Mantle-Derived Peridotite Xenoliths from the Western Intermontane Belt, Whitesail Lake map area (NTS 093E), Western British Columbia

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KEYWORDS: mantle petrology, volcanology, peridotite, dike, mantle xenoliths, Whitesail Lake, Hazelton Group

INTRODUCTION

Recently the Whitesail Lake map area (NTS 093E), immediately north and east of Bella Coola, BC has been the focus of regional mapping programs, including the current Geoscience BC funded mapping program of Mahoney *et al.* (2006) and the mapping conducted in 2004 under the Rocks to Riches program (Mahoney *et al.*, 2005). The regional mapping exercise discovered a new occurrence of mantle-derived peridotitic xenoliths in the BC Cordillera (Fig. 1). Specifically, they located a mafic dike near Mt. Preston that intrudes Hazelton Group rocks. The dike appears to post-date the regional metamorphism and deformation recorded by Hazelton rocks, and is therefore inferred to be Tertiary to Neogene in age. The dike contains abundant crustal and mantle-derived peridotite xenoliths, which are very fresh and unaltered in appearance.

The peridotite xenoliths are samples of lithospheric mantle, and they represent the only available means of directly studying the underpinnings of the crust. The Mount Preston dike has several attributes that make this particular suite of mantle xenoliths especially interesting. Firstly, the relatively young age of the dike suggests sampling of 'near-present-day' mantle lithosphere underlying this portion of British Columbia. The implication is that the petrological, structural and geochemical insights gathered from these xenoliths can be related directly to large-scale geophysical datasets (*e.g.*, seismic surveys). Secondly, the Mount Preston locality has a unique position geographically and geologically because it is on the western margin of the Intermontane Belt and within 40 km of Coast Belt rocks (Fig. 2). All other occurrences of mantle xenoliths from the northern Canadian Cordillera are situated well within the Intermontane Belt (*e.g.*, Edwards and Russell, 2000). Thus, this study of these mantle xenoliths will provide evidence for the thermal and structural state of the mantle lithosphere underlying the western margin of the Intermontane Belt. Furthermore, it should provide constraints on the nature of

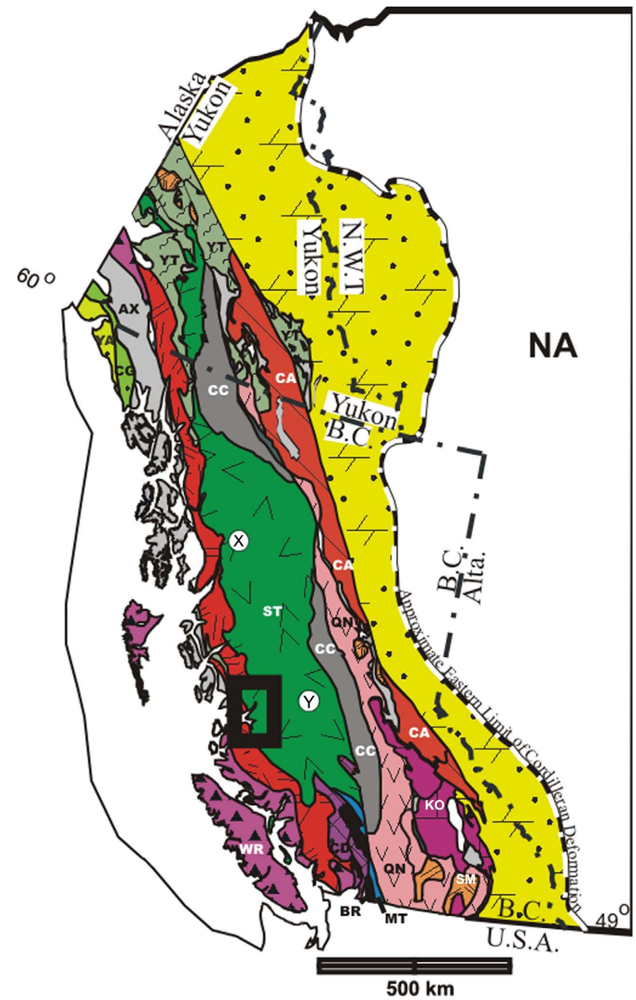

Figure 1. Location of area containing xenolith-bearing dike shown against the distribution of terranes that make up the Canadian Cordillera (modified from Wheeler and McFeely, 1991). Terranes are categorized as pericratonic (Kootenay [KO], Cassiar [CA] and Slide Mountain [SM]), Stikinia (Stikinia [ST], Quesnellia [QN], Cache Creek [CC] and Yukon-Tanana [YT]) and Insular (Alexander [AX], Wrangellia [WR], Chugach [CG] and Yukatat [YA]). Terranes that make up the southern Cordillera include the Cadwallader (CD), Bridge River (BR) and Methow (MT). Also shown are the approximate margin of ancestral North America and the eastern extent of Cordilleran deformation extending into western Canada. 'X' indicates the approximate location of Konigus Creek, the closest mantle xenolith – bearing edifice within the northern Cordilleran volcanic province (NCVP; Edwards and Russell, 2000; Evenchick and Thorkelson, 1993). 'Y' indicates the Itcha Mountains mantle xenolith locality of Nicholls *et al.* (1982). Outline indicates the area shown in Figure 2 (*i.e.*, NTS sheets 093D [Bella Coola] and 093E [Whitesail]).

