Geochemical constraints on the tectonic setting of basaltic host rocks to the Windy Craggy Cu-Co-Au massive sulphide deposit, northwestern British Columbia

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Windy Craggy is an approximately 300 Mt Cu-Co-Au volcanogenic massive sulphide (VMS) deposit in northwestern British Columbia, Canada. The Windy Craggy deposit is hosted by the Middle Tats Volcanics (MTV), a Late Triassic volcano-sedimentary sequence of intercalated mafic pillow to massive volcanic flows and sills and calcareous argillite that are part of the Alexander terrane. The host footwall and hangingwall flows and sills are predominantly alkalic basalts (Nb/Y > 0.70). MTV alkali basalts at Windy Craggy are enriched in light rare earth elements (LREEs) >100X chondrite compared to chondrite, have steep REE patterns [(La/Yb)chondrite = 7.1–25.4], and generally lack the Ta and Nb depletions relative to primitive mantle (e.g. [Nb/Th]chondrite = 0.68–1.94) characteristic of arc environments, although most have [Nb/La]pm < 1. By contrast, volcanic rocks away from the deposit (and regionally; Lower Tats Volcanics, LTV) as well as late dikes that cross-cut all lithologies including metamorphic and deformational fabrics are sub-alkalic tholeiitic to calc-alkaline basalts and basaltic andesites that are less enriched in the LREEs (10–100X chondrite), have less steep REE patterns [(La/Yb)chondrite = 0.41–10.6], and show well-developed Ta and Nb depletions (arc signatures; [Nb/Th]pm = 0.20–0.79), consistent with formation in an oceanic arc environment. The co-occurrence of tholeiitic/calc-alkaline arc rocks with alkalic rocks indicates that the LTV (former) and MTV (latter) formed from melts that were influenced to varying degrees by subducted oceanic crust, and likely formed within a back-arc basin setting formed on a rifting oceanic arc. There is no geochemical or isotopic evidence for major involvement of continental crust. The LTV basalts likely were produced by progressive depletion in the source by partial melting of mantle overlying the subducting oceanic crust. The presence of the MTV alkalic Windy Craggy rocks overlying the LTV is consistent with the presence of a slab-window, perhaps related to subduction of a spreading centre, which allowed more enriched magmas to reach the surface with only minimal interaction with subduction-modified mantle. The presence of this slab-window might have provided the mechanism for the generation of anomalously high heat flow close to the seafloor, which initiated and sustained vigorous, long-lived hydrothermal activity necessary for the precipitation of large accumulations of massive sulphide. To our knowledge, this is the first example of a large VMS deposit associated with a slab-window.

Keywords: volcanogenic massive sulphide deposit; VMS deposit; mafic volcanic geochemistry; petrochemistry; palaeotectonic setting

Introduction

Determining the tectonic environment of volcanogenic massive sulphide (VMS) formation is critical to understanding their genesis and locational siting, as well as to the development and refinement of VMS exploration models (Tornos et al., submitted). Numerous studies have shown that VMS deposits formed in a wide variety of tectonic and geological settings, including back/intra-arc basins on both oceanic and continental crusts. The tectonic setting influences heat flow, rifting, and stage of rifting, and together these govern water depth, one of the salient controls on the style of mineralization. Nascent rifts are more conducive to the formation of bathymetric depressions within which anoxic conditions may have prevailed, whereas mature rifts are more conducive for oxic ambient environments.

High-temperature venting (black smokers) from seafloor hydrothermal deposits was discovered on mid-ocean ridges in the 1970s, and most research in modern systems has been focused on this tectonic setting (e.g. Baker et al. 1985, 2002). However, in the ancient rock record, many of the largest VMS and associated deposits are believed to be associated with rifted-arc and back-arc volcanism (Hannington et al. 2005).

Although modern seafloor massive sulphide mineralization provides an analogue for ancient VMS deposits, the latter are generally much larger than modern deposits (Hannington et al. 2010). This is partly because the morphology and style, and limits of VMS deposits are more readily determined through surface mapping, diamond drilling, and mining development, whereas the extent of most modern deposits remains largely unknown due to technological difficulties and financial considerations. However, it remains true that the largest VMS deposits greatly exceed the largest known seafloor sulphide

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deposits (Hannington et al. 2010). In many ancient VMS deposits, metamorphism and deformation obscure primary geological relationships and geochemical signatures because they occur near plate margins in extensional basins (Allen et al. 2002). Because the exploration strategy is commonly focused on locating the very largest ore deposits, it is critically important to elucidate the factors that can control the size of VMS deposits.

The extremely large Windy Craggy deposit, northwestern British Columbia, Canada, offers an excellent opportunity for investigating the primary geological and tectonic relationships through the application of geochemistry because the deposit and its host volcanic and sedimentary rocks are largely undeformed and have undergone only relatively low-grade metamorphism (Peter 1992; Peter and Scott 1999). The Windy Craggy deposit has many similarities to the ‘Besshi-type’ massive sulphide deposits of Japan and elsewhere (Peter and Scott 1999). Windy Craggy is the largest VMS deposit in Canada (Galley et al. 2007) with reserves as of December 1991 standing at 297.4 million tonnes grading 1.38% Cu at a cut-off grade of 0.5% Cu (Peter and Scott 1999). Here we present geochemical data for the mafic flows and sills that, together with intercalated calcareous, fine-grained turbiditic argillites host the Windy Craggy deposit. The goals of this study were to: (1) better understand the tectonic setting of this giant deposit and its host rocks; (2) place the Windy Craggy deposit into a broader geological, tectonic, and metallogenic context; and (3) provide a possible explanation for the anomalously large size of the deposit.

