 0.1257 | 0.512184 | 471 | -4.6 | -0.36 | 1485 | 0.56 |
| 15JH036 | 567519 | 5349096 | Felsic-intermediate volcanic | 7.99 | 36.08 | 0.1339 | 0.512225 | 471 | -4.3 | -0.32 | 1559 | 0.54 |
| 15JH071 | 606819 | 5354153 | Felsic-intermediate volcanic | 6.67 | 31.18 | 0.1293 | 0.512180 | 471 | -4.9 | -0.34 | 1555 | 0.57 |
| JHC-15-119 | DDH K-14 (33.5–33.9 m) | | trondhjemite | 2.34 | 6.97 | 0.2026 | 0.512957 | 496 | 5.9 | 0.03 | n/a | 0.02 |
| JHC-15-121 | DDH K-14 (50.5–50.4 m) | | Felsic-intermediate volcanic | 7.05 | 33.62 | 0.1267 | 0.512201 | 471 | -4.3 | -0.36 | 1472 | 0.54 |
| JHC-15-183 | DDH K-27 (103.0–103.4 m) | | trondhjemite | 3.99 | 11.31 | 0.2135 | 0.512981 | 496 | 5.6 | 0.09 | n/a | 0.03 |
| JHC-15-184 | DDH K-27 (112.4–112.7 m) | | Felsic-intermediate volcanic | 4.63 | 20.28 | 0.1381 | 0.512456 | 471 | -1.0 | -0.30 | 1184 | 0.37 |

**Notes:** [a]Estimated based on stratigraphic location. [b]Calculated using present day chondritic uniform reservoir with $^{143}$Nd/$^{144}$Nd = 0.512638 and $^{147}$Sm/$^{144}$Nd = 0.1967. [c]Fractiontion factor. [d]T$_{(DM)}$ calculated from DePaolo (1981). [e]NCI= neodymium crustal index.

Selected samples from both the NSPF and the CPC were also analyzed for Sm–Nd isotopic compositions by Isotope Dilution–Thermal Ionization Mass Spectrometry techniques at Memorial University of Newfoundland. Analytical details can be found in Hinchey (2021). Table 2 provides the Sm–Nd data. In the following geochemical diagrams, the multi-element patterns for selected archived samples of equigranular granodiorite of the Partridgeberry Hills Granite (sampled from Colman-Sadd, 1985) are shown for comparison.

## ELEMENT MOBILITY CONSIDERATIONS – HYDROTHERAL ALTERATION

On a Spitz and Darling (1978) plot (Figure 6A), felsic to intermediate rocks of the NSPF (Unit 1A–C) plot with trends extending from the fresh to weakly altered fields (2–5% $Na_2O$ and <10% $Al_2O_3/Na_2O$), through to samples displaying chemical attributes corresponding to Na-loss (<2 wt % $Na_2O$; $Al_2O_3$ conserved with $Al_2O_3/Na_2O$ >10 %) related to feldspar destruction by hydrothermal fluids. The box

