Wrangellia Terrane on Vancouver Island, British Columbia: Distribution of Flood Basalts with Implications for Potential Ni-Cu-PGE Mineralization in Southwestern British Columbia

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KEYWORDS: Wrangellia, large igneous province, basalt, contamination, Ni-Cu-PGE mineralization

INTRODUCTION

Wrangellia consists largely of an oceanic plateau, a vast outpouring of basalt and more Mg-rich magma that erupted onto the ocean floor and was subsequently accreted to the western margin of the North American plate. Flood basalts form extensive sequences on Vancouver Island and are believed to have formed by melting in a mantle plume (an upwelling zone of hot mantle rock). They form the oceanic variety of a Large Igneous Province (LIP). A peculiarity of the Wrangellia plateau is that it erupted into an extinct island arc.

The continental equivalents of oceanic plateaus are the hosts of world-class ore deposits. The Ni-Cu-PGE (platinum group elements) deposit of the Noril'sk-Talnakh region in Siberia, arguably the richest ore deposit in the world, is located in intrusions related to the Siberian LIP. Here the assimilation of S-bearing sedimentary rocks by picritic (high-MgO) magma led to the segregation of Ni- and PGE-rich magmatic sulphides. Other examples are the deposits of the Raglan region in northern Quebec, and possibly those of the Manitoba Ni belt, where komatiitic magmas interacted with argillaceous sediments, again leading to the formation of large and rich magmatic sulphide deposits.

Although many showings of Ni-sulphides are present in Wrangellia, no major ore deposits are known. Hulbert (1997) undertook a long-term appraisal of the intrusive complexes in the Yukon segment of the terrane. Although he showed that the mineralization resembles that at Noril'sk and Raglan, no large economically exploitable accumulations have as yet been found. This is surprising, because the essential ingredients required to form a Noril'sk-type deposit — the emplacement of hot, Ni- and PGE-rich picritic magmas into S-bearing sediments — appear to be present. In this respect, Wrangellia is a much more reasonable exploration target than many other oceanic and continental plateaus where the underlying crust consists mainly of granitic or ultramafic rocks.

The ongoing study seeks to provide insight into the potential for Ni-Cu-PGE mineralization for the portion of the Wrangellia Terrane on Vancouver Island. This overview is a preliminary report of fieldwork and a summary of previous research. This study represents one important aspect of a larger study on the significance of the Wrangellia Terrane as a giant accreted oceanic plateau. Oceanic plateaus are enigmatic phenomena that represent the largest known magmatic events on Earth. Such enormous volumes of magma erupt over geologically short time intervals (several million years) and, in addition to potentially generating world-class ore deposits, their formation may have catastrophic effects on the climate and biosphere. There are few well-preserved examples of accreted oceanic plateaus. Exposures of Triassic Wrangellia flood-volcanic sequences represent one of the finest examples of an accreted oceanic plateau worldwide. These lava sequences offer an exceptional opportunity to closely examine the on-land remains of an oceanic plateau and to assess criteria for evaluating Ni-Cu-PGE mineralization potential.

TECTONIC SETTING OF THE WRANGELLIA TERRANE

The Wrangellia Terrane is a complex and variable terrane that extends from Vancouver Island to central Alaska (Fig. 1). Wrangellia is most commonly characterized by widespread exposures of Triassic flood basalts and complementary intrusive rocks (Jones *et al.*, 1977). Triassic flood basalts extend in a discontinuous belt from Vancouver and Queen Charlotte Islands (Karmutsen Formation), through southeast Alaska and the Kluane Ranges in southwest Yukon, and into the Wrangell Mountains and Alaska Range in east and central Alaska (Nikolai Formation). This belt of flood basalt sequences has distinct similarities and is recognized as representing a once-contiguous terrane (Jones *et al.*, 1977).

