Ordovician volcanogenic sulphides in the southern Alexander terrane, coastal NW British Columbia: geology, Pb isotopic signature, and a case for correlation with Appalachian and Scandinavian deposits

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Abstract

The southern part of the Craig subterrane of the Alexander terrane, which extends from Prince of Wales Island southward into coastal British Columbia, contains an Ordovician volcanic-sedimentary-intrusive suite of probable back-arc affinity, the Moira Sound unit. Mapping, prospecting, and geochronological work as part of the GEM-Edges project in 2009-2011 identified small sulphide occurrences within and adjacent to Ordovician rhyolites and rhyolite breccias of this unit. The previously known Pitt VMS occurrence on Pitt Island consists of a 3.5 kilometre-long trend of base-metal sulphide bodies aligned along a major shear zone that marks the southwestern limit of ductile shearing related to the mid-Cretaceous Grenville Channel fault. Deformation of the sulphides and their host quartz-muscovite schists is so intense that an epigenetic, synkinematic origin cannot be ruled out on geological grounds. However, chalcopyrite and sphalerite separates from the main Pitt showing yield lead isotopic ratios of $^{206}Pb/^{204}Pb$: 18.1701-18.1911; $^{207}Pb/^{204}Pb$: 15.5643-15.5660 and $^{208}Pb/^{204}Pb$: 38.1015-38.0893. These values, in particular the $^{206}Pb/^{204}Pb$ ratio, are significantly lower than those of Cretaceous syngenetic and epigenetic deposits elsewhere in the Coast belt (ca. 18.4 – 18.7) and are thus incompatible with an epigenetic origin linked to the Grenville Channel fault or its splays, the spatial association notwithstanding. Instead, they closely match leads from Ordovician volcanogenic deposits of New Brunswick, Newfoundland, Quebec, and Norway. In terms of $^{208}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$, the Pitt lead is identical to that of the Bathurst camp. Current tectonic models place the Alexander terrane near the northern end of the Caledonide chain in early to mid-Paleozoic time, based on faunal affinities and Baltican-Caledonian detrital zircon patterns. The Pitt Pb isotopic data support these models. They indicate that Ordovician volcanogenic massive sulphides in the Alexander terrane may link to a chain of deposits that originated in now dismembered arcs and back arcs that constituted a circum-Iapetus ocean ring of fire.

Keywords: Alexander terrane, volcanogenic massive sulphides, Ordovician, Pb isotopes, Pitt prospect

1. Introduction

The Alexander terrane is a composite allochthonous crustal fragment that extends for over 1500 kilometres, from the St. Elias Range in southwestern Yukon, through northwestern British Columbia and southeastern Alaska, and into the coastal area of British Columbia (Fig. 1). The history of the Alexander terrane, as recorded by Neoproterozoic to Triassic rocks, differs profoundly from that of more inboard, peri-Laurentian terranes and the adjacent Laurentian continental margin (Nelson and Colpron, 2007 Colpron and Nelson, 2009). Its early history more closely resembles terranes in the Caledonides. For example, Silurian limestones in the southern part of the terrane contain unusual microbial-aphrosalpingid sponge reef faunas (rather than the more common coralline reefs); the only known coeval and correlative faunas are in the western Baltican Urals and near Salair in northern Siberia (Soja, 1994; Soja and Antoshkina, 1997).

Furthermore, the Devonian Karheen Formation and the Silurian Heceta Formation contain coarse alluvial deposits similar to the Old Red Sandstone of the northern Caledonides (Bazard et al., 1995; Soja and Krutikov, 2008). Based on the Uralian faunas, evidence of a low-latitude Devonian paleopole, and preliminary detrital zircon data, Bazard et al. (1995) proposed that the Alexander terrane lay close to the Scandinavian Baltic margin in mid-Paleozoic time (Fig. 2). If this is correct, then the Alexander terrane should have a shared history with the pericratonic and oceanic allochthons of the Scandinavian Caledonides. In particular, Neoproterozoic and early Paleozoic VMS deposits in the Alexander terrane may be a continuation of metallogenetic belts of the northern Caledonides and Baltica. Herein we present

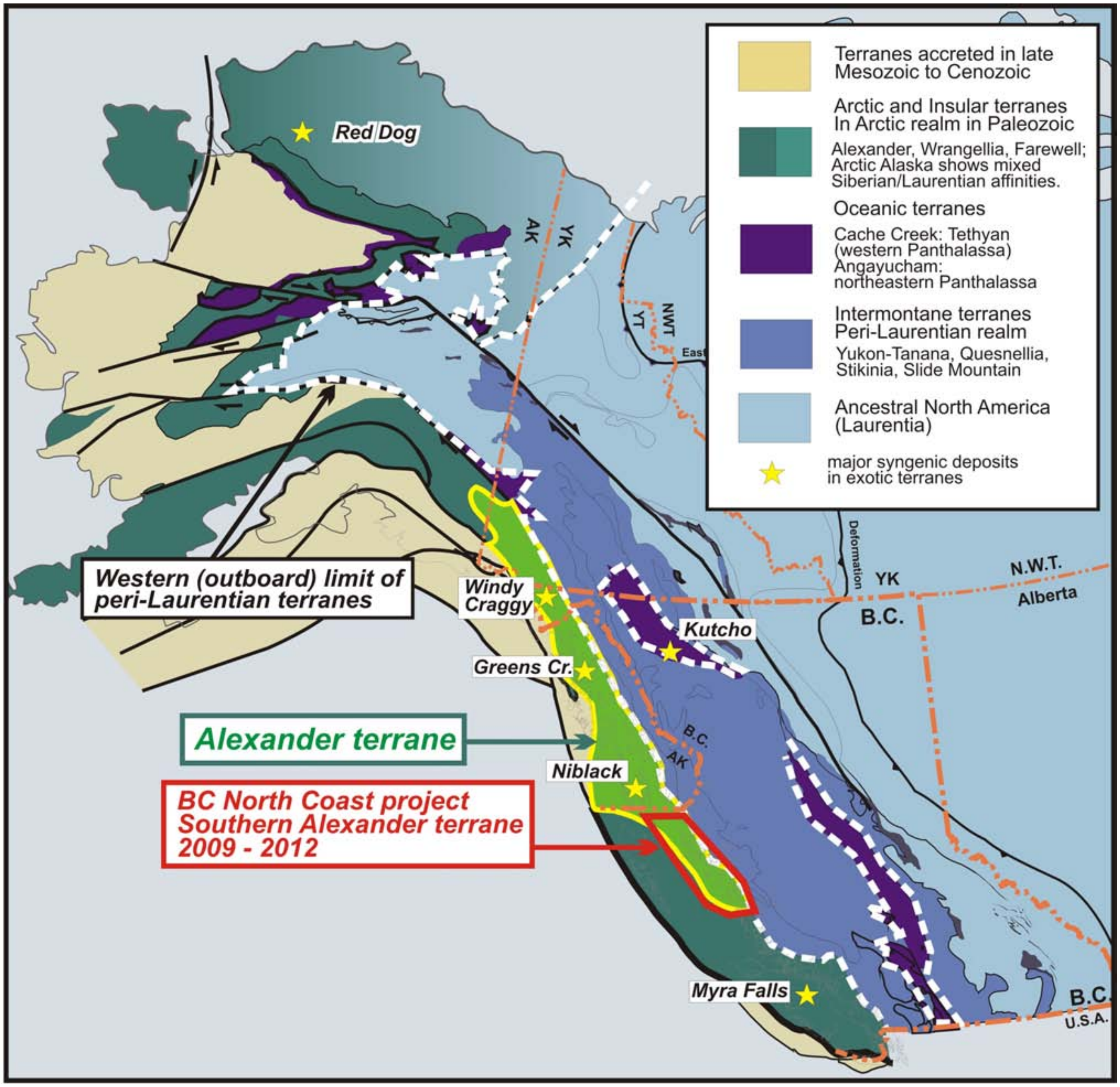

Fig. 1. Location of the Alexander terrane and BC North Coast project 2009-2012.

Pb isotopic data from an Ordovician VMS deposit in the Alexander terrane that support this hypothesis.

The southern Alexander terrane in southeastern Alaska hosts three suites of VMS deposits, Neoproterozoic, Ordovician, and Triassic (Fig. 3; Gehrels, et al., 1983). The Neoproterozoic and Ordovician suites are particularly significant because VMS deposits of this antiquity are unknown elsewhere in the North American Cordillera. The Neoproterozoic deposits, notably the Niblack, are hosted by the Neoproterozoic Wales Group. The Ordovician deposits are in the Moira Sound unit on southern Prince of Wales Island, an informal stratigraphic term introduced by Ayuso et al. (2005) and Slack et al. (2005), which is age-equivalent to, but lithologically distinct from, the Descon Formation as defined on northwestern Prince of Wales Island by Eberlein and Churkin (1970). Although Gehrels and Saleeby (1987) included Moira Sound unit rocks on southern Prince of Wales Island as part of the Descon Formation, their unique character and role as host of volcanogenic deposits are worthy of distinction as a separate unit.