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the fundamental boundary between the Coast and Intermontane belts in this region. This will complement the new BATHOLITHS geophysical project, which is designed to explore the crustal structure of the Coast Belt but will also probe the underlying mantle lithosphere (Andronicos and Ducea, 2004). The BATHOLITHS operational area will encompass the Mt. Preston site (Fig. 2).

The purpose of this paper is to,

- report on the occurrence and properties of this young volcanic dike;
- describe the nature and distribution of mantle and crustal xenoliths within the dike; and
- explore some of the implications of these observations for the transport and emplacement of this mantle-derived magma.

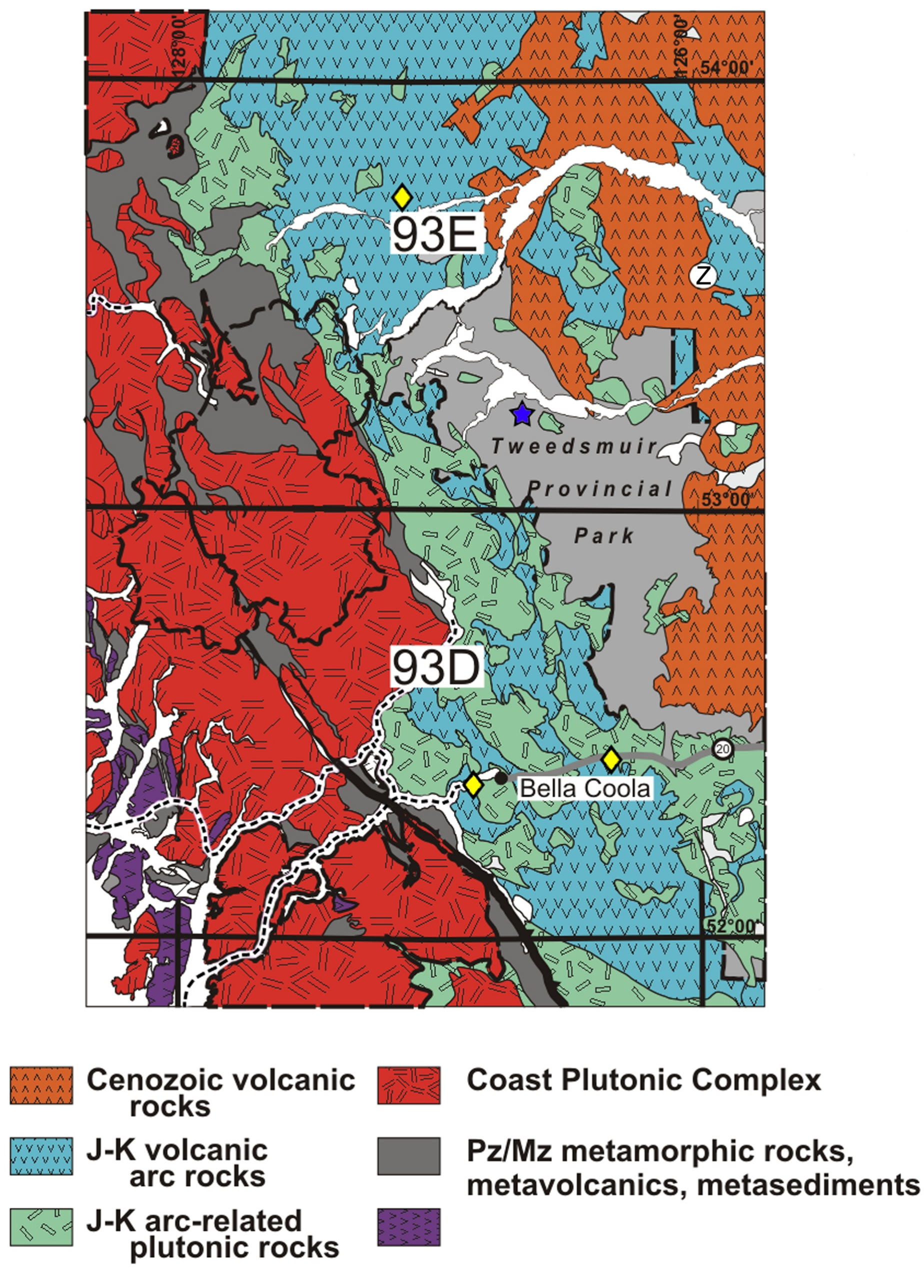


Figure 2. Schematic geology of the region surrounding Mt. Preston. The area is mainly underlain by Coast Belt plutonic rocks to the west and Jurassic (Hazelton) or Cretaceous (Monarch) volcanic and plutonic arc rocks to the north, immediate west and south. Cenozoic volcanic rocks of the Nechako Plateau outcrop in the extreme northeast. The study area (star) is situated immediately south of Eutsuk Lake, approximately 40 km east of the Coast Belt. Planned BATHOLITHS shot locations (diamonds) and marine geophysics survey tracks (dashed lines) are also shown. 'Z' indicates the nearest mantle xenolith occurrence to Mt. Preston, one of the Nechako River localities of Resnick *et al.* (1999).