**Geological setting**

The Windy Craggy deposit occurs within the Alexander terrane (Berg 1979; Campbell and Dodds 1983; Taylor et al. 2010), one of the largest ‘suspect terranes’ of the North American Cordillera (Coney et al. 1980; Taylor et al. 2008) (Figure 1). The Alexander terrane extends over 1000 km from coastal British Columbia, through southeastern Alaska to the Saint Elias Mountains in the Yukon Territory and eastern Alaska. The Alexander terrane comprises a thick succession of Precambrian to Permian basinal and platformal carbonate and clastic rocks with a subordinate volcanic component that is unconformably overlain by Upper Triassic calcareous turbidites and a bimodal volcanic suite (Figure 2(A); Mihalynuk et al. 1993; Taylor et al. 2008). The Alexander terrane hosts numerous VMS deposits, including Windy Craggy and Greens Creek (Figure 1; Taylor et al. 2008). The Alexander terrane has been sutured to the Wrangellia terrane since at least 309 Ma (Gardner et al. 1988) and both terranes have been near the Peninsular terrane since at least the Late Jurassic (Coney et al. 1980; Jones and Siberling 1982). Early–Middle Jurassic deformation along the eastern margin of the Alexander terrane has been interpreted to be a consequence of its initial docking with North America (McClelland and Gehrels 1990; Monger et al. 1994; Dostal et al. 2013; Beranek et al. 2013b). Recent work has shown a Baltican crustal provenance for Cambro-Ordovician rocks of the Alexander terrane (Colpron and Nelson 2009, 2011; Beranek et al. 2013a).

The Late Triassic section in the immediate area of the Windy Craggy deposit comprises mafic submarine volcano rocks with interbedded calcareous argillaceous sedimentary rocks (Figures 2(B) and 3). The informally named Tats Volcanic Complex is a volcano-sedimentary sequence of intercalated mafic volcanic and fine-grained sedimentary rocks. Previous work has defined five major subdivisions of the Tats Volcanic Complex (1 = youngest to 5 = oldest) (MacIntyre 1983, 1984, 1986; Prince 1983), which include: (1) Upper Tats Volcanics (UTV): mainly Late Triassic pillow basalt (at least 1500 m thick); (2) Middle Tats Volcanics (MTV): Late Triassic (based on conodont faunal assemblages; Orchard 1986) interbedded graphitic and calcareous argillite, massive (Figure 4(A)) and pillowed (Figure 4(B)) mafic amygdaloidal (Figure 4(C)) flows, tuff, agglomerate, and limestone (∼2000 m thick); (3) Lower Tats Volcanics (LTV): Late Triassic mafic flows and sills (∼1000 m thick); (4) Graphitic Shale Unit; calcareous and graphitic shale, argillite, and limestone of unknown age; and (5) Limestone Unit; grey limestone.

The age of the volcanic rocks in the Windy Craggy area has been established as early Norian (~225 Ma) on the basis of conodonts collected from graphitic and calcareous interbeds in volcanic flows hosting the deposit, and from underlying graphitic and calcareous shales (Orchard 1986). Felsic volcanic rocks or their metamorphosed equivalents are absent from the Late Triassic mafic volcanic sequence in the Windy Craggy area, but occur elsewhere in the Alexander terrane, indicating that volcanism was regionally bimodal (Taylor et al. 2008).

The lower part of the MTV contains the Windy Craggy deposit. Sills predominate in the lower portion of the stratigraphic section (Figures 3 and 4(D)), and are distinguished from dikes based on field relationships and geochemistry. In some drill holes, diabase bodies occur spatially and stratigraphically beneath massive sulphide mineralization. Intersection widths vary from 1 to 40 m. In places, diabase is the host rock for stockwork or stringer sulphide mineralization.

Basalts also host the Tats Showing, a small chalcopyrite-pyrrhotite-magnetite occurrence approximately 7 km south of Windy Craggy. The rocks there are predominantly pillowed to massive basalt flows, with minor agglomerates and hyaloclastites. MacIntyre (1984) included these basalts with the LTV, and therefore they are stratigraphically below the MTV that host the Windy Craggy deposit (Figure 3). However, both the LTV and MTV are Early
Norian (Upper Triassic), based on conodont assemblages (Orchard 1986). Basalt also hosts the ‘X Showing’, a massive sulphide occurrence located about 8 km to the east-southeast that has several similarities to Windy Craggy. Basalts of the X Showing have been grouped with those hosting the Tats Showing as LTV by MacIntyre (1984).