This paper reports the results of mineral deposit documentation and Pb isotopic sampling and analysis completed as part of a three-year regional geological and metallogenetic study of the Alexander terrane in coastal northwest British Columbia. The project, designed to upgrade previous reconnaissance-level geoscience (see Nelson *et al.* 2010, 2011, 2012a) was part of the

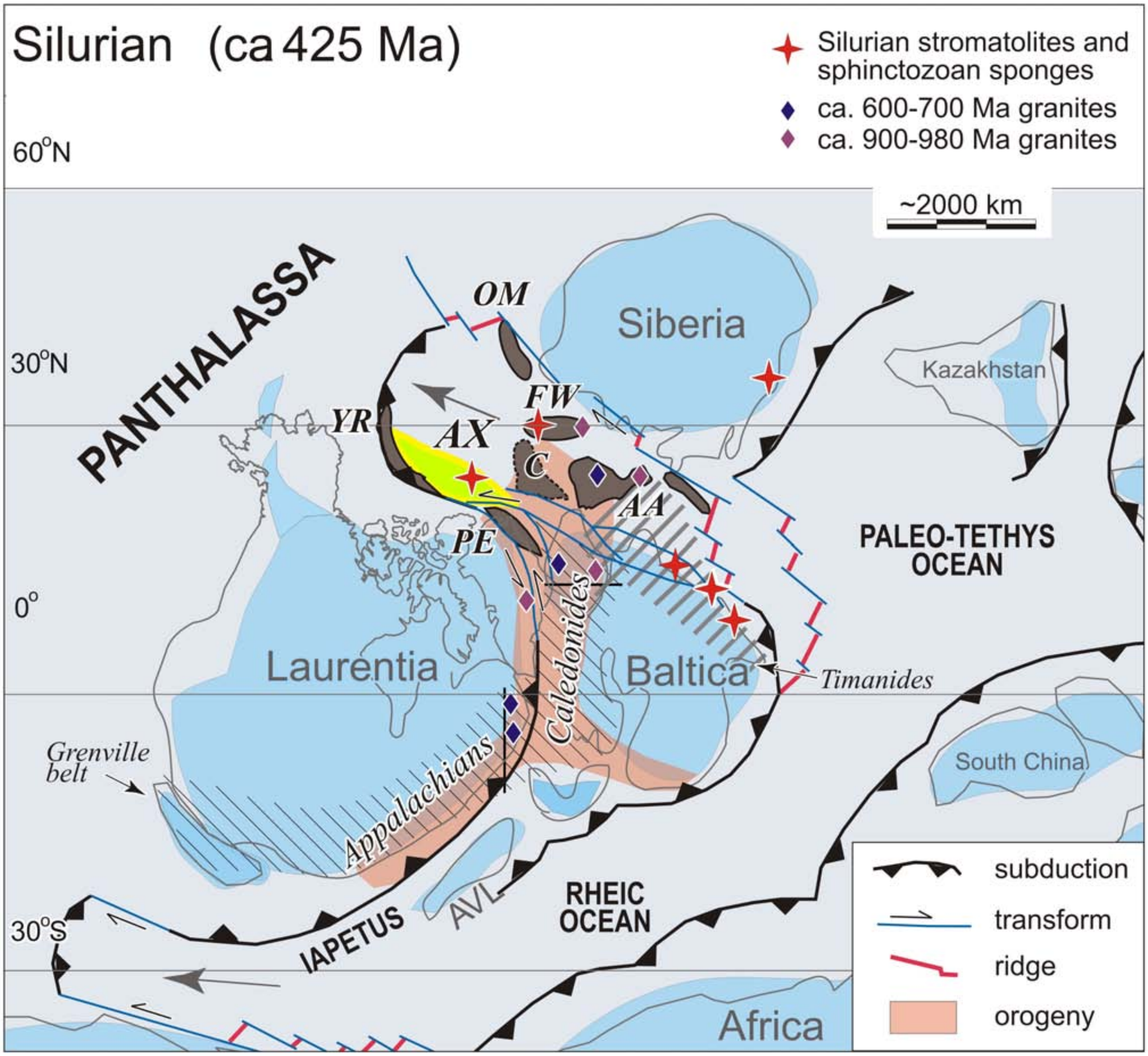

Fig. 2. Inferred paleogeographic position of Alexander terrane in Silurian time (based on Bazard et al., 1995, Colpron and Nelson, 2009, 2011; Nelson et al., 2012a). AX = Alexander terrane; FW = Farewell, YR = Yreka, Northern Sierra, Okanagan, AA = Arctic Alaska-Chukotka; OM = Omolon; P = Pearya. Alexander shown in yellow, other mobile terranes in brown.

GEM-Edges (Cordilleran Multiple Metals) initiative, a collaboration between the Geological Survey of Canada, British Columbia Geological Survey, and Yukon Geological Survey. The BC North Coast component also involved co-research with Brian Mahoney (University of Wisconsin at Eau Claire) and George Gehrels and Mark Pecha (University of Arizona.) A primary goal was to document volcanogenic occurrences and the age and character of their enclosing volcanic sequences, and to correlate them with the much better known deposits on Prince of Wales Island. The only well-described set of VMS-type occurrences in the Alexander terrane of northwestern British Columbia, the Pitt prospect on Pitt Island, was specifically targeted for study.

2. Regional geology and VMS mineralization of the Alexander terrane

The Alexander terrane comprises three distinct tectonostratigraphic entities, the Craig, Admiralty and informal "St. Elias" subterranes (Fig. 3). The Craig subterrane, the most widespread and best documented, has been the subject of many stratigraphic and geochronological studies in southeastern Alaska (Eberlein and Churkin, 1970; Gehrels and Saleeby, 1987; Gehrels and Berg, 1992, 1994). Basal units include primitive arc-related volcanic and lesser sedimentary strata of the Neoproterozoic Wales Group. Host felsic rocks of the Niblack deposit on southern Prince of Wales Island have yielded ca. 565 Ma U-Pb zircon ages (J. Oliver et al., 2011 oral communication). As of March 2011, combined

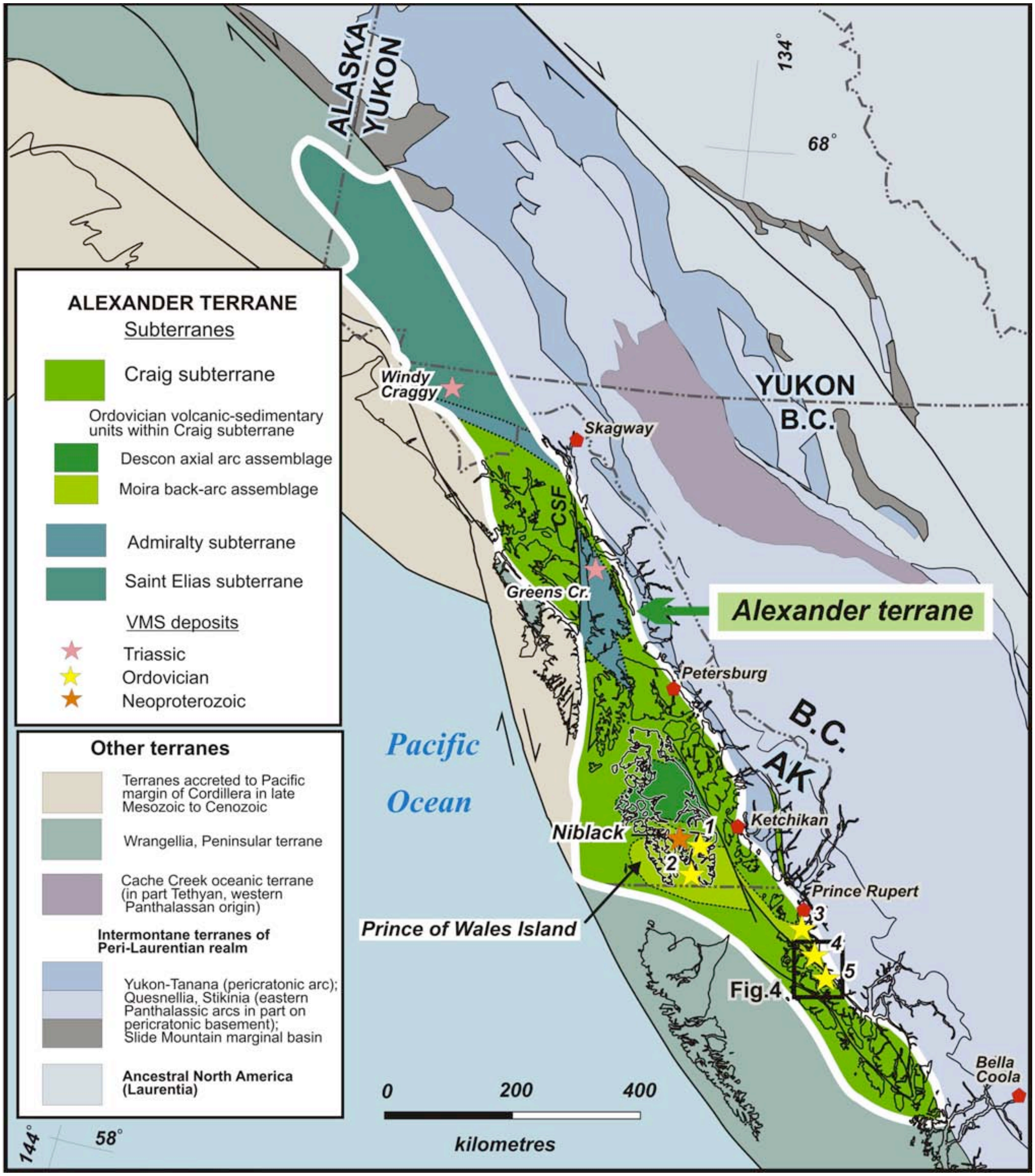

Fig. 3. Regional geology of the Alexander terrane. Craig and Admiralty subterranes from Gehrels and Berg (1994). Saint Elias subterrane is an informally defined and very approximately delimited. Approximate outline of Descon Formation from Gehrels and Berg (1992). Outline of Moira Sound unit on Prince of Wales Island from Ayuso et al. (2005). Ordovician rocks in NW British Columbia, assigned here to the Moira back-arc assemblage, are from mapping and geochronological studies conducted during the present project. POW = Prince of Wales Island. CSF = Chatham Strait fault. Ordovician volcanogenic sulphide occurrences: 1. Moira Copper 2. Barrier Islands 3. Digby Island 4. Kennedy Island 5. Pitt prospect, Pitt Island.

indicated and inferred resources at this deposit were 6.63 Mt at 1.16% Cu, 2.11 g/t Au, 2.28% Zn and 33.89 g/t Ag (J. Oliver et al., 2011 oral communication).

Deformed and metamorphosed Wales Group strata and post-kinematic Neoproterozoic-Cambrian plutons are unconformably overlain by Ordovician volcanic and sedimentary strata on southern Prince of Wales Island (Fig. 3). Although Gehrels (1992) included these rocks in the Descon Formation, Ayuso et al., (2005) and Slack et al. (2005) redefined them as a separate unit, the Moira Sound unit. Volcanic rocks in the Moira Sound unit are markedly bimodal, and interbedded with deep-water sedimentary strata, including siltstone, mudstone, greywacke, carbonaceous argillite, and minor conglomerate and limestone. This stratigraphy differs markedly from the Descon Formation farther north on Prince of Wales Island, which consists of voluminous intermediate volcanic and volcaniclastic accumulations typical of the central region of an island arc. The Moira Sound unit unconformably overlies the Wales Group (Ayuso et al., 2005), whereas the basement of the Descon Formation is unknown because its base is unexposed. There is evidence for local Devonian tectonism in the shear zone separating the Moira Sound unit and underlying Wales Group on southern Prince of Wales Island from the Descon Formation farther north (S. Karl, unpublished data and personal communication, 2010). It is thus possible that either the Moira Sound unit represents a collapsed back-arc sequence linked to the Descon arc, or a separate and unrelated crustal fragment. In any event, the distribution of known Ordovician VMS deposits (Moira Copper and Barrier Islands, Fig. 3) suggests that the Moira Sound unit is the exploration target of choice, rather than the arc-central Descon Formation proper (S. Karl, written communication, 2009). North of Prince of Wales Island, Silurian and younger clastic and carbonate units blanket the Craig subterrane (Gehrels and Berg, 1992).