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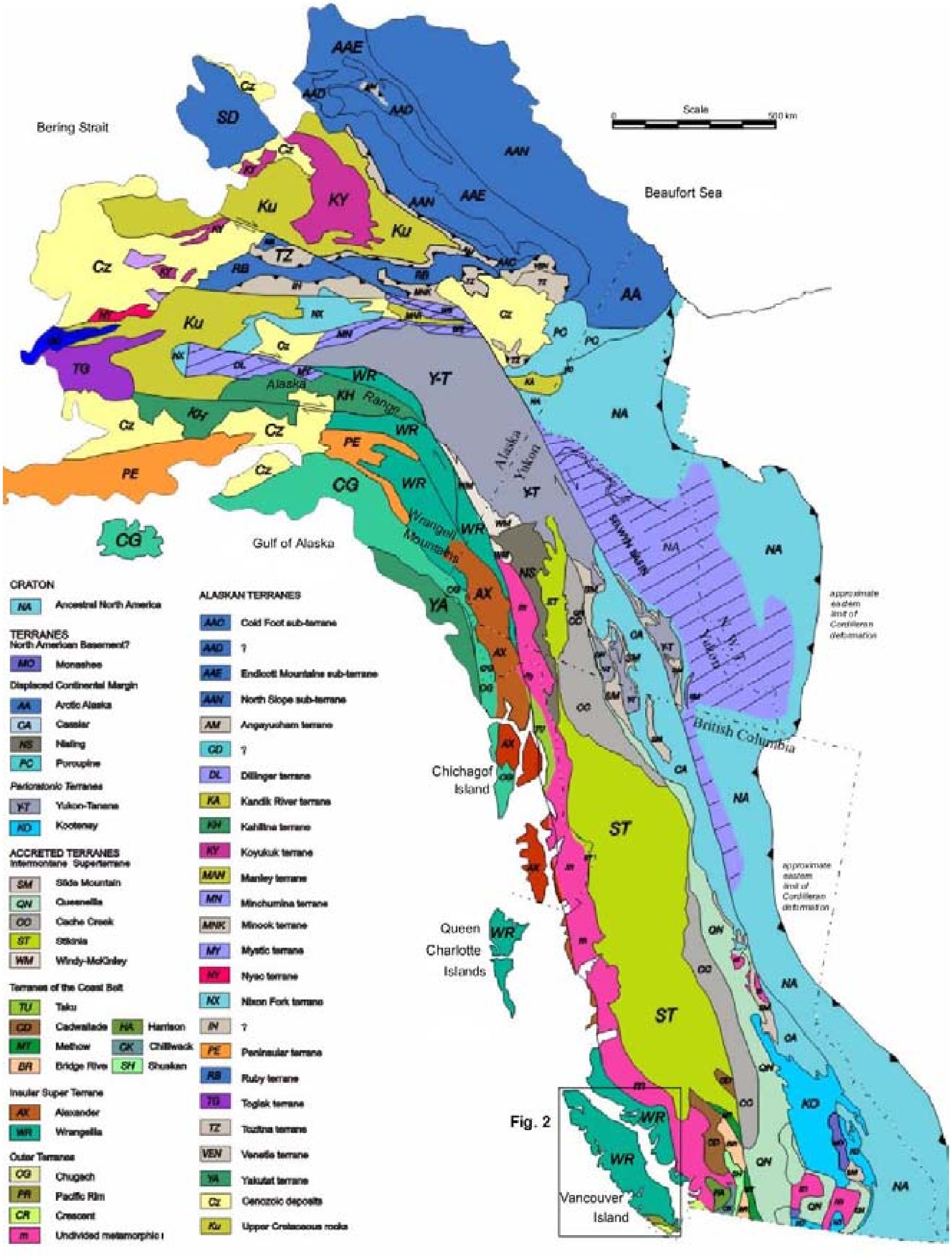

Figure 1. Terrane map of western Canada and Alaska (modified after Wheeler *et al.* [1991]) showing the distribution of the Wrangellia Terrane (WR) in British Columbia, the Yukon and Alaska.