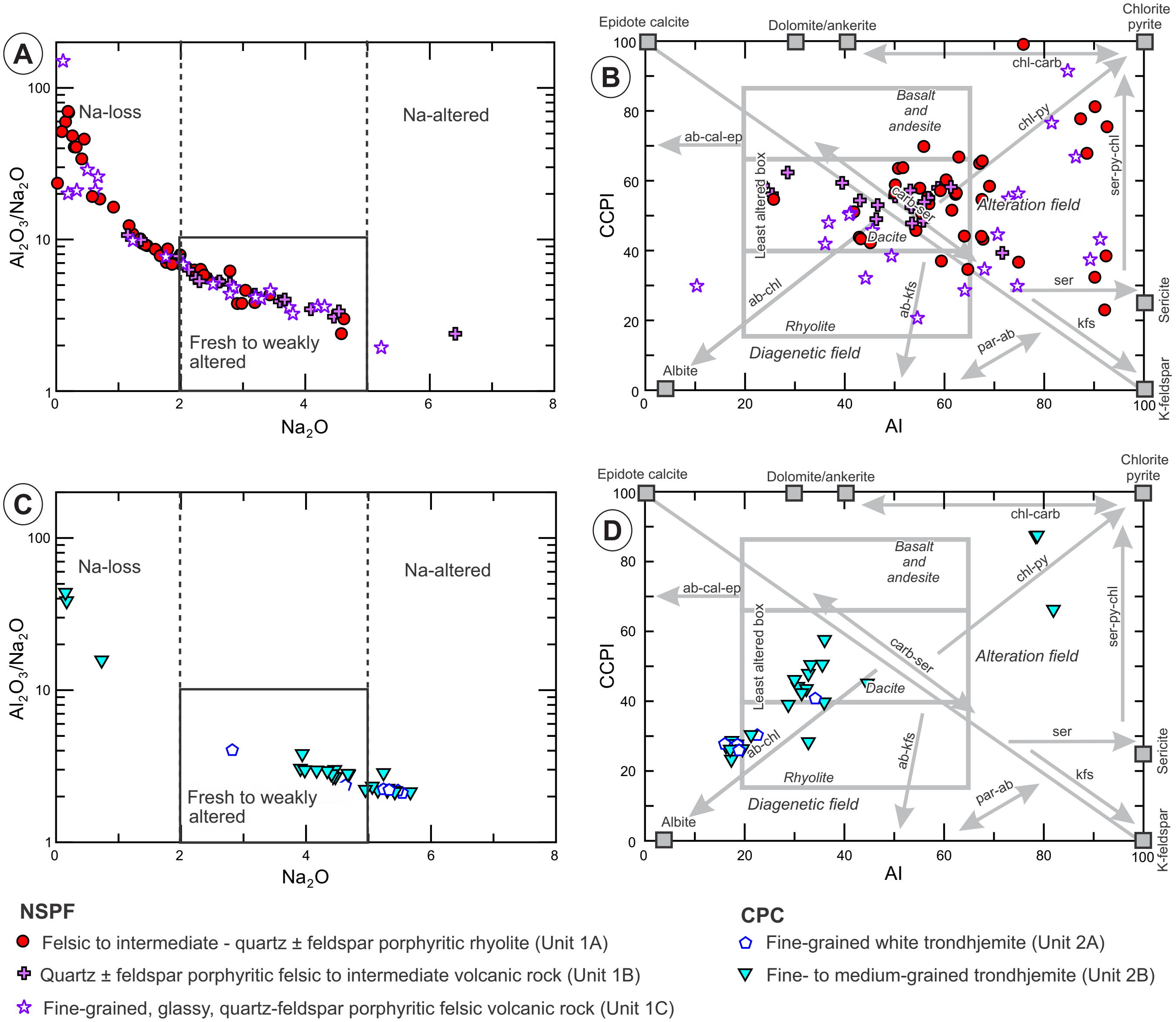

**Figure 6.** *Major-element plots for the felsic to intermediate rocks of the NSPF and trondhjemite samples of the Coy Pond Complex. A)* $Na_2O$ *vs.* $Al_2O_3/Na_2O$ *(Spitz and Darling, 1978) for NSPF rocks; B) Alteration box plot with Hashimoto Alteration index( AI =* $100*[(MgO+K_2O)/(MgO+K_2O+Na_2O+CaO)]$*, Ishikawa* et al.*, 1976) vs. chlorite–carbonate–pyrite index (CCPI =* $100*[(MgO+FeO^*/(MgO+FeO^*+K_2O+Na_2O)]$*, Large* et al.*, 2001) for the NSPF rocks; C)* $Na_2O$ *vs.* $Al_2O_3/Na_2O$ *for CPC rocks; D) Alteration box plot for CPC rocks.*

plot of Large *et al.* (2001: Figure 6B), displays the Hashimoto index (AI; Ishikawa *et al.*, 1976), to account for chemical change (gains of MgO and $K_2O$ and loss of $Na_2O$ and CaO) associated with chlorite and sericite alteration during the breakdown of Na-feldspar and glass to sericite, and the chlorite–carbonate–pyrite index (CCPI) to account for chlorite, Fe–Mg carbonate and pyrite alteration associated with VMS-style alteration. Samples of the NSPF range from plotting in the least altered dacite field through to samples plotting in the alteration fields for sericite–pyrite–chlorite. In both plots, samples with visible alteration ± sulphide mineralization from drillcore, from outcrop samples near the Katie VMS prospect, and from some of the new alteration zones identified to the west of the PHG all plot within the altered fields.

Samples of the fine- to medium-grained, trondhjemite (Unit 2A, B) mostly plot within the fresh to weakly altered and Na-altered portions of a Spitz and Darling (1978) plot (Figure 6C). The Na alteration is likely represented by variable albitization of primary feldspar. A small subset of samples from diamond-drill core samples plot within the Na-loss field. However, petrography reveals that these samples have undergone intense silica–sericite–chlorite–pyrite alteration, making identification of the precursor host difficult; hence these samples potentially represent rocks of the NSPF or, a mixture of the NSPF and the trondhjemite of the CPC. The extended trace-element plots of these anomalous samples could not resolve the ambiguity. The trondhjemite samples show a similar distribution on the box plot of Large *et al.* (2001), whereby most samples plot within the least altered field of dacite but trend through to the field for albite–chlorite alteration (Figure 6D), whereas the small subset of anomalous samples plot in the chlorite–pyrite–carbonate alteration field.