STRATIGRAPHIC RELATIONSHIPS

The focus of this work is a mafic dike that strikes 145° across a saddle on a ridge 3 km southeast of the peak of Mt. Preston (Fig. 3a). The dike is exposed on the ridge crest and in the south-facing cliff that forms the east-trending ridge. The ridge crest exposes the top of the dike and is situated 2063 m above mean sea level (amsl) at Zone 9, 653722E, 5898712N (NAD 27). Exposure begins at the top of the ridge, continuing intermittently down the southern face for about 110 m (60 m vertical; Fig. 3b, c). Much of the dike is covered by talus, but the contact between dike and country rock is locally well exposed. Where exposed, the contact dips steeply (between 50 and 64°). The dike is not exposed on the north side of the ridge.

The country rock to the dike comprises intermediate to felsic, subhorizontally bedded volcaniclastic rocks of the Early to Middle Jurassic Hazelton Group (Fig. 3b, c; Gordee *et al.*, 2005; Mahoney *et al.*, 2005). The Hazelton Group rocks are intruded by several sets of mafic dikes that, based on alteration and composition, appear to be Cretaceous or older. The mantle-xenolith – bearing dike crosscuts all other stratigraphic units and has a fresh, less altered appearance. A small normal fault, striking 102°, dipping 76°S and having an offset of ~1 m, crosscuts Hazelton stratigraphy in the nearby outcrop but does not crosscut the main dike.

Edwards and Russell (2000) have summarized xenolith localities in the northern Cordilleran volcanic province (NCVP). The nearest xenolith-bearing volcanic site in the NCVP is Konigus Creek (Fig. 1; Evenchick and Thorkelson, 1993). Several other papers (Littlejohn and Greenwood, 1974; Nicholls *et al.*, 1982; Ross, 1983; Mitchell, 1987) have summarized distributions in other parts of BC. The nearest occurrences of mantle peridotitic xenoliths to this new locale are the Nechako River centres (NTS 093F; Resnick *et al.*, 1999) and the Itcha Mountains complex (NTS 093C; Nicholls *et al.*, 1982; Fig. 1, 2).

