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The Wernecke igneous clasts in Yukon, Canada: Fragments of the Paleoproterozoic volcanic arc terrane Bonnetia

Alexander B. Nielsen*, Derek J. Thorkelson**, H. Daniel Gibson, Daniel D. Marshall

Department of Earth Sciences, Simon Fraser University, Burnaby, BC V5A 1S6, Canada

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ABSTRACT

The Wernecke igneous clasts consist of blocks of plutonic and volcanic rock that range up to hundreds of metres in size. These clasts occur exclusively within zones of hydrothermal breccia (Wernecke Breccia) which are widespread in central and northern Yukon. The breccia zones are hosted by the Wernecke Supergroup and have been dated by U–Pb titanite at 1599 Ma. Four U–Pb zircon ages on the Wernecke igneous clasts (1714–1706 Ma) demonstrate that the clasts are older than the Wernecke Supergroup (<1.64 Ga) and indicate that the clasts were not derived from dykes within the Wernecke Supergroup. Instead, the clasts were derived from an obducted terrane named Bonnetia. Geochemical characteristics of the Wernecke igneous clasts infer that Bonnetia formed as a volcanic arc with a component of within-plate magmatism. Neodymium mantle depletion ages of 2080–2760 Ma suggest that the arc was built on older continental crust. Consequently, Bonnetia may have been a volcanic arc, possibly built on a rifted fragment of Laurentia, on another continental fragment, or possibly on the leading edge of another continent. The subsequent event of breccia-formation may represent a hydrothermal response to obduction-caused tectonic loading of the crust. The characterization of Bonnetia as a volcanic arc complex that underwent obduction requires that northwestern Laurentia was flanked by an ocean basin in the late Paleoproterozoic.

1. Introduction

Accretion of volcanic arc terranes, especially continental arcs, to continental margins is a key process in the growth of cratons (e.g., Windley, 1993; Rudnick, 1995; Kusky et al., 2007; Windley et al., 2007; Condie and Kröner, 2013). During the late Paleoproterozoic, juvenile arc terranes accreted to the southern and eastern margins of Laurentia (current coordinates) during the Makkovikian, Yavapai, Mazatzal, and Labradorian orogenies (e.g., Condie, 1982; Windley, 1992; Karlstrom et al., 2001; Gower and Krogh, 2002; Ketchum et al., 2002; Whitmeyer and Karlstrom, 2007). These accretions substantially broadened the Laurentian craton (Whitmeyer and Karlstrom, 2007) which resided within the supercontinent Columbia (Zhao et al., 2004). Concurrent deformation along other margins of Columbia led to a sinuous orogenic belt that extended from Laurentia to Baltica and Amazonia (Ketchum et al., 2002; Johansson, 2009).

The northwestern margin of Laurentia underwent a series of deformational events that were broadly contemporaneous with the Yavapai and Mazatzal orogenies. These events, collectively termed the Racklan orogeny, produced thin-skinned contraction of Paleoproterozoic strata in Yukon Territory, Canada (Mitchelmore and Cook, 1994; Thorkelson, 2000; Thorkelson et al., 2001a, 2005; Brideau et al., 2002; Laughton et al., 2005; Furlanetto et al., 2013). The final stage of Racklan orogeny involved obduction of a hypothetical volcanic arc terrane named Bonnetia (Furlanetto et al., 2013); therefore the Racklan orogeny was similar to the Yavapai and Mazatzal orogenies in not only timing but also style. The orogeny was followed by post-orogenic surges of hydrothermal fluids that produced widespread breccia zones (called Wernecke Breccia) that host abundant iron oxide–copper–gold (IOCG) occurrences (Hitzman et al., 1992; Thorkelson et al., 2001b; Hunt et al., 2005, 2007). Down-dropped and metasomatically altered clasts within the breccia zones, herein referred to as the "Wernecke igneous clasts," are exotic to Laurentia and are the only known remnants of the inferred terrane Bonnetia (Nielsen, 2011; Furlanetto et al., 2013).

In this paper, we explore the hypothesis of terrane obduction in Yukon Territory, Canada, by examining the geological characteristics of the Wernecke Breccias and the Wernecke igneous clasts. Using new geological maps, major and trace element geochemistry, and Nd isotope geochemistry, we peer through a metasomatic veil that has partly obscured the primary characteristics of the exotic clasts. The results allow us to reconstruct the petrologic nature

* Corresponding author. Tel.: +1 778 689 4820.
** Corresponding author.
E-mail addresses: onielsen@sfu.ca, nielsen.oscar@gmail.com (A.B. Nielsen), dthorkel@sfu.ca (D.J. Thorkelson).

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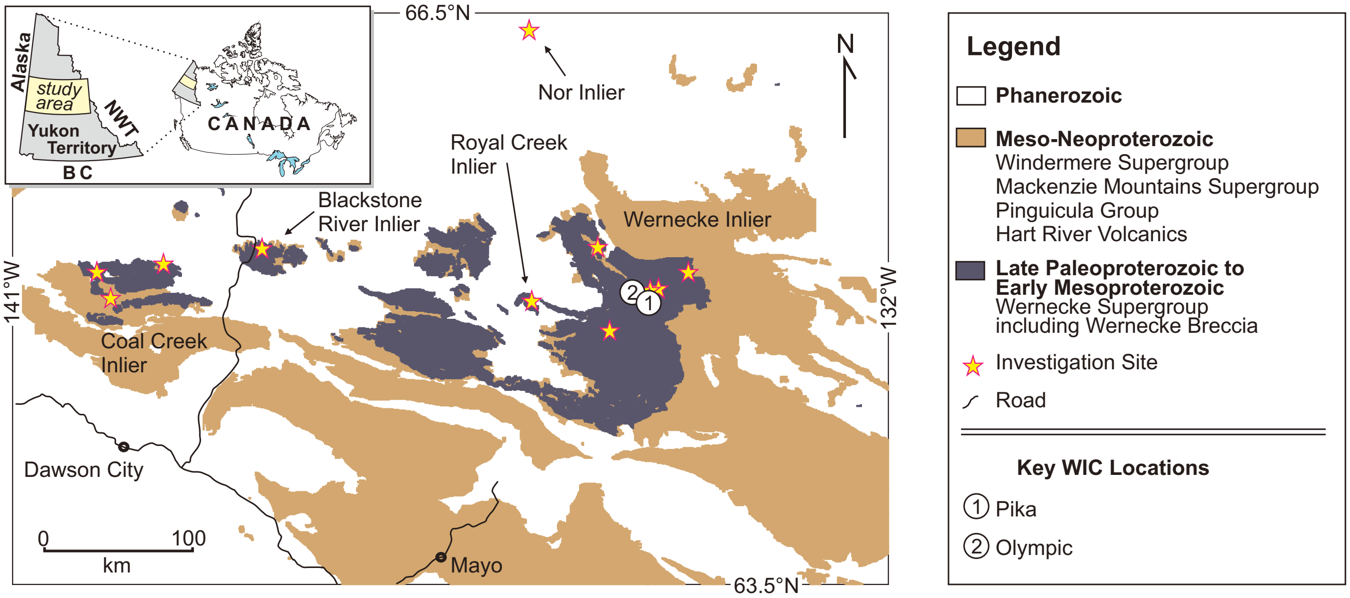

Fig. 1. Location map of central Yukon showing the extent of the Wernecke Supergroup and Proterozoic inliers, key locations where the Wernecke igneous clasts are exposed (numbered circles), and locations which were investigated as part of this study (stars and numbered circles).

of Bonnetia, identify its likely environment of formation, speculate on the causes of hydrothermal brecciation, and present new constraints on the paleo-continental configuration of Columbia.

2. Regional geology

2.1. Laurentia

The Proterozoic history of northwestern Laurentia (current geographical coordinates) is understood from numerous studies of well-exposed inliers in the Yukon (Fig. 1). In the late Paleoproterozoic to Neoproterozoic, northwestern Laurentia underwent a series of geological events that involved both continental growth and destruction (Fig. 2) (Thorkelson et al., 2005). Four of these events involved extensional basin formation and the deposition of four temporally distinct sedimentary successions: the Wernecke Supergroup, the Pinguicula Group, the Mackenzie Mountains Supergroup, and the Windermere Supergroup (Eisbacher, 1978; Young et al., 1979; Delaney, 1981; Aitken and McMechan, 1991; Ross, 1991; Medig et al., 2010). These events thinned and weakened the Laurentian lithosphere, and one or more of them may have led to continental separation between Laurentia and other landmasses (Thorkelson et al., 2005). However, these basin-forming events were interspersed with orogenesis, metamorphism, magmatism, and hydrothermal activity (Fig. 2) (Thorkelson et al., 2005; Hunt et al., 2007; Milidragovic et al., 2011). By the Neoproterozoic, northwestern Laurentia was a complexly deformed and locally metamorphosed continental margin which may have undergone tectonic interactions with oceanic terranes and/or continents such as Australia, Cathaysia, and Siberia (e.g., Hoffman, 1988; Sears and Price, 2000; Karlstrom et al., 2001; Thorkelson et al., 2001a; Betts et al., 2008; Li et al., 2008a,b; Johansson, 2009; Milidragovic et al., 2011).

2.2. The Wernecke Supergroup

The Wernecke Supergroup is a late Paleoproterozoic sedimentary succession with a minimum thickness of 13 km, comprising two clastic-carbonate grand cycles (Delaney, 1981; Norris, 1997; Thorkelson, 2000). As understood from surface exposures and shallow drill holes, the Wernecke Supergroup consists of three conformable groups: the Fairchild Lake Group (lowest known unit, ≥4.8 km thick), which consists primarily of siltstone and fine sandstone with minor dolostone and marble; the Quartet Group (~3.4 km thick), which consists of locally pyritic shale, siltstone, and very fine sandstone with fine quartz arenite near the top; and the Gillespie Lake Group (≥4.7 km thick), which consists of orange weathering dolostone with interbeds of shale, siltstone and sandstone (Delaney, 1981; Thorkelson, 2000). The Wernecke Supergroup is generally weakly metamorphosed although the lowest unit, the Fairchild Lake Group, is locally metamorphosed to fine-grained schist. The nature of any deeper parts of the Wernecke Supergroup remains unclear, as does the age and composition of the underlying crystalline basement (Hoffman, 1987; Cook et al., 1992; Cook, 2000; Lynn et al., 2005; Thorkelson et al., 2005; Pilkington and Saltus, 2009; Crawford et al., 2010).