Caution is warranted when using lithogeochemistry to make inferences about primary rock compositions, particularly in rock units that have been exposed to metamorphism and/or alteration processes that can effect element mobility. In this study, the replacement of primary feldspar by secondary hydrothermal minerals, predominantly sericite with lesser chlorite and carbonate, likely affected some elements; this is particularly true of the rocks of the NSPF. Sericite alteration of primary feldspar results in a gain of K+ from hydrothermal fluids and a corresponding loss of Na and Ca from the primary rock, whereas the local replacement of feldspars and sericite by chlorite and carbonate results in an addition of Mg ± Fe to the rocks (Gifkins *et al.*, 2005). Hence, given the observed alteration within the felsic to intermediate volcanic rocks from the NSPF, the alkalis, Mg, Fe, and $SiO_2$ are likely mobile and should not be used to infer primary petrogenetic processes. The low-field strength elements (LFSE; *e.g.*, Ba, Rb, Cs, Sr) are also considered to be mobile under the alteration conditions in this study (*e.g.*, MacLean and Barrett, 1993; Jenner, 1996). In most cases the REE, with the exception of Eu (*e.g.*, Sverjensky, 1984; Whitford *et al.*, 1988), are generally considered to be immobile except under extreme hydrothermal alteration conditions, where the light REE may become mobile (Campbell *et al.*, 1984; MacLean and Barrett, 1993). In this study, the REE generally behave coherently, and for the most part, are assumed to have been immobile during alteration. However, a subset of samples of the felsic to intermediate volcanic rocks in the immediate vicinity of the Katie VMS prospect (Unit 1A), as well as in the vicinity of the mineralized zones discovered to the west of the PHG (Unit 1C), display significant scatter and do not exhibit comparable REE patterns; hence these elements are interpreted to have been locally impacted by alteration. Similarly, whereas the high-field strength elements (HFSE: *e.g.*, Zr, Hf, Nb, Ta, Y, Th) are immobile in almost all cases (*e.g.*, Barrett and MacLean, 1999; Lentz, 1999) and display coherent behaviour for most samples, there has been some mobility of these elements in the vicinity of alteration and mineralization in this study. The samples that display obvious chemical effects of alteration are plotted on the diagrams used to portray alteration effects (Figure 6) but have been removed from the detailed trace-element and multi-element plots (Figures 7 and 8).

## LITHOGEOCHEMICAL RESULTS

The alteration plots indicate that many of the major elements were mobile during post-emplacement alteration and metamorphism, nevertheless a normative plot illustrating the granitoid classification scheme of Barker (1979; Figure 7A) is still valuable for comparing between the NSPF felsic to intermediate volcanic rocks and the trondhjemitic rocks of the area. Although there is some overlap between fields for samples (Figure 7A), for the most part, the units mapped and logged as white rhyolite and blue-quartz porphyritic leucogranite plot as trondhjemites; in contrast to most of the felsic to intermediate volcanic rocks of the NSPF, which plot as granite to granodiorite.

Using the most immobile elements, the felsic to intermediate, quartz ± feldspar porphyritic volcanic rocks of the NSPF (Unit 1A, B) plot mainly as andesite–basaltic andesite varying to dacite, whereas the dark-grey to black, fine-grained, quartz and feldspar siliceous volcanic/rhyolite to the west of PHG (Unit 1C) plot as rhyolite–dacite (Figure 7B). The trondhjemite samples (inclusive of the fine- and medium-grained varieties: Unit 2A, B) are also andesite–basaltic andesite varying to the rhyolite–dacite; albeit with lower concentrations of the HFSE's Zr and Nb (Figure 7B, C). On the Y *vs.* Nb trace-element discrimination plot of Pearce *et al.* (1984), the NSPF felsic to intermediate volcanic rocks (Unit 1A–C) plot in the field for volcanic-arc

