Picritic Lavas and Basal Sills in the Karmutsen Flood Basalt Province, Wrangellia, Northern Vancouver Island, British Columbia

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KEYWORDS: Wrangellia, Vancouver Island, large igneous province, oceanic plateau, flood basalt, picrite

INTRODUCTION

This paper presents the first evidence of high-MgO picritic lavas, herein named the Keogh Lake picrite, within the Triassic Karmutsen flood basalt province of Wrangellia on Vancouver Island. Previously published work has revealed MgO contents up to approximately 12 wt%, compared to the high-MgO contents (13–20 wt%) for mafic pillow basalt reported here. The recognition of picritic volcanism within the Middle Triassic Karmutsen Formation on northern Vancouver Island is strong evidence that the flood basalts originated from initiation of a mantle plume. The presence of the picrite also has important implications for mineral exploration, as there may well be a higher potential for magmatic Ni-Cu-platinum-group-element (PGE) mineralization in this part of Wrangellia. Accordingly, a preliminary examination was made of part of the sediment-sill complex at the base of the Karmutsen near Schoen Lake Provincial Park. The field studies conducted in these two separate areas increase understanding of the architecture and development of a large oceanic plateau. This contribution is a review of several significant geological features of an accreted oceanic plateau based on these new data.

WRANGELLIA: AN ACCRETED OCEANIC PLATEAU

The Triassic Karmutsen Formation on Vancouver Island is an extensive flood basalt province that is perhaps the thickest accreted section of an oceanic plateau worldwide. An ongoing study involves using this accreted oceanic plateau, which forms most of the Wrangellia Terrane, to address several major questions about the phenomena of oceanic plateaus and large igneous provinces (LIPs) in general. A great deal of research over the past several decades has focused on LIPs, which are defined as large-scale, transitory emplacements of predominantly mafic extrusive and intrusive rocks (Coffin and Eldholm, 1994). Most researchers believe that these vast volcanic fields originate by decompression melting in the head of a mantle plume (Condie, 2001). If mantle plumes rise beneath the continents, they form continental flood basalts, such as the Siberian Traps or Columbia River Basalts; if they rise beneath oceanic crust, they form oceanic plateaus, such as Kerguelen, Ontong Java and the Caribbean Plateau. These enormous magmatic events occur over geologically short time spans (several million years) and likely have catastrophic effects on the climate and biosphere (Wignall, 2001).

Continental flood basalts are more extensively studied than its oceanic counterpart because it is much more easily accessible. One of the major issues when studying oceanic plateaus in the ocean basins is the difficulty of sampling their interior, since only the uppermost flood basalts can be sampled by drilling. For example, although several small sections of the Ontong Java Plateau are exposed on land in the Solomon Islands, drilling of the oceanic plateau, which is estimated to be as much as 35 km thick, has only penetrated 338 m of the uppermost flows (Fitton *et al.*, 2004). In contrast, Wrangellia presents a thickness of more than 6 km of flood basalts on Vancouver Island and upwards of 4 km in large areas of Alaska (Wrangell Mountains and Alaska Range), allowing the opportunity to sample the complete succession of erupted flood basalts.

The Wrangellia oceanic plateau formed by vast outpourings of basaltic and Mg-rich picritic magmas (documented here) that appear to have been emplaced within several million years (*ca.* 230 Ma), and eventually became accreted to the western margin of North America (Richards *et al.*, 1991; Lassiter *et al.*, 1995). Currently, there is a lack of detailed information about the volcanic stratigraphy of oceanic plateaus. The Karmutsen offers an invaluable opportunity to explore the remnants of an oceanic plateau and thus gain an understanding of the internal volcanic stratigraphy. A better understanding of oceanic plateaus will provide insights into several important processes, including the generation of magmas in mantle plumes (White and McKenzie, 1995), the role of accretion of oceanic plateaus for the growth of continental crust (Albarède, 1998) and the climatic effects of such large-scale eruptions (Wignall, 2001).

This contribution is an initial step toward addressing three important aspects of flood basalt volcanism in oceanic settings: 1) the architecture of oceanic plateaus, 2) the source of basaltic magmas, and 3) the potential for magmatic Ni-Cu-PGE mineralization.

GEOLOGICAL HISTORY OF THE WRANGELLIA TERRANE

The Wrangellia Terrane consists of several distinct allochthonous blocks, extending from Vancouver Island to

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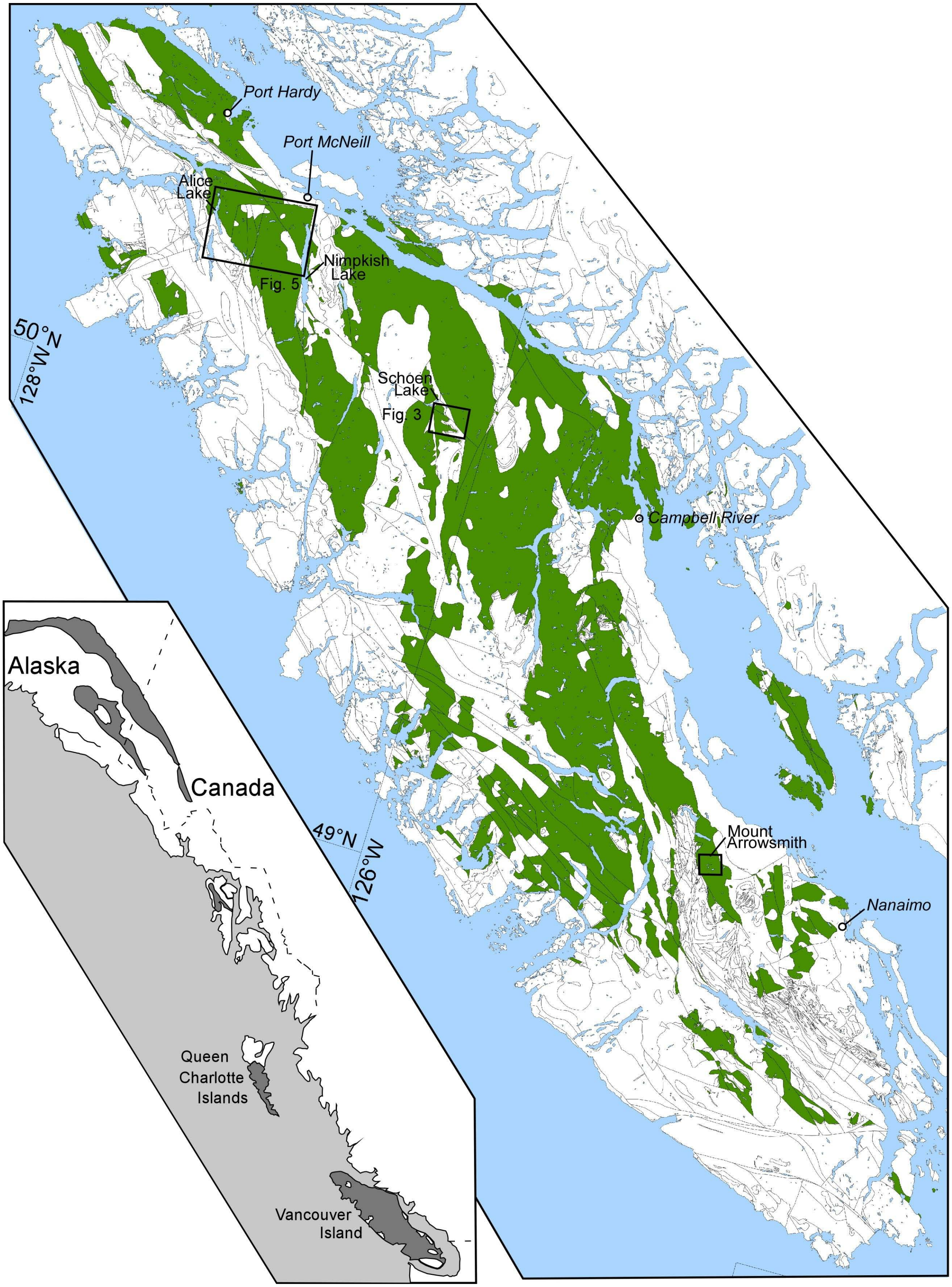