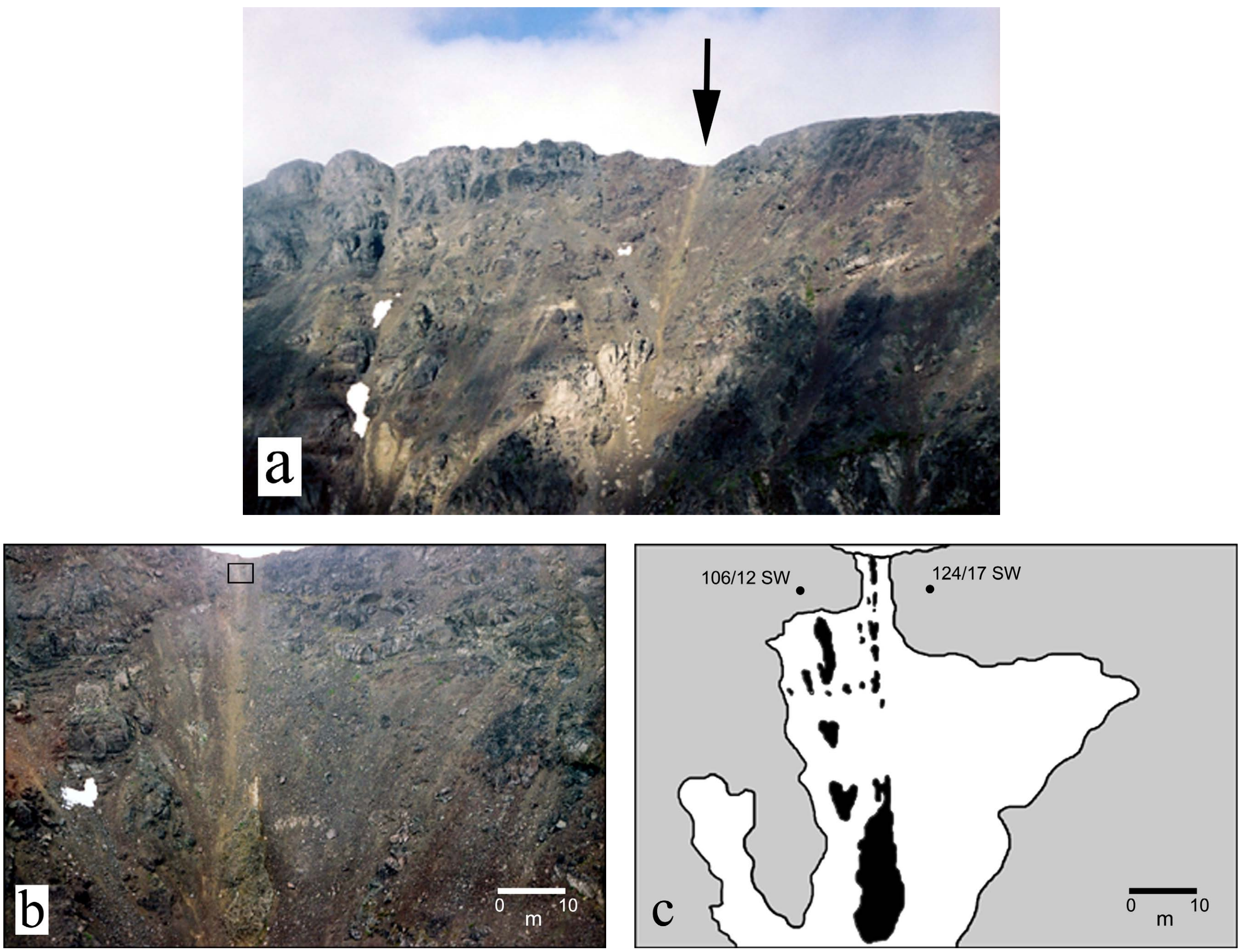


Figure 3. Field photographs showing the large-scale features of the mafic dike intruding older volcanic stratigraphic units: a) dike (arrow) exposed in a 300 m steep cliff face, its trace downslope highlighted by light green-grey talus; b) orientation of dike is approximately 145°/55°W and it intrudes Hazelton volcanic stratigraphic units that have bedding orientations of about 115°/15°S; dike is 1 m wide at the top of the cliff but widens downslope to 7 m; it appears to postdate regional metamorphism and deformation events that are recorded by the Hazelton Group rocks; solid box denotes portion of dike that is most enriched in mantle-derived xenoliths (see Fig. 6); c) geological sketch map of cliff face depicted in (b), showing distribution of dike and associated country rock outcrop (black) and layered Hazelton Group volcaniclastic rocks (grey); areas of talus are denoted by white; two approximate locations of bedding measurements on Hazelton rocks are shown.

GEOLOGY

Dike

The following observations are based on a five-day field mapping program designed to delineate the extent of the dike, its stratigraphic relationships and the physical nature of its contacts against country rocks, and to collect a comprehensive sample suite of the xenoliths of mantle lithosphere origin. The extent of the exposed dike was mapped to constrain the contacts and to understand the dike morphology (Fig. 4).

The mafic dike varies in thickness, from about 1 m where both contacts are visible to at least 7 m. At its widest point, only a single contact is exposed (Fig. 4). The outcrop is intermittent due to talus coverage, but visible outcrop extends 107 m downslope, or more than 60 vertical metres. At the lowest elevation of the exposure, the dike is defined by a large 7 m wide outcrop. At higher elevations, it bifurcates to form two lithologically identical, connected dikes separated by 2–3 m of talus. Specifically, the body splits at 2025 m elevation into a 1–4 m thick arm that strikes directly upslope (325°) to the ridge top and another wider, shorter arm that strikes 310° uphill but terminates at 2049 m absolute elevation (Fig. 3, 4).

The dike is aphanitic and grey to tan coloured on fresh surfaces. Weathered surfaces are light grey to dark brown, or sometimes oxidized to a reddish brown colour. The dike is vesicular in many places, locally up to 30% (Fig. 5a, b), with the vesicles varying from 0.5 to 10 mm in diameter. Flow banding on the scale of 5–10 cm is common, and is commonly accentuated by changes in vesicularity (Fig. 5c, d). The larger vesicles are sometimes stretched. Vesicles are frequently filled or coated; on the basis of powder x-ray diffraction, the minerals are vermiculite and calcite.

Locally, the dike has a fragmental character or appearance, with 'clasts' of melt visible within the dike. The clasts are commonly identified by changes in colour and vesicle characteristics (Fig. 5a, b). Clasts are only weakly vesicular but are surrounded by highly vesicular material. Clasts up to 10 cm in size were observed. The contact between clast and host magma is sharp and melting does not appear to have occurred. However, the clast boundaries are locally accentuated by oxidation rinds up to 1 cm in width. These melt clasts constitute <1% of the dike.

Contacts with country rock are abundant and sharply defined. The dike often displays one or more chilled margins (Fig. 5e, f). Physical properties such as xenolith content or vesicularity do not appear to change near the contact. Wherever contacts are visible, the country rock near the contact is partially melted. Melt is segregated into patches and lenses, which are sometimes vesicular. Commonly the lenses impart a foliation parallel to the contact. This contact zone varies in width from 10–30 cm.