The Admiralty subterrane outcrops on Admiralty and Kupreanof islands and the Chilkat Mountains west of Skagway, separated by approximately 180 km of dextral motion across the Chatham Strait fault (Fig. 3; Karl et al., 2010). It includes metamorphic equivalents of some Craig subterrane units, such as Neoproterozoic volcanic and plutonic rocks equivalent to the Wales Group (Karl et al., 2006). Some Paleozoic strata within it represent deep-water facies: graphitic schist of the Precambrian-early Paleozoic Retreat Group; chert, argillite, greywacke, limestone, and basalt of the overlying Ordovician-Devonian Hood Bay Formation; and ribbon chert, argillite, greywacke, and basalt of the Devonian to Early Permian Cannery Formation (Karl et al., 2010). Both Devonian (Forbes et al., 1987) and Permian (Haeussler et al., 1999; Karl et al., 2010) metamorphic ages are recorded within this subterrane. The oldest overlap unit between it and the Craig subterrane is the Permian Pybus Formation (Gehrels and Berg, 1994). The Greens Creek mine on Admiralty Island (Fig. 3) is developed on a Triassic silver-rich polymetallic VMS orebody, which formed in a rift that cut the Alexander terrane along its length (Taylor et al., 2008), after juxtaposition of the Craig and Admiralty subterranes.

The St. Elias subterrane is a pericratonic crustal fragment that contains a > 2000 m thick sequence of Cambro-Ordovician siliciclastic, carbonate, and mafic volcanic rocks, and Paleozoic carbonate and siliciclastic strata (Mihalynuk et al., 1993). It contrasts strongly with the primitive arc assemblages on Prince of Wales Island. Beranek et al. (2012) suggested that the Cambro-Ordovician basalts represent the peri-continental backarc region corresponding to the Descon arc. The St. Elias subterrane hosts the Triassic Windy Craggy VMS deposit. This very large Cu-Zn-Au-Co deposit formed in the same rift as Greens Creek; their contrasting ore compositions reflect immediate host rocks: mafic at Windy Craggy; felsic calcalkaline at Greens Creek (Taylor et al., 2008).

3. Ordovician VMS mineralization in the Alexander terrane of NW British Columbia

3.1. Setting

A volcano-sedimentary suite with high-level intrusions underlies northeastern Porcher Island and extends southwards to eastern Pitt Island and the mainland coast east of Grenville Channel (Figs. 3, 4). These rocks were assigned to the Alexander terrane by Wheeler and McFeely (1991), but because they failed to yield fossils and only one U-Pb age was available (482 Ma, trondhjemite intrusion, Gehrels and Boghossian, 2000), their age and affinity were uncertain. Five new U-Pb age determinations from plutonic, volcanic and volcaniclastic units, ranging from 495 to 472 Ma (J.B. Mahoney, unpublished data, 2012), confirm an Early Ordovician age, coeval with the Descon Formation and Moira Sound unit. The suite most resembles the Moira Sound unit. It includes a variety of lithologic units (shown in detail on Nelson et al., 2010; 2012b, fig. 5). Far northern Porcher Island is underlain by metamorphosed thin-bedded to laminated andesitic to dacitic tuffs, volcaniclastic sandstone and conglomerate, and metre- to decimetre-scale interbeds of tuff, breccia and limestone. Rhyolites and subvolcanic trondhjemite-diorite intrusions form a belt along the islands east of Porcher Island. This belt appears to continue southeastwards onto the northeastern shoulder of Pitt Island. Small felsic centres on Kennedy Island host the Kennedy and Dogfish showings. The most eastern exposures of the Moira Sound unit are of mainly mafic metavolcanic rocks and biotite schist. Metamorphic grades range from greenschist on far northern Porcher Island through lower amphibolite on Kennedy Island to upper amphibolite on northeastern Pitt Island and the mainland coast.

3.2. Volcanogenic-style mineralization

Volcanogenic mineralization and associated alteration zones in the area include: 1) the Pitt prospect (103H 066), a 3.5 kilometre-long trend of small polymetallic sulphide bodies on northeastern Pitt Island, classified as a probable VMS-style trend, that was explored, geologically mapped, and drilled in the 1990s (Bradley, 1987; Lo, 1992; Bohme, 1993); 2) zones of pyrite-pyrrhotite (± chalcopyrite-sphalerite) stockwork and partial replacement in metarhyolite, (Kennedy or Hard Case and Dogfish) discovered on the shores of

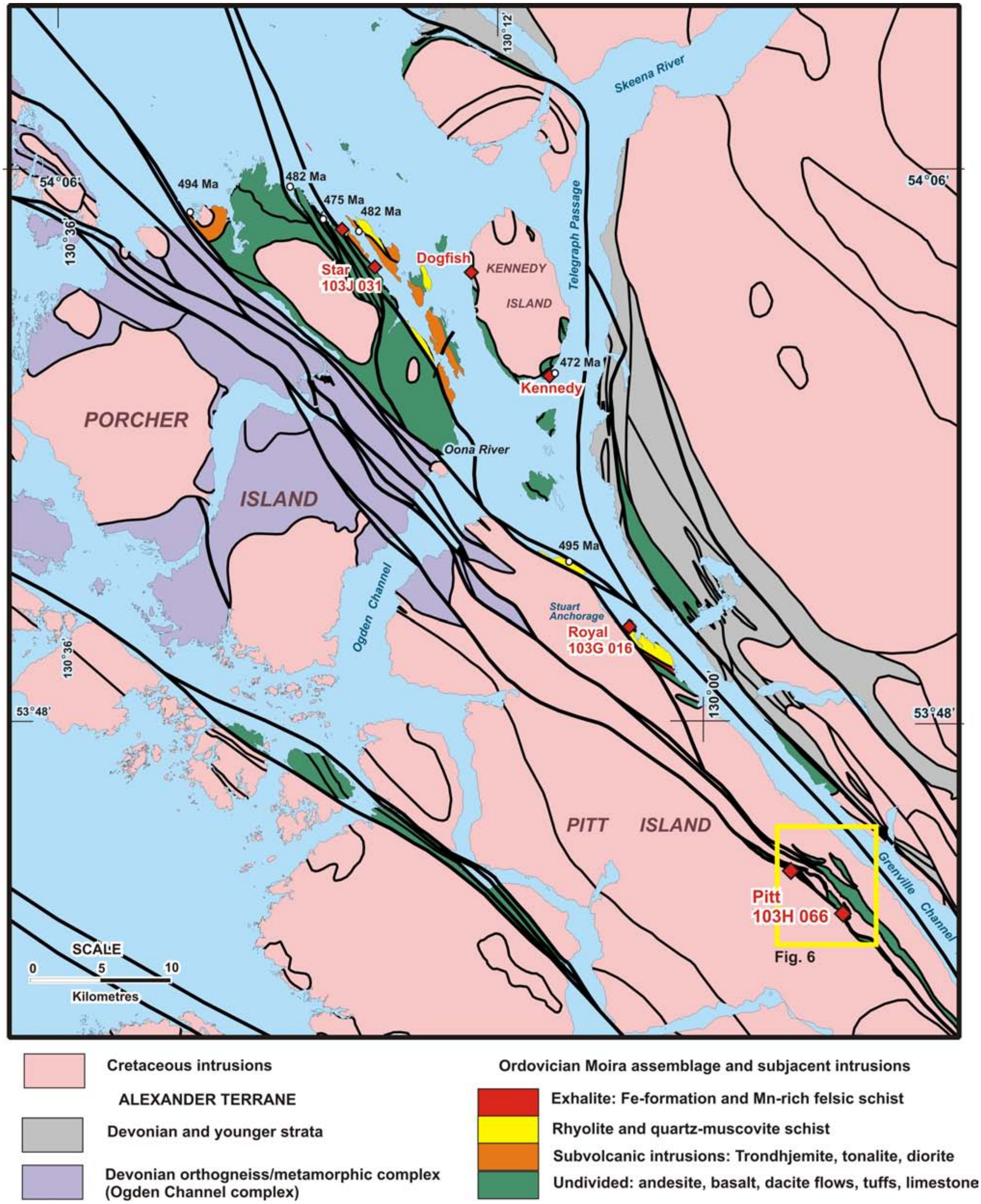

Fig. 4. Generalized geological map of Porcher and Pitt islands, showing Ordovician Moira assemblage exposures, volcanogenic sulphide and related occurrences, and locations of U-Pb ages. All U-Pb data are J.B. Mahoney, unpublished, except for the ca. 482 Ma date on trondhjemite from McMicking Island (Gehrels and Boghossian, 2000).

Kennedy Island in 2011 (Nelson et al., 2012b); and 3) meta-exhalite(?) and magnetite iron formation, including MINFILE localities, 103G 016 Royal and 103J 031 Star (Fig. 3). Because of its extensive exploration history, followed up by our 2011 field investigations and analytical results, the Pitt prospect is discussed in more detail in a following section.

On Kennedy Island, the Kennedy showing (Fig. 4) comprises massive pyrite-pyrrhotite with accessory chalcopyrite and sphalerite and stockwork-like mineralization hosted by a felsic pyroclastic rock, components of which have been replaced by sulphide (Fig. 5a). At the Dogfish showing, mineralization occurs in intensely quartz-sericite-altered volcanic protoliths as: disseminated pyrite and pyrrhotite; massive pyrrhotite, local pyrite, sphalerite, and minor chalcopyrite; and brecciated, sulphide-bearing quartz-sericite schist veined by pyrrhotite and sphalerite (Fig. 5b). Because Kennedy Island is protected as part of the Kennedy Island Conservancy Area, these two new occurrences are not potential exploration targets in themselves. However, they demonstrate the potential for VMS-style mineralization in the Moira Sound unit. The sulphide textures and lithic associations resemble the massive marcasite-pyrite stockwork and replacement in Ordovician felsic breccia (Figs. 5c, d) on the western side of Digby Island (near Prince Rupert, Fig. 3). The Digby Island site yielded a U-Pb zircon age of ca. 472 Ma (Gehrels and Boghossian 2000), identical to that of felsic lapilli tuff at the Kennedy showing.