Figure 1. Simplified map of Vancouver Island showing exposures of flood basalts (green) of the Karmutsen Formation (after Massey *et al.*, 2003a, b). Areas of field study are outlined with solid boxes. Inset shows the extent of the Wrangellia Terrane (dark grey) in western Canada and Alaska (modified after Jones *et al.*, 1977).

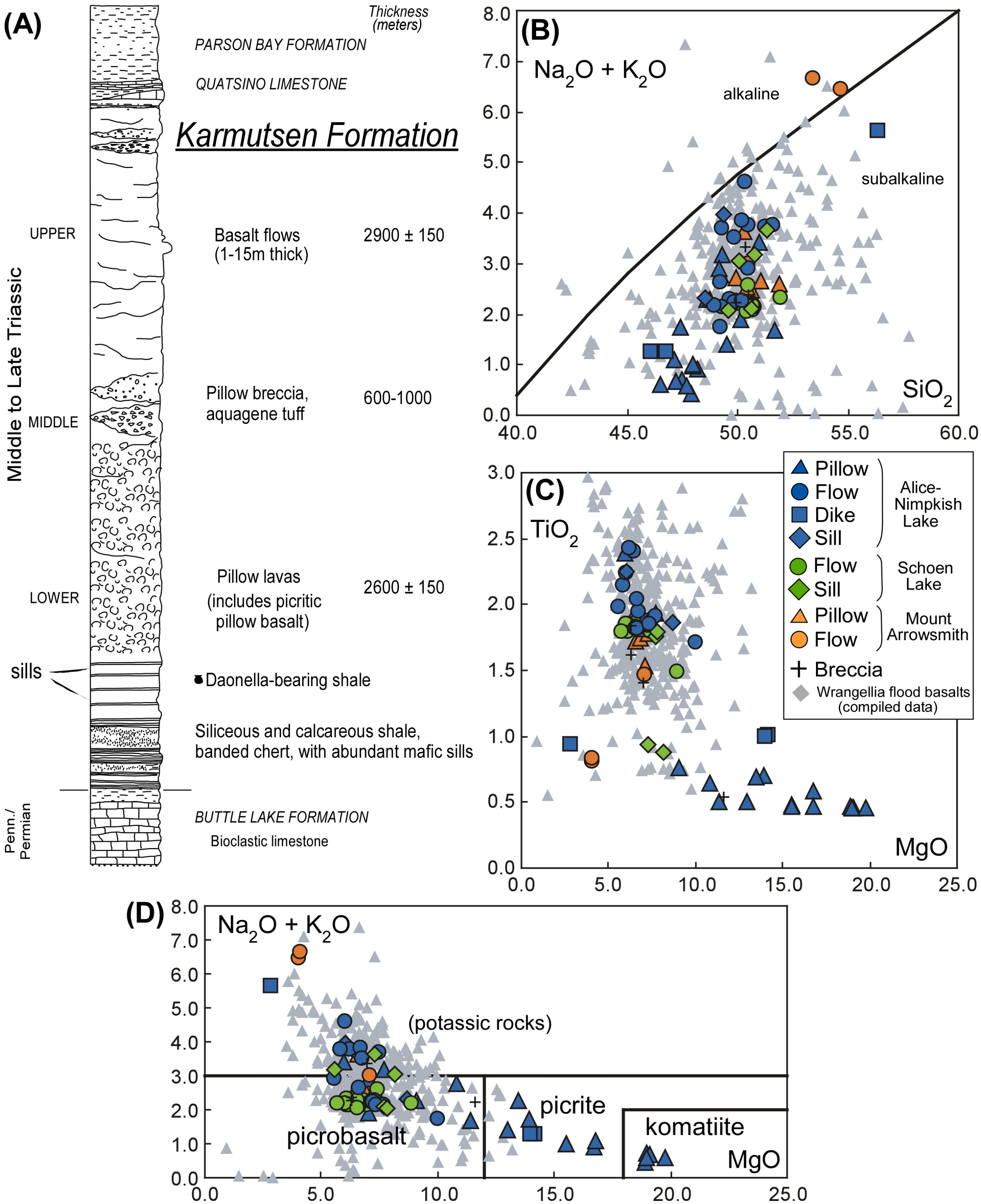

Figure 2. A) Composite stratigraphic column depicting flood basalt sequences of the Karmutsen Formation and major underlying and overlying sedimentary sequences on northern Vancouver Island (modified after Carlisle and Susuki, 1974). B) Total alkalis vs. silica diagram (wt%) for Keogh Lake picrite and other samples collected in 2004 and 2005, along with compiled data from published literature for the Karmutsen Formation and correlative Nikolai Formation. The vast majority of volcanic rocks is subalkaline basalt. Note that the Mount Arrowsmith flows are mildly alkalic. The boundary of the alkaline and subalkaline fields is that of Irvine and Baragar (1971). C) TiO_2 vs. MgO plot (wt%) for the samples shown in B. D) Plot of total alkalis vs. MgO (wt%), showing the IUGS classification fields (Le Bas, 2000). Note the Mg-rich nature of the Keogh Lake picrite. Oxides are plotted on an anhydrous, normalized basis in all diagrams.