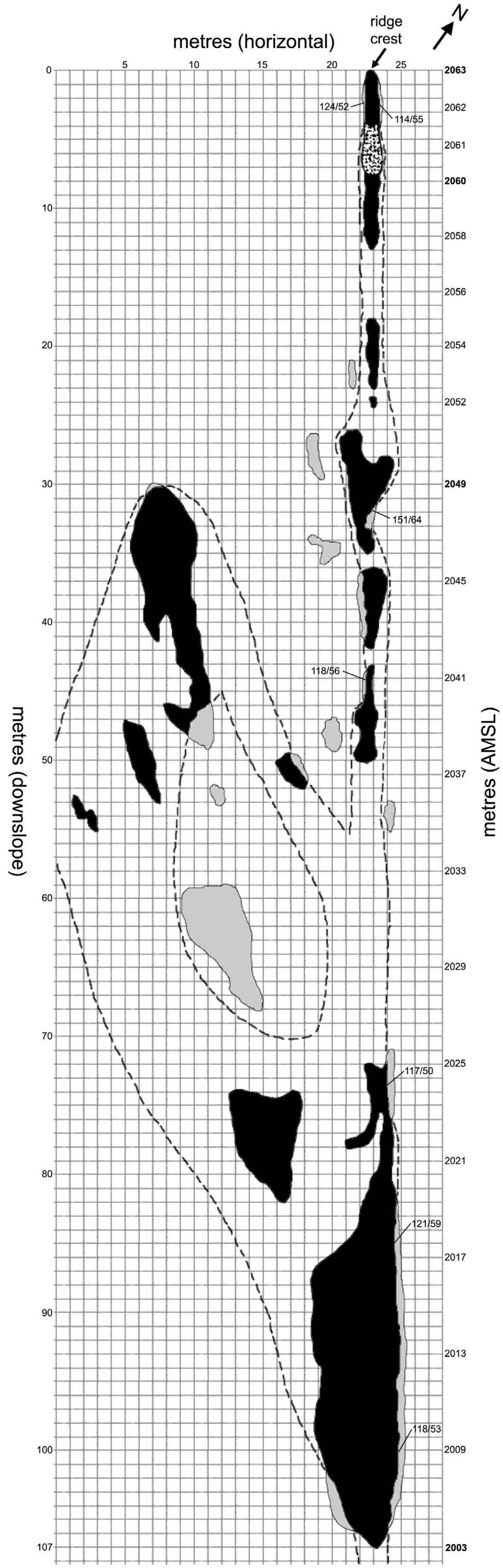


Figure 4. Geology of dike (black) and country rock (grey) outcrop, with xenolith-rich interval shown as textured. Dike exposures are limited by talus cover, but inferred contacts against Hazelton Group wallrocks are shown (dashed lines). The dike has an exposure length of 107 m and an apparent thickness ranging from 1 to >7 m. On the basis of the mapped exposure and the textural features of the dike, the body is interpreted to be a single dike below 2025 m and then to bifurcate into two main branches that terminate at 2049 m and 2063 m amsl. Absolute elevations listed in bold mark a change in slope (and thus scale of elevation markers).

Mantle Xenoliths

Peridotite xenoliths are especially abundant in the interval 4–8 m from the top of the outcrop, where the dike narrows to 1 m in width (Fig. 4, 6a, b). They constitute 50–80% of the dike over this interval and are present over the entire width of the dike (Fig. 6c, d). This concentration of xenoliths appears to often be clast supported within the dike rock. The mean diameter of xenoliths at this locality is ~15 cm; the largest peridotite was approximately 40 cm in diameter. There is no discernible sorting of the xenoliths down the dike or across it. In other areas of the dike, peridotite xenoliths constitute <1% and none are more than 5 cm in diameter. There is no gradient in xenolith concentration. The upper contact between xenolith-rich and xenolith-poor magma is horizontal, and the lower contact is unclear, though xenolith abundance drops suddenly (Fig. 6a, b). The peridotite xenoliths are very well preserved and show no signs of reacting with the host magma, although thin (1–5 mm) veins of melt are common within the peridotite blocks. Large xenoliths are rounded, but angularity increases with decreasing size. The xenoliths are dominantly lherzolite in composition, though some websterite and dunite were observed.

Individual xenoliths are equigranular, although there are substantial grain size variations (0.1–5 mm) between xenoliths. Larger grained xenoliths are more friable than fine grained ones. About a third of the xenoliths show planar fabrics at the hand-sample scale. These fabrics are most easily seen in the finer grained samples and are less apparent in coarser grained samples. Planar fabrics include mineralogical banding and mineral foliation. Banding is observed as 1–3 mm wide bands of spinel, repeating on a 1 cm scale, or 2–3 mm wide indistinct bands of clinopyroxene, repeating on an approximately 1–2 cm scale. Larger scale segregations or possibly bands of olivine and clinopyroxene (1 cm width or greater) also occur. Disaggregation of well-banded lherzolitic nodules may serve as an explanation for the small amounts of dunite and websterite that were found. Foliation tends to be strong in fine-grained samples, weakening with increasing grain size. Most commonly, the foliation is defined by flattened and elongated spinel grains, though clinopyroxene foliation was often noted in the same samples.

Xenocrysts and Crustal Xenoliths

Xenocrysts and crustal xenoliths also appear in the dike. Xenocrysts of olivine (1–2 mm), derived from the mechanical breakdown of peridotite, are ubiquitous, as are large (2–5 cm) xenocrysts of black augite (possibly from xenoliths), although both types make up <1% of the dike. Crustal xenoliths are more abundant and constitute more than 10% of the dike in some areas (Fig. 5g, h). Crustal xenoliths are generally <5 cm in diameter, although two were observed that were ~30 cm in diameter. Angularity seems inversely related to size, ranging from angular to rounded. Some crustal xenoliths resemble nearby country rock, and are not extensively altered. In contrast, others show textures indicating partial melting of the clasts and internal vesiculation, which cannot be correlated with observable wallrocks. One sample is of a 20 cm diameter granitoid xenolith; it is relatively fresh and does not resemble any observable country rock. At the upper contact of the short arm of the dike, the contact with country rock is well exposed; the country rock appears melted, and angular clasts of the same are entrained within the dike. Crustal xenoliths are more abundant in the lower, more massive parts of the dike; in the upper 25 m of outcrop, the dike is more vesicular to massive, with less crustal xenoliths. Where crustal xenoliths are most abundant, the dike surface often appears 'knobby' in texture.