Stratabound, stratiform magnetite is widely scattered along the northeastern side of Porcher Island, and on the eastern side of Pitt Island near Stuart Anchorage (Fig. 4, including MINFILE localities, 103G 016 Royal and 103J 031 Star). The bodies are continuous over tens to hundreds of metres, enclosed in highly strained meta-tuffs. The Royal occurrence and its southern extension lie immediately above a felsic meta-tuff body. Individual layers vary in thickness from tens of centimetres to a maximum at the Royal showing of several metres, which is interpreted as a thickened fold hinge zone. Most commonly, mineralization consists of pure, fine-grained magnetite with shiny grey hematite partings (Fig. 5e). Magnetite also forms fine laminae and blebs within meta-tuff (Fig. 5f).

Atypical of skarns, calcsilicates are minor; epidote and epidote-garnet accompany the magnetite only in a few cases. Carbonate rocks, common elsewhere in the volcanic sequences, are not in direct association with the magnetite bodies. Hence we argue that the magnetite layers record exhalative processes during volcanism, rather than metamorphic replacement, and that they represent the distal equivalents of a regional system that included more proximal sulphide-rich facies. Schists containing manganoan zoisite and axinite occur within tens of metres of the iron formation in Stuart Anchorage, (Fig. 4). Their unusual compositions and association with felsic metatuffs support an exhalative origin.

3.3. The Pitt prospect: Geology, mineralization and modelling

The Pitt prospect or Pitt/Trinity claim group (MINFILE 103H 066), is a 3.5 km long trend of sulphide showings on northeastern Pitt Island distributed along the ridges near Grenville Channel (Figs. 4, 6). Prospecting near a rusty gossan in Pyrite Creek in 1980 led to the discovery of massive sulphides. The discovery was followed by further exploration and preliminary mapping to determine the geological setting of the polymetallic mineralization (Bradley, 1987). Detailed geological mapping at 1:10 000 scale, prospecting, sampling and airborne geophysical surveys were carried out in 1992 (Bohme, 1993; Lo, 1992). Figure 6 depicts the major units and faults identified in the 1992 mapping, along with new information and interpretations from the present project.

Mineralization at Pitt consists of zones in two NW-trending metasedimentary-metavolcanic inliers within foliated Cretaceous plutons (Fig. 6; Bohme, 1993). Layering is aligned along the regional steeply dipping, northwest-trending foliation. Greenish to brown metapelite and metatuff are the main host rocks. Minor in abundance, but important to modelling the deposit, are rusty, pyritic metarhyolite (Fig. 7a), quartz-muscovite schist and massive quartz-rich schist with relics of pre-metamorphic stockworking (referred to as “quartzite” by Bohme, 1993). The Pyrite Creek and Pitt zones are the most significant of the known showings. Located 3.5 kilometres apart along strike, they coincide with a prominent northwest-trending topographic lineament, which is marked by incised drainage and rusty oxidized gossans. Along the lineament, the supracrustal rocks and Cretaceous plutons display shear, locally mylonitic, fabrics. In both zones, pyrite-rich, semimassive and massive sulphides occur in quartz-muscovite schist interlayered with quartz-rich zones, garnet-quartz-biotite schist, and carbonaceous argillite (Fig. 6). The true thickness of sulphides varies between 0.2 and 1.6 metres (Bohme, 1993). Principal sulphide minerals consist of pyrite, chalcopyrite, sphalerite, pyrrhotite, galena, covellite and, possibly, bornite. Based on values of 1.0-5.5% Ba in assays, barite is suspected. Drill intersections of the Pyrite Creek zone returned between 0.94 and 2.2% Cu, 0.41 to 1.2% Pb, and 1.5 to 4.9% Zn over 2-metre widths.

In 2011, a brief property visit aimed to verify map relationships of Bohme (1993). At the Pyrite Creek showing, sulphides are hosted by decimetre-scale layers of quartzose schist that alternate with laminated garnet biotite schist. Coarse quartz-muscovite schist comprises a half-metre thick, friable weathered layer exposed at creek level in a steep, incised gully. It is composed mainly of muscovite and quartz with disseminated and semimassive millimetre-thick bands of pyrite-chalcopyrite ± sphalerite ± galena. Thus, our field investigations demonstrated that both showings are associated with metamorphosed felsic and/or altered hosts: rusty metarhyolite at the Pitt zone (Fig. 7a), and quartz-muscovite schist at the northern end

Fig. 5. Mineralization in Ordovician felsic volcanic hosts on Digby and southern Kennedy islands. **a)** Kennedy showing, with crosscutting massive sulphides, also replacing clasts in felsic breccia. **b)** Dogfish showing, displaying brecciated sulphide bearing quartz sericite schist surrounded by pyrrhotite and sphalerite. **c)** Massive marcasite-pyrite gossan in Ordovician metarhyolite, Digby Island; George Gehrels examining the site of ca. 472 Ma U-Pb zircon sample reported in Gehrels and Boghossian (2000). **d)** Digby Island metarhyolite breccia with irregular replacement and fracture-filling sulphides. **e)** Layer of magnetite in thinly laminated Wales Group meta-tuff, northeastern Porcher Island. **f)** Magnetite laminations in siliceous, iron-rich meta-tuff, Stuart Anchorage.

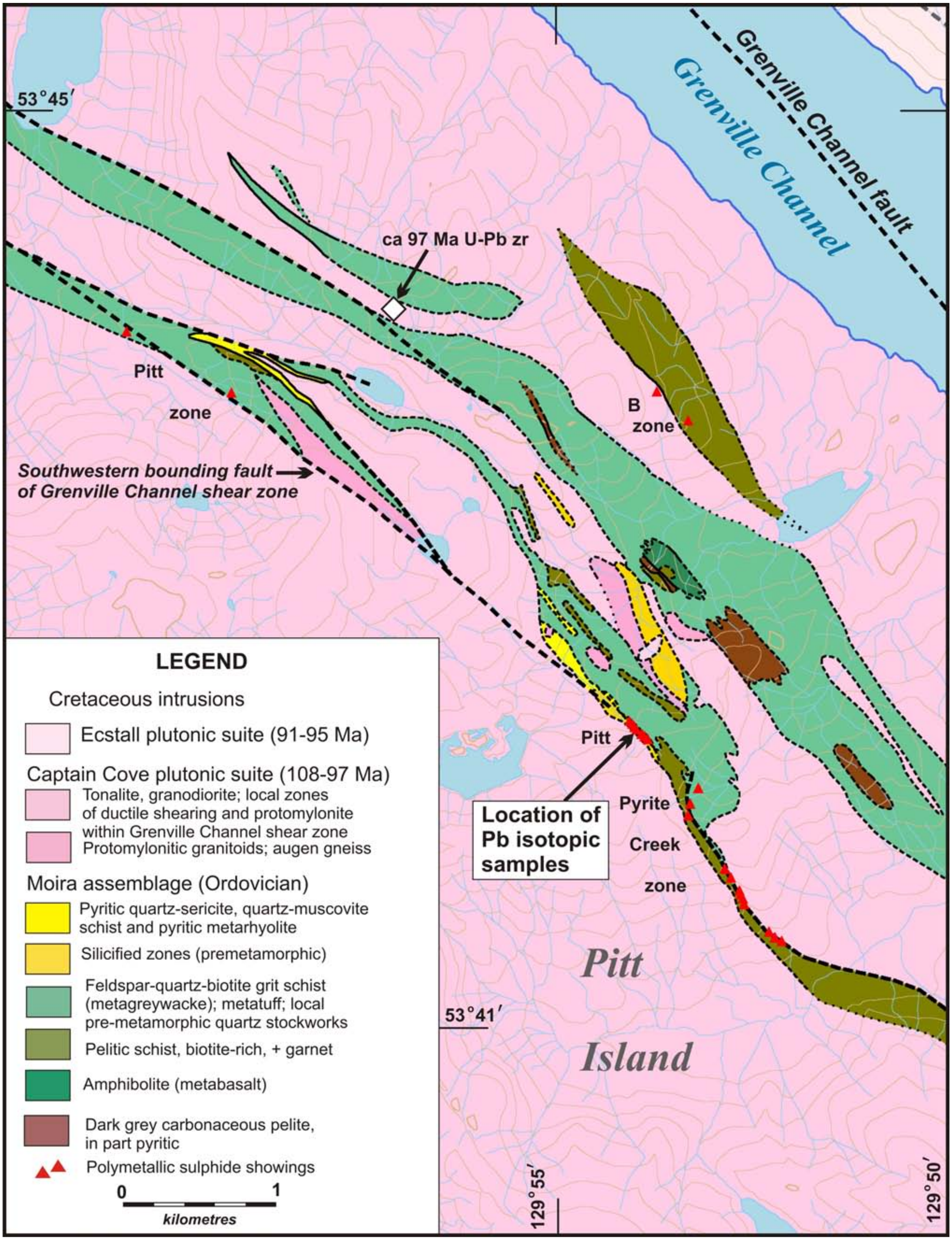

Fig. 6. Detailed geologic map of the Pitt prospect and vicinity. Geology from Bohme (1993) and field observations in 2011. Location of Pb isotopic samples shown (11LDi02-01). U-Pb age, M. Pecha, unpublished data 2011.