Wrangellia has a long and diverse geologic history spanning much of the Phanerozoic. On Vancouver Island, the oldest rocks of Wrangellia, which lie at the top of an imbricated stack of northeast-dipping thrust sheets (Monger and Journeay, 1994), are Late Silurian to Early Permian arc sequences (Muller, 1980; Brandon *et al.*, 1986; Sutherland Brown *et al.*, 1986). In the Late Triassic, rapid uplift associated with a rising plume head lead to eruption of voluminous flood basalts as part of an extensive oceanic plateau (Richards *et al.*, 1991). As volcanism ceased, the oceanic plateau soon began to subside and accumulate deep-water carbonate sediments (Jeletzky, 1970; Carlisle and Suzuki, 1974). Sedimentation within the Wrangellia Terrane lasted until the Early Jurassic, when the resurgence of arc volcanism developed in reponse to subduction, forming the Bonanza arc (Armstrong and MacKevett, 1977; DeBari, 1990)

The enormous exposures of the Karmutsen appear 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) relatively limited geochemical data, (2) the nature of the underlying and overlying formations, (3) rapid uplift prior to volcanism, (4) the lack of evidence of rifting associated with volcanism and (5) the short duration and high eruption rate of volcanism (Richards *et al.*, 1991). The basalt flows are estimated to have erupted a minimum volume of $1x10^6$ km^3 (Panuska, 1990) within a maximum of five million years (Carlisle and Suzuki, 1974).

During the 80 million years or so between arc activity and emergence of oceanic plateau flood basalts, as the continents gathered into a great landmass, Wrangellia became part of a composite terrane (Plafker *et al.*, 1989). By the Middle Pennsylvanian, Wrangellia may have joined with the Alexander Terrane (Gardner *et al.*, 1988) or been in close proximity (stratigraphic continuity) with the Alexander Terrane (Yorath *et al.*, 1985). The ocean-bound Wrangellia Terrane amalgamated with the Taku Terrane of southeast Alaska and the Peninsular Terrane of southern Alaska by as early as the Late Triassic (Plafker *et al.*, 1989). Paleomagnetic and faunal evidence indicate the Wrangellia Terrane originated far to the south of its present position (Hillhouse, 1977; Yole and Irving, 1980; Hillhouse *et al.*, 1982; Hillhouse and Gromme, 1984). Wrangellia accreted to the North American craton by the Late Jurassic or Early Cretaceous (Monger *et al.*, 1982; Tipper, 1984; Plafker *et al.*, 1989; Gehrels and Greig, 1991; van der Heyden, 1992; Monger *et al.*, 1994).

GEOLOGIC SETTING OF THE KARMUTSEN FORMATION

Widespread areas of British Columbia are underlain by the distinctive flood basalt sequences of the Karmutsen Formation (Fig. 2). Approximately 35% of northern and central Vancouver Island consists of Karmutsen basalt (Barker *et al.*, 1989). Exposures of the Karmutsen are also extensive on the southern Queen Charlotte Islands, although the base of the formation is not exposed. On Vancouver Island, both underlying island arc rocks of the Paleozoic Sicker Group and the Karmutsen Formation are intruded by mafic sills thought to be associated with the Karmutsen (Barker *et al.*, 1989). The Karmutsen Formation is commonly intercalated with small lenses of marine sediments and is capped by shallow-water limestone (Carlisle and Suzuki, 1974).