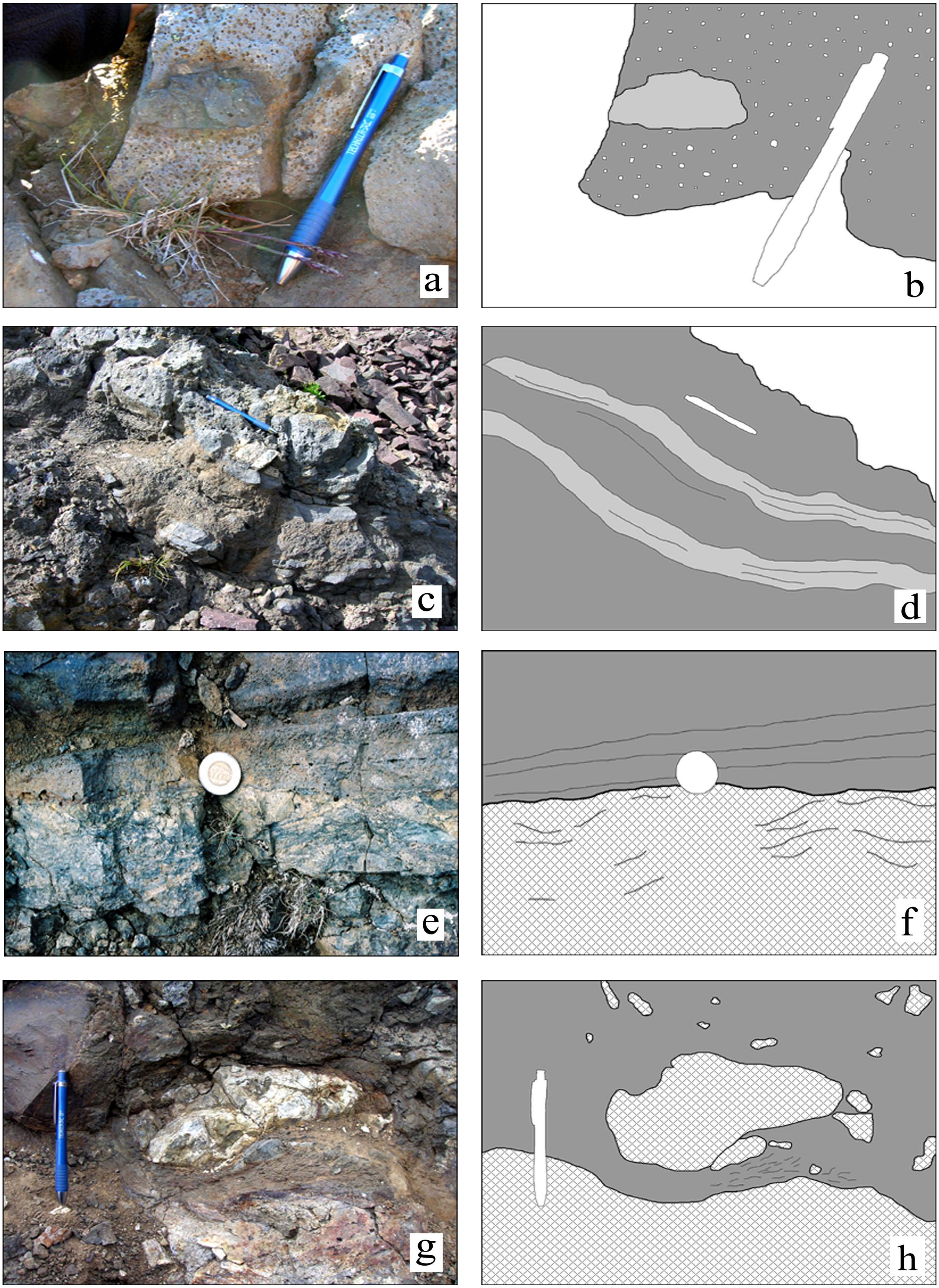
DISCUSSION

During magma transport, this dike was probably inflated to several times its current width. Melted wallrock implies sustained heat transfer from the dike, and thus sustained or possibly pulsed magma flow (Petcovic and Dufek, 2005). Discrete energetic pulses of magma within the dike may explain the abundance of crustal xenoliths and apparent autobrecciation: when flow waned and the dike relaxed, brittle failure of the wallrock margins and the chilled dike margin may have occurred. Another possibility is that there was sufficient vesiculation to promote fragmentation of the magma by primary vesiculation (Dingwell, 1996; Cashman *et al.*, 2000) or fragmentation of the wallrock and chilled margin (Tuffen *et al.*, 2003) by differential strain. The existence of flow banding indicates differential strain and possibly magma fragmentation followed by annealing. In any case, dike vesicularity indicates that the exposed portion of this dike was shallow (<1–2 km) during emplacement (Massol and Jaupart, 1999). Parrish (1983) calculated uplift in the area of approximately 1 km in the last 10 m.y., based on fission track data. The fact that the upper limit of mantle xenolith concentration is horizontal suggests that, if the high xenolith concentration was gravitationally controlled, no tectonic tilting has occurred since dike emplacement.