central Alaska, that are related by widespread exposures of Triassic flood basalts and rarely their plutonic complements (Fig. 1; Jones *et al.*, 1977). Impressive successions of Middle Triassic flood basalts extend in a discontinuous belt from Vancouver Island and the Queen Charlotte Islands (Karmutsen Formation), through southeastern Alaska and the Kluane Ranges in southwest Yukon, and into the Wrangell Mountains and Alaska Range in eastern and central Alaska (Nikolai Formation). This belt of flood basalt sequences has distinct similarities and, as first suggested by Jones and et al. (1977), represents a once-contiguous terrane that probably formed within 15° of the paleoequator (Hillhouse, 1977).

Wrangellia developed as an extensive oceanic terrane with a geological history that extends from the middle Paleozoic through the Mesozoic (Richards *et al.*, 1991). The

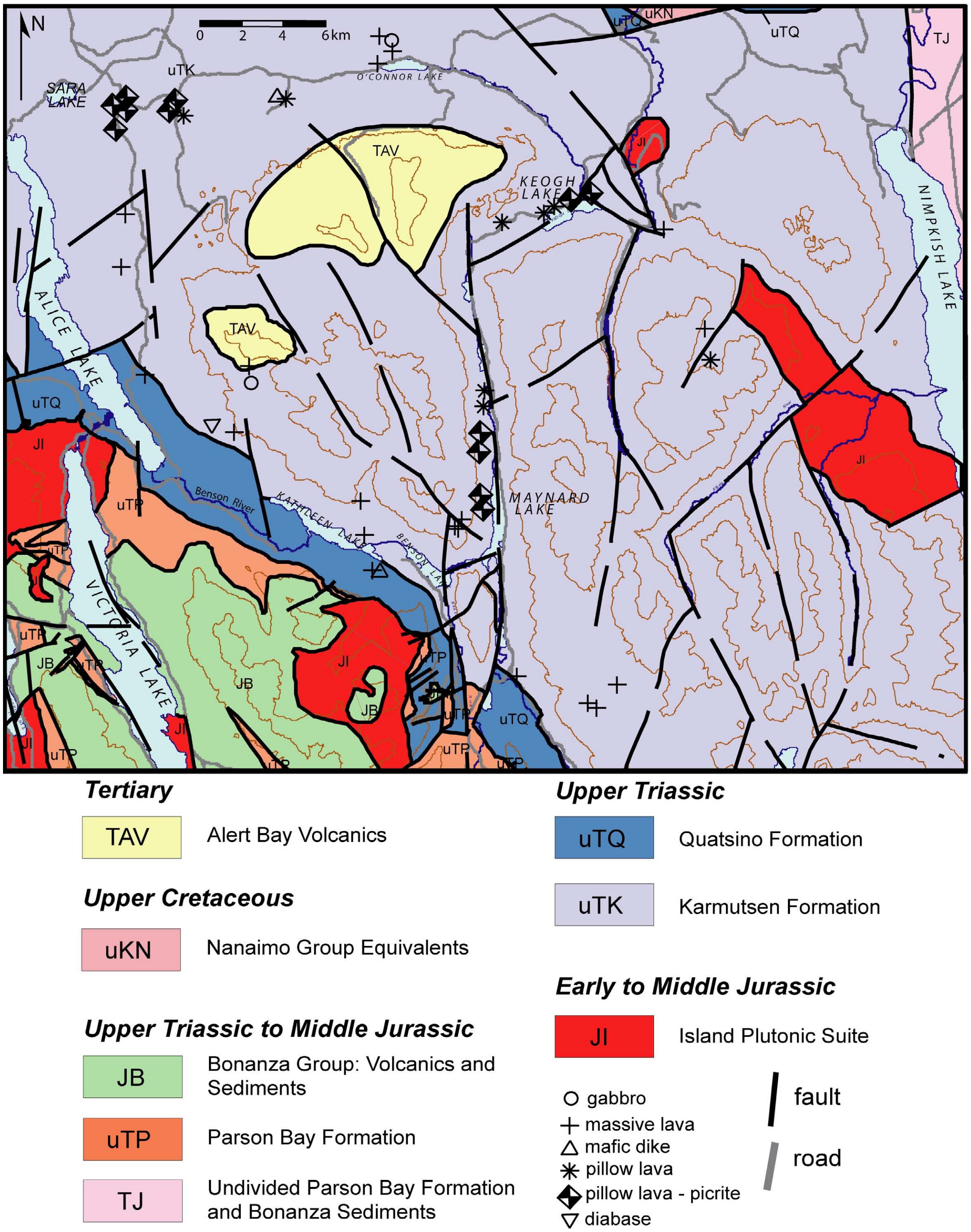

Figure 3. Generalized geology of the region between Alice and Nimpkish Lakes, northern Vancouver Island (location shown in Fig. 1). Sample sites and rock types are denoted in the legend. Contour lines are at 500 m intervals.

flood basalts form the core of the terrane and is bounded above and below by marine sedimentary sequences. Continentally derived sedimentary rocks are almost entirely absent, with the exception of a kilometre-thick continental-margin sedimentary sequence at the base of flood basalts in the Talkeetna Mountains of Alaska (Schmidt *et al.*, 2003). The Wrangellia Terrane preserves two broad cycles of uplift and subsidence, beginning with a Paleozoic volcanic arc and succeeded by Middle Triassic volcanism (Ben-Avraham *et al.*, 1981). Triassic uplift and subsidence are recorded by chert, minor limestone and *Daonella*-bearing shale at the base of the flood basalts, and a limestone sequence above the flood basalts. These events are consistent with the rise and cessation of a mantle plume beneath the lithosphere (Richards *et al.*, 1991). Sedimentation and volcanism in the Wrangellia Terrane continued through the Early and Middle Jurassic with the resurgence of arc volcanism in the form of the Bonanza arc (Jeletzky, 1970; Northcote and Muller, 1972; DeBari *et al.*, 1999)

The Karmutsen Formation appears to represent a single flood basalt event (Richards *et al.*, 1989). A mantle plume initiation model has been proposed for the Wrangellia flood basalts based on 1) the nature of the underlying and overlying sedimentary rocks, 2) rapid uplift prior to volcanism, 3) the lack of evidence of rifting associated with volcanism (few dikes and abundant sills), 4) the short duration and high eruption rate of volcanism, and 5) relatively limited geochemical data (Richards *et al.*, 1991). The basalt flows are estimated to constitute a minimum volume of 1 x 10^6 km^3 (Panuska, 1990) and were originally interpreted to have erupted within 5 m.y. (Carlisle and Suzuki, 1974).