The earliest in-depth studies of the Karmutsen Formation on Vancouver Island were made by J.E. Muller and co-workers (Muller, 1967; Muller and Carson, 1969; Muller *et al.*, 1974; Muller, 1977, 1981; Muller *et al.*, 1981) and D. Carlisle and his students (Carlisle, 1963; Surdam, 1968; Carlisle, 1972; Kuniyoshi, 1972; Carlisle and Suzuki, 1974). This initial work established the location, characteristics, and depositional history of the Triassic volcanic sequences. Units were subsequently mapped and described in further detail by G.T. Nixon and co-workers (Nixon *et al.*, 1993; Nixon *et al.*, 1994; Nixon *et al.*, 1994) on northern Vancouver Island and N.W.D. Massey and co-workers (Massey and Friday, 1988, 1989; Massey, 1995a, 1995b, 1995c) on central Vancouver Island.

The Karmutsen Formation forms thick flood-volcanic sequences throughout the densely-forested regions of northern and central Vancouver Island. The predominantly extrusive, marine sequences locally exceed 6000 m in thickness (Carlisle and Suzuki, 1974), however, extensive faulting throughout the Karmutsen makes reconstruction of the stratigraphic thickness challenging. Diagnostic units of the Karmutsen are often divided into (1) a lower member of exclusively pillow lava (2500 ± 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) (Carlisle & Suzuki, 1974) (Fig. 3).

Basalts of the Upper Triassic Karmutsen preserve both a submarine and subaerial history of eruption for the oceanic plateau. The Karmutsen Formation contains a much larger proportion of submarine basalts than the predominantly subaerial Nikolai “Greenstone” in Alaska, however, there are subaerial flows in the uppermost sequences of the Karmutsen and submarine basalts near the base of the Nikolai (Muller *et al.*, 1974; Jones *et al.*, 1977). Concordant massive subaerial flows preserve no evidence of erosional surfaces between flows and lack any significantly thick or laterally continuous trace of intravolcanic sediments. The “essentially homogeneous” flood basalts (Barker *et al.*, 1989; Richards *et al.*, 1991; Lassiter *et al.*, 1995; Yorath *et al.*, 1999) formed as an enormous lava pile beneath, close to, and above the surface of the ocean within a geologically short time span.

The age of flood basalts of the Karmutsen is bracketed by fossils in the underlying and overlying sedimentary units. Eruption of Wrangellia flood basalts possibly occurred in their entirety within 2.5 to 3.5 million years (early Upper Ladinian to early Upper Car-