2.3. Racklan orogeny

The Racklan orogeny applies to deformational events that affected the Wernecke Supergroup prior to the emplacement of Wernecke Breccia at approximately 1.60 Ga (Fig. 2) (Laughton et al., 2005; Furlanetto et al., 2013). Three phases of orogenic deformation have been identified (Brideau et al., 2002; Thorkelson et al., 2005). The first produced east-verging folds and a fabric that ranges from slaty cleavage to schistose foliation. The second produced upright to overturned, south-verging folds, and likely caused the tightening and overturning of the older fold set. This phase of deformation may have been associated with the formation of tight, asymmetric crenulations and crenulation cleavage. The third phase produced kink bands with inconsistent orientations. The metamorphic effects of the Racklan are most notable in the Fairchild Lake Group, which was locally metamorphosed to chloritoid–garnet–biotite–quartz–muscovite schist, with peak conditions estimated at 450–550 °C and 3–6 kbar (Brideau et al., 2002; Furlanetto et al., 2013). The Racklan orogeny was thin-skinned and appears to be broadly equivalent to the thick-skinned Forward orogeny to the east, in the Northwest Territories, which

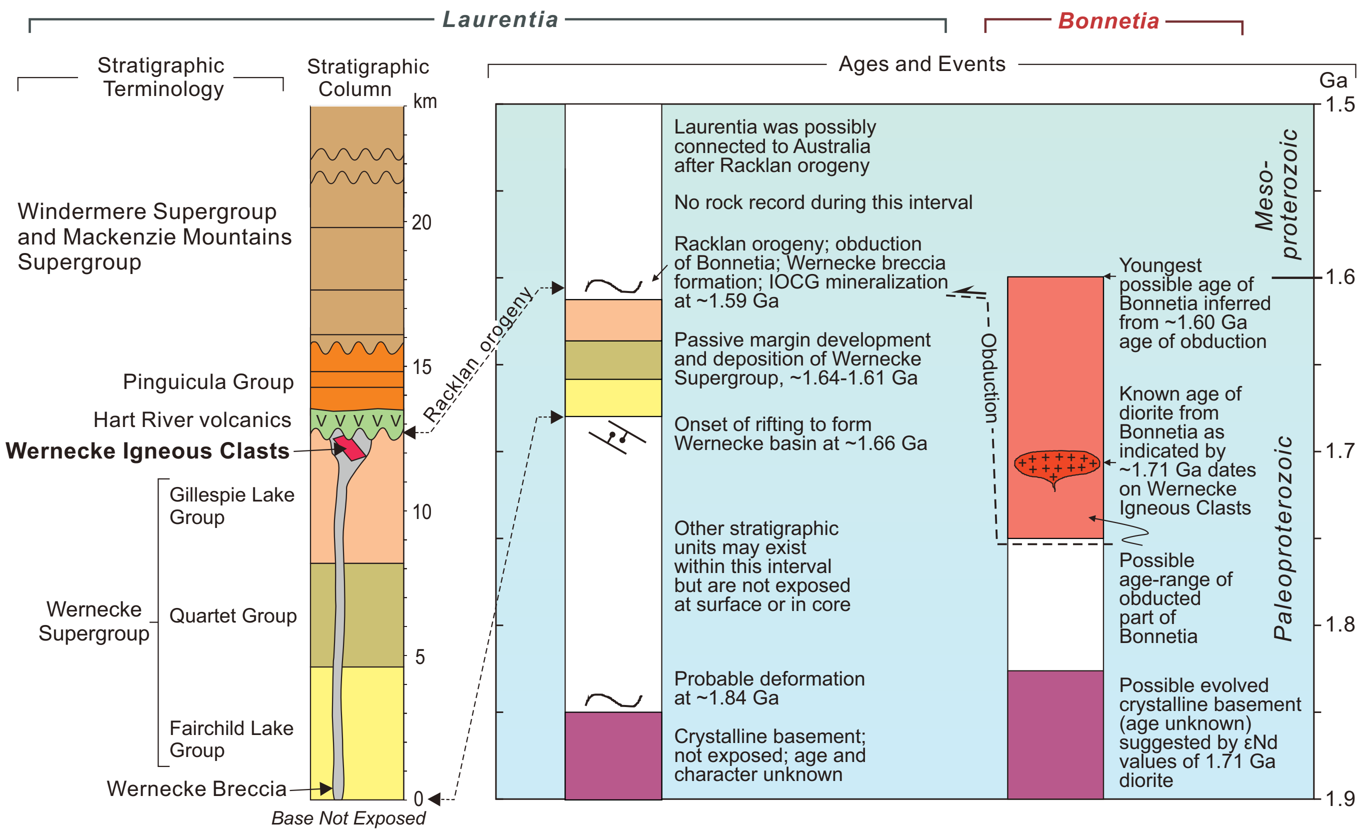

Fig. 2. Time and thickness stratigraphy of the late Paleoproterozoic to Neoproterozoic sequences, showing key events in the development of Yukon geology, modified after Thorkelson et al. (2005).

is characterized by Laramide-style reverse faulting (Cook and MacLean, 1995; Thorkelson et al., 2003; MacLean and Cook, 2004).

2.4. Wernecke Breccia

The Wernecke Breccias are early Mesoproterozoic and have been dated at 1598.8 ± 1.0 Ma by U–Pb dating of hydrothermal titanite (Furlanetto et al., 2013). The breccias occur within the Wernecke Supergroup (Fig. 2) (Bell, 1986; Thorkelson, 2000) as numerous zones that are scattered throughout Paleoproterozoic inliers of central and northern Yukon (Fig. 1). The breccias range up to several kilometres long and hundreds of metres wide and cross-cut the metamorphic fabrics that developed during the Racklan orogeny (Thorkelson, 2000). The breccias are unconformably overlain by the Pinguicula Group (Thorkelson et al., 2005). According to fluid inclusion and stable isotope studies, the Wernecke Breccias formed at depths between 5.7 and 11.3 km (Hunt et al., 2011).

The majority of clasts in the Wernecke Breccias are sedimentary in character and most appear to have been derived from the Paleoproterozoic Wernecke Supergroup. Large igneous clasts known as the Wernecke igneous clasts are also present and form a less abundant, but critically important clast population. Most of the breccia clasts are pebble to cobble-sized (Fig. 3), but some are mega-clasts that have areas of exposure up to hundreds of metres across (Figs. 4 and 5) (Thorkelson et al., 2001b; Nielsen, 2011). Notably, clasts derived from the underlying crustal basement or mantle such as gneiss and peridotite are absent in the Wernecke Breccias (Thorkelson, 2000; Thorkelson et al., 2001b).

The clasts are set in a matrix composed of microclasts and minerals precipitated from the brecciating fluid. The breccia fluids precipitated primarily hematite, magnetite, dolomite, siderite, chlorite, biotite, albite, microcline, rutile, titanite, apatite, and muscovite, with local occurrences of pyrite, chalcopyrite, cobaltite, pitchblende, brannerite, and gold (Thorkelson et al., 2001b; Hunt et al., 2007). The fluids that formed the Wernecke Breccias were most likely a mixture of crustal brines and metamorphic waters (Hunt et al., 2005, 2011; Gillen, 2010). Alteration of clasts and wall-rock is typically extensive, and generally divisible into potassic and

Fig. 3. Typical, potassic–hematitic Wernecke Breccia with variably metasomatized, cm–dm scale clasts predominantly derived from the local country rock of the Wernecke Supergroup.

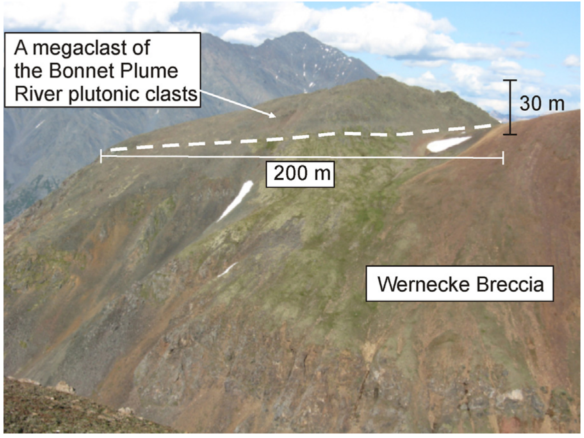

Fig. 4. A large dioritic Bonnet Plume River plutonic clast with dimensions of 900 m × 200 m × 30 m, near the Olympic mineral occurrence (Fig. 5b).

sodic varieties. Potassic alteration is regionally dominant (Laznicka and Edwards, 1979; Hitzman et al., 1992; Laughton et al., 2005). Many Wernecke Breccia occurrences host iron oxide–copper–gold mineral occurrences (Hunt et al., 2007). The breccias occur at all stratigraphic levels within the Wernecke Supergroup, representing a difference in stratigraphic height of approximately 10 km (Fig. 2) (Delaney, 1981; Norris, 1997; Thorkelson, 2000).

3. Wernecke igneous clasts

The Wernecke igneous clasts are fragments of igneous rock derived from Bonnetia (Furlanetto et al., 2013) that occur within zones of Wernecke Breccia. Three main types of igneous clasts have been identified in the Wernecke Breccias: the Bonnet Plume River plutonic clasts (Thorkelson et al., 2001a), the Slab volcanic clasts (Laughton et al., 2005), and the Devil volcanic clasts (Nielsen, 2011). Wernecke Breccia occurrences that contain Wernecke igneous clasts crop out across the central to northern Yukon comprising an area approximately 300 km east–west and 200 km north–south (Fig. 1). The igneous clasts range from pebble-size to giant blocks hundreds of metres long (millions of cubic metres in volume) (Figs. 4 and 5). The largest megaclast is a block of diorite that is 900 m long, 200 m wide and at least 30 m thick (Thorkelson and Wallace, 1998), with a volume likely greater than 5.4 million cubic metres. Unlike the sedimentary clasts in the Wernecke breccia, which appear to have been derived from the Wernecke Supergroup, none of the Wernecke igneous clasts can be correlated with any known stratigraphic unit or plutonic body.

3.1. Bonnet Plume River plutonic clasts

The Bonnet Plume River plutonic clasts (Thorkelson et al., 2001a) are fragments of inferred late Paleoproterozoic plutons that compose most of the Wernecke igneous clasts. Previous authors have referred to the clasts as the Bonnet Plume River intrusions; however this nomenclature is misleading because they exist only as clasts. The Bonnet Plume River plutonic clasts were originally identified as breccia clasts in the Wernecke inlier (Fig. 1) by Thorkelson (2000). Subsequently, lithologically indistinguishable clasts were discovered in other localities including the Nor and Hart River inliers (Hunt and Thorkelson, 2006) and the Coal Creek inlier (Lane, 1990; Nielsen, 2011) (Fig. 1). The fairly uniform petrologic and geochemical characteristics of this clast type (Hunt and Thorkelson, 2006; Nielsen, 2011) suggest that they all belong to the Bonnet Plume River plutonic clasts and were derived from similar sources within Bonnetia.