The timing and location of the accretion of Wrangellia to western North American and postaccretionary translation are highly debated (Trop *et al.*, 2002). Estimates of the timing of initial collision range from the Middle Jurassic to Late Cretaceous (*e.g.*, Tipper, 1984; Plafker *et al.*, 1989; Gehrels and Greig, 1991; McClelland *et al.*, 1992; van der Heyden, 1992; Monger *et al.*, 1982; Nokleberg *et al.*, 1994, 2000; Trop *et al.*, 2002). Paleomagnetic and faunal evidence indicate that the Wrangellia Terrane originated at low latitude, far to the south of its present position (Hillhouse,

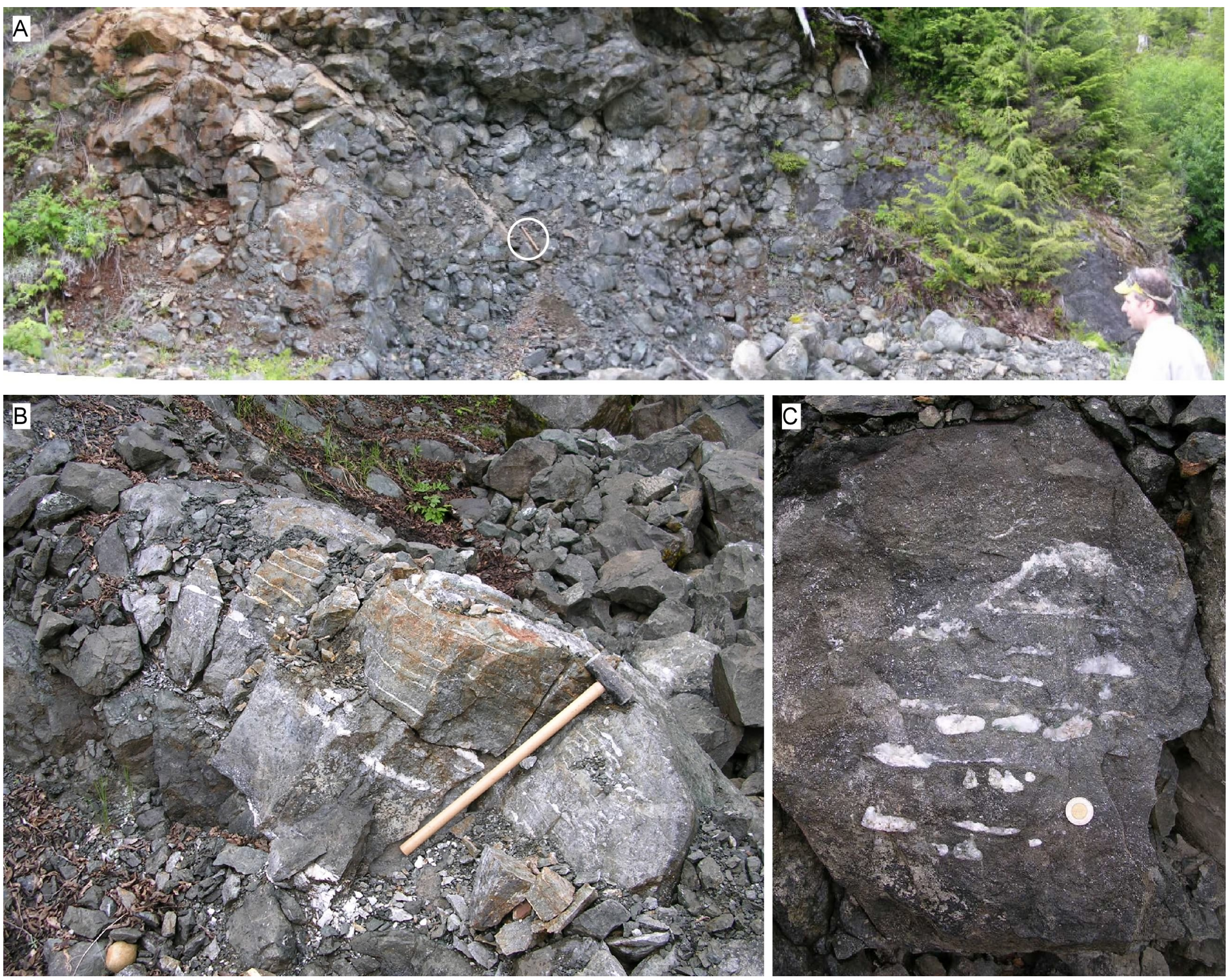

Figure 4. Photographs of picritic pillow basalt from the Alice-Nimpkish lakes area: A) stack of dense, closely packed, asymmetric picritic pillows with radial vesicle infillings (sledgehammer for scale [circled] ~80 cm long; UTM Zone 11, 626824E, 5586126N); B) cross-section of a large pillow lobe with infilling of quartz in tension cracks (sledgehammer for scale; UTM Zone 11, 616507E, 5598448N). C) drain-back ledges formed in a picritic pillow tube formed after lava drained from the pillow (shown by quartz infilling; coin for scale ~2.7 cm diameter; same location as B).

1977; Yole and Irving, 1980; Hillhouse *et al.*, 1982; Hillhouse and Gromme, 1984). Wrangellia may have joined or been in close proximity (stratigraphic continuity) with the Alexander Terrane by the Middle Pennsylvanian (Yorath *et al.*, 1985; Gardner *et al.*, 1988). As early as the Late Triassic, the oceanic Wrangellia Terrane amalgamated with the Taku Terrane of southeastern Alaska and the Peninsular Terrane of southern Alaska (Plafker *et al.*, 1989).