Dikes cross-cut all lithologies, including massive sulphide mineralization (Figures. 3 and 4(E)), and range from less than 10 cm to several metres in width. Dikes cross-cut the regional penetrative foliation (Figure 4(F)), although in places, they are themselves slightly to moderately foliated; on this basis, dike emplacement is interpreted to post-date peak metamorphism and deformation, which occurred mainly during mid-Jurassic through Cretaceous accretion of the Alexander terrane to inboard Cordilleran terranes (Berg et al. 1972; Coney et al. 1980). Dikes generally possess 1 to 20 cm-wide chloritic chilled margins. The
Figure 2. (A) Regional geology map of the Tatshenshini River area (adapted from Mihalynuk et al. 1993). Box outlines area shown in Figure 2(B); (B) Surface geology map of the Windy Craggy area (after Geddes Resources Ltd., unpublished map, 1991).
host rocks to the Windy Craggy deposit have been metamorphosed to lower greenschist grade and primary textures and fabrics are preserved, except where the rocks have been faulted or intensely hydrothermally altered.

Sample selection and analytical techniques
Thirty-four samples of mafic flows, 11 samples of mafic sills, and nine samples of mafic dikes were collected from drill core, surface, and underground workings (Supplementary Table 1, see http://dx.doi.org/10.1080/00206814.2014.947335). These samples represent all of the lithologies, including footwall and hangingwall sills intercalated with argillite stratigraphically about 1000 m beneath the deposit, and dikes that cross-cut all other lithologies. Least visibly altered samples were selected for analysis.

Samples were pulverized in an alumina mill/shatterbox at the University of Toronto; alumina contamination is estimated to account for less than 0.1% of the total alumina values. Major elements were analysed on fused glass discs at X-Ray Assay Laboratories Ltd., Don Mills, Ontario, Canada. Trace element analyses (Zr, Nb, Y, Rb, Sr, Cr, and Ni) were determined by X-ray fluorescence spectrometry at the University of Toronto on pressed powder pellets. Rare earth elements (REEs), Ta, Th, Hf, Sc, and Co were analysed by instrumental neutron activation analysis (INAA) at the University of Toronto. Samples were irradiated at the University’s Slowpoke reactor and counted in the Department of Geology using the method of Barnes and Gorton (1984). Precision and accuracy were determined using an in-house standard (UTB–1) and are within 5% of the recommended values for Zr, Nb, La, Ce, Sm, Yb, Y, Sc, and Co; better than 10% of the recommended values for Hf, Eu, Cr, Ni, and Rb; and better than 20% of the recommended values for Th, Nd, Tb, Ta, and Ba.

Prior to metamorphism, the Windy Craggy host rocks within and adjacent to the stockwork zone were hydrothermally altered (chloritized and silicified) to varying degrees. The characterization of the alteration mineral assemblage, as well as an assessment of its influence on the geochemistry of the host rocks, is addressed elsewhere (Peter 1992). Except where rocks have been intensely silicified, trace and REEs were found to be relatively immobile (Peter 1992; Peter and Scott 1999).
the Windy Craggy host rocks were metamorphosed to greenschist-facies, primary textures and structures typically are well preserved (Supplementary Table 1). Greenschist-facies metamorphic minerals are chlorite, albite, epidote, actinolite, sphene, and leucoxene.

Basalt flows predominate in the upper part of the stratigraphic section (Figure 3). Mafic flows are fine-grained, range from medium grey to dark green, and commonly are vesicular to amygdaloidal with amygdules 1–5 mm in diameter composed of white, fine-grained calcite and, rarely, fine-grained pyrrhotite. In places, amygdules comprise up to 4 volume % of the rock. Less commonly, the flows are porphyritic, with euhedral phenocrysts of plagioclase 3–8 mm in diameter and/or hornblende 0.5–3.0 mm in diameter. The hornblende phenocrysts are variably pseudomorphed by chlorite.

Figure 4. Photographs of macro- and micro-textures of mafic volcanic rocks at Windy Craggy. (A) scalloped, bleached flow contact with underlying argillite; underground, north cross-cut. (B) Basalt pillows with chlorite ± calcite interpillow material; underground, north cross-cut. (C) Chlorite-filled amygdales in basalt flow, with inner rim of quartz, in chlorite-plagioclase-rich matrix. Sample from north cross-cut; the large amygdales is 0.4 mm across. (D) 2 m-wide, folded mafic sill (lighter coloured) intercalated with dark grey argillite in northwest ridge of Windy Peak. (E) Late mafic dikes with chloritic chill margins cross-cutting massive sulphide mineralization; north cross-cut, underground. (F) Late mafic dikes cross-cutting folded, deformed argillites; outcrop on east face of Windy Peak. Rock hammer in photograph is 11" (28 cm) long.
Flows are pervasively chloritized and carbonatized. Much of this alteration is related to a regional, lower greenschist-facies metamorphic event (Forbes 1986), although we cannot rule out the possibility that some is due to hydrothermal alteration attendant with deposit formation. Flows are generally only slightly foliated. Where present, pillows vary from 10 to 70 cm in diameter and generally have fine-grained chloritized rims. Individual flow units are up to 100 m thick and average 10–15 m.

In the porphyritic basalts, epidote and chlorite form pseudomorphs of hornblende, which in turn likely replaced primary pyroxene phenocrysts. Primary clinopyroxene, still present in the groundmass of some samples, ranges from nearly fresh grains showing only narrow actinolite reaction rims to small anhedral remnants in the centres of chlorite-actinolite pseudomorphs. The primary clinopyroxene is typically clear to pale brown augite. Groundmass plagioclase, similar to the phenocrysts, is altered to white mica and albite. The opaque phases are mostly titanomagnetite with replacement rims of titanite, and small, disseminated pyrite crystals. Blue-green actinolite and pale green chlorite are also present as randomly oriented needles and patches in the groundmass; the lack of any obvious relation to primary minerals indicates they most likely replace glass. In addition, anhedral grains of epidote and calcite are abundant in the groundmass of some samples. The amygdules are filled primarily with chlorite, calcite, and quartz, with minor actinolite and epidote (e.g. Figure 4(C)).