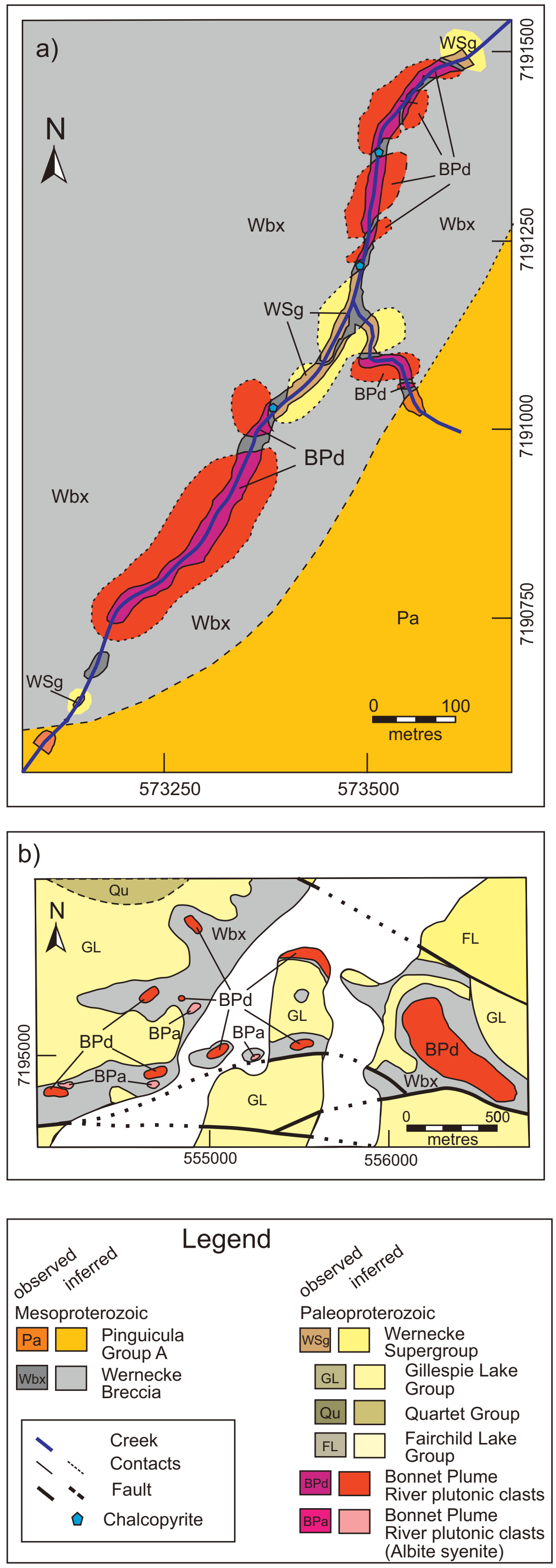

Fig. 5. Geological maps of key field localities demonstrating field relations. (a) Pika Mineral occurrence. (b) Olympic mineral occurrence, modified after Thorkelson (2000). All co-ordinates are UTM zone 8, North American Datum 83 (NAD 83).

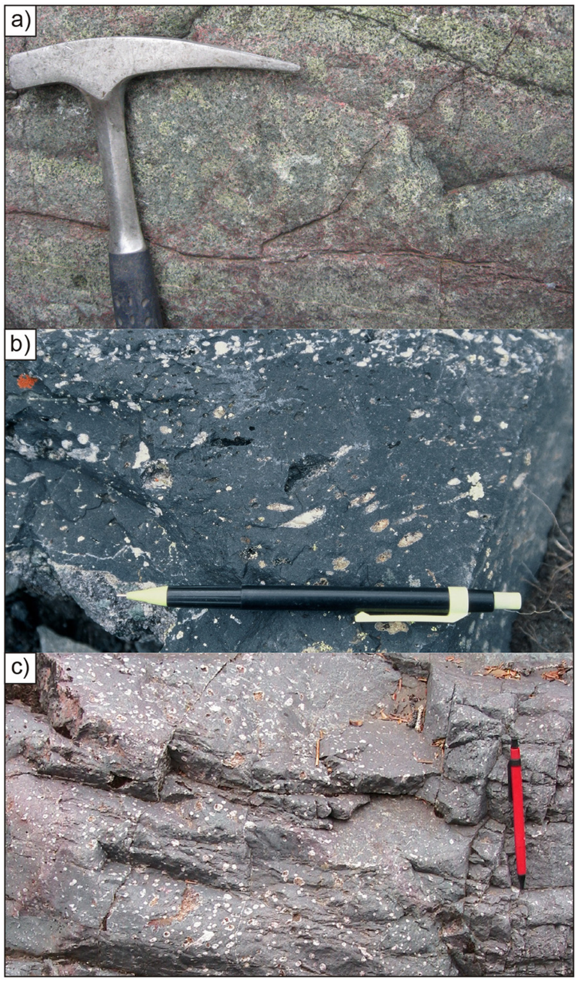

Fig. 6. (a) A medium-grained dioritic Bonnet Plume River plutonic clast showing pervasive chlorite alteration and fracture-controlled potassic (red) and epidote (yellowish green) alteration, near the Pika mineral occurrence. (b) An amygdaloidal basalt clast from the Slab volcanic clasts, near the Slab mineral occurrence, Wernecke Inlier. (c) An amygdaloidal basalt clast from the Devil volcanic clasts, near the Yukon Olympic mineral occurrence, Blackstone River inlier. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

Four of the Bonnet Plume River plutonic clasts from the Wernecke inlier (Fig. 1) have been dated (1705.9 ± 0.7 Ma, 1709.4 ±1.4 Ma, 1711.1 ±5.1 Ma, and 1713.6 ± 12.7 Ma, U–Pb zircon) (Thorkelson et al., 2001a). The majority of Bonnet Plume River plutonic clasts are fine to medium-grained diorite and gabbro (Fig. 6a). Clasts with more felsic compositions are also present, including a fine-grained albite-alkali feldspar syenite megaclasts present at the Olympic mineral occurrence (Fig. 5b), and a fine-grained quartz-albite syenite megaclast exposed at the Porphyry mineral occurrence (Thorkelson et al., 2001a). All of the Bonnet Plume River plutonic clasts have been altered to some degree, with chlorite, epidote, sericite, Na–Ca zeolites, and iron oxides as common alteration minerals. In addition, potassium feldspar is common in clasts affected by potassic-alteration, and albite is common in clasts affected by sodic alteration. More rarely, scapolite is present as a replacement of plagioclase. Veins composed primarily of calcite, commonly with quartz, epidote, hematite, and other minor phases commonly crosscut the Bonnet Plume Rive plutonic clasts.

3.2. Slab volcanic clasts

The Slab volcanic clasts (previously described as the Slab volcanics) comprise a set of mafic volcanic clasts (Fig. 6b) located within Wernecke Breccia zones at or near the Slab mineral occurrence. The largest clast is 160 m wide and 380 m long, and consists of 34 thin (5 m average thickness) mafic to intermediate lava flows, with well-preserved primary textures including ropey to scoriaceous flow tops (Laughton et al., 2002; Laughton, 2004). Beds of sandstone and breccia are intercalated with these flows. The lavas are composed of albite, phlogopite, scapolite, hematite, magnetite, and trace amounts of rutile, are crosscut by veins of scapolite and actinolite, and are infilled by vugs of orange calcite. This mineral assemblage was interpreted by Laughton (2004) to be entirely secondary and generated mainly as a result of Wernecke Breccia-related metasomatism. The rutile within the breccia was dated by U–Pb at ca. 1383 Ma (Thorkelson et al., 2001b), inferring another episode of hydrothermal activity some 220 Ma after original breccia formation. The renewed hydrothermal activity is believed to be related to the nearby Hart River sills, which are approximately the same age (Abbott, 1997; Thorkelson et al., 2001b; Laughton, 2004).

3.3. Devil volcanic clasts

The Devil volcanic clasts are located in the Blackstone River inlier (Fig. 1), within a zone of Wernecke Breccia that forms part of the Yukon Olympic mineral occurrence. Three megaclasts (>100 m^2) and numerous smaller clasts were identified during field investigations. The clasts consist of massive, amygdaloidal basalt and andesite (Fig. 6c). They have been altered to chlorite and sericite and their vesicles filled by quartz and hematite. They are crosscut by veins of epidote, quartz, carbonate, and hematite. Their generally massive character suggests a possible origin as a submarine volcanic succession, and contrasts with the subaerially deposited flows that were the source of the Slab volcanic clasts.

4. Geochemistry of the Wernecke igneous clasts

This paper integrates the results of previous studies on the Wernecke igneous clasts with new geochemical and isotopic information to provide a more comprehensive investigation of their primary composition, tectonic affinity and metasomatic alteration. Previous studies examined the Bonnet Plume River plutonic clasts (Thorkelson, 2000; Thorkelson et al., 2001a; Hunt and Thorkelson, 2006) and the Slab volcanic clasts (Laughton, 2004). The studies on the Bonnet Plume River plutonic clasts, which were focused mainly on the Wernecke inlier, concluded that they are tholeiitic diorites and gabbros which were emplaced in a continental extensional environment and subsequently metasomatized by the fluids of the Wernecke Breccias (Thorkelson et al., 2001a). The Slab volcanic clasts were described as tholeiitic, mafic to intermediate sub-alkaline to alkaline basalts, andesites, and trachyandesites emplaced in a within-plate tectonic environment (Laughton, 2004). This study re-evaluates these previous findings and clarifies the geochemical composition and tectonic affinity of the Wernecke igneous clasts.

Thirty new samples of Wernecke igneous clasts were collected from locations in all of the major inliers in the Yukon and analyzed for major and trace elements; a subset was analyzed for Nd isotopes. The results of this study along with a reinterpretation of the findings of the previous studies indicate that both the plutonic and volcanic clasts have geochemical compositions that are subalkaline to transitional, with mostly basaltic and andesitic compositions that have been modified by metasomatism. Location and geochemical data for all the samples are provided in Appendices A and B, respectively.