No young volcanic rocks have been reported in the immediate area (Mahoney *et al.*, 2005). There were also no young volcanic rocks noted in the talus on the top or north side of the ridge. As a high altitude area, this location would be subject to more intense erosion than surrounding lowlands. Any relatively fragile cinder cone would likely erode quickly, with any lava flows following. The vesicular nature of the dike, indicating shallow intrusion levels, and its significant size suggest that it would have produced surface volcanic rocks, though none are extant.

The only constraint on age of intrusion is that the dike crosscuts all Jurassic stratigraphy. However, the fresh appearance of the xenoliths and the absence of any crosscutting faults or other dikes suggest a young age, whereas the absence of a cinder cone or associated volcanic rocks, plus the large vertical exposure of the dike (indicating high erosion since intrusion) limits its youth. The tectonic regime of this part of BC has seen the production of many small volcanic centres in the last 15 m.y. (Edwards and Russell, 2000); a time of intrusion within the last 15 m.y. would be reasonable, allowing for subsequent erosion.

The concentration of peridotite xenoliths in a 4 m interval in the dike is very unusual and has not been reported previously in the Cordillera. Through this interval, the width of the dike is ~1 m. It is possible that this narrow passage resulted in a blockage of xenoliths, either as they were carried through this bottleneck or as they descended through the column of magma when flow became insufficient to buoy the rocks. Considering the grain-supported nature of the xenoliths in this interval, it may represent relaxation of the dike, trapping the xenoliths as the dike closed.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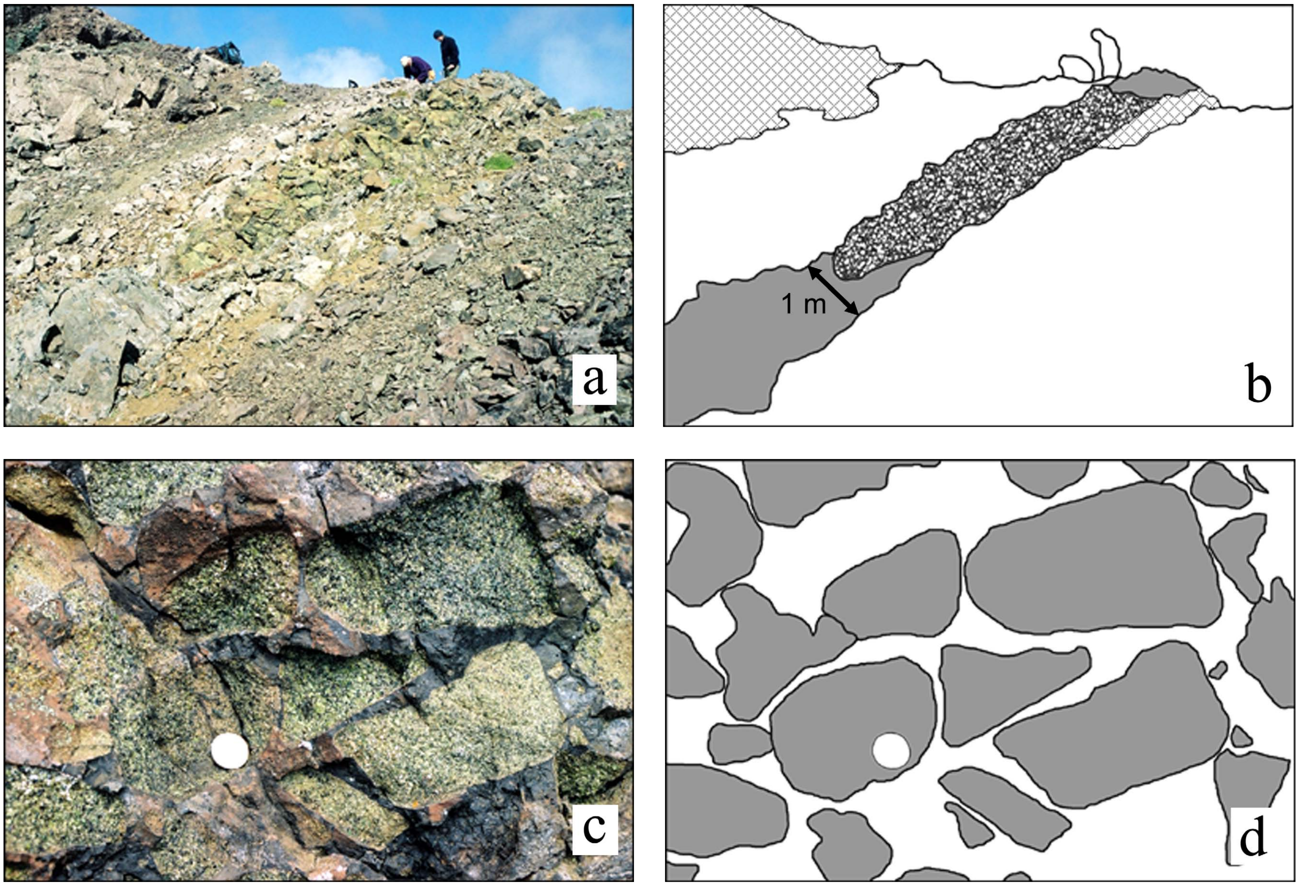