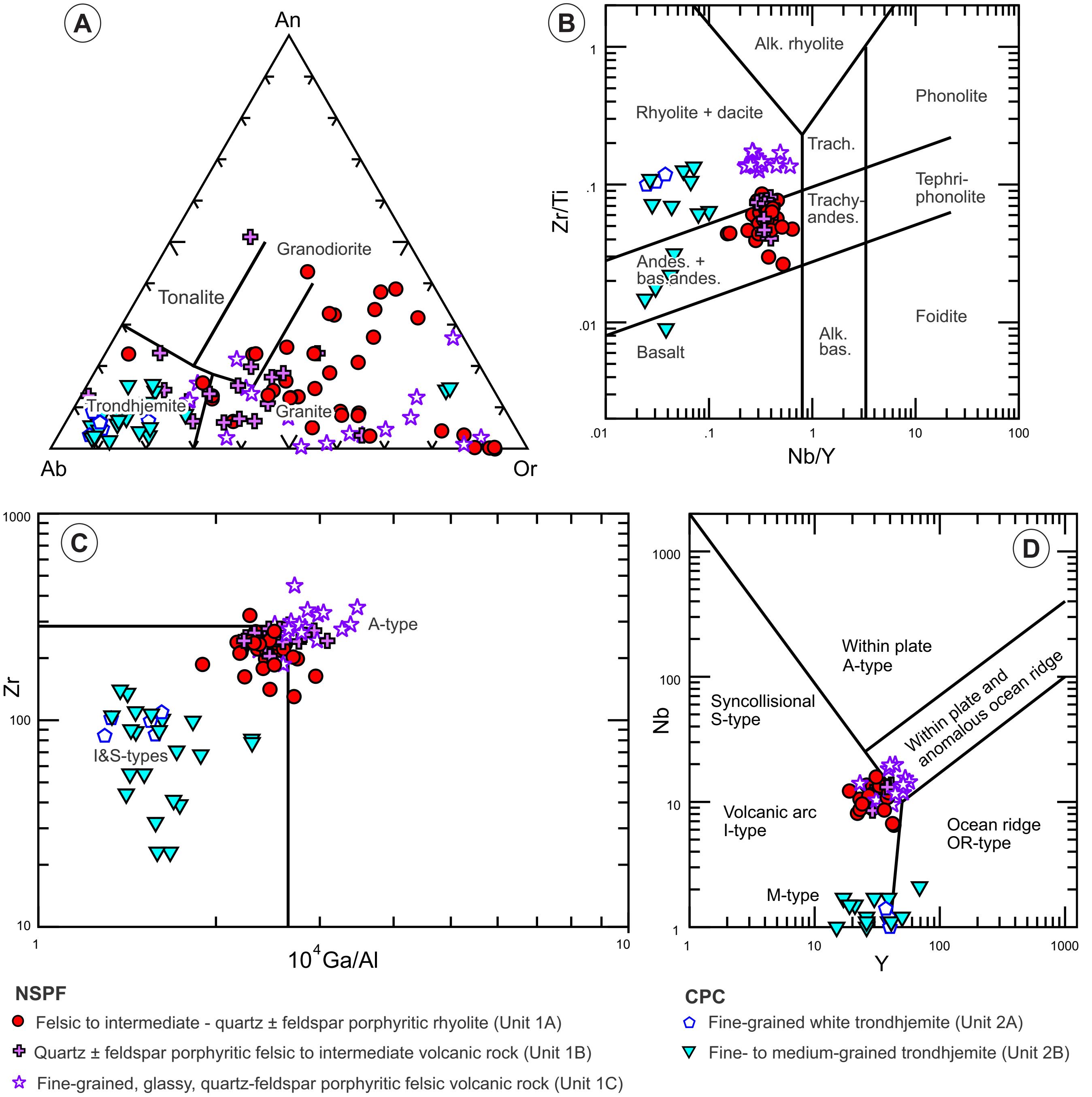

**Figure 7.** *Major- and trace-element plots of the NSPF and CPC rocks. A) CIPW normative classification of the NSPF and CPC rocks (Barker, 1979); B) Nb/Y vs. Zr/Ti (Winchester and Floyd, 1975; Pearce, 1996); C) Ga/Al* vs. *Zr (Whalen* et al., *1987); D) Y* vs. *Nb (Pearce* et al., *1984).*

type granites (I-type) transitional to A-type, whereas the trondhjemite samples (Unit 2A, B) have significantly lower Zr, Ga/Al and Nb concentrations and plot in the I-S domain (Whalen and Currie, 1987; Figure 7C) and in the field for M-type (*e.g.*, derived from a mafic substrate or supra-subduction zone, fore-arc basin ridge) granitoids of Pearce *et al.* (1984; Figure 7D).

On normal mid-ocean ridge basalt (NMORB; Sun and McDonough, 1989) normalized multi-element plots (Figure 8), the NSPF felsic to intermediate volcanic rocks (Unit 1A–C) have fractionated, LREE-enriched patterns (average $(La/Yb)_{cn}$ = 6.3; n=78), with prominent negative Nb and Ti anomalies (Figure 8A–C); patterns similar to those associated with volcanic-arc derived volcanic rocks, or by melting