4.1. Sodic and potassic alteration

The Wernecke igneous clasts were exposed to the hydrothermal fluids that formed Wernecke Breccia. These fluids ranged in temperature from 110 to 400 °C (Hunt et al., 2007, 2011; Gillen, 2010), and metasomatically affected the clasts and wall rocks to produce potassic, sodic, carbonic and iron oxide alteration (Laznicka and Edwards, 1979; Hitzman et al., 1992; Thorkelson et al., 2001b; Laughton et al., 2005). Characterizing elemental mobility was therefore a major concern in our evaluation of the geochemical character of the Wernecke igneous clasts and the processes that affected them.

In order to characterize elemental mobility in Wernecke Breccia metasomatism, we applied the concepts of potassic and sodic metasomatism, which are widely recognized as important alteration types, especially in iron oxide–copper–gold deposits and porphyry deposits (e.g., Laznicka and Edwards, 1979; Carten, 1986; Hitzman, 2000; Williams et al., 2005; Sillitoe, 2010). This approach has been successfully used to understand alteration patterns in the Wernecke Breccias and their wallrocks (Laznicka and Edwards, 1979; Hitzman et al., 1992; Thorkelson et al., 2001b; Hunt et al., 2005, 2011; Laughton et al., 2005; Gillen, 2010).

In this study, we use K/Na ratios to classify the type and degree of alteration of the Wernecke igneous clasts. We recognize five categories, ranging from extreme potassic (K/Na > 10) to moderate potassic (K/Na from 2 to 10), to normal (K/Na from 2 to 0.5), to moderate sodic (K/Na from 0.1 to 0.5), and extreme sodic (K/Na < 0.1). The normal category accords with the range of most (unaltered) igneous rocks (Wilkinson, 1986; Foley et al., 1987; LeMaitre, 2002) whereas the other categories reflect variable degrees of potassic or sodic metasomatism. Using this method we explore variations in the major and trace element abundances and Nd isotopic composition of the Wernecke igneous clasts.

4.2. Major and minor oxides

The Bonnet Plume River plutonic clasts display a wide range of compositions. SiO_2 ranges from 45 to 68 wt% with the majority of samples between 47 and 57 wt%. The concentrations of the other oxides (in weight%) vary widely: Al_2O_3 from 11.38 to 17.77, CaO from 0.2 to 12, Na_2O from 0.01 to 8.5, K_2O from 0.12 to 9.76, and TiO_2 from 0.6 to 3.1. FeO* (all Fe as Fe^{2+}) ranges from 6.3 to 23, MgO from 1.50 to 13.3, and Mg-number ($[100\,Mg/(Mg+Fe)]_{atomic}$, with all Fe as Fe^{2+}) ranges from 21.4 to 68.2 (Fig. 7a–j).

The Slab volcanic clasts are more restricted in their geochemical range. In weight%, SiO_2 ranges from 47 to 59, with most samples between 50 and 55 and Al_2O_3 from 12.50 to 15.74. The alkali and alkaline earth elements vary widely within the Slab volcanic clasts, but overall have a higher concentration than in the Bonnet Plume River plutonic clasts: CaO from 2 to 10, Na_2O from 0.9 to 10, K_2O from 0.45 to 8.0, TiO_2 from −1.4 to 2.5, FeO* from 9 to 18, and Mg-number from 19 to 55 (Fig. 7a–j). The Devil volcanic clasts have not been sufficiently sampled to permit a firm description of their geochemical variation; however, the compositions of the two samples analyzed fall within the range of the Bonnet Plume River plutonic clasts.

The total alkali–silica (TAS) plot (LeMaitre, 2002) shows a large scatter in apparent rock types of the Wernecke igneous clasts. The Bonnet Plume River plutonic clasts plot mainly in the fields of basalt, trachybasalt, and basaltic trachyandesite and the least altered Bonnet Plume River plutonic clasts plot predominantly in the fields of basalt and andesite (Fig. 7k). The wide range of rock types does not reflect the predominantly dioritic composition of the Bonnet Plume River plutonic clasts that is apparent from relict minerals, textures, and pseudomorphs, in hand sample and thin section. The geochemical scatter likely reflects the mobility of the alkali elements and silica during Wernecke Breccia metasomatism. The Slab volcanic clasts are generally more alkalic than the Bonnet Plume River plutonic clasts and plot mainly in the fields of basaltic trachyandesite, trachyandesite and tephriphonolite (Fig. 7k). The Devil volcanic clasts samples plot in the fields of basaltic andesite and tephrite–phonolite.

The minor oxides MnO, P_2O_5 and TiO_2 further distinguish the Slab volcanic clasts from the Bonnet Plume River plutonic clasts and Devil volcanic clasts, with notably higher TiO_2/MnO ratios in the Slab volcanic clasts. Consequently, on the tectonic affinity plot of Mullen (1983), the Slab volcanic clasts plot almost entirely within the ocean island – alkalic basalt field whereas the Bonnet Plume River plutonic clasts and Devil volcanic clasts plot predominantly in volcanic arc and mid-ocean ridge basalt fields (Fig. 7l).

4.3. Trace elements

The trace element distributions of the Bonnet Plume River plutonic clasts vary markedly. The large ion lithophile elements (LILE) are scattered chaotically and have large ranges; for example, Ba ranges from 30 to 3159 ppm. The high field strength elements (HFSE) are less scattered than the LILE. Some elements display a wide range of concentration; for example, Y varies from 8 to 43 ppm whereas Zr ranges from 18 to 516 ppm. Abundances of the transition metals are also fairly scattered; for example Cr ranges from less than 0.5 ppm to 490 ppm and Ni ranges from 10 to 255 ppm (Fig. 8).

The Slab volcanic clasts are more restricted in their trace element concentration ranges than the Bonnet Plume River plutonic clasts. The LILE also display chaotic concentrations, but they are not as wide ranging as in the Bonnet Plume River plutonic clasts. The HFSE are generally more enriched in the Slab volcanic clasts than in the Bonnet Plume River plutonic clasts; for example, Zr ranges from 204 to 482 ppm and Y ranges from 34 to 88 ppm. In contrast, transition metal abundances in the Slab volcanic clasts are generally depleted relative to the Bonnet Plume River plutonic clasts; for example, Cr ranges from 1.2 to 7.5 ppm and Ni ranges from 3.5 to 43 ppm. The Slab volcanic clasts are enriched in the rare earth elements (REE), Nb, and Ta relative to the Bonnet Plume River plutonic clasts (Fig. 8). The Devil volcanic clasts have trace element concentrations that lie within the range of the Bonnet Plume River plutonic clasts.

4.4. Trace Element Mobility

The effects of sodic and potassic metasomatism are shown in Fig. 9. The LILE show chaotic enrichments and depletions with sodic and potassic alteration. The HFSE (except Y), show enrichments with both sodic and potassic alteration, whereas Y shows a slight depletion with strong potassic alteration. Sodic alteration is marked by increased concentration of the REE overall, whereas weak potassic alteration shows depleted concentrations of the REE. Strong potassic alteration is linked to increased concentration in the light rare earth elements (LREE) up to Nd and decreased concentration in the REE heavier than Nd. Among the transition metals, Cu, Cr, Zn, and Sc are depleted with both sodic and potassic alteration, though Sc only weakly so. Ni and Co show depletions only with sodic alteration. Ti and V show enrichment by potassic alteration and depletion by sodic alteration.

4.5. Rock classification

Geochemical classification systems that are appropriate for the Wernecke igneous clasts must be relatively insensitive to Wernecke Breccia metasomatism and they must display the effects of metasomatism on the plotted points. Both of these approaches

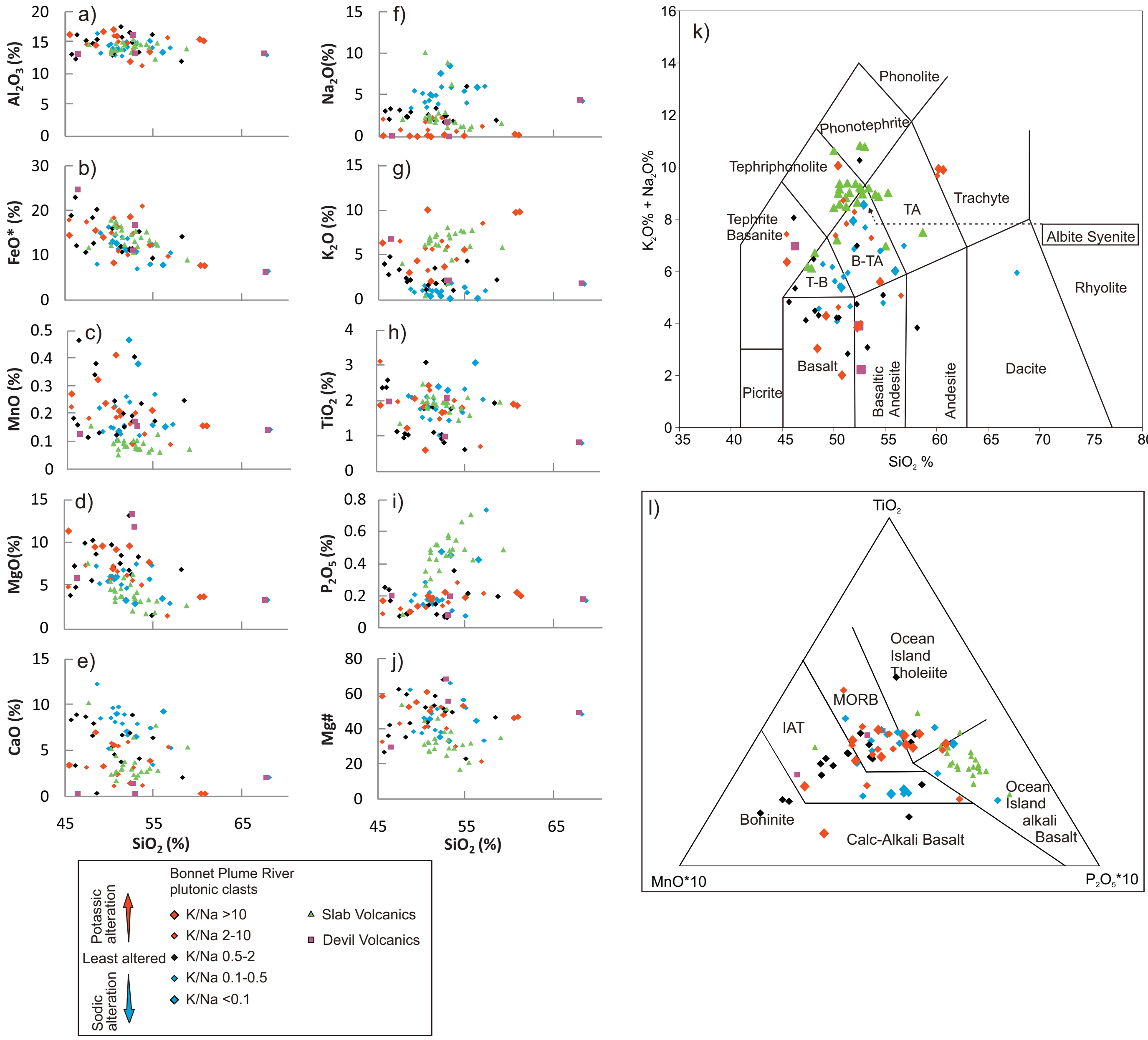

Fig. 7. (a–j) Harker variation diagrams, (k) total alkali–silica diagram after LeMaitre (2002), field T-B is trachybasalt, field B-TA is basaltic trachyandesite, field TA is trachyandesite. (l) Tectonic discrimination diagram after Mullen (1983), IAT field is island arc tholeiite; MORB field is mid-ocean ridge basalt.