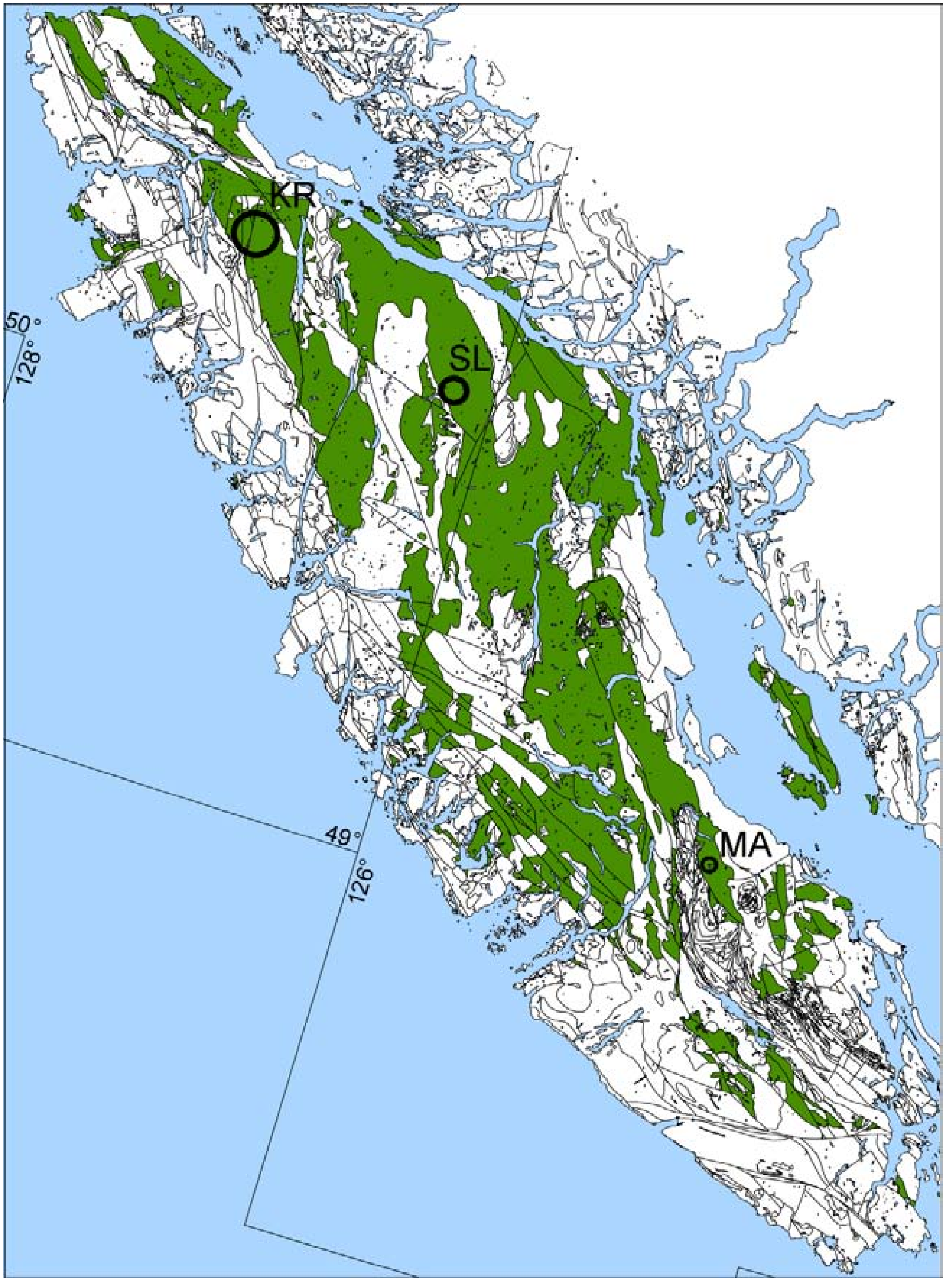

Figure 2. Map of Vancouver Island showing exposures of flood basalt from the Karmutsen Formation (green) (after Massey *et al.*, [2003a, 2003b]). Areas of field study discussed in the text are outlined with black circles, from north to south (west of the Karmutsen Range [KR], east of Schoen Lake [SL], and Mount Arrowsmith [MA]).