GEOLOGICAL SETTING OF THE KARMUTSEN VOLCANIC ROCKS

Approximately 35% of the area of northern and central Vancouver Island is directly underlain by the distinctive flood basalt sequences of the Karmutsen Formation (Fig. 1; Barker *et al.*, 1989). On Vancouver Island, the oldest rocks of Wrangellia are the Devonian arc sequences of the Sicker Group and Mississippian to Early Permian siliciclastic and carbonate rocks of the Buttle Lake Group (Muller, 1980; Brandon *et al.*, 1986; Sutherland Brown *et al.*, 1986). The Sicker and Buttle Lake groups and the Karmutsen Formation are intruded by gabbro and basaltic sills that are most likely related to Karmutsen flood basalts (Carlisle and Suzuki, 1974; Barker *et al.*, 1989). The uppermost part of the Karmutsen Formation is locally intercalated with small lenses of marine sedimentary rocks and overlain by the shallow-water Quatsino Limestone (Carlisle and Suzuki, 1974).

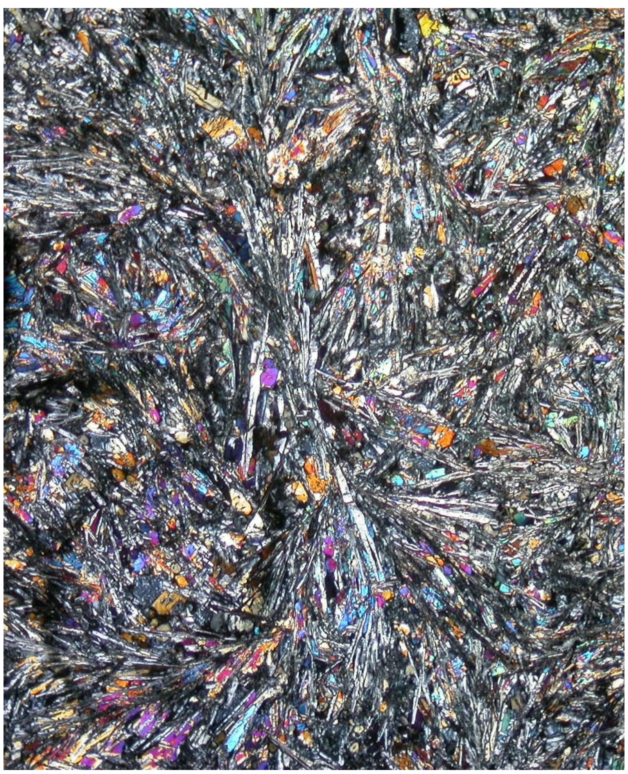

Figure 5. Photomicrograph under cross-polarized light (~10 mm high) of picrobasalt from just west of Maynard Lake (UTM Zone 11, 626698E, 5588266N). This sample shows the striking variolitic texture with wavy, branching sheaves of intergrown plagioclase and clinopyroxene that is typical of the picritic pillows (sample 4723A2; 10.8 wt% $MgO_{anhydrous}$).

The earliest in-depth studies of the Karmutsen Formation on Vancouver Island were made by H.C. Gunning (Gunning, 1930, 1932), J.A. Jeletzky (*e.g.*, Jeletzky, 1950, 1970), J.E. Muller and coworkers (Muller, 1967, 1977, 1981; Muller and Carson, 1969; Muller *et al.*, 1974, 1981) and D. Carlisle and students (Carlisle, 1963, 1972; Surdam, 1968; Kuniyoshi, 1972; Carlisle and Suzuki, 1974). This extensive work established the location, characteristics and depositional history of the Wrangellia Terrane on Vancouver Island. More recent descriptions of Karmutsen basalts were incorporated during regional mapping studies (1:50 000 scale) conducted by G.T. Nixon and coworkers (Nixon *et al.*, 1993, 1994a, b) on northern Vancouver Island and N.W.D. Massey and coworkers (Massey and Friday, 1988, 1989; Massey, 1995a, b, c) on central Vancouver Island.

The Karmutsen volcanic rocks represent perhaps the thickest accreted section of an oceanic plateau worldwide, along with the 3–4 km thick section of Ontong Java exposed in the Solomon Islands (Petterson *et al.*, 1997) and a 5 km thick section of the Caribbean Plateau on the island of Curacao, north of Venezuela (Klaver, 1987).

Within the densely forested regions of northern and central Vancouver Island, the volcanic stratigraphy of the Karmutsen Formation is estimated to exceed 6 km in thickness (Carlisle and Suzuki, 1974). Extensive faulting throughout this region makes reconstruction of the true stratigraphic thickness challenging. Nevertheless, the diagnostic units of the Karmutsen have been divided by Carlisle and Suzuki (1974) into 1) a lower member of exclusively pillow lava (2900 ±150 m), 2) a middle member of pillow breccia and aquagene tuff (600–1100 m), and 3) an upper member of massive basalt flows (2600 ±150 m; Fig. 2).

The Karmutsen volcanic rocks were emplaced in a predominantly submarine environment. Impressive successions of submarine pillow basalt at the base of the Karmutsen Formation overlie a thick sediment-sill unit comprising mafic sills intruding black shale of the Middle Triassic '*Daonella* beds'. Dense, picritic pillow lavas (described below) have been identified within the succession

Figure 6. Photomicrograph under cross-polarized light (~10 mm across) of a picrite pillow from the roadcut along the north side of Keogh Lake (UTM Zone 11, 629490E, 5595528N). This sample has abundant altered euhedral olivine phenocrysts up to several millimetres long (sample 4722A4; 19.0–19.8 wt% $MgO_{anhydrous}$, 4 analyses).

of pillow basalt. Massive amygdaloidal flows form most of the middle and upper crust of the Wrangellia plateau, interspersed with minor pillow-breccia units. Intravolcanic sedimentary rocks within the volcanic rocks of the uppermost Karmutsen are well-documented by Carlisle and Suzuki (1974).