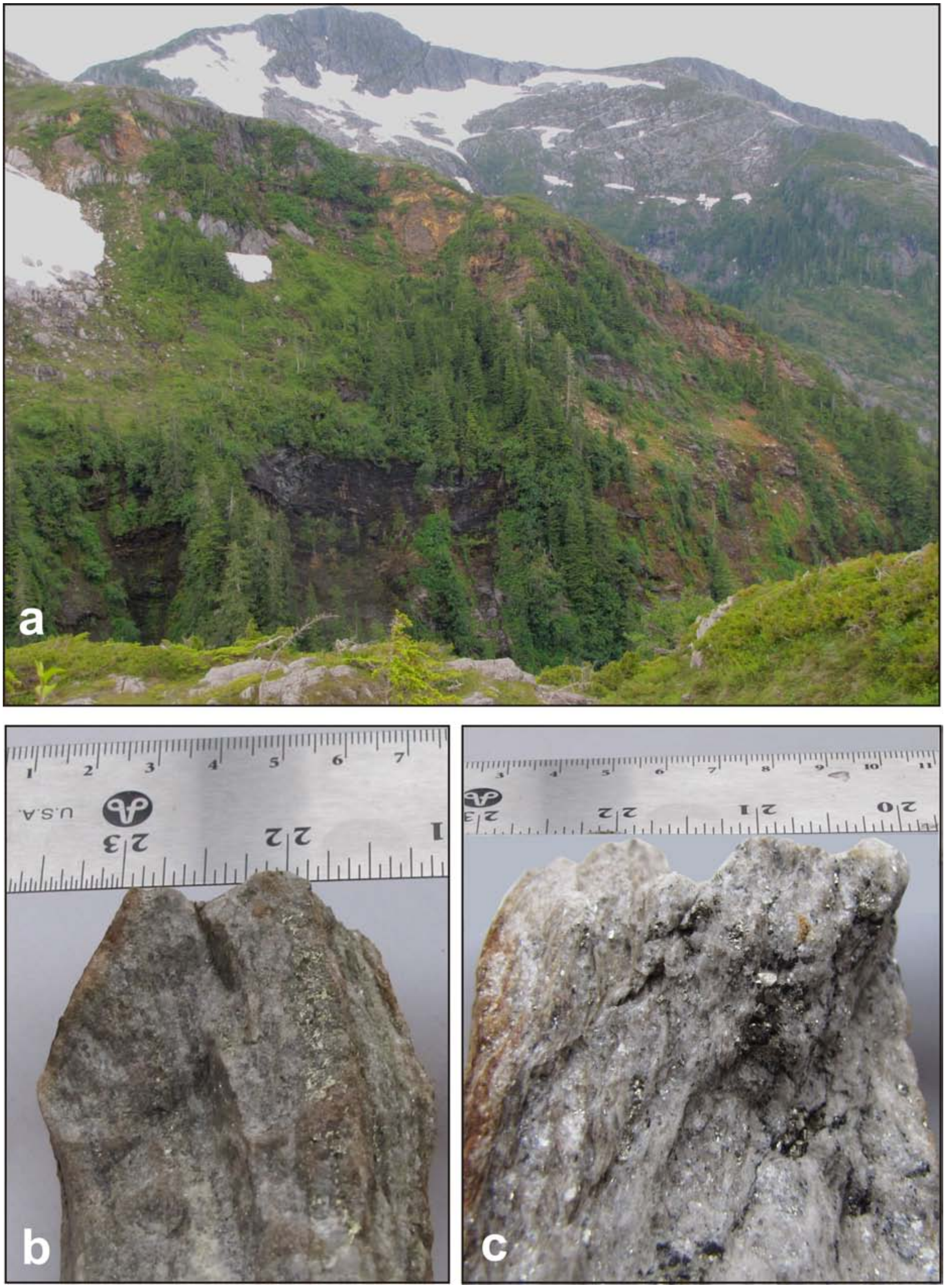

Fig. 7. Mineralization at the Pitt prospect. **a)** Rusty, pyritic quartz sericite schist (metarhyolite) along the Pitt zone lineament. For location of this body see Figure 4. **b)** Close-up of Pb isotopic sample 11LDi02-01a, showing chalcopyrite-rich laminae in quartz-muscovite schist. **c)** Close-up of Pb isotopic sample 11LDi02-01b, showing apparently crosscutting sphalerite-pyrite veinlets in quartz-muscovite schist.

of the Pyrite Creek zone (Figs. 7b, 7c).

However, our work also confirmed the strong structural control on the 3.5 km long trend of mineralization that comprises the main Pyrite Creek and Pitt zones. All of the mineralization, except the B zone (Fig. 6), lies within a major Cretaceous shear zone. Regionally, the host fault forms the most southwesterly strand of the Grenville Channel fault system, a mid-Cretaceous sinistral transpressive ductile shear zone recognized over a 200 km strike length from northern Porcher Island to south of Klemtu (Nelson et al., 2012b). The shear zone is particularly wide and well developed around Grenville Channel. The strand that hosts the Pitt showing displays a crustal-scale strain discontinuity. East of the fault, Cretaceous granitoids as young as 97 Ma (Fig. 6; M. Pecha, unpublished U-Pb data 2012) display pervasive mylonite fabrics, whereas to the southwest, large granitoid bodies of the mid-Cretaceous (108-97 Ma) Captain Cove suite are undeformed.

Field evidence at the Pitt prospect supports two alternative models for its origin. First, the association of layered, apparently stratabound mineralization with metatuffs, pelitic rocks, meta-rhyolites, and metamorphosed quartz-sericite and siliceous alteration assemblages led Bohme (1993) to classify it as volcanogenic. Alternatively, the localization of most mineralization along the trace of a major Cretaceous fault could be taken as support for an epigenetic origin. To address this question, we collected samples of host felsic rocks (quartz-muscovite schist) for U-Pb geochronology, and of stratiform sulphide mineralization for Pb-Pb isotopic analysis. The schist failed to yield zircons. Pb-isotopic analytical results for two sulphide samples are reported below.

4. Pb isotopic analysis of sulphides

Two sulphide-bearing samples were collected from the northern end of the Pyrite Creek zone. Both consist of sulphide laminae and stockworks within coarse-grained quartz-muscovite schist (Figs. 7b, c). Therefore, if this mineralization is part of a volcanogenic system, it is more likely to be "stringer ore" from a feeder zone, rather than bedded massive sulphide. The lack of zircon yield from the host could indicate that it was a metamorphosed altered mafic rock rather than a rhyolite. The sulphide textures are also consistent with an epigenetic origin overprinted by shear. Sample 11LDi02-1a contains centimetre-scale chalcopyrite laminae; 11LDi02-1b contains veinlets of sphalerite and pyrite.

4.1. Analytical procedures

Meaningful Pb isotopic analysis of sulphides requires that the sample be free of silicate grains, particularly those such as micas that contain uranium and thus cause a change in the isotopic ratios after crystallization of the sulphides. Concentrates of 300-500 mg of chalcopyrite and sphalerite were separated by selection of sulphide-rich areas in the sample, followed by crushing, milling, and concentrating, and finally by hand picking to ensure purity (Overburden Drilling Management Ltd.).

The lead isotopic analyses were performed at Queen's University Facility for Isotope Research. Approximately 5 g of each sample was weighed into a clean Savillex beaker. Savillex beakers without samples, but containing all reagents, were included as procedure blanks to monitor contamination. To each beaker, 5 mL of 50% HNO_3 (distilled HNO_3 and >18.2 MegaOhm H_2O) was added. The closed beakers were heated on a hotplate at 120˚C for 24 hours to dissolve the sulphides. Samples were cooled and centrifuged to remove remaining solids. The solutions were then evaporated to dry on a hotplate at 70˚C. 2% HNO_3 was added to dissolve the sample and dilute appropriately for measurement. All sample preparation was performed in a class 100 clean lab. Measurement of the lead isotope ratios was by Thermo Finnigan Neptune MC-ICP-MS. All masses (^{200}Hg, ^{202}Hg, ^{203}Tl, ^{204}Pb, ^{205}Tl, ^{206}Pb, ^{207}Pb and ^{208}Pb) were measured on Faraday detectors in low resolution. Mercury was measured for correction of the mass 204 signal (^{204}Hg+^{204}Pb). Samples were bracketed with NIST 981 standards during measurement. Tl spikes (^{205}Tl/^{203}Tl=2.388) were added to each sample, as well as to each standard and each procedure blank, for the purpose of mass bias correction. Sample uptake was 100 microlitres per minute using a ESI PFA nebulizer. All gas flows and lenses were optimized for maximum stability and signal intensity (Table 1).

Table 1. Conditions and specifications for isotopic analysis on Thermo Finnigan Neptune MC-ICP-MS.

RF Power	1250W
Cool gas flow	17 L/min.
Aux gas flow	1 +/- 0.1 L/min.
Sample gas flow	0.9 L/min.
Integration time	4 sec.
Number of integrations	60

4.2. Analytical results and local comparisons

Lead isotopic ratios for the two samples are shown in Table 2. Isotopic ratios for the chalcopyrite are: ^{206}Pb/^{204}Pb, 18.1911; ^{207}Pb/^{204}Pb, 15.5643 and ^{208}Pb/^{204}Pb, 38.1015. For the sphalerite they are: ^{206}Pb/^{204}Pb, 18.1701, ^{207}Pb/^{204}Pb, 15.5660, and ^{208}Pb/^{204}Pb, 38.0893. Radiogenic isotopes are presented in their ratios to common, non-radiogenic ^{204}Pb. The isotopic ratios for the two concentrates are very close, although not quite within analytical error of each other. Their consistency is comparable to that of deposits with notably uniform Pb isotopic compositions such as Pine Point (Cumming et al., 1990), suggesting that lead isotopic homogenization took place in the original hydrothermal system, and that these Pb isotopic values preserve a record of the ore chemistry of the original deposit.

Table 2. Lead isotopic analytical data for sulphide samples from the Pitt showing.

Sample locations and descriptions

Pitt samples	**UTM east**	**UTM north**	**Description**
11LDi02-1a	442372	5950488	Chalcopyrite-rich laminae in quartz-muscovite schist
11LDi02-1b	442372	5950488	Quartz-muscovite schist with sphalerite-pyrite veinlets

Analytical results

Sample		$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	$^{207}Pb/^{206}Pb$	$^{208}Pb/^{206}Pb$
Standards						
NIST NBS 981 correct values		16.937	15.492	36.722	0.91464	2.16810
981A	Mean	16.9317	15.4860	36.6823	0.91461	2.16647
	StdErr (abs)	0.0004	0.0004	0.0009	0.00001	0.00001
981B	Mean	16.9313	15.4861	36.6812	0.91463	2.16647
	StdErr (abs)	0.0004	0.0003	0.0008	0.000005	0.00001
981C	Mean	16.9313	15.4856	36.6808	0.91462	2.16647
	StdErr (abs)	0.0004	0.0004	0.0009	0.00001	0.00001
Pitt samples						
11LDI02-1a	Mean	18.1911	15.5643	38.1015	0.85560	2.09452
chalcopyrite	StdErr (abs)	0.0007	0.0006	0.0015	0.00001	0.00003
11LDi02-16	Mean	18.1701	15.5660	38.0893	0.85668	2.09626
sphalerite	StdErr (abs)	0.0002	0.0002	0.0006	0.000004	0.00001