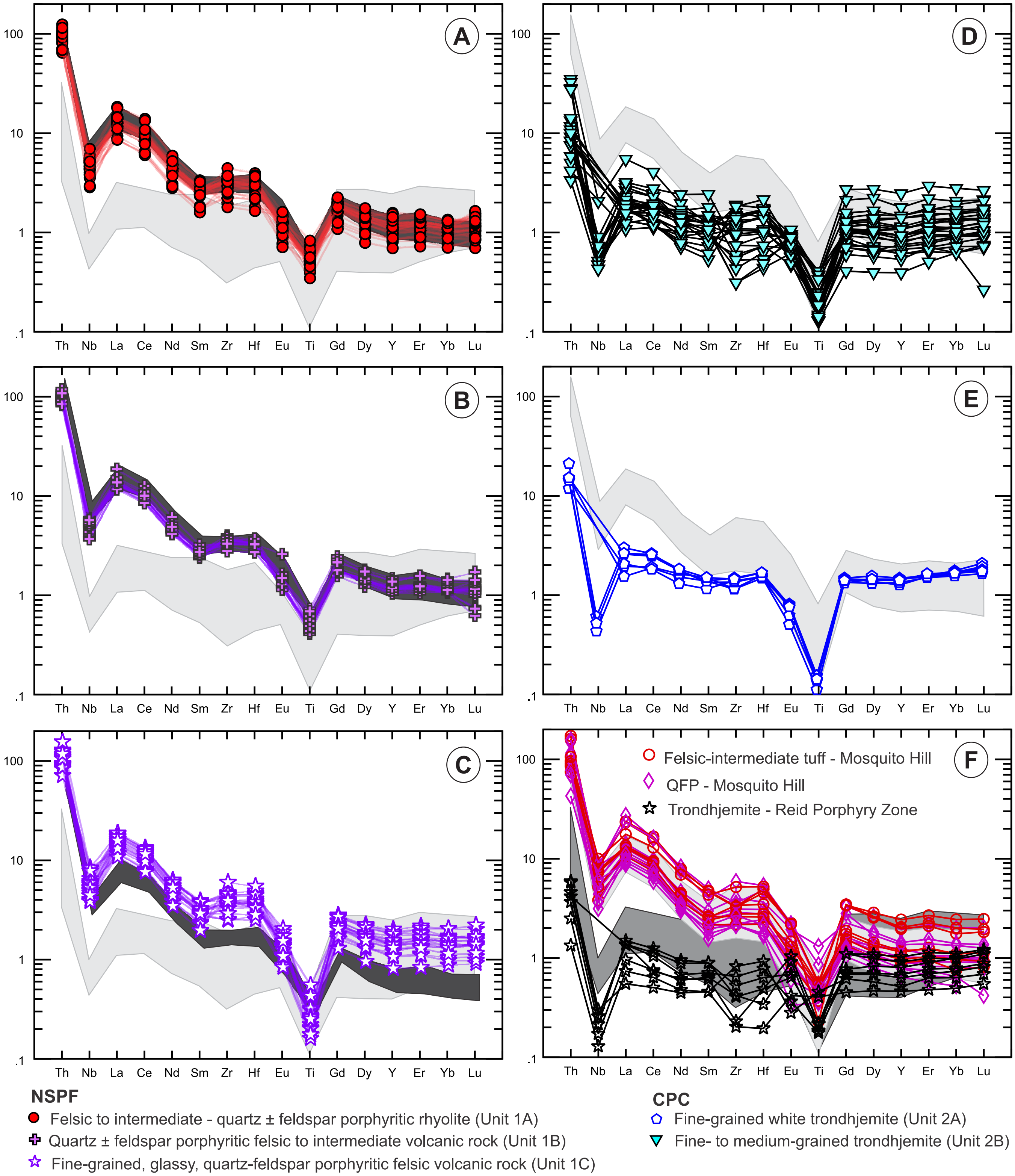

**Figure 8.** *Normal mid-ocean ridge basalt (NMORB: Sun and McDonough, 1989) normalized multi-element plots for rocks of the NSPF. A, B and C) Light-grey shaded field represents average values for CPC samples as shown in D and E; dark-grey-black shaded field represents re-analyzed samples of equigranular granodiorite of the PHG (from Colman Sadd 1985), and rocks from the CPC; D and E) Shaded fields represent average values for NSPF samples as shown in A, B and C; F) Samples of NSPF and CPC trondhjemite from Sandeman* et al. *(2012) as well as Sandeman (unpublished data, 2021) from the Mosquito Hill and Reid prospects, approximately 15 km to the north-northwest for comparison; shaded fields show average values of NSPF and CPC samples from this study as shown in A to E.*

of such rocks. In contrast, the trondhjemite samples (Unit 2A, B) all have relatively flat multi-element patterns (average $(La/Yb)_{cn}$ = 1.6; n=34), with Nb and Ti troughs (Figure 8D, E). For comparison, re-analyzed samples of equigranular granodiorite of the PHG (from Colman-Sadd, 1985) are plotted in Figure 8A–C, whereas samples of NSPF felsic to intermediate tuff and QFP from the Mosquito Hill (gold) prospect, as well as trondhjemite from the Reid (gold) prospect, both approximately 15 km to the north-northwest, are illustrated in Figure 8F (Sandeman *et al.*, 2012 and unpublished data, 2022). As shown in Figure 8F, the samples from Sandeman *et al.*, 2012 and Sandeman (unpublished data, 2022) for the felsic volcanic rocks from the area of the Mosquito Hill prospect (*see* location on Figure 1) are essentially identical to the felsic to intermediate samples of the NSPF displayed herein; as are the re-analyzed samples of the equigranular granodiorite of the PHG (Figure 8A–C). Although the trondhjemite samples from the Reid prospect (Sandeman *et al.*, 2012; Sandeman, unpublished data, 2021) have relatively lower concentrations of all incompatible trace elements compared to the trondhjemite samples of the CPC from this study, both trondhjemite sample suites show near identical, parallel elemental patterns.