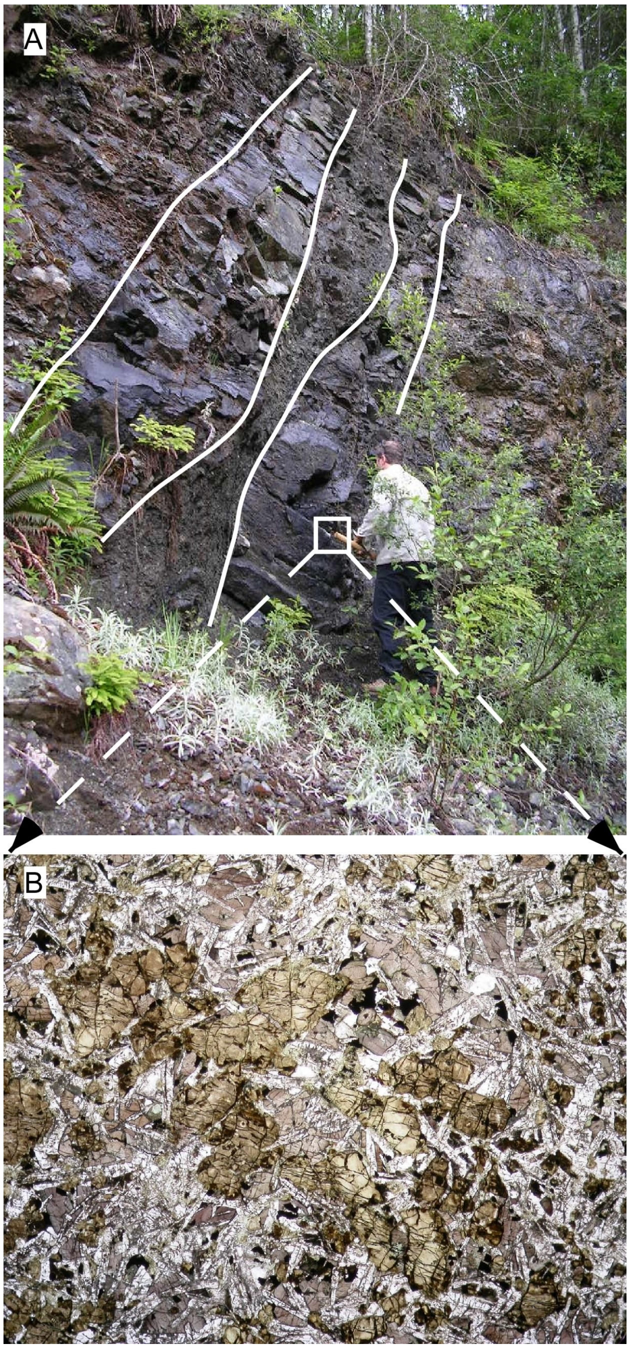

Figure 7. Olivine-rich dike cutting tholeiitic pillow basalt (UTM Zone 11, 620187E, 5599424N): A) photograph of subvertical mafic dikes approximately 1 m wide; B) photomicrograph under plane-polarized light (~10 mm across) of subophitic mafic dike from A with abundant, large, altered olivine crystals and altered plagioclase surrounded by clinopyroxene (sample 5615A2; 14.0–14.2 wt% $MgO_{anhydrous}$, 2 analyses).

AGE OF THE KARMUTSEN FORMATION AND CORRELATIVE FLOOD BASALTS

Despite its enormous size, there are relatively few precise geochronological constraints on the age and duration of Wrangellia flood basalt volcanism. Constraints on the age and duration of Karmutsen volcanism include fossils in the underlying and overlying sedimentary units and several isotopic age determinations. *Daonella*-bearing shale, 100–200 m below the base of the pillow basalt on Schoen Mountain, and *Halobia*-rich shale, interlayered with flows in the upper part of the Karmutsen, indicate that eruption of the flood basalts possibly occurred entirely within the early Upper Ladinian (Middle Triassic) to early Upper Carnian (Late Triassic; Carlisle and Suzuki, 1974). Uranium-lead zircon geochronology of several sills and dikes potentially related to the Karmutsen yields ages of 217–222 Ma (Isachsen *et al.*, 1985), 227 ±3 Ma (Parrish and McNicoll, 1992) and 228 ±2.5 Ma (Sluggett, 2003). Plutonic rocks related to the correlative Nikolai Formation in Yukon yielded K-Ar ages of 224 ±16 and 225 ±14 Ma (Campbell, 1981). A U-Pb zircon age from a gabbro sill considered to be con-

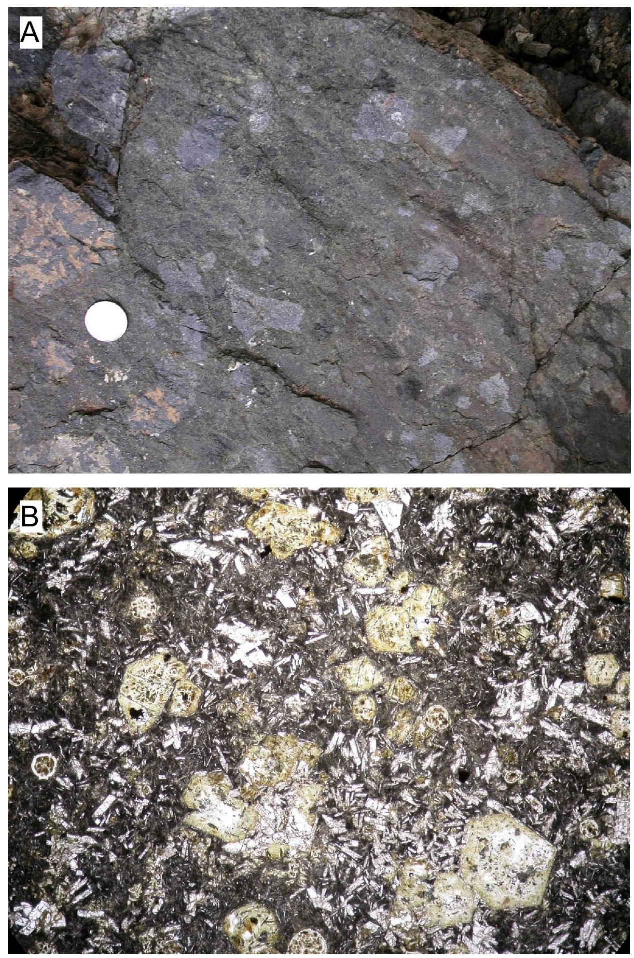

Figure 8. A) Photograph of pillow breccia with angular, blocky clasts in a fine-grained tuffaceous matrix east of Alice Lake (UTM Zone 11, 614756E, 5599192N; coin for scale ~2.7 cm in diameter). B) Photomicrograph under plane-polarized light (~10 mm across) showing altered euhedral olivine in seriate-textured basalt clasts within the pillow breccia from A (sample 5614A5; 11.6 wt% $MgO_{anhydrous}$).