Figure 6. Field photographs and matching sketch maps showing the detailed aspects of the peridotite-bearing facies of the mafic dike: a) photo showing the width of the dike where it intersects the ridge top; the dike is very rich in xenoliths (green colour); b) sketch map of (a) showing the distributions of xenoliths (patterned) in the dike (dark grey) and in contact with Hazelton Group volcaniclastic rocks (patterned); much of the contact cannot be observed directly; locally, the exact contact relationships between the dike and country rocks can be observed (see Fig. 5e–h); c) photo showing the local relationships between the melt phase and the peridotitic mantle-derived xenoliths; xenoliths vary in diameter from 1 to 40 cm and appear to be clast supported; coin is 2.8 cm in diameter; d) sketch map of (c) showing the shapes and sizes of the xenoliths, the proportions of melt to xenolith, and the character of the peridotite clasts (see text); xenoliths make up ~60% of the view.

IMPLICATIONS

This site is well suited for mantle studies for several reasons. The largest xenolith transported to the surface is approximately 40 cm in diameter, indicating that all of the xenoliths were rapidly transported to the surface (Spera, 1984). The source for this magma is within or below the mantle lithosphere, thus providing an opportunity for this magma to sample the complete spectrum of rock types within the mantle lithosphere. North of this locale within the northern Cordilleran volcanic province (NCVP), geophysics and xenolith thermobarometry have constrained the crust-mantle boundary (CMB) to 30–40 km in depth (Welford *et al.*, 2001; Harder and Russell, 2005). Because the dike is aphyric and mafic in composition, it likely would have had a low yield strength (if any) and a high temperature during flow, and therefore low magma viscosity. This also implies rapid transport, if large, dense xenoliths are to be transported from the lithospheric mantle without settling out of suspension. Conventional ascent velocities for such magmas (Fujii and Scarfe, 1982; Spera, 1984) vary between 0.1 and 10 m/s, thus suggesting total transit times of between 1.4 hours and 5.8 days (assuming a source depth within the mantle lithosphere of 50 km). Given these estimated residence times, the xenoliths would have had limited time to react with the magma, ensuring preservation of pristine mantle mineral compositions (Edwards and Russell, 1998; Canil and Fedortchouk, 1999).

Figure 5. Field photographs and matching sketch maps showing specific volcanological aspects of the mafic dike: a), b) vesicular nature of the dike, with porosity estimated to be between 10 and 20%, rising up to 30% elsewhere in the dike; locally, the rock is amygdaloidal where vesicles are lined or infilled by vermiculite and calcite; photo also shows a subrounded clast of melt within the vesicular dike, the clast showing several amygdules and presumed to be accessory to juvenile in nature; pencil is 14 cm long; c), d) well-developed flow banding in the dike, defined by high (dark grey) versus low (light grey) vesicularity; e), f) nature of contact between the dike and the country rock, showing quenched margin(s) within dike and altered country rock; g), h) crustal xenolith derived from local country rock within the dike; contact between dike and wallrock is sharp.

The main goal of future research is to constrain mantle lithosphere properties. To that end, the 80 mantle xenoliths collected from Mt. Preston will be examined for composition, as well as equilibration T and P (using geothermobarometry). The fact that the mantle xenoliths on Mt. Preston are only weakly weathered indicates fairly recent exhumation and good potential for preservation of mantle mineral compositions. Consequently, the peridotitic samples will be ideal for geothermometric studies aimed at recovering mantle equilibration temperatures (Littlejohn and Greenwood, 1974). Although many mantle xenolith localities feature anomalously high concentrations of xenoliths, the host magmas, in all likelihood, sampled the lithospheric mantle randomly (Ross, 1983; Harder and Russell, 2005). Thus, geothermobarometry on a suite of nodules should provide a minimum temperature and pressure interval between the CMB and the asthenosphere (Ross, 1983), which constrains minimum lithospheric mantle thickness (Harder and Russell, 2005).

Variations in chemical composition (Littlejohn and Greenwood, 1974; Ross, 1983), texture and fabric (Ross, 1983) between xenolith localities (*e.g.* Edwards and Russell, 2000) allow regional mantle properties to be determined. The unique location of the Mt. Preston locality is fortuitous in this regard. A recently developed technique uses geothermobarometry along with geophysically derived heat-flow data to create an accurate geotherm and determine minimum lithospheric mantle thickness and depth (Russell and Kopylova, 1999; Russell *et al.*, 2001; Harder and Russell, 2005). When combined with heat-flow data from the BATHOLITHS seismic survey, the minimum depth and thickness of the mantle lithosphere will be obtained. Crustal xenoliths will also be examined for composition, in an attempt to correlate them with underlying stratigraphy and a possible source region for the dike magma. These results will be a powerful tool when combined with BATHOLITHS deep seismic data, which will image those interfaces.

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