### Sm–Nd ISOTOPE GEOCHEMISTRY

Neodymium isotopic data are presented in Table 2 and shown in Figure 9. Data was determined for 5 samples of the felsic to intermediate volcanic rocks of the NSPF (Unit 1A, B, two samples from diamond-drill core and three samples from outcrop) and two samples of trondhjemite of the CPC (Unit 2B, both from diamond-drill core). Based on the U–Pb geochronological constraints (*see* above), initial $\varepsilon Nd_{(t)}$ values of the felsic to intermediate volcanic rocks of the NSPF were recalculated to 470 Ma, whereas those for the trondhjemite were recalculated to 496 Ma (Table 2). As observed in the lithogeochemistry, the felsic to intermediate volcanic samples of the NSPF have overlapping Nd isotopic ratios, and are treated as one group. The felsic to intermediate volcanic samples of the NSPF (Unit 1A, B) have $^{143}Nd/^{144}Nd(m)$ values ranging from 0.512180–0.512225, and all samples have negative $\varepsilon Nd_{(t=470Ma)}$ of -4.3 to -4.9 (Table 2; Figure 9), essentially overlapping within error (~0.5 $\varepsilon Nd_{(470Ma)}$ units). Depleted mantle model ages (DePaolo, 1981) for most of the felsic to intermediate volcanic samples range from 1559 to 1472 Ma, indicating that they likely formed through partial melting of Mesoproterozoic crustal rocks. The CPC trondhjemite samples (Unit 2B) have $^{143}Nd/^{144}Nd(m)$ values ranging from 0.512957–0.512981, and have positive $\varepsilon Nd_{(t=496Ma)}$ of +5.6 to +5.9, overlapping within error (Table 2; Figure 9). As the $^{147}Sm/^{144}Nd$ ratios from the trondhjemite samples are high (>0.15), depleted mantle model ages are spurious and hence are not reported.

## DISCUSSION

### IMPLICATIONS FOR REGIONAL TECTONOSTRATIGRAPHIC ARCHITECTURE

The detailed field work, as well as lithogeochemical, Nd isotopic, and geochronological data presented have impor-