Basalt sills are dominantly composed of plagioclase and hornblende phenocrysts, typically up to several mm in diameter, in a finer grained matrix. Minor minerals include fine-grained rutile, anatase, and titanite. Dikes are generally lighter coloured (pale grey-green) and finer grained than the sills.

Diabase bodies are dark green, medium- to coarse-grained, and are composed of interlocking crystals of plagioclase, amphibole, and pyroxene, and are commonly ophitic. The post-deformational dikes are moderately to intensely hydrothermally altered and contain calcite, chlorite, and epidote that are the result of fluid flow associated with post-peak metamorphism. In places, dikes contain biotite pseudomorphs after hornblende phenocrysts, and these are likely also the product of metamorphism.

Geochemical results
Alteration of most samples has been appreciable, as seen by high H2O and CO2 and low Na2O and K2O contents, particularly in the stratigraphic hangingwall of the deposit (Supplementary Table 2). To compensate for these alteration effects, analyses have been recalculated to a 100% loss on ignition (LOI)-free basis for plotting purposes. On the plots the samples have been subdivided based on position within the Windy Craggy stratigraphy (footwall flows, footwall sills, and hangingwall flows) and relationship to the deposit (dikes and proximal volcanic rocks; ‘X’ and Tats Showings).

Whereas large-ion lithophile element (LIL) ratios (Rb/Sr, K/Rb, and K/Ba; Supplementary Table 2) are highly variable and indicate that the alkali and alkaline earth elements have been variably mobilized during metamorphism and hydrothermal alteration (e.g. Figure 5), the high field strength elements (HFSEs) Zr, Y, REE, Hf, Nb, and Ta are relatively immobile during hydrothermal alteration processes at Windy Craggy (Peter 1992). Values of Zr/Hf (≈39) and Nb/Ta (≈16) are typically constant in unaltered basalts and can serve as indicators of severe alteration (MacLean and Kranidiotis 1987). The Nb, Hf, Ta, and Zr contents of the Windy Craggy samples do not vary greatly, and show relatively uniform Zr/Hf (34–51) and Nb/Ta (13–22) values. Given the degree of alteration, including potential addition of Fe and Si by hydrothermal fluids, the rocks have been classified using immobile elements (Figure 6; Winchester and Floyd 1977). All the rocks we sampled from Windy Craggy are mafic (Figure 6). Hangingwall and footwall flows and sills are alkalic, whereas the later dikes and rocks from the Tats and X Showings are subalkaline and tholeiitic.

Alkaline basalts
The footwall flows and sills, and hangingwall flows are all alkali basalts on the basis of Zr/TiO2 and Nb/Y (Figure 6). Because of the potential for Fe and Mg mobility during metamorphism and hydrothermal alteration (e.g. Figure 5), we use Zr contents as a measure of differentiation (Figures 6 and 7). The footwall and hangingwall flows at the Windy Craggy deposit are broadly similar in terms of immobile major and trace element chemistry (Figure 7). In contrast, the footwall sills extend to higher HFSE contents. For example, the footwall and hangingwall flows range from 64 to 168 ppm Zr, 1.3 to 38.6 ppm Nb, 1.4 to 4.6 ppm Th, and 13.6 to 24 ppm Y. The footwall sills, however, range from 93 to 284 ppm Zr, 14.9 to 73.5 ppm Nb, 1.9 to 7.3 ppm Th, and 18.4 to 32 ppm Y (Zr shown in Figure 7; Supplementary Table 2). The CaO, K2O, and Na2O contents show little or no relationship with MgO contents due to depletion or enrichment (alteration) unrelated to primary differentiation trends. These alkali basalts have moderately high Cr (up to 795 ppm), Ni (up to 1082 ppm), and Sc (up to 45 ppm) contents that, uncharacteristically, lack correlation with MgO, likely resulting from alteration and MgO gain/loss.

Trace element patterns for the Windy Craggy alkalic basalts show moderate to steep LREE enrichment with significant variation in the extent of LREE enrichment ([La/Yb]n = 7.1–25.4) (Figure 8). Most of the REE patterns for these alkalic rocks are characteristically parallel between La and Sm, but the slopes vary slightly among the different groups. This is illustrated by the average ([La/Sm]n ratios
and their standard deviations (hangingwall flows: 5.7 ± 3.7, $n = 12$; footwall flows: 3.9 ± 0.9, $n = 15$; footwall sills: 4.6 ± 0.9, $n = 11$). Compared to primitive mantle (note, only relatively immobile elements are plotted in Figure 8), the Windy Craggy alkalic rocks show enrichment in the most incompatible HFSE and LREEs. Although these rocks have patterns similar to OIB (Figure 8), the most significant distinction is the subtle depletion in Nb (and Ta) relative to La ($[\text{Nb/La}]_{\text{pm}} = 0.41$–1.08, average = 0.68) (Figure 9). Despite these subtle depletions in Nb and Ta, the Windy Craggy alkalic rocks plot in the within-plate alkalic (to tholeiitic) fields in tectonic discrimination diagrams (e.g. Figure 10) and at the OIB end of the mantle array on a plot of Th/Yb versus Ta/Yb (Figure 11).