Note: Procedure blank measured less than 0.02% of sample signal

Figure 8 is a standard uranogenic lead plot of $^{207}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$. The Pitt samples plot close to the "orogene" curve of Doe and Zartman (1979) and Zartman and Doe (1981). This theoretical curve depicts mixing between upper crustal and mantle sources such as is common at convergent plate boundaries, for instance in back-arc basins where fluid systems sample both primitive mantle-derived volcanic rocks and continent-derived sediments (Bjørlykke et al., 1993). Modern back-arc seabed sulphide deposits, such as in the Lau Basin (Fouquet and Marcoux, 1995) and central Okinawa trough (Halbach et al., 1997), show such intermediate, mixed signatures due to continent-derived sediments and attenuated continental crust in the source area. Mixing lines can be drawn between values at a given age on all three curves. The Pitt data lie between the 500 and 400 Ma mixing lines, indicating that the Pitt mineralization formed in the Ordovician, coeval with the Moira Sound units dated locally, without subsequent introduction of radiogenic Pb during Cretaceous metamorphism and deformation. Note that, because of the shorter half life of ^{235}U (which decays to ^{207}Pb) compared to ^{238}U (^{206}Pb), in Phanerozoic reservoirs the $^{206}Pb/^{204}Pb$ ratio increases rapidly with decreasing age. For comparison, data for the Late Devonian (ca. 370 Ma) Myra Falls VMS deposit of Wrangellia shows comparatively higher $^{206}Pb/^{204}Pb$, consistent with a younger age of mineralization. Furthermore, representative Cretaceous deposits from the Coast belt, the Britannia VMS deposit and gold-polymetallic mesothermal veins at Bralorne and Banks Island, show even higher $^{206}Pb/^{204}Pb$, plotting on a very young mixing curve between mantle and orogene values. Two samples from Ordovician deposits on Prince of Wales Island plot near or below the mantle curve but at "future" lead positions (Fig. 8; data from Ayuso et al., 2005). Enriched mantle sources may have contributed to these leads (Ayuso et al., 2005) but because of uncertain modelling, these data are not considered further in this study.

Figure 9 shows the Pitt data relative to Neoproterozoic and Triassic VMS deposits in the Alexander terrane. Also included are Devonian and Mississippian syngenetic deposits of Arctic Alaska and the Devonian Myra Falls deposit of Wrangellia, because

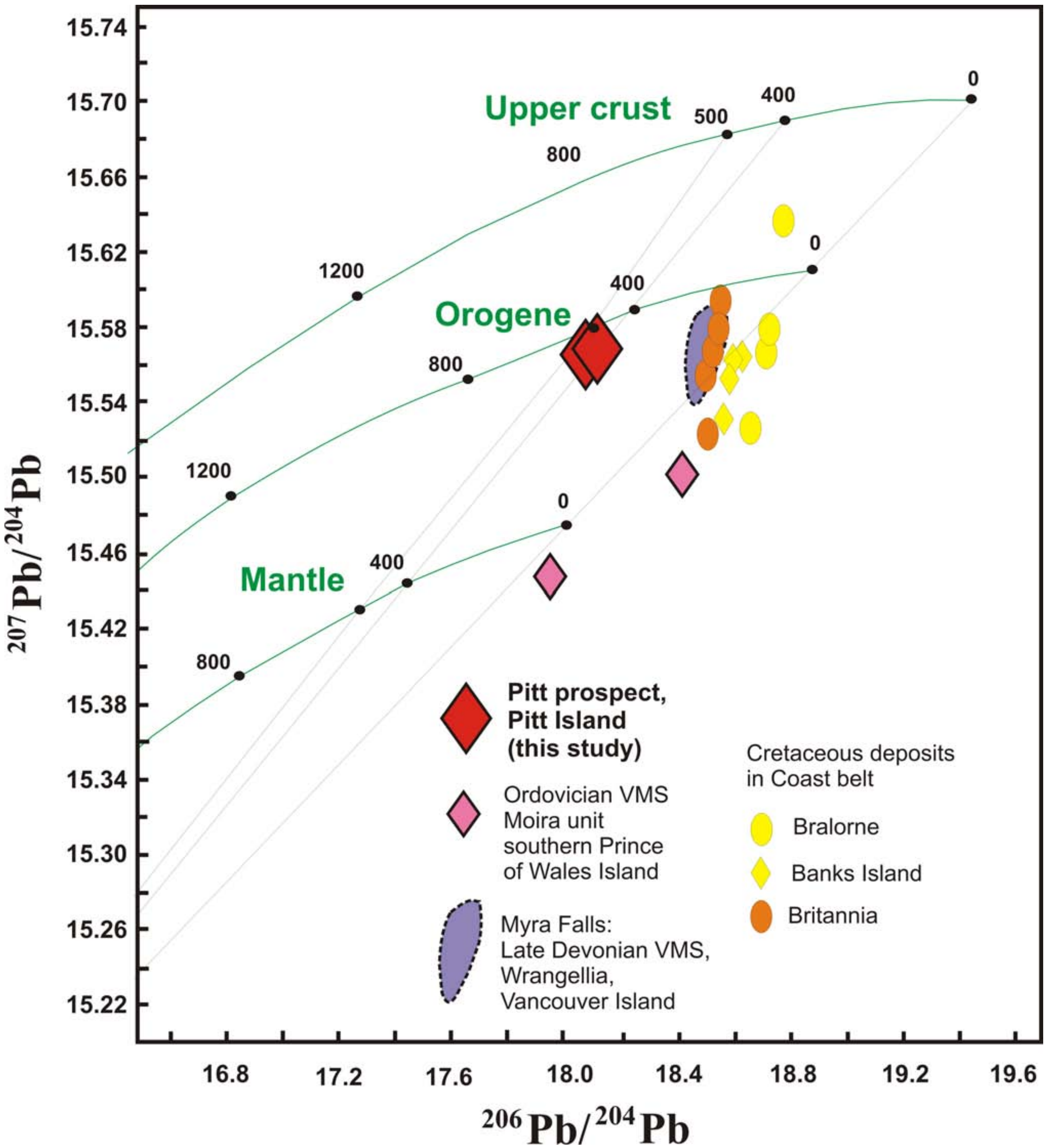

Fig. 8. $^{207}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ plot comparing the Pitt occurrence with the Devonian Myra Falls volcanogenic deposit on Vancouver Island (Wrangellia) and Cretaceous deposits of the Coast belt. Data from Godwin et al. (1988). Also shown are two analyses from the Moira Copper and Barrier Islands Ordovician volcanogenic occurrences in the Alexander terrane on Prince of Wales Island (Ayuso et al., 2005; S. Karl, unpublished data).

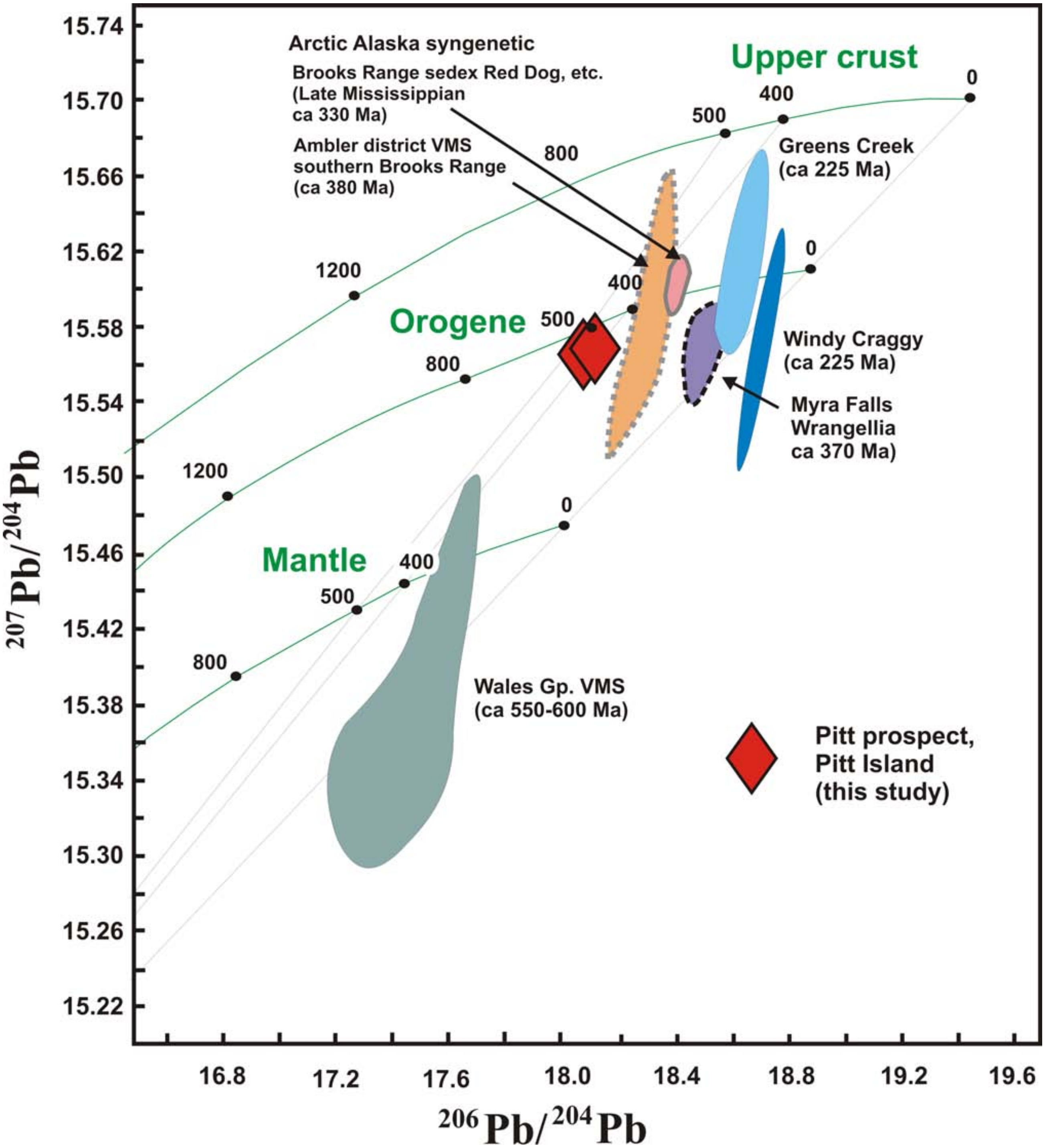

Fig. 9. $^{207}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ plot of Neoproterozoic, Ordovician and Triassic volcanogenic deposits of the Alexander terrane. Except for the Neoproterozoic leads, which exhibit extremely unradiogenic values, all of the deposits plot on the “orogene” (mixed upper crustal and mantle) lead isotopic growth curve (Doe and Zartman, 1979; Zartman and Doe, 1981). Arctic Alaska Devonian and Mississippian leads (Church et al., 1987) and Myra Falls (Godwin et al., 1988) are also shown for comparison.