are used in this analysis. The most suitable system for determining the rock type of the Wernecke igneous clasts is Zr/Ti vs. Nb/Y (Winchester and Floyd, 1977), which shows that the they are primarily subalkaline basalt and andesite (Fig. 10a). Some samples plot in the fields of alkali basalt and rhyolite however, these samples display strong sodic and potassic alteration therefore this is unlikely to represent their original igneous composition. Using equivalent names for phaneritic rocks, the Bonnet Plume River plutonic clasts are geochemically classified as diorite and gabbro. The Slab volcanic clasts are generally more enriched, and plot in the fields of subalkaline basalt, andesite–basalt, andesite, rhyodacite–dacite, alkaline basalt, and trachyandesite.

In order to further describe the nature of the Wernecke igneous clasts, the method of determining rock series based on immobile elements developed by Ross and Bédard (2009) was applied because it is less susceptible to metasomatic alteration than the standard methods of differentiating the magma series of rocks (e.g., Irvine and Baragar, 1971; Miyashiro, 1974; Pecerillo and Taylor, 1976). This method indicates that the Bonnet Plume River plutonic clasts and Devil volcanic clasts follow the transitional to mildly calc-alkaline series trend, as opposed to a tholeiitic one (Fig. 10b). Some samples show strong calc-alkaline affinity; however, these samples have been strongly affected by Wernecke Breccia metasomatism. The Slab volcanic clasts also plot in the transitional and calc-alkaline fields, although overall they are more calc-alkaline than the Bonnet Plume River plutonic clasts and the Devil volcanic clasts.

4.6. *Arc to intraplate affinity of the Wernecke igneous clasts*

Two discriminant plots were used in order to determine the tectonic affinity of the Bonnet Plume River plutonic clasts and Devil volcanic clasts. Nb, Zr, Y, Th, Hf, and Ta were used because they are relatively immobile, especially with potassic alteration. The Zr/4–Y–Nbx2 plot of Meschede (1986) (Fig. 10c) shows the Bonnet Plume River plutonic clasts and Devil volcanic clasts plotting in the fields of volcanic arcs. Strongly altered samples are scattered with

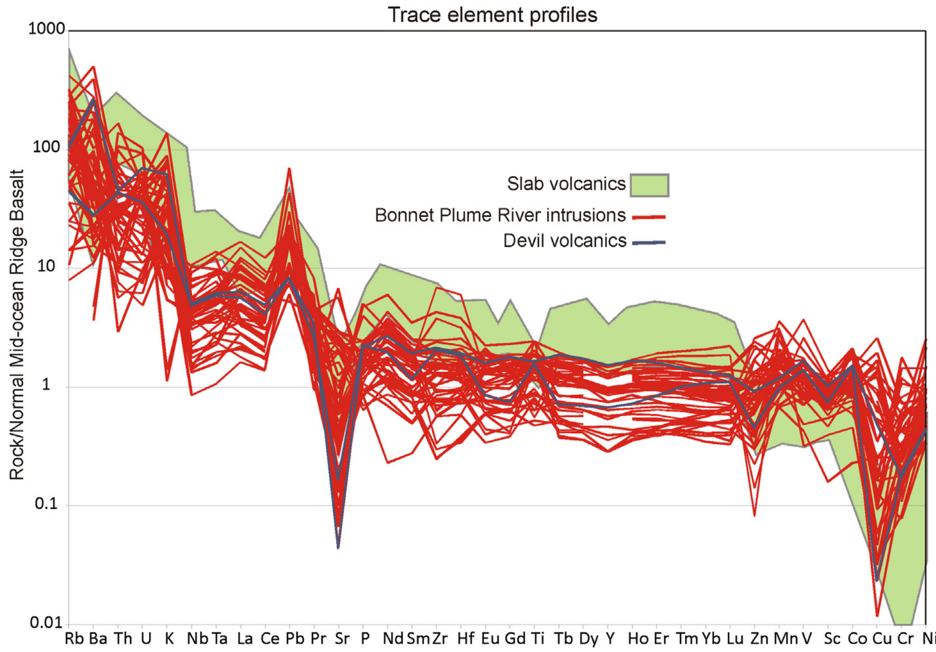

Fig. 8. N-MORB normalized multi-element diagram. Data for the Slab volcanic clasts from Laughton (2004). Normalizing values Rb–Lu after Sun and McDonough (1989); Zn to Ni except Cu and Zn, after Pearce and Parkinson (1993); Zn, Cu estimated from Basaltic Volcanism Study Project (1981).

no distinct pattern. The field of Slab volcanic clasts lies in the fields of mantle plume-influenced mid-ocean ridge basalt (P-MORB), within-plate tholeiites (WPT), and within-plate alkaline basalt (WPA).

The Ta–Th–Hf ternary of Wood (1980) (Fig. 10d) shows the Bonnet Plume River plutonic clasts and Devil volcanic clasts plotting mainly in the field of calc-alkaline arc basalt. Several samples, particularly those with potassic alteration, lie adjacent to this field in an undefined part of the diagram. The alteration in these elements has biased the position of the samples away from the Hf corner with a slight bias towards the Th corner; however, this has not changed the outcome of the plot significantly. The field of Slab volcanic clasts plots on the margin of calc-alkaline arc basalts and overlaps the fields of E-MORB/tholeiitic within-plate basalts and alkaline within-plate basalts.

The dominant geochemical signal from the Bonnet Plume River plutonic clasts and the Devil volcanic clasts indicates that they were derived from hydrous mantle above a subducting slab and were emplaced or erupted in a volcanic arc. The Slab volcanic clasts have a distinct intraplate geochemical signal that indicates involvement of enriched mantle. Such an involvement could have occurred from the subduction of a spreading ridge and formation of a slab window, which are known to cause intraplate-style magmatism in volcanic arc environments (e.g., Marshak and Karig, 1977; Hole et al., 1991; Thorkelson et al., 2011). Alternatively, the geochemical characteristics of the Slab volcanic clasts could have been produced by a mantle plume that contaminated the source region of the volcanic arc (cf. Johnston and Thorkelson, 1997; Wyman and Kerrich, 2010; Gazel et al., 2011).

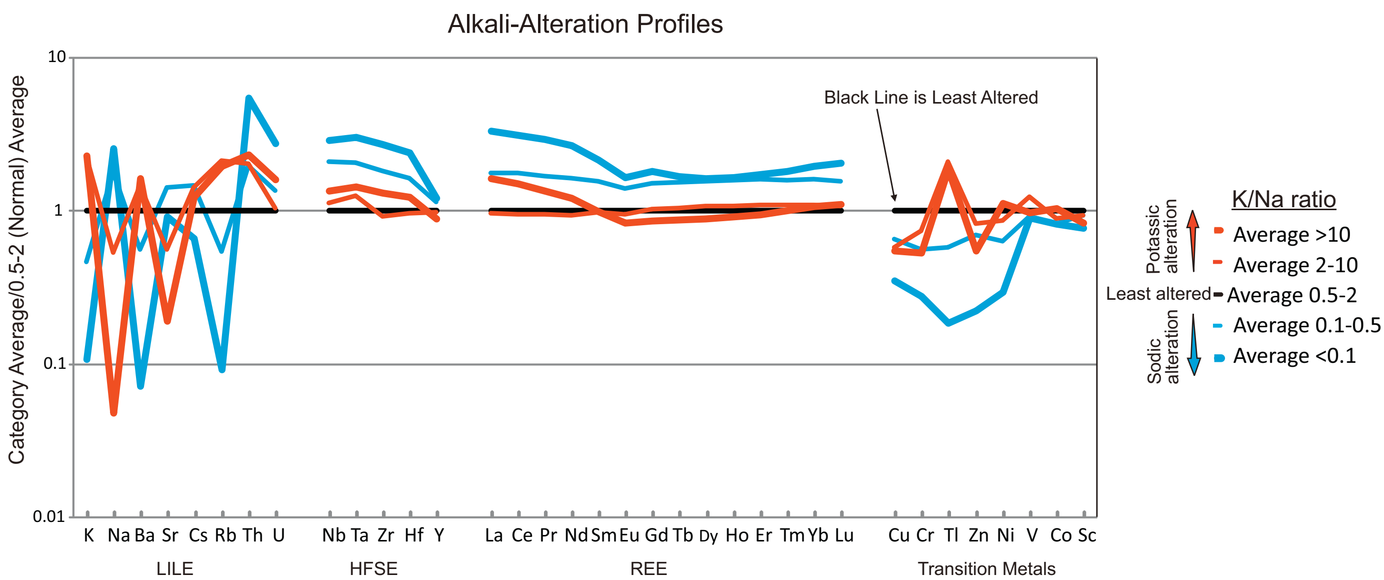

Fig. 9. Multi-element diagram-style isocon diagram for selected elements showing enrichments and depletions due to alkali metasomatism, normalized to the average elemental concentration of samples with "normal" K/Na values (0.5–2). LILE – large ion lithophile elements, HFSE – high field strength elements, REE – rare earth elements.