Subalkalic mafic rocks
The cross-cutting dikes at the Windy Craggy deposit and basalt flows from the surrounding area (Tats Showing; LTV) are chemically distinct from the alkalic flows and sills that host the deposit on the basis of Zr/TiO$_2$ versus Nb/Y; the dikes and Tats volcanic rocks are classified as subalkalic basalts and basaltic andesites (Figure 6). The dikes and Tats Showing subalkalic rocks range from tholeiitic to calc-alkalic based on discrimination diagrams using less mobile elements (Figure 10).

The subalkalic rocks are characterized by lower Zr contents (57–136 ppm for the dikes and Tats rocks) and lower Zr/TiO$_2$ values than the alkalic rocks (Figures 6 and 7). Similarly, Nb (1.33–11.1 ppm) and Th (0.36–3.8 ppm) are lower in the tholeiitic basalts than the alkali basalts, although Y (13.5–33.3 ppm) extends to higher contents.
(Supplementary Table 2). Consistent with the subalkalic characteristics, the dikes and Tats Showing flows have lower TiO$_2$ contents than the alkalic rocks (up to 1.33 wt. %), lower Ni contents (up to 276 ppm) but extend to higher Cr contents (up to 921 ppm) (Figure 7).

The Windy Craggy subalkalic basalts and basaltic andesites have slightly LREE-depleted to moderately LREE-enriched REE patterns, with LREE-enrichment ($\text{La/Yb}_n$) ranging from 0.41 to 10.61, which are considerably depleted compared to the Windy Craggy alkali basalts (Figure 8). The dikes have higher LREE and MREE contents compared to the Tats Showing flows, which have higher HREE contents (Figure 8). Compared to primitive mantle, the subalkalic dikes and Tats Showing flows are less enriched in the HFSEs compared with the alkali basalts, and they also have significant depletions in Nb, Ta, and Ti (e.g. $\text{[Nb/La]}_{\text{pm}}$ ranges from 0.05 to 0.80, = 0.41–1.08, average = 0.38) (Figures 8 and 9).

The subalkalic rocks all plot as arc-related, either tholeiitic (Tats Showing) or calc-alkalic (dikes) (e.g. Figures 10 and 11), and plot above the mantle array on a plot of Th/Yb versus Ta/Yb (Figure 11).
**Discussion**

**Fractionation and post-magmatic alteration**

Primitive basaltic magma that has equilibrated with mantle peridotite requires Mg-numbers of 68–75 for up to 30% melting (Frey et al. 1978) based on Fe/Mg K\textsubscript{ol}liq = 0.3 (Roeder and Emslie 1970). Most of the samples analysed in this study have Mg-numbers that are well below this range, with only six samples in the required range (Supplementary Table 2). Frey et al. (1978) estimated the compatible trace element contents of 1 to 20% partial melts of lherzolite to be Ni = 90–670; Co = 27–80, and Sc = 15–28. The samples in this study have mean values of Ni = 112, Co = 24.6, and Sc = 23.8, and, except for Co, meet these criteria. The somewhat lower abundances of Co suggest crystal fractionation of mafic minerals (olivine ± clinopyroxene). Almost all of the basalts lack significant (negative) Eu anomalies (Figure 8; Supplementary Table 2), implying that little or no plagioclase fractionation occurred during magmatic processes. These basalts are assumed to have retained their original immobile element ratios, although the low Mg-number and compatible element contents of a few of the samples suggest that they have undergone some mafic mineral fractionation. Olivine ± clinopyroxene fractionation will produce an increase in the abundances of the incompatible elements, but any change in the ratios of these elements will be small.

The antipathetic relationship between Al\textsubscript{2}O\textsubscript{3} and MgO indicates removal of olivine and/or clinopyroxene from the magma. The flows have low titanium contents, and the antipathetic variation between TiO\textsubscript{2} and MgO is consistent with crystal fractionation of plagioclase ± olivine ± clinopyroxene (Walker et al. 1979). On a Zr versus Ti diagram of Pearce and Cann (1973) (not shown, but see Figure 6 of Taylor et al. 2008), samples plot in the calc-alkaline basalt, ocean floor basalt, and low-K tholeiite fields and the data define a broad linear array that projects towards the origin. Such a trend also occurs on other plots involving incompatible elements (e.g. Zr versus Nb; not shown). These are primary fractionation trends with superimposed enrichment or dilution of these immobile elements by subtraction or addition of other components, including phenocrysts. Some scatter in the data may result from minor elemental mobility or variation in the amount of partial melting, source heterogeneity, or assimilation.