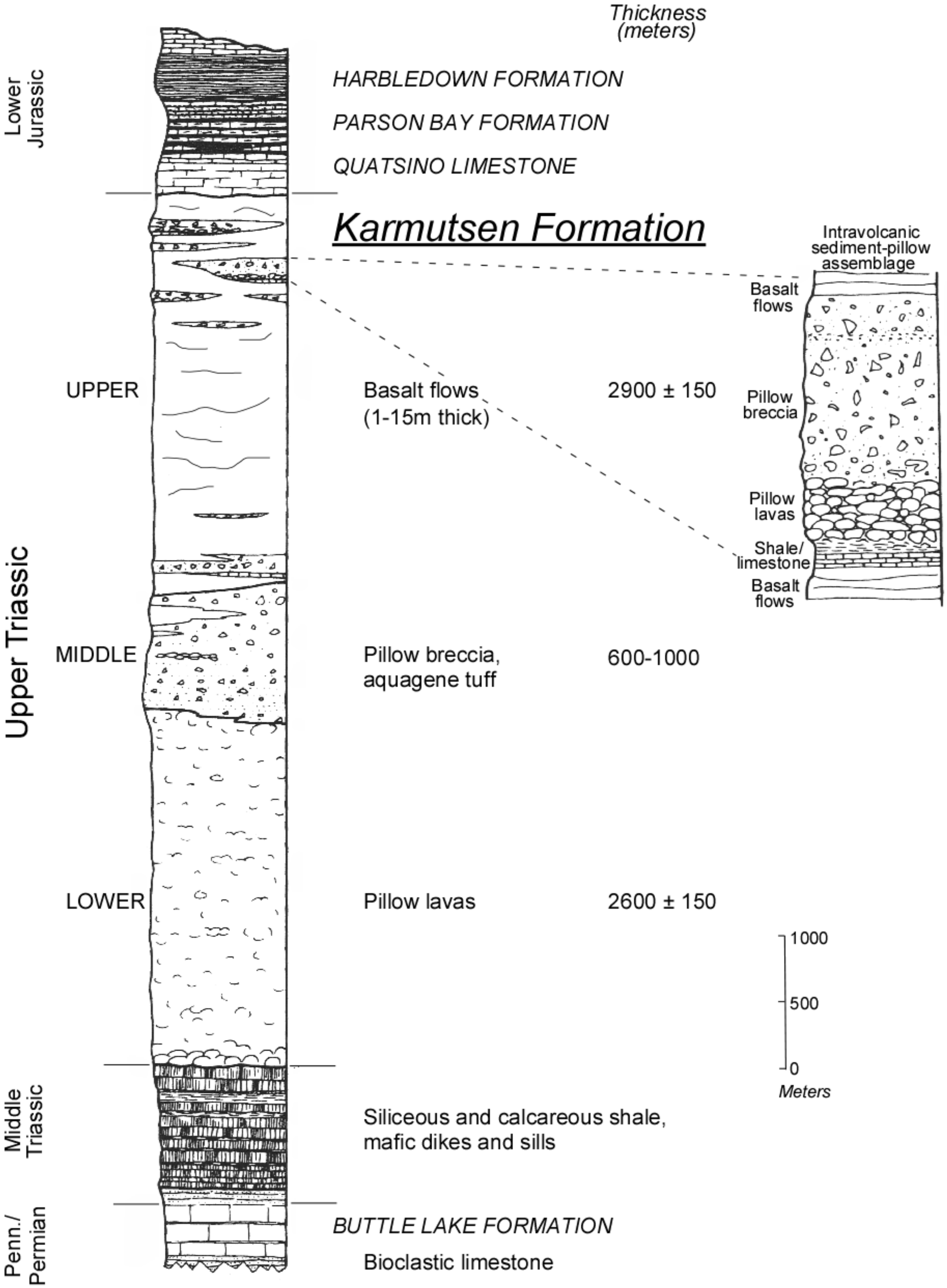

Figure 3. Composite stratigraphic column depicting flood basalt sequences of the Karmutsen Formation and major sedimentary sequences on northern Vancouver Island (modified after Carlisle and Susuki [1974]).

nian—middle Triassic) (Carlisle and Suzuki, 1974). Zircon ages for related intrusive units on Vancouver Island corroborate these bracketing ages (217-222 Ma [Isachsen *et al.*, 1985]; 227 ± 3 Ma [Parrish and McNicoll, 1992]). Conodonts and zircons dated in Nikolai volcanics in Alaska and the Yukon also indicate a Carnian age (Plafker *et al.*, 1989; Mortensen and Hulbert, 1991).

The size of the area sampled in this study represents a small portion of the overall exposure of Wrangellia flood basalts. However, these areas consist of exposures of each of the three members in previously unsampled areas for high-precision isotopic and trace-element analyses. In addition, field observations and sampling in the Yukon and Alaska will be beneficial for comparison to relationships on Vancouver Island.

DESCRIPTION OF THE STUDY AREA

Field studies were undertaken in July, 2004 to investigate Wrangellia flood basalts on Vancouver Island. Prior to undertaking fieldwork, published literature and maps were evaluated for the selection of target areas. Discussions with Nick Massey and Graham