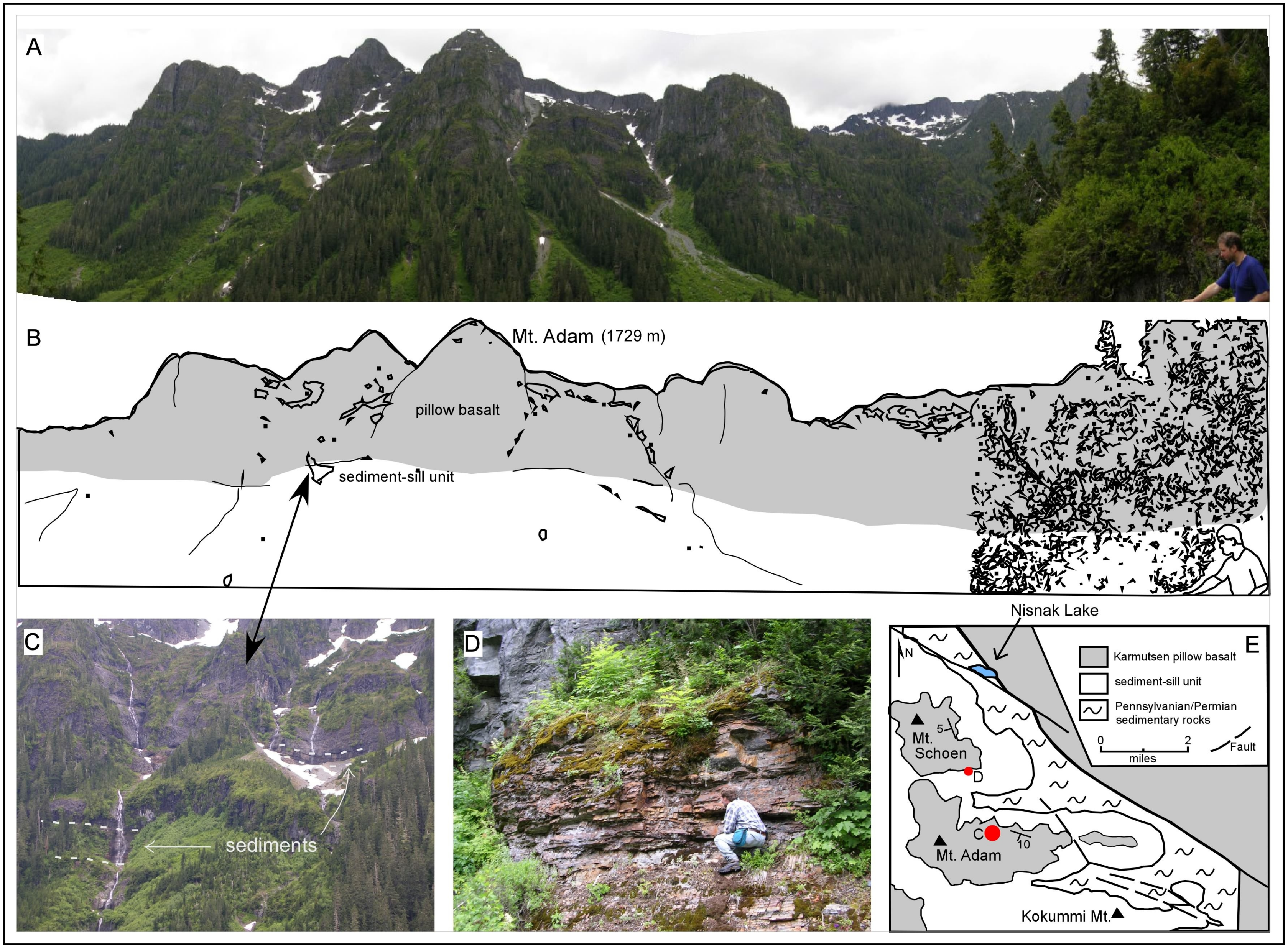

Figure 9. Sediment-sill unit around Schoen Lake Provincial Park (location shown on Fig. 1): A) Panorama of the north flank of Mount Adam. B) Interpretive sketch of A. C) Close-up view of sediment-sill unit. D) Laminated siliceous shale from sediment-sill unit on Mount Schoen. E) Simplified geological map of the area (modified from Carlisle, 1972, showing locations of photos in the figure.

Figure 10. Photograph of sediment-sill unit on Mount Schoen, location D on Figure 9D (UTM Zone 11, 700905E, 5557712N). Several mafic sills are interlayered with deformed, finely banded chert and shale.

temporaneous with eruption of the Nikolai volcanic rocks in the Yukon yielded an age of 232.2 ±1.0 Ma (Mortensen and Hulbert, 1991). Most recently, Bittenbender et al. (2002) published two Ar/Ar ages of 228.3 ±1.1 and 230.4 ±1.3 Ma from phlogopite in gabbro likely related to Wrangellia flood basalts in the Alaska Range. An additional Ar/Ar age from the Alaska Range of 231.1 Ma by J. Schmidt (pers. Comm., 2005) corroborates these ages. According to previously published geochronological results, the timing of emplacement of the plateau may have been between 233 and 217 Ma. This is based on very sparse data, however, and there are presently no ages for the entire succession of flood basalts from Vancouver Island to Alaska.

KEOGH LAKE PICRITE

During fieldwork in the summer of 2004, a succession of high-MgO picritic pillow lavas was discovered within the Karmutsen Formation on northern Vancouver Island. Fieldwork in 2005 was focused in the area where the picrite was found, west of the Karmutsen Range between Alice and Nimpkish Lakes (Fig. 3). The outcrops lie in a roughly triangular area (~28 km across) bounded by Keogh, Maynard and Sara lakes. An extensive network of logging roads provides good exposures in roadcuts and quarries adjacent to the roads. Excellent exposures of picritic pillow lavas occur in roadcuts along the north shore of Keogh Lake, the type locality. The picrite forms stacks of pillows (typically <1 m in diameter) close to tholeiitic pillows, massive flows, pillow breccia units and mafic dikes (Fig. 4).