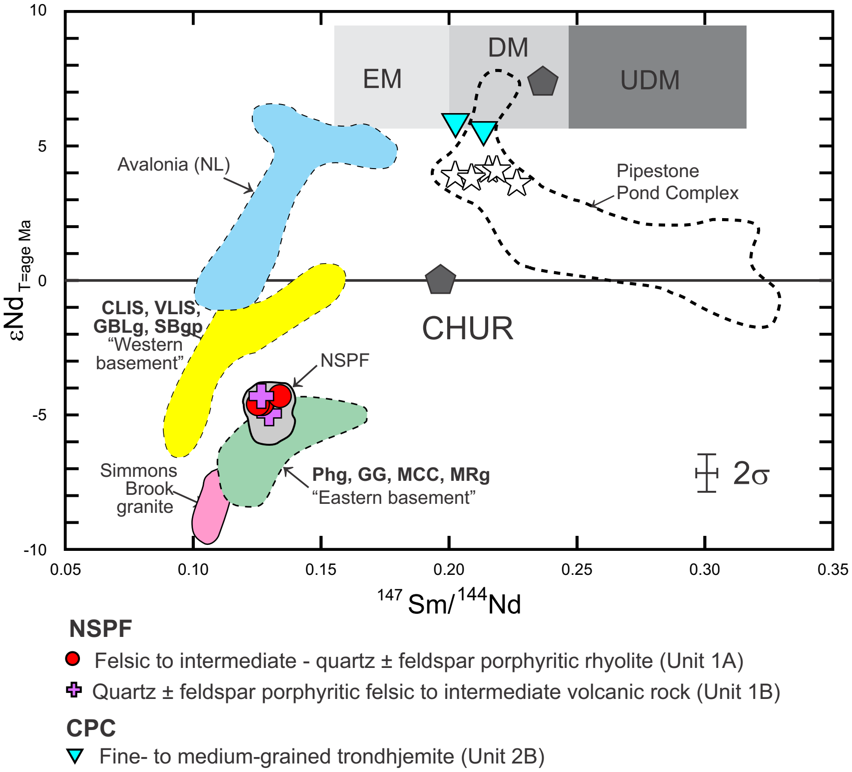

**Figure 9.** *Plot of* $^{147}Sm/^{144}Nd$ vs. $\varepsilon Nd_{(t)}$. *CHUR - chondritic uniform reservoir. DM - depleted mantle* ($T_{DM}$ *values calculated according to DePaolo, 1981). Key: Phg - Partridgeberry Hills Granite; GG - Gander Group sediments; MCC - Mount Cormack Complex sediments; MRg - middle ridge granite; CLIS - Crippleback Lake Intrusive Suite; VLIS - Valentine Lake Intrusive Suite; GBLg - Great Burnt lake granite; SBgp - Sandy Brook group. All regional comparative samples recalculated to 500 Ma (very minor difference in εNd values). Grey field and open stars include unpublished data on NSPF and Reid trondhjemite, respectively (Sandeman) and the heavy dashed field are samples from the PPC from Jenner and Swinden (1993). Basement data from Kerr* et al. *(1995), D'Lemos and Holdsworth (1995), Rogers* et al. *(2006) and Mills* et al. *(2020).*

tant implications for the tectonostratigraphic architecture, as well as for the mineral exploration models employed in the study area. The main observation stemming from this study is that the tectonostratigraphy of the study area is much more structurally complex than that previously recognized.

The U–Pb geochronological results presented in this report identified different packages of rocks within the stratigraphy, and establish that the NSPF, host to the Katie VMS prospect, formed at *ca.* 471 Ma, and was tectonically juxtaposed in repeated, imbricate thrust stacks with *ca.* 496 Ma trondhjemite of the CPC. This interpretation was postulated by Sandeman *et al.* (2013) based on research conducted at the Mosquito Hill prospect that occurs structurally proximal to the mapped contact of the NSPF and the CPC. The postulate is further supported through detailed examination of diamond-drill hole contact relationships that identified numerous structural contacts (mylonite zones, fault zones, intense shearing) between the two distinct units.

The new lithogeochemical data also highlight different packages of rocks, and indicate that the stratigraphy hosting the Katie VMS prospect is composed of two visually and chemically different packages of igneous rocks that were derived in distinct tectonic settings; an observation first proposed by Dean and Wilton (2002), where they suggested that there were chemical differences between their "Huxter Pond Volcanics" and "mixed granite-granite breccia-tuff" units. Whereas the felsic to intermediate volcanic rocks of the NSPF that host the Katie VMS prospect (Unit 1) were derived in a classic volcanic arc-type environment, the fine- to medium-grained trondhjemitic rocks (Unit 2) that occur tectonically interleaved with the NSPF are more typical of introceanic, depleted, M-type volcanic arc granitoids and are herein interpreted to represent trondhjemitic rocks of the CPC. This inference is also supported by Sm–Nd isotopic studies that indicate that the NSPF rocks were derived from partial melting of a Mesoproterozoic crustal substrate, whereas, the CPC trondjhemite rocks formed through either fractionation of, or partial melting of, relatively depleted MORB-like mantle source with little influence of continental crust. This is supported by the neodymium crustal index (NCI) values calculated in Table 2.

This new data place numerous imbricated thrust panels of CPC trondhjemite approximately 3 km farther east than currently recognized. Sandeman *et al.* (2012) and Sandeman (unpublished data, 2021) also presented similar age relationships to those presented here, as well as geochemical and isotopic relationships, from the host rocks of the Reid and Mosquito Hill prospects occurring approximately 15 km to the northwest. Whereas the earlier studies demonstrated the structural nature of the contact of the NSPF and the CPC in proximity to the mapped contact, this study has extended these relationships much farther to the east; necessitating revision of the regional stratigraphy and a re-interpretation of the structural history of the area.

A major outcome of this investigation, given the current structural disposition of the distinct chronostratigraphic units (mainly striking north-northeast to northeast and dipping moderately to the south), is that if the shear zones separating the units are Ordovician, then they must be overturned, or perhaps subsequently tilted to the southeast during doming of the Mt. Cormack Subzone. If the shear zones are Ordovician, then northwest-directed thrusting must be post 468 Ma (age of NSPF Mosquito Hill porphyry sample (H. Sandeman, unpublished data, 2021)); late to be associated with Penobscot orogenesis (~486–478 Ma; van Staal and Barr, 2012). Alternatively, the shear zones could be significantly younger than mid-Ordovician. If this is the case, the next most significant documented orogenic event impacting the area would be *ca.* 421–400 Ma Acadian orogenesis (van Staal and Barr, 2012), resulting in the north-northwest to north-directed thrusts.