It has been argued that LILE enrichment may be due to secondary alteration (Hart et al. 1974; Polat et al. 2012). However, Th is one of the only LILEs that are relatively immobile during hydrothermal alteration (e.g. Stern et al. 2006; Xiao et al. 2013) and low to moderate grades (i.e. up to at least greenschist-facies) of metamorphism of basalt, and it can be determined with high precision by neutron activation analysis. The good linear correlation passing...
through the origin on a plot of Zr versus Th (not shown) illustrates the immobility of Th in the Windy Craggy rocks and demonstrates that Th (and possibly other LILE) enrichments are due to primary magmatic processes. Furthermore, a lack of correlation between (La/Yb)\textsubscript{pm} and highly mobile major elements such as CaO (plots not shown) also indicate that LREE enrichment is not a result of alteration. Frey \textit{et al.} (1978) drew attention to the strong correlation between P\textsubscript{2}O\textsubscript{5} and the LREEs in oceanic basalts, as well as the incompatible behaviour of P\textsubscript{2}O\textsubscript{5} during partial melting, and used P\textsubscript{2}O\textsubscript{5} as an indicator of the degree of partial melting; a P\textsubscript{2}O\textsubscript{5}/Ce value of 75 was considered typical of primary alkali basalts. The Windy Craggy flows plot along a line of P\textsubscript{2}O\textsubscript{5}/Ce \approx 80, close to this value for primary alkali basalts. In contrast, the subalkalic dikes and Tats flows have higher P\textsubscript{2}O\textsubscript{5}/Ce values (up to 200), likely reflecting lower
relative LREE (Ce) contents. The alkalic sills have somewhat lower $P_2O_5$/Ce values than the flows and may have originated from a different magma. The positive correlation between $P_2O_5$ and Ce for all the data ($r^2 = 0.80$) indicates that apatite was not a residual phase at the time of magma separation (Sun and Hanson 1975).

**Are the dikes and sills cogenetic with the Windy Craggy flows?**

The geochemical data indicate that the alkalic Windy Craggy sills and flows were derived from a common magmatic source (Figures 6, 10, and 11). The sills are typically more fractionated than the flows, i.e. generally
higher Zr and TiO$_2$ contents (Figure 7). The sills are much less enriched in Fe$_2$O$_3$ than the flows (Figure 7), partly as a result of fractionation but also in part an artefact of iron-enrichment due to alteration superimposed on the primary geochemical trend, as the sill samples were collected much further from the deposit than the flows. Sill samples, therefore, have been much less altered than the flows. There is no systematic chemical variation between footwall and hangingwall flows (e.g. Figure 8).

The dikes at Windy Craggy are geochemically distinct from the alkali basalt flows and sills (Figures 6–11) and are geochemically similar to the Tats volcanic rocks more distal from the Windy Craggy deposit. The LTV and the dikes at Windy Craggy are tholeiitic to calc-alkalic, indicating that this style of magmatism pre-dated (LTV) and post-dated (dikes) alkalic volcanism at Windy Craggy.

**Tectonic setting**

The broad subdivision of the Windy Craggy igneous rocks into alkalic and tholeiitic/calc-alkalic groups is also reflected in trace element discrimination diagrams. In most diagrams (e.g. Th-Hf/3-Ta and Zr/4-Nb*2-Y; Figure 10), the footwall and hangingwall flows and footwall sills plot in the within-plate basalts fields, whereas the dikes, Tats, and X Showing rocks typically plot in the arc (both tholeiitic and calc-alkalic) volcanic fields.

A common feature of basalts formed in arc environments is their characteristic depletions in the HFSE Ti, Ta, Nb, and Y (e.g. Pearce and Norry 1979; Thirlwall et al. 1994; Grégoire et al. 2001; Stern et al. 2006; Chadwick et al. 2009; Todd et al. 2010). Although the Windy Craggy dikes display HFSE depletions (Figure 8), they are not temporally related to the formation of the Windy Craggy deposit as they cross-cut mineralization and even post-date peak metamorphism (see Figure 4(F)). Footwall and hangingwall basalt flows and sills at Windy Craggy lack HFSE depletions that are characteristic of arc-derived volcanics, and, on this basis, an arc-related setting for the Windy Craggy basalts and sills would be ruled out. However, the samples used in this study are from a relatively restricted area in and around the Windy Craggy deposit, and the lack of an ‘arc signature’ at Windy Craggy may be related to spatial heterogeneities in mantle chemistry (Hofmann 1997) or to temporal geochemical effects related to rifting.

To elucidate the source of the alkaline basalts, we examined the geochemistry of the tholeiitic and calc-alkaline basalts that are farther from the deposit but are stratigraphically equivalent or coeval with the Windy Craggy
basalts. Smith and Fox (1989a, 1989b) conducted a study of basalts that host the Tats Showing, and our study provides data for one sample of amygdaloidal basalt from the X Showing. The X and Tats Showing basalts have REE patterns that range from depleted N-MORB through non-LREE depleted to E-MORB (Figures 8 and 10 and Supplementary Tables 2 and 3). For the Tats Showing basalts, (La/Yb)n values range from 0.4 to 2.1 and all samples display variable Eu depletions indicative of plagioclase crystallization.

The Tats and X Showing basalts show mild LILE enrichment (Figure 8), albeit less pronounced than that displayed by the Windy Craggy samples. However, an important feature of the former basalts is their variable depletion of Ta relative to adjacent Th.

The LTV basalts display the distinctive Ta-Nb ‘troughs’ characteristic of arc environments (e.g. Pearce and Norry 1979; Thirlwall et al. 1994; Grégoire et al. 2001; Stern et al. 2006; Chadwick et al. 2009; Todd et al. 2010). Because LTV and MTV are approximately coeval, this indicates that the Windy Craggy basalt flows and sills (and LTV) formed in the vicinity of a volcanic arc, or formed from melts that were influenced to varying degrees by subducted oceanic crust. Such a scenario is consistent with a back-arc setting, where back-arc basin basalts (BABB) with negative Nb-Ta-Ti anomalies are restricted to those basins formed behind a well-developed island arc.