these terranes are potentially related to the Paleozoic Alexander terrane in paleogeographic position and crustal composition (Gardner et al., 1988; Beranek et al., 2012). The data for the Neoproterozoic Niblack and related deposits are diffuse and generally plot below the mantle curve. Ayuso et al. (2005) considered the possibility of plume-related mantle contributions to the very primitive Wales Group arc. The younger deposits however, all lie on or near the "orogene" curve, more or less in order of decreasing age. Myra Falls lies closer to the mantle curve than Ambler or Red Dog but also at slightly higher $^{206}Pb/^{204}Pb$ values, which indicates a slightly different crustal source. Greens Creek shows a greater degree of upper crustal influence than does Windy Craggy, consistent with their evolved vs. primitive volcanic hosts. Overall, the Ordovician through Triassic deposits define an Insular-Arctic terrane growth curve that is roughly equivalent to the worldwide "orogene" curve. The marked departure of this growth trend from the Wales Group population suggests that the Wales Group primitive arc was amalgamated with more evolved crustal elements prior to the Ordovician. The Wales orogeny (Gehrels and Saleeby, 1987), which affected the Wales Group prior to deposition of the Ordovician Descon Formation, resulted from collision of the Wales arc with another, unidentified crustal block. The affinity of that block is uncertain because it is not preserved at surface; however the overall lead growth pattern between Ordovician and Triassic provides indirect evidence that the basement of the Alexander terrane in Paleozoic and Mesozoic time was partly pericratonic.

4.3. The Pitt lead signature and its Caledonian counterparts

In Figure 10, Pitt lead isotopic values are compared to Ordovician VMS deposits from the Paleozoic Caledonian orogen that surrounds the present-day Atlantic ocean, and formed during closing of the Iapetus ocean, precursor to the Atlantic. These deposits originated in arcs and back arcs settings fringing and within the Iapetus ocean (Fig. 11). They are now preserved in allochthons derived from the eastern peri-Laurentian realm, from the borders of Gondwana, and from Baltica in the Scandinavian Caledonides (van Staal, 2007; Bjørlykke et al., 1993). Among them is the Bathurst district of New Brunswick, in which the giant Bathurst No. 12 mine has produced 230 million tonnes of ore (van Staal, 2007).

The Appalachian leads are from a compilation of Newfoundland, New Brunswick and Quebec data by Swinden and Thorpe (1984). They represent terranes on both the peri-Laurentian and peri-Gondwanan sides of the Iapetus ocean (Fig. 11; also see maps and discussion in Swinden and Thorpe 1984, and van Staal, 2007 for modern terrane assignments and tectonic analysis). All of the deposits lie on a single mixing line between mantle and Grenvillian upper crust (Swinden and Thorpe 1984). The "old" (i.e. unevolved) intersection of this line with the model upper crustal lead reservoir of Doe and Zartman is due to the comparatively young age of the Grenville orogen (ca. 1100 Ma) compared to average cratonic crust (Swinden and Thorpe 1984). The most radiogenic leads are from the Bathurst camp in New Brunswick and from deposits in the Tetagouche-Exploits back-arc basin that separated the Victoria Lake arc from the peri-Gondwanan Ganderia microcontinent in Newfoundland (Fig. 11; van Staal, 2007). In general, Pb in the peri-Laurentian deposits tends to be closer to mantle values. Their hosts are for the most part extremely juvenile arc and back-arc sequences. The Pitt signature nearly centres the Appalachian data, and falls near the least-radiogenic end of the peri-Gondwanan trend. It is nearly identical to that of the Tulks Hill, Burnt Pond, and Tally Pond deposits (Swinden and Thorpe 1984). They lie within the part of the Tetagouche-Exploits back-arc that is closest to the Victoria Lake arc, immediately south of the Red Indian Line, which represents the closed Iapetus ocean (van Staal, 2007).

The Pitt lead signature is also centred within the linear trend of leads from Ordovician VMS deposits in the Upper and Uppermost allochthons of the Norwegian Caledonides (Fig. 11; Bjørlykke et al., 1993). The elongate linear trend for $^{207}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ from these deposits results from their origin in diverse tectonic environments including ensialic back-arc basins with radiogenic lead signatures and marginal basin ophiolitic crust with comparatively primitive, mantle-like lead (Bjørlykke et al., 1993). The Uppermost allochthon is considered to be of peri-Laurentian origin, but the "homeland" of the Upper Allochthon is debated. Although Bjørlykke et al. (1993) interpreted it as entirely of Baltican affinity, some of the nappes within it are of peri-Laurentian origin (Gee, 2005). Lead trends within the Upper and Uppermost allochthons are distinct, with higher $^{207}Pb/^{206}Pb$ in the Uppermost Allochthon. Generally lead becomes less radiogenic upwards within the Upper Allochthon: the most mantle-like leads come from the Løkken ophiolite near its structural top. This led Bjørlykke et al. (1993) to model the Upper Allochthon as a collapsed peri-Baltican margin in which the amount and influence of craton-derived sediments lessened away from the continent. They also point out that the anomalously 'young' intersection of the Scandinavian trend with the upper crustal curve reflects a concentration of very radiogenic Middle Proterozoic granites in the Baltican shield. The Pitt signature is centred within the Norwegian trend, closest to deposits of the Sulitjelma district, which Bjørlykke et al. (1993) place in a peri-Baltican marginal basin.

A plot of $^{208}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ (Fig. 12) provides a further means to compare the Pitt and Caledonian deposits, as it combines uranogenic and thorogenic lead. On this diagram, the Pitt data plot at the upper, most thorogenic end of Appalachian trend, nearly coincident with the Bathurst camp. The Pitt signature is more thorogenic than the Norwegian leads from either Baltica or Laurentia, and reflects mixing of lead from primitive mantle and pericratonic sources. By comparison

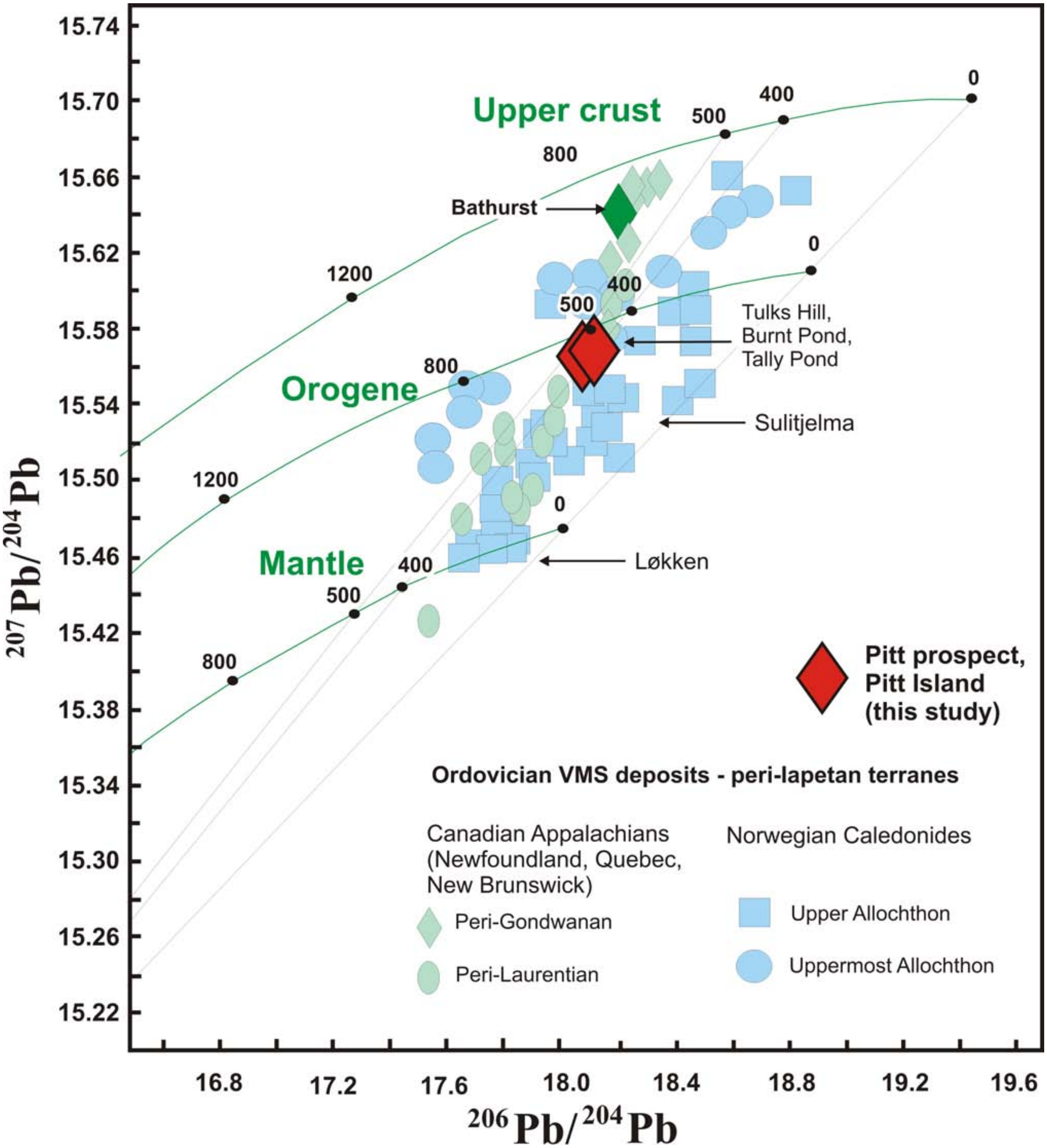

Fig. 10. $^{207}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ plot for Alexander leads vs. Ordovician VMS deposits of the Caledonides. Appalachian deposits from Swinden and Thorpe (1984); Norwegian deposits from Bjørlykke et al. (1993).