One outstanding issue to the proposed geotectonic history of the area is the apparently conflicting U–Pb SHRIMP zircon age of 510 ± 4 Ma for mineralized trondhjemite of the CPC at the Reid prospect (Sandeman *et al.*, 2012; sample BO-09-17_123.1–123.34 m). Compared to the age of 496.6 ± 1.2 Ma presented herein for the CPC trondhjemite in the Katie drillcore (JHC-15-119), to the historical physical abrasion TIMS U–Pb zircon age of 494 +3/-2 Ma on the Pipestone Pond Complex to the west of the Mt. Cormack Subzone (Dunning and Krogh, 1985) and to an unpublished CA-TIMS zircon age for the main Coy Pond trondhjemite of *ca.* 490 Ma (H. Sandeman, unpublished data, 2021; sample HS16-094), the *ca.* 510 Ma age is significantly older than any other known ophiolite in the region. This significantly older age should be re-tested using CA-TIMS zircon U–Pb geochronology.

## IMPLICATIONS ON EXPLORATION FOR VMS-STYLE MINERALIZATION

The study area has been the focus of periodic base metal, VMS-style mineral exploration since the 1970s, where focused exploration activity has been met with variable success, and where some of the best results are the discovery of in-situ base-metal mineralization, in trenched outcrops, by Alterra Resources in 2009 and 2010. The limited success can now be partially attributed to the variable interpretation of the 'leucogranite' and 'rhyolite' units within the stratigraphy and their ages. This study has shown these units as being *ca.* 496 Ma trondhjemite of the CPC that are tectonically imbricated with rocks of the *ca.* 471 Ma NSPF that hosts the Katie VMS prospect mineralization. Previously, there have been a number of conflicting interpretations on the origin of these rocks; early work by BHP interpreted the leucogranitic rocks (trondhjemite) as the source of the sulphide mineralization in the NSPF felsic to intermediate volcanic rocks, as well as the sericite and quartz alteration. This was envisaged to occur via contact alteration related to quartz veins originating from the intrusion of granitic bodies into the felsic to intermediate volcanic rocks (Williamson, 1994). BHP interpreted the 'leucogranite' (trondhjemite) as the equivalent to the Partridgeberry Hills Granite, which has been considered to cut all lithologies (Colman-Sadd *et al.*, 1992; Williamson, 1994). It is now known that the age of the Partridgeberry Hills Granite is 474 +6/-3 Ma (Colman-Sadd *et al.*, *op. cit.*), and hence is synchronous with, or slightly older than the rocks of the NSPF (471 ± 1.4 Ma from sample 15JH071 at the Katie trench; *ca.* 468 Ma for the Mosquito Hill Porphyry sample HS09-121 (H. Sandeman, unpublished data, 2021).

More recent work on the VMS potential of the NSPF interpreted the white rhyolite and leucogranite units (trondhjemite) to represent brecciated white-rhyolite domes and subvolcanic granitic feeders to the NSPF volcanic rocks, respectively (*e.g.*, *see* Wilton 2001; Delaney, 2010; Patey, 2016). Those authors interpreted the stratigraphy in view of the prevailing models for VMS-style mineralization; particularly Zn–Pb–Cu-rich (Kuroko-type) VMS deposits in which models invoke subvolcanic white rhyolite domes as evidence of a vent-proximal environment, and the presence of subvolcanic granitic intrusions as evidence for a sufficient heat source to drive hydrothermal convection required for mineralization (*e.g.*, Franklin *et al.*, 2005).

The data and results from this study refute both of these interpretations for the formation and evolution of the rhyolite and leucogranite (trondhjemite) units exposed at the Katie VMS prospect. The trondhjemite is Late Cambrian, and formed in an intra-oceanic tectonic environment with a subduction modified, depleted mantle source, whereas the NSPF, and likely the broadly contemporaneous Partridgeberry Hills Granite, represent relatively mature, calc-alkaline volcanic arc products. Hence any role, or primary syn-genetic influence, of the trondhjemite on *ca.* 471 Ma VMS-style mineralization is impossible. The observation that the *ca.* 496 Ma CPC trondhjemite has been repeatedly tectonically imbricated with the VMS-bearing *ca.* 471 Ma NSPF units suggests that previous models targeting this unit, as part of the mineralized package, were misguided by incorrect inferred geological relationships and ages. The tectonic juxtaposition of the trondhjemite and the NSPF volcanic rocks would necessitate a new focus of any future exploration campaigns exploring for VMS-style mineralization in the area. Based on the tectonic imbricated contact relationships and the structural overprinting associated with these tectonic events, any primary exhalative or sub-seafloor replacement VMS-style mineralization that formed during a *ca.* 471 Ma volcanic associated mineralizing event could be expected to be tectonically dismembered and structurally overprinted rather than maintaining any primary geometries associated with original metal precipitation mechanisms. Although this newly recognized imbrication would not negate any potential for the NSPF rocks to host VMS-style mineralization, a target ore body would most likely be sheared and/or dismembered and locally discontinuous. Additionally, the similarities in lithological, compositional and structural relationships of the study area with those observed at the Mosquito Hill and Reid Porphyry gold deposits ~15 km to the north, could indicate an enhanced gold prospectivity in the Katie area; an inference supported by the numerous auriferous showings.

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