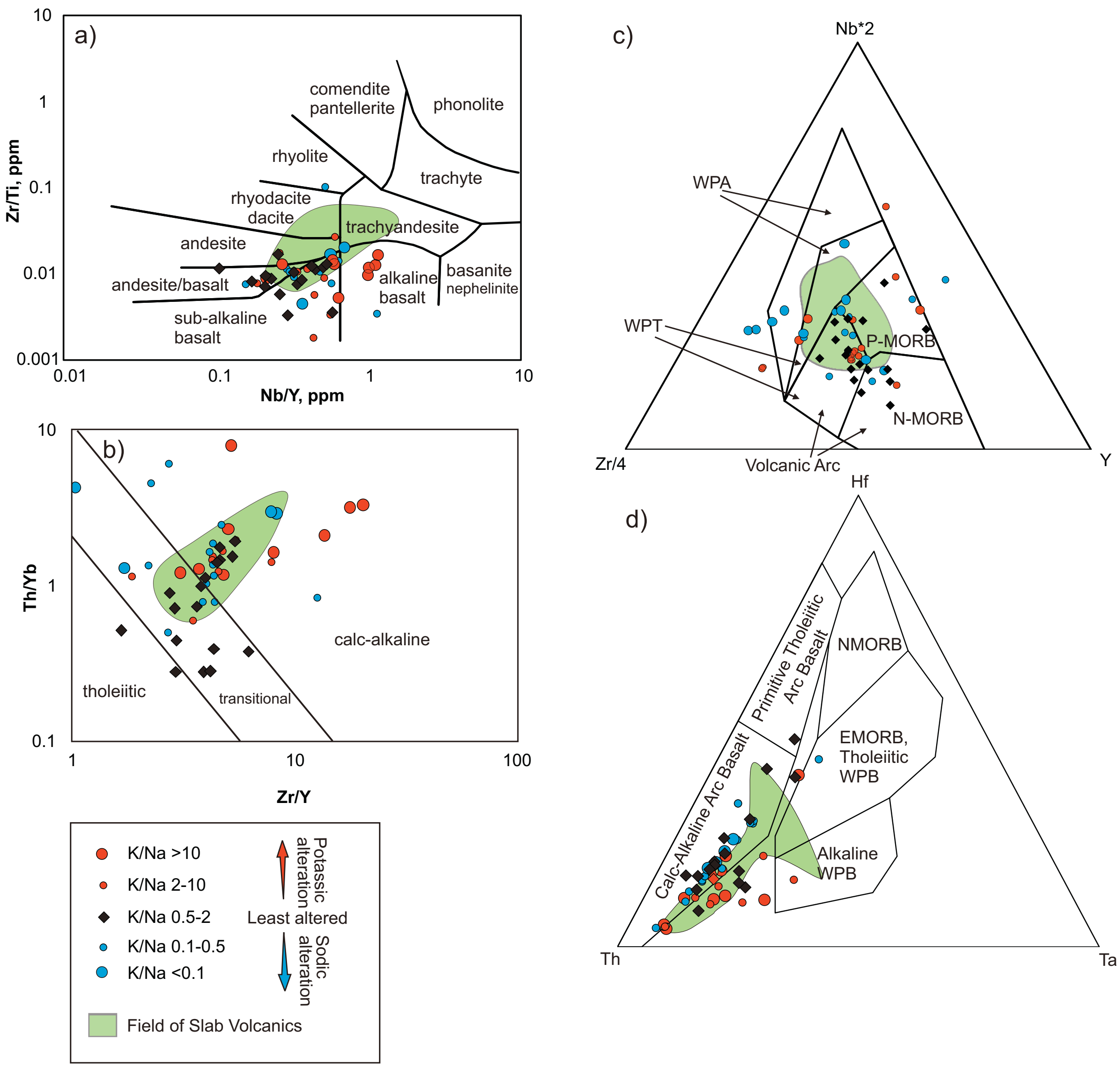

Fig. 10. Geochemical characterization plots using immobile elements for Bonnet Plume River plutonic clasts, Devil volcanic clasts, and Slab volcanic clasts: (a) rock classification plot after Winchester and Floyd (1977), (b) rock series determination plot after Ross and Bédard (2009), (c) tectonic affinity plot after Meschede (1986) and (d) tectonic affinity plot after Wood (1980). WPB – within plate basalt; WPT – within plate tholeiite; WPA – within plate alkali basalt; NMORB – normal mid-ocean ridge basalt; EMORB – enriched mid-ocean ridge basalt; PMORB – plume-influenced mid-ocean ridge basalt.

5. Sm–Nd isotope analysis

Neodymium isotope analysis was performed on nine samples selected from the Bonnet Plume River plutonic clasts and one sample of the Devil volcanic clasts by the Pacific Centre for Isotopic and Geochemical Research at the University of British Columbia. Previous analyses were performed on the Bonnet Plume River plutonic clasts, the Wernecke Breccia, the Gillespie Lake Group and the Quartet Group (Thorkelson, 2000), and all of the available data were used in this study.

εNd_0 values for the Bonnet Plume River plutonic clasts and Devil volcanic clasts range from 0.0 to −18.5 and TDM values are between 2.08 and 2.76 Ga (Table 1 and Fig. 11) (depleted mantle model of Nägler and Kramers, 1998). The wide range of isotopic compositions among the Bonnet Plume River plutonic clasts and Devil volcanic clasts is an effect of Wernecke Breccia metasomatism. The samples can be grouped into two distinct categories: relatively unaltered samples with high Sm/Nd, high ^{143}Nd values and moderate εNd values at present; and altered samples with low Sm/Nd, low ^{143}Nd values and low εNd values at present (DePaolo and Wasserburg, 1976).

5.1. Least altered samples

The first group of samples (black lines in Fig. 11) is dissimilar in isotopic composition and light rare earth element slope to the Wernecke Supergroup. In thin section, this group shows the least amount of secondary mineral growth and commonly displays primary textures. Geochemically, this group belongs to the set of samples with “normal” K/Na values therefore they are considered the least altered samples and the most likely to represent the primary isotopic composition of the Bonnet Plume River plutonic clasts and Devil volcanic clasts. The TDM model ages (DePaolo, 1981a; Nägler and Kramers, 1998) for these samples are 2.36 Ga, 2.39 Ga and 2.67 Ga. The Bonnet Plume River plutonic clasts are considered to be approximately 1710 Ma based on U–Pb zircon dates (Thorkelson et al., 2001b), although these ages were obtained from only four samples from a restricted area.

Table 1
Sm–Nd analyses for selected Bonnet Plume River plutonic clasts and a Devil volcanic clast (ABN 09 19-02-02). OAE – older than the age of the Earth.

	K/Na	Sample	Sm (ppm)	Nd (ppm)	Sm/Nd	147Sm/144Nd	143Nd/144Nd	Uncertainty[a]	TDM (NK98[b])	T Ma	εNd_0	εNd_{1710}	εNd_{1595}
Most potassic	127	ABN09 04-11-01b	3	13	0.23	0.139495060	0.511801	0.00000724	2.54	1710	−16.3	−3.9	−4.7
	55.6	ABN09 12-04-01b	2.28	9.9	0.23	0.139209505	0.511688	0.00000702	2.76	1710	−18.5	−6.0	−6.8
	49.6	ABN09 17-02-01b	1.56	7.4	0.21	0.127430043	0.511782	0.00000676	2.23	1710	−16.7	−1.6	−2.6
	49.0	ABN-09 19-02-02b	5.11	19.7	0.26	0.156808680	0.512135	0.00000664	2.43	1710	−9.8	−1.1	−1.7
	6.96	ABN-09 20-02-01b	1.33	5.74	0.23	0.140067123	0.511951	0.00000732	2.27	1710	−13.4	−1.1	−1.8
	6.60	DT-93-163-1b	1.27	3.97	0.32	0.193200000	0.512249	0.00001900	OAE	1714	−7.6	−6.9	−6.9
Least altered	1.86	ABN09 06-01-01b	2.35	8.24	0.29	0.172418536	0.512405	0.00000690	2.36	1710	−4.6	0.7	0.4
	0.70	ABN09 12.5-01-01	1.96	6.31	0.31	0.187799410	0.512639	0.00000618	2.39	1710	0.0	1.9	1.8
	0.52	ABN09 14-02-01b	2.18	8.02	0.27	0.164324241	0.512174	0.00000658	2.67	1710	−9.0	−2.0	−2.5
	0.34	ABN09 18-03-01b	3.85	12.9	0.30	0.180421095	0.512143	0.00000628	OAE	1710	−9.6	−6.1	−6.4
	0.31	DT-94-20-1b	5.63	24.89	0.23	0.136700000	0.512003	0.00000600	2.08	1706	−12.4	−4.0	−5.3
	0.16	DT-94-22-1b	16.73	81.51	0.21	0.124100000	0.511736	0.00000900	2.23	1709	−17.6	−6.5	−8.0
	0.02	ABN09 11-02-01b	4.92	22.4	0.22	0.132768023	0.511757	0.00000774	2.42	1710	−17.2	−3.3	−4.1
	0.01	ABN09 12-01-01b	9.15	43.4	0.21	0.127441930	0.511802	0.00000910	2.20	1710	−16.3	−1.2	−2.2
Most sodic	0.01	DT-93-52-1b	19.02	79.3	0.24	0.145000000	0.511997	0.00000900	2.32	1711	−12.5	−6.0	−7.1

[a] Uncertainty is expressed as 2σ.
[b] Depleted mantle model of Nägler and Kramers (1998).

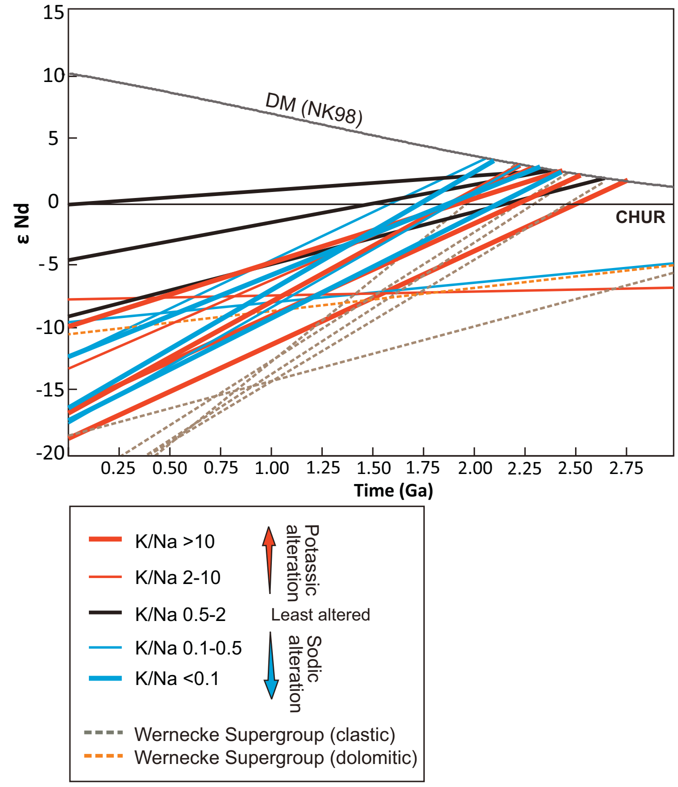

Fig. 11. εNd plot after DePaolo (1981a) showing the depleted mantle (DM) (model of Nägler and Kramers, 1998), CHUR (chondritic uniform reservoir), Wernecke Supergroup (Thorkelson et al., 2005), and Bonnet Plume River plutonic clasts and Devil volcanic clasts (Thorkelson et al., 2001a; this study). (For interpretation of the references to color in the text, the reader is referred to the web version of the article.)