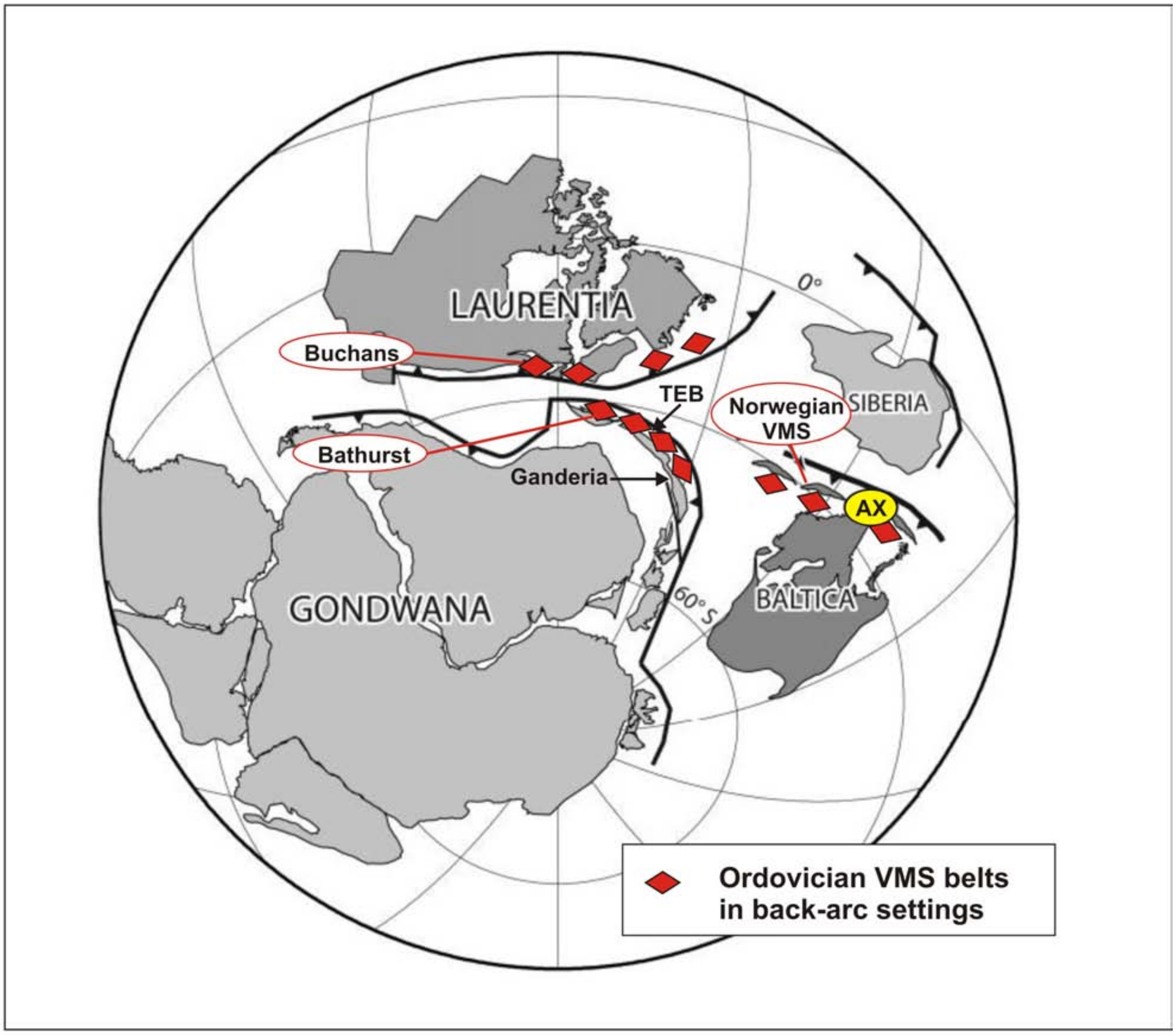

Fig. 11. Suggested paleogeographic position of Alexander terrane in Ordovician time. Global reconstruction from figure 18 of Beranek et al. (2012). Inferred locations of VMS deposits based on van Staal (2007). AX = Alexander terrane; TEB = Tetagouche-Exploits back-arc.

with Swinden and Thorpe's (1984) analysis of the Appalachian $^{207}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ trend on Figure 10, the most likely pericratonic source would be the Grenville orogen. As Grenvillian basement is found throughout the Caledonides, it does not provide a specific constraint.

However, the lead isotopic signature of the Pitt deposit clearly allies it with Ordovician deposits of peri-Iapetan origin, coinciding with the centres of both Appalachian and Norwegian data sets. Given the other strong evidence that the Alexander terrane was located north of the Scandinavian Caledonides in mid-Paleozoic time (Bazard et al., 1995; Beranek et al., 2012), a case can be built that its Ordovician arc and back-arc assemblages, and their enclosed VMS deposits, are an "orphaned" fragment of the circum-Iapetan volcanogenic metallotect (Fig. 11).

5. Conclusions

Geological mapping, supported by geochronology, has established that the Ordovician Moira Sound unit, of southern Prince of Wales Island extends as far south as Grenville Channel in northwestern coastal British Columbia. Indicators of volcanogenic potential within this belt include: the polymetallic massive and stringer zone showings at the Pitt prospect (103H 066); sulphide-laced rhyolites on Digby and Kennedy islands; and probable exhalites and magnetite iron formation on northeastern Pitt and Porcher islands. Pb isotopic results from the Pitt

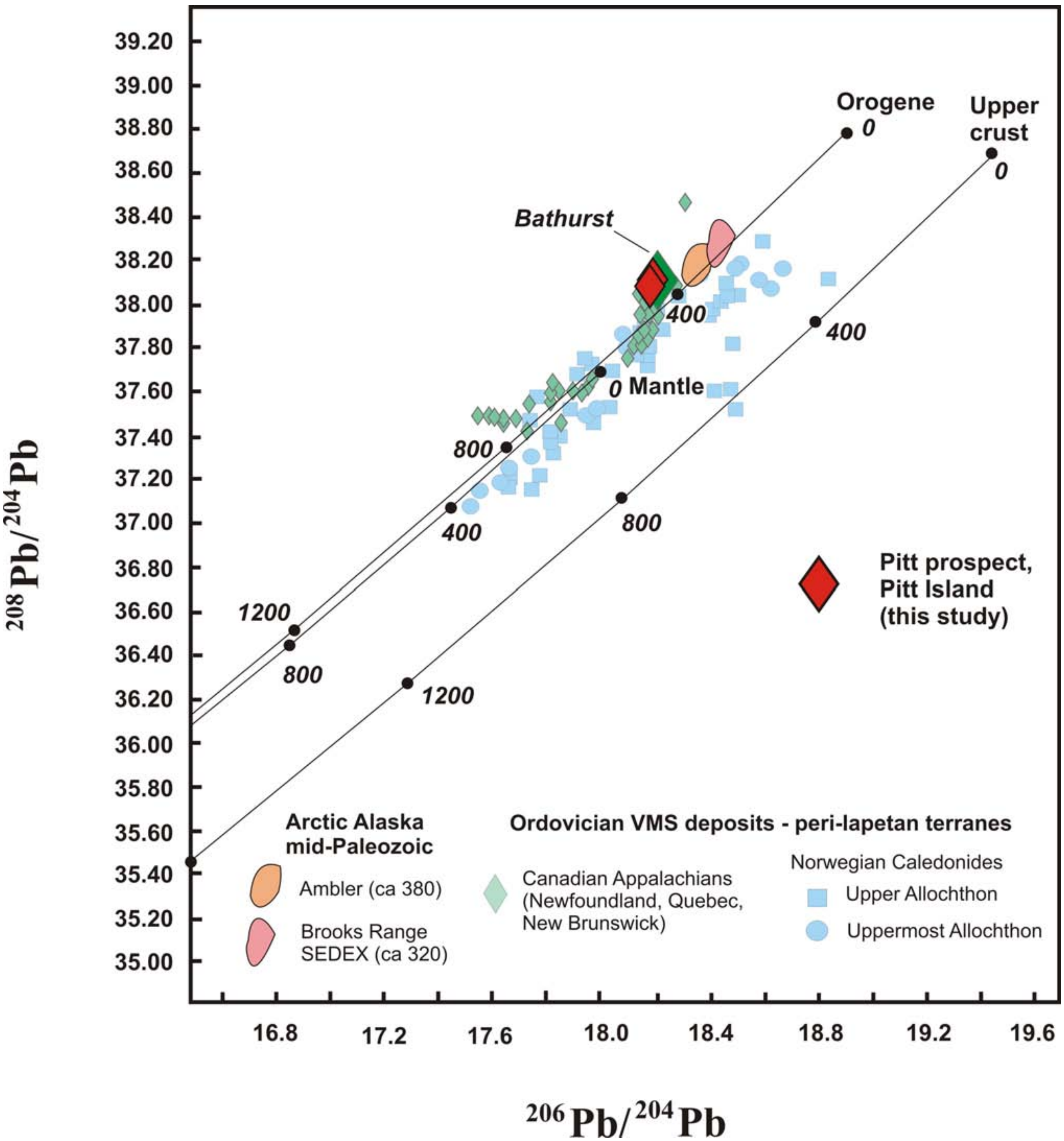

Fig. 12. $^{208}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ for Alexander leads vs. Ordovician VMS deposits of the Caledonides. Appalachian deposits from Swinden and Thorpe (1984) and Stacey and Kramers (1975); Norwegian deposits from Bjørlykke et al. (1993).

prospect confirm that it is Ordovician, syngenetic mineralization, rather than a Cretaceous epigenetic occurrence.

The strong structural control of the Pitt trend, the elongation of the sulphide-rich zone, and stringer-style (as opposed to bedded) mineralization suggest that it was a feeder zone to seabed massive sulphides, likely controlled by penecontemporaneous, basin-bounding faults. The Pitt trend structure was remobilized during the Early Cretaceous to form the southwestern boundary of the Grenville Channel shear zone on Pitt Island. Reactivation of original normal faults into thrusts and/or transcurrent faults is common in syngenetic mineralized systems, and has been observed at tectonised volcanogenic deposits such as Britannia and Tulsequah Chief, as well as SEDEX deposits (Nelson, 1998).

The Pitt Pb isotopic signature lies within the field of Ordovician VMS deposits of eastern Canada and Scandinavia. The Caledonian leads represent a mixing of sources between primitive Ordovician mantle and upper continental crust, most likely Grenvillian. Previously, the southern Alexander terrane was considered entirely primitive and ensimatic (Samson et al., 1989), although recent detrital zircon studies have offered strong evidence for nearby pericratonic crust (Gehrels and Boghossian, 2000; Nelson et al., 2012b; Beranek et al., 2012). The Moira Sound unit was probably deposited in a pericontinental marginal basin similar to modern sites of seafloor sulphide mineralization such as the Lau Basin and the Central Okinawa Trough.

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