The Keogh Lake picrite is geochemically distinguished from normal Karmutsen tholeiitic basalt pillows and flows by its elevated MgO contents (13–20 wt% MgO, on an anhydrous, normalized basis) and incompatible-element depletion (Fig. 2). In the IUGS classification scheme, the picrite has >12 wt% MgO, <3 wt% (K_2O+Na_2O), and <52 wt% SiO_2 (Le Bas, 2000). Picrite is a petrologically significant composition because it is the best candidate for least-modified partial melt of its mantle source region.

The picritic pillow basalt is distinguishable in the field by its density and nonmagnetic character. It appears to have a lower proportion of interpillow space than the more tholeiitic basalt pillows, perhaps resulting from the lower viscosity of the Mg-rich lava. The pillow lavas preserve numerous features from subaqueous eruption, such as spalled rims and drain-back ledges (Fig. 4). The picritic pillow lavas have striking features in thin section. The dense, closely packed pillows exhibit sheaf-like variolitic textures comprising numerous fans (or cone-shaped bundles) of diverging acicular plagioclase intergrown with clinopyroxene (Fig. 5). Many samples contain clusters of altered olivine (<2 mm in length) set in a matrix of curved and branching sheaves of plagioclase needles, commonly exhibiting swallow-tailed terminations. All the olivine has been replaced by serpentine (±talc), although plagioclase and clinopyroxene are mostly unaltered. Abundant pseudomorphs of euhedral olivine phenocrysts up to several millimetres long occupy 30–40 vol% of some picritic pillows (Fig. 6).

Mafic dikes in the Alice-Nimpkish lakes area may represent feeders to the Karmutsen flood basalts. Several of these dikes evidently fed the picritic lavas and comprise dense, fine-grained rocks containing up to 40 vol% coarse-grained olivine (Fig. 7). A volumetrically small proportion

Figure 11. Photograph of the base of the upper mafic sill in Figure 10. Note the presence of a prominent 25 cm thick sulphide-stained zone along the lower contact with the underlying shale.

of the rocks in this area is pillow breccia that incorporates broken pillow fragments containing abundant altered olivine phenocrysts (Fig. 8).

SIGNIFICANCE OF PICRITIC VOLCANISM IN THE WRANGELLIA OCEANIC PLATEAU

The Keogh Lake picrite of northern Vancouver Island may provide insight into the source of basaltic magmas and the potential for Ni-Cu-PGE mineralization in this part of Wrangellia. Picrite is usually linked to large igneous provinces (LIPs) and the initiation of mantle plumes, where mantle temperatures 200–300°C higher than ambient mantle result in higher degrees of partial melting (Herzberg and O'Hara, 1998). Picrite is much more common in Archean greenstone belts than in Phanerozoic LIPs because Archean mantle plumes were evidently hotter than Phanerozoic plumes (Nisbet *et al.*, 1993). Among Phanerozoic LIPs, picrite is commonly found in continental environments (*e.g.*, Deccan, Karoo, Paraná-Etendeka) and has only rarely been recognized in oceanic plateaus (*e.g.*, Caribbean plateau; Gibson, 2002).

Picrite is significant because it potentially originates near the axis of the plume where the temperature is highest (Campbell *et al.*, 1989) and, because it may result from high-temperature melting, it may preserve incompatible trace-element ratios of the mantle source (Campbell, 2002). The recognition of picritic volcanism within the Karmutsen Formation on northern Vancouver Island is strong evidence that the flood basalts originated from initiation of a mantle plume. The Keogh Lake picrite may represent the least differentiated rocks in Wrangellia.

BASAL SEDIMENT-SILL COMPLEX

During fieldwork in 2005, an exceptional sediment-sill complex was examined at the base of the Karmutsen Formation in the vicinity of Schoen Lake Provincial Park (Fig. 1, 9). Here, Middle Triassic marine sedimentary rocks overlie Pennsylvanian to Permian limestone and siliceous sedimentary rocks (Sicker Group), and both successions are intruded by thick mafic sills related to the overlying flood basalts (Carlisle, 1972). This sedimentary package represents the ocean floor at the initiation of Karmutsen volcanism and, indeed, presents a rare opportunity to examine the base of an oceanic flood basalt province.

Carlisle (1972) estimated the sediment-sill unit to be approximately 600–900 m thick, with a total thickness of roughly 150–200 m of pre-intrusive sedimentary rocks. The Triassic sedimentary rocks range from thinly bedded siliceous and calcareous shale to banded chert and finely laminated, *Daonella*-bearing shale (Fig. 9, 10; Carlisle, 1972). The younger, fissile Triassic units were more vulnerable to sill intrusion than the older, more massive underlying Paleozoic limestone (Carlisle, 1972). In some areas, the sills preserve evidence of intrusion into unlithified, wet sediments. The mafic sills (1–15 m thick) are fairly dense, coarse-grained intrusions, locally with columnar jointing. On Mount Schoen, a single sill is characterized by a prominent 25 cm thick sulphide-stained zone along the lower contact with the underlying shale (Fig. 11). A sample from this zone contains 1–2% blebby and interstitial sulphide composed of >95 vol% pyrrhotite with minor amounts of chalcopyrite. The restriction of pyrrhotite to the basal contact zone of the sill, combined with the petrographic observation that some of the sulphide blebs are cored by quartz within this 25 cm wide zone, suggests that local sulphide segregation occurred in the mafic magma in response to assimilation of the underlying shale during emplacement.

PICRITE AND Ni-Cu-PGE MINERALIZATION IN THE WRANGELLIA TERRANE OF BC?

This ongoing study will also provide insight into the potential for Ni-Cu-PGE mineralization for the portion of the Wrangellia Terrane on Vancouver Island. The continental equivalents of oceanic plateaus are the hosts of world-class ore deposits. The giant Ni-Cu-PGE deposits of the Noril'sk-Talnakh region in Siberia are located in picritic intrusions related to the Siberian continental flood basalt (CFB) province. In Wrangellia, some of the essential ingredients required to form a Noril'sk-type deposit — the emplacement of hot, picritic magmas into S-bearing sedimentary rocks — appear to be present. The S and Ba-rich Late Paleozoic and Middle Triassic sedimentary rocks underlying the Wrangellia flood basalts on Vancouver Island may have been assimilated by the picritic magmas and initiated sulphide liquid immiscibility. Future work will evaluate the PGE contents of the Wrangellia flood basalts from northern Vancouver Island and the extent and nature of any crustal contamination.

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