5.2. Sodically and potassically altered samples

The second group of samples (red and blue lines in Fig. 11) has Sm/Nd, εNd_{1595}, and εNd_0 values approaching those of the Wernecke Supergroup (Fig. 12a and b). When viewed in thin section, the samples in this group show growth of secondary minerals such as apatite, epidote, sericite, albite, and potassium feldspar, indicating significant metasomatism. The samples in this group belong to the sodic or potassic metasomatized geochemical series. Their compositions and isotopic characteristics likely represent a trend towards rare earth element and isotopic equilibration with the Wernecke Supergroup host rocks.

5.3. Effect of metasomatism on neodymium isotope evolution

Depleted mantle model ages (DePaolo, 1981a; Nägler and Kramers, 1998) for the altered Bonnet Plume River plutonic clasts and Devil volcanic clasts range from 2.08 Ga to 2.76 Ga (depleted mantle model of Nägler and Kramers, 1998). This metasomatism has predominantly decreased the εNd_0 value of the altered samples and made their TDM model age younger (Figs. 11 and 12b). LREE slopes (La/Gd) in the Bonnet Plume River plutonic clasts and Devil volcanic clasts are predominantly increased by Wernecke Breccia metasomatism (Fig. 12a and b); therefore, their Sm/Nd values are decreased, though some altered samples have had their Sm/Nd value increased. If Sm/Nd values are increased or decreased by metasomatism, their rate of evolution away from the chondritic uniform reservoir (CHUR) is affected, which in turn affects their TDM (Rosing, 1990; Gruau et al., 1996) and their εNd_0. If the Sm/Nd of a rock derived from the depleted mantle is decreased, its TDM decreases and its εNd_0 increases. Conversely, when the

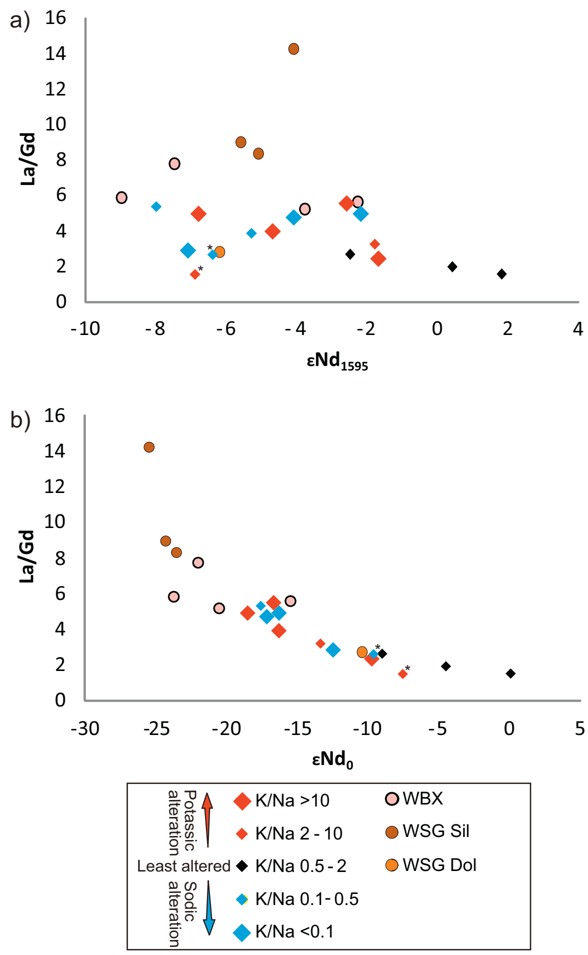

Fig. 12. Epsilon neodymium and La/Gd at (1) the time of brecciation and metasomatism (1595 Ma) and (2) present. Asterisks indicate altered Wernecke igneous clast samples that have high Sm/Nd, relatively low epsilon neodymium values and TDM older than the age of the earth.

Sm/Nd of a rock derived from the depleted mantle is increased, its TDM also increases and its εNd_0 decreases (Rosing, 1990). The samples in Fig. 11 with steep slopes have had their Sm/Nd ratio decreased whereas the sample in Fig. 11 with a very shallow slope has had its Sm/Nd ratio increased. Wernecke Breccia metasomatism also affected the $^{143}Nd/^{144}Nd$ ratio (εNd_{1595}) of the altered Bonnet Plume River plutonic clasts and Devil volcanic clasts at the time of brecciation (Fig. 12a). The cause of the steep or very shallow slopes of the evolution paths of altered Bonnet Plume River plutonic clasts and Devil volcanic clasts in Fig. 11 and their low εNd_0 is Wernecke Breccia metasomatism.

5.4. *Neodymium isotope signature of the Bonnet Plume River plutonic clasts is not juvenile*

Most of the Bonnet Plume River plutonic clasts and Devil volcanic clasts have been altered, masking their primary isotopic composition. By identifying the least altered samples, we have been able to make meaningful determinations of the original isotopic characteristics of the Bonnet Plume River plutonic clasts and Devil volcanic clasts. These characteristics indicate that the Bonnet Plume River plutonic clasts and Devil volcanic clasts are not juvenile, since their TDMs are greater than their zircon crystallization ages, but are significantly less evolved than indicated by the more altered samples. The εNd_{1710} values of the least altered Bonnet Plume River plutonic clasts and Devil volcanic clast samples indicate that they were more evolved than the depleted mantle when they crystallized at 1710 Ma (model of Nägler and Kramers, 1998).

6. Origin and emplacement of the Wernecke igneous clasts

Our results support and provide additional constraints on the Bonnetia terrane obduction model (Furlanetto et al., 2009a,b, 2013), and lead to a revised interpretation of the origins of the Wernecke igneous clasts. Our analysis indicates that Bonnetia had the geochemical characteristics of calc-alkaline volcanic arcs (Wood, 1980; Gill, 1981), based on the composition of the widespread Bonnet Plume River plutonic clasts however, it also contained the Slab volcanic clasts with compositions that are intermediate between those of calc-alkaline volcanic arcs and alkalic ocean-islands. The neodymium signature of the Bonnet Plume River plutonic clasts and Devil volcanic clasts has an evolved component (DePaolo, 1981b), suggesting that the magmas that formed them either passed through an older continental basement during emplacement or were derived from mantle with an εNd value enriched relative to depleted mantle (Nägler and Kramers, 1998).

6.1. *A refined model of the obduction, brecciation, and foundering of Bonnetia*

6.1.1. *Formation of Bonnetia*

The proposed model (Fig. 14a–e) depicts the genesis, emplacement, and exhumation of the Wernecke igneous clasts. The source rocks to the Wernecke igneous clasts were formed in an offshore terrane (Bonnetia) above a subducting slab of oceanic crust at 1.71 Ga (Fig. 13a). The neodymium signature of the Bonnet Plume River plutonic clasts and Devil volcanic clasts suggests that Bonnetia was built upon a continental fragment or above enriched mantle related to a mantle plume (e.g., Thompson et al., 1983) or a slab window (Thorkelson et al., 2011).

The combination of petrologically distinct components within Bonnetia may have been caused by separate formation of the components followed by tectonic amalgamation, such as collision between a volcanic arc and an ocean island or oceanic plateau. Alternatively, the pairing of calc-alkaline arc and alkalic ocean island compositions may have occurred by variations in the source of the magmas through time. In one scenario, subduction of a mid-ocean spreading ridge occurred beneath the arc, forming a slab window and allowing more enriched mantle to upwell beneath the arc, leading to alkalic ocean island magma compositions (e.g., Hole et al., 1991; Gorring and Kay, 2001). In another, a mantle plume impinged on the region, temporarily contaminating the source of the arc magmas with more enriched peridotite (e.g., Johnston and Thorkelson, 1997; Wyman and Kerrich, 2010; Gazel et al., 2011).

6.1.2. *Formation, metamorphism, deformation, and exhumation of the Wernecke Supergroup*

Formation of the Wernecke basin at or after 1.66 Ga (Furlanetto et al., 2013) was likely related to rifting of a continental block away from Laurentia, which existed within Columbia (Rogers and Santosh, 2002; Zhao et al., 2004). The Wernecke Supergroup began to be deposited into this basin on the rifted margin of Laurentia (Fig. 13b). After sedimentation, the region was affected by contractional deformation of Racklan orogeny, causing cratonward directed transport of the passive margin sedimentary rocks. The Wernecke Supergroup was locally metamorphosed to lower greenschist facies. Following metamorphism, the deformed Wernecke Supergroup was exhumed, exposing all units of the Wernecke Supergroup at a single erosional surface (Fig. 13c) (Laughton et al., 2005; Furlanetto et al., 2013).