**Back-arc setting, slab roll-back, and slab-windows**

The pronounced LILE- and LREE-enriched nature of the Windy Craggy volcanic rocks and sills, coupled with the arc-signatures (HFSE depletion, LILE enrichment) of the LTV and dikes, provides evidence that negates a typical mid-ocean spreading ridge setting. Such sites are characterized by basalts of depleted N-MORB composition, although transitional (T-MORB), plume (P-MORB), or enriched (E-MORB) basalts are also present along mid-ocean ridges (e.g. Van Wagoner and Leybourne 1991; Paullick et al. 2010; Stracke 2012; Hanan et al. 2013). The pillowed nature of many of the flows, together with the evidence for their extrusion onto wet, unconsolidated sediments (Peter and Scott 1990), the presence of well-developed turbidites with marine micro- and macro-fossils, the style of mineralization, and the fluid inclusion petrography and microthermometry (lack of boiling requires a minimum of 1950 m water depth to suppress boiling), all indicate a deep-water, marine setting (Peter and Scott 1992; Peter and Scott 1993). The lack of a thickened volcanic pile and the presence of abundant turbiditic argilite in the sequence are inconsistent with a hot spot or mantle plume setting of an ocean island for Windy Craggy. This association of alkaline rocks with arc/back-arc settings has increasingly been recognized in both modern and ancient tectonic settings (DeLong et al. 1975; Thorkelson 1994; D’Orazio et al. 2004; Chadwick et al. 2009). For example, alkaline rocks with subtle to no arc signatures have been recovered from the north Fiji Basin (Price et al. 1990), Patagonia (D’Orazio et al. 2004, 2005; Massaferro et al. 2006; Van Wagoner et al. 2006), and the northern Cascadia arc (Mullen and Weis 2013).

Supporting evidence for a back-arc setting for Windy Craggy comes from radiogenic isotopes. There are important differences in the Pb-isotope geochemistry of basalts from different tectonic settings (Zartman and Haines 1988; Ishikawa and Nakamura 1994; Mullen and Weis 2013). In general, lead from oceanic island basalts (OIB) is more radiogenic than that of typical mid-ocean ridge basalt and OIB shows a wider spread in its 206Pb/204Pb, 207Pb/204Pb, and 208Pb/204Pb values. Pb-isotope data for Windy Craggy basalt, sill, and argillite samples (Peter et al. in prep.) indicate that the initial ratios for these rocks are 206Pb/204Pb = 18.70, 207Pb/204Pb = 38.35, and 208Pb/204Pb = 15.585, which is just outside the MORB field, but within the fields for oceanic island basalt (OIB) as well as oceanic island arc basalt (IAB) (e.g. Mariana arc), and continental tholeiites. The alkaline rocks at Windy Craggy lack the distinctive geochemical signatures of arc volcanic rocks, and the [Nb/La]pm values are <1, unlike OIB (Figure 9), consistent with minor influence from subduction-modified mantle. Existing Nd isotopic data for the Windy Craggy area indicate a lack of interaction with continental crust, also consistent with the lack of felsic rocks in the sequence, despite their presence in correlative units to the south (Taylor et al. 2008). In modern settings, oceanic volcanic rocks typically have positive εNd values, whereas values are typically negative where there has been interaction with continental crust (Allegr and Rousseau 1984). The more depleted mantle reservoir, the higher the εNd value; present-day N-MORBs generally have εNd values from +8 to +12, whereas OIBs and other alkaline rocks are typically in the range +4.5 and +6. Sm and Nd isotopic data for Windy Craggy basalt flows and sills (Smith and Fox 1989a, 1989b) give εNd (220 Ma) values of +2.4 to +3.6, which is within the range for alkaline basalts derived from undepleted (primitive) mantle (DePaolo and Daley 2000; Vervoort et al. 2000). The εNd values for the Tats Showing basalts (LTV) range between +5.5 and +7.8 (Smith and Fox 1989a, 1989b), similar to values for depleted arc, back-arc, and MORB at that time.

There have been a number of processes invoked to explain the presence of alkaline rocks within arc-back-arc settings. These include slab roll-back, slab-windows, or edge effects (e.g. Hole and LeMasurier 1994; Thorkelson 1994; D’Orazio et al. 2005; Thorkelson and Breitsprecher 2005; Whittaker et al. 2007; Chadwick et al. 2009; Dilek and Altunkaynak 2009; Mullen and Weis 2013).
Essentially these models are variations on the theme of permitting a window or break in the subducting slab, or asthenospheric flow around the edge of a subducting slab, to permit deeper, less-depleted asthenosphere to erupt essentially coevally with arc and back-arc volcanic rocks. Indeed, recent work along the Tonga arc has used seismological data to indicate slab detachment along part of the subducting slab (Bonnardot et al. 2009). Slab-windows are formed in particular through oblique subduction, subduction of a spreading centre, or subduction of a plate boundary or fracture zone (e.g. Hole and LeMasurier 1994; Thorkelson 1994; D’Orazio et al. 2005; Thorkelson and Breitsprecher 2005; Chadwick et al. 2009; Mullen and Weis 2013). The Windy Craggy alkalic rocks have trace element contents and ratios that are similar to alkalic rocks associated with slab-windows in modern settings. Figures 9 and 10 show the Windy Craggy rocks compared to slab-window alkalic rocks from Patagonia. The [Nb/La]pm values of the Windy Craggy alkalic rocks are lower than is typical for alkalic rocks associated with oceanic islands, and lower than many similar rocks in Patagonia (Figure 9 (A)). The alkalic rocks from Windy Craggy have Zr/Nb and Ba/Nb values that overlap those from Patagonia and from the northern Cascade arc (D’Orazio et al. 2004, 2005; Mullen and Weis, 2013) (Figure 9(C)).