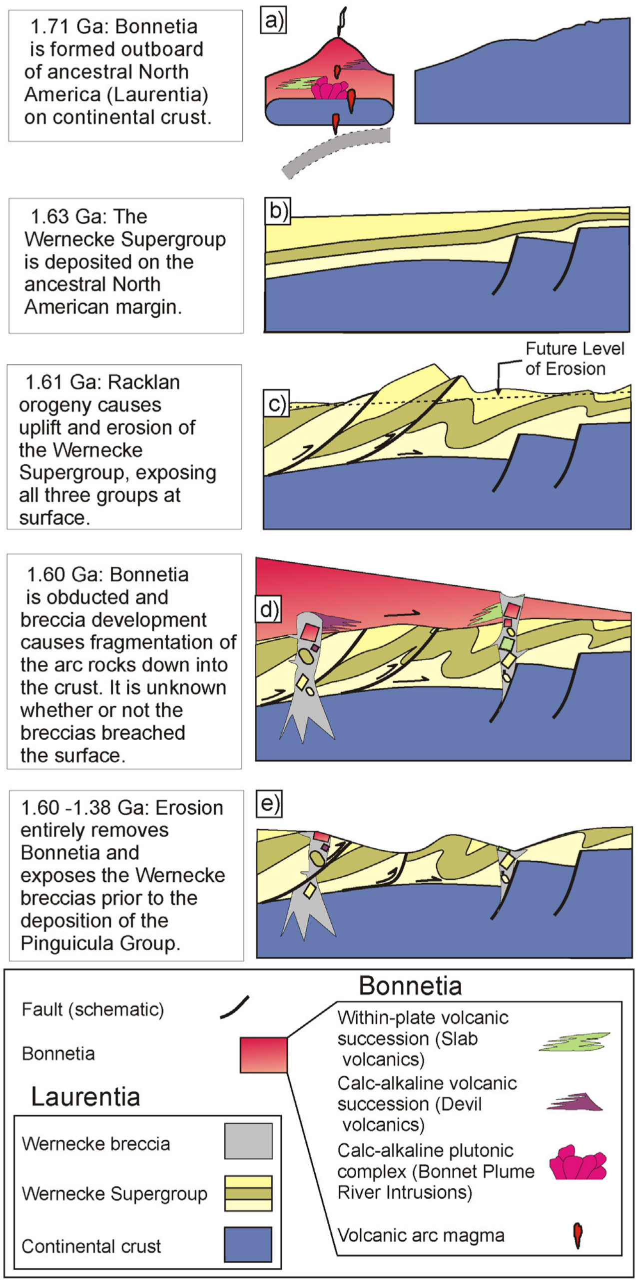

Fig. 13. Schematic history of the Wernecke igneous clasts, the obduction of Bonnetia onto Laurentia, the Wernecke Breccia, and the Wernecke Supergroup from 1.71 Ga to 1.38 Ga.

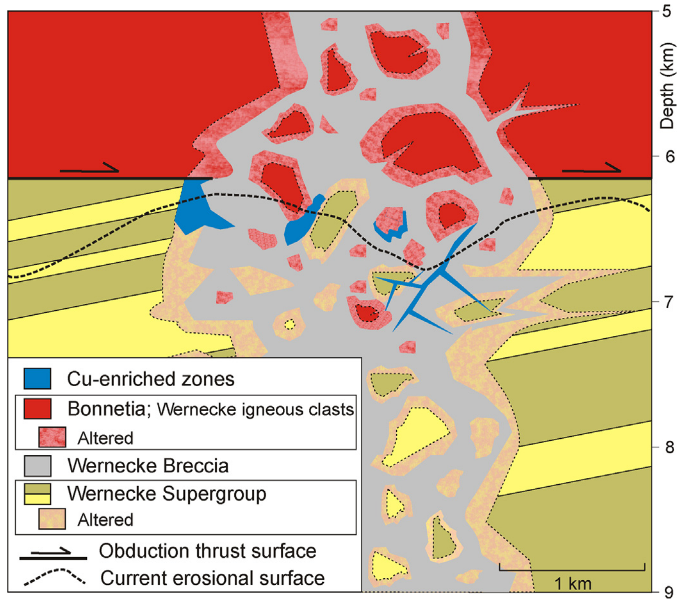

Fig. 14. Conceptual model of a Wernecke Breccia system showing the emplacement of the Wernecke igneous clasts, the Wernecke Supergroup and related clasts, the distribution of altered zones, and typical areas of copper concentration.

6.1.3. Obduction of Bonnetia, brecciation of Bonnetia and the Wernecke Supergroup

At some time between 1.64 and 1.60 Ga, part of Bonnetia collided with and obducted over the Laurentian continental margin (cf. Shervais, 2001; Whitmeyer and Karlstrom, 2007; Windley et al., 2007), covering at least the 300 km × 200 km area that contains Wernecke Breccias that sampled Wernecke igneous clasts. The absence of ultramafic clasts within Wernecke Breccia (Thorkelson, 2000) suggests that the entire 4–9 km-thick nappe that overrode the Wernecke Supergroup consisted of crustal material. The obduction was followed by voluminous surges of hydrothermal fluids and the formation of numerous zones of Wernecke Breccia.

The process of obduction may have caused the Wernecke Breccia hydrothermal episode by overpressuring relict crustal fluids (Kendrick et al., 2008; Gillen, 2010; Hunt et al., 2011) trapped within the Wernecke Supergroup (Furlanetto et al., 2013). Alternately the fluids may have derived from the release of metamorphic waters (Kendrick et al., 2008; Gillen, 2010; Hunt et al., 2011) from the Wernecke Supergroup (e.g., Walther and Orville, 1982; Connolly, 1997) as a consequence of the added thickness of the overlying terrane. Both of these scenarios, or a combination of the two, are consistent with the near-absence of evidence for a contemporaneous magmatic source for the breccia-forming fluids, as indicated by fluid inclusion, stable isotope and noble gas studies (Hunt et al., 2005, 2011; Kendrick et al., 2008; Gillen, 2010).

In the model, the brecciating fluids affected both the Wernecke Supergroup and the overthrust potions of Bonnetia, leading to metasomatism of Bonnetia and Bonnetia-derived rocks. As has been suggested by other authors, the variable leaching of copper from the Wernecke igneous clasts may have formed the concentrations of copper bearing minerals in the IOCG occurrences of the Wernecke breccia bodies (Laznicka and Edwards, 1979; Thorkelson, 2000; Thorkelson et al., 2001b; Gillen, 2010). During the process of brecciation, clasts and megaclasts of the Wernecke igneous clasts foundered and travelled downward in the breccia zones, some coming to rest at the level of the Wernecke Supergroup (Figs. 13d and 14). To allow for the foundering of large blocks in the Wernecke Breccias, these hydrothermal brecciation episodes must have opened sufficient space in the crust. The open space may have been generated by violent expansion of the hydrothermal fluids (Thorkelson et al., 2005). The breccias may have nucleated at crustal weaknesses such as fault zones as suggested by Thorkelson et al. (2001b) and Crawford et al. (2010) or in cases where there is no relationship with faults, they may have nucleated near surface and cascaded deeper into the crust in a similar manner (though on a larger scale) to the hydrothermal eruption craters described in Browne and Lawless (2001).

Hunt et al. (2011) estimated the range of depths of the presently exposed parts of the Wernecke Breccias, at the time of their formation, to be from 5.7 to 11.3 km. This depth would equal the sum of the thickness of the obducted terrane and the depth to which the Wernecke igneous clasts travelled downward beneath the decollement of the terrane and into the Wernecke Supergroup (Fig. 14). Given their size, it is likely that the clasts moved rather short distances within the crust. However, the approximately 1 km of vertical relief in some Wernecke Breccia with igneous clasts throughout suggests that some clasts moved vertically more than 1 km. Since it is unlikely that the Bonnetia-Laurentia decollement was just above the current erosional surface everywhere, we recognize that the vertical distance travelled for the lowest clasts was >1 km. However, we find it difficult to imagine that such large clasts moved downward for considerably larger distances, and suggest 2 km as a likely maximum. Accordingly, we suggest that most of the currently exposed clasts were derived from the structurally lowest parts of Bonnetia (after obduction) in order to reduce the need for even larger downward transport distances. Consequently, the thickness of the terrane could be estimated as the depth values provided by Hunt et al. (2011), minus the estimated downward transport distance (2 km), resulting in a calculated terrane thickness range of 4–9 km.

6.1.4. Complete erosion of the terrane

Following the formation of the Wernecke Breccias, erosion denuded the obducted terrane, exposing zones of Wernecke Breccia and the Wernecke igneous clasts (Fig. 13e). The interval available for erosion of the terrane and re-exhumation of Wernecke Supergroup is constrained between the formation of the Wernecke Breccia (1598.8 ± 1.0 Ma) and the deposition of the Pinguicula Group (1380–1000 Ma) (Thorkelson, 2000; Thorkelson et al., 2001b; Medig et al., 2010; Furlanetto et al., 2013). Therefore at least 219 m.y., and possibly as long as 599 m.y. were available for the complete removal of the terrane.

7. Conclusions

The Wernecke igneous clasts comprise the Bonnet Plume River plutonic clasts, the Slab volcanic clasts, and the Devil volcanic clasts. The Bonnet Plume River plutonic clasts are mainly represented by diorite and gabbro. The Slab volcanic clasts and Devil volcanic clasts are mafic to intermediate in composition.

The geochemical and isotopic signature of the Bonnet Plume River plutonic clasts and Devil volcanic clasts indicate derivation from a calc-alkaline to weakly tholeiitic volcanic arc. U–Pb zircon age determinations indicate that this arc was active at approximately 1.71 Ga and possibly at other times but no later than approximately 1.60 Ga. The geochemical signature of the Slab volcanic clasts is distinct from the other Wernecke igneous clasts and indicates the involvement of an enriched mantle source related to a mantle plume or slab window.

The Wernecke igneous clasts were derived from an inferred Paleoproterozoic terrane known as Bonnetia that was obducted onto Laurentia prior to fragmentation and clast formation. The clasts foundered into the Wernecke Breccias during massive surges of hydrothermal fluids, with many clasts travelling downward as much as 2 km and coming to rest at the level of the Wernecke Supergroup (Figs. 13d and 14).

During Wernecke Breccia formation, hydrothermal activity led to metasomatism of the Wernecke igneous clasts and the wallrocks of Laurentia and Bonnetia. The metasomatism ranged from sodic to potassic and resulted in redistribution of major and trace elements and the formation of IOCG occurrences. The alteration also affected the isotopic evolution of the Wernecke igneous clasts by modifying their Sm and Nd abundances and Nd isotope ratios at the time of brecciation.

The tectonic affinity of Bonnetia, as determined from the chemical and isotopic characteristics of the Wernecke igneous clasts, provides new constraints on the paleo-continental configuration of Columbia. The characterization of Bonnetia as a volcanic arc complex that underwent obduction requires that northwestern Laurentia was flanked by an ocean basin in the late Paleoproterozoic. The additional geochemical expression of a mantle plume or slab window in the Wernecke igneous clasts indicates that Bonnetia had a pre-obduction history that involved variations in tectonics and mantle dynamics. Whether Bonnetia was built on a continental fragment or the leading edge of another continent remains unknown. The process of obduction may have been related to collision between Laurentia and another continent, such as Australia.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.precamres.2013.09.017.

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