Consideration of geochemical data for modern back-arc environments, combined with geological evidence, suggests that the most likely tectonic setting in which Windy Craggy formed was a back-arc basin. The involvement of continental crust is considered to have been negligible, based on the Pb and Nd isotope geochemistry of Windy Craggy host rocks (Smith and Fox 1989a, 1989b; Peter and Scott 1999; Taylor et al. 2008), consistent with the lack of felsic volcanic rocks and the mafic geochemical characteristics of the argillites (Peter and Scott 1999). At Windy Craggy, basalt and argillite samples define a linear trend on a 204Pb/206Pb versus 206Pb/204Pb plot, extending from a least radiogenic point defined by Windy Craggy sulphides (Peter and Scott 1999). This least radiogenic point is interpreted to be the initial composition for the basalts and argillites, and the linear trend of the host rocks is due to in situ radiogenic growth since the time of mineralization, a conclusion supported by bulk U and Th analyses. The Pb isotopic co-linearity indicates that the argillites intercalated with the basalt flows and sills have inherited their initial Pb-isotope compositions from precursor mafic volcanic rocks (i.e. eroded basalts of similar geochemical composition and age to the basalts that host Windy Craggy). The most likely source for these volcanic rocks is the arc itself, as LREE-enriched arc basalts have the required precursor compositions. Additionally, the trace and REE geochemistry of fine-grained sediments intercalated with the volcanic rocks suggests that the sediments were derived from arc basalts (Peter 1992).

Based on the geochemistry, isotopic values, and geological relationships, our preferred interpretation for the tectonic setting of the Windy Craggy deposit is that it formed within an arc/back-arc environment (Figure 12). This setting is consistent with the characteristics of the late dikes at Windy Craggy and the Tats volcanics. These rocks are chemically similar to coeval rocks to the north and south of Windy Craggy (Taylor et al. 2008). Within this subduction zone setting, a break in the subducting slab formed (slab-window; Figure 12), although it is not possible to determine whether this was the result of oblique subduction or subduction of a spreading centre. However, the result was that deeper asthenospheric low-degree partial melts were able to traverse through the subduction environment with minimal influence from subduction zone fluids/melts. This localization of alkalic volcanism within a convergent margin geodynamic setting may also account for excessive heat and volcanism that permitted the accumulation of such a large copper deposit.

Taylor et al. (2008) described the mineral deposits of the ~800 km-long belt of rocks (Alexander Triassic Metallogenic Belt) that includes the Windy Craggy deposit. Deposits in the southern part of the belt are associated with felsic volcanic rocks, and are commonly epithermal in character. In the central portions of the belt, deposits are hosted by bimodal volcanic rocks and formed in shallow-water settings proximal to a volcanic arc (Taylor et al. 2008). Deposits within the belt are progressively deeper water and hosted primarily by back-arc or intra-arc rift-related mafic volcanic rocks towards the north (Taylor et al. 2008), consistent with our model for the formation of the Windy Craggy deposit.

Conclusions
The Upper Triassic sequence of intercalated basalts and turbiditic argillite in the Windy Craggy area was deposited in a marine deep-water setting, based on the presence of well-developed pillows, turbiditic argillite, and marine macro- and micro-fossils. The flows and sills are alkalic in composition. Most of the samples analysed lack the geochemical characteristics of a primary, unmodified, mantle-derived magma; Mg-numbers are generally less than 68 (except for six samples that are marginally higher than 68). Some samples with Mg-numbers around 42 are strongly fractionated.

Windy Craggy basalt and sill samples are LREE-enriched and have minor and trace element abundance patterns similar to those observed in alkalic basalts in general. The trace and minor element abundance patterns of the Windy Craggy basalts are similar to alkalic rocks formed in oceanic islands, but are most similar to alkalic rocks formed via asthenospheric upwelling through slab-windows within a subduction zone setting.
The presence of N-MORB-type basalts with arc or subduction signatures within the Late Triassic section in the vicinity of Windy Craggy (e.g. Windy Craggy dikes, Tats volcanics) must be taken into account in a model for the tectonic setting of the Windy Craggy area. A back-arc basin setting that is distal from the continental crust best explains the presence of both arc tholeiitic/calc-alkalic basalts and more enriched basalts without a trace element subduction signature. Published Pb and Nd isotopic values for rocks at Windy Craggy and proximal to the deposit are consistent with a setting without influence from the continental crust. Our preferred tectonic environment for the Windy Craggy deposit is a back-arc setting although associated with a slab-window, which permitted the formation of alkaline volcanic rocks within the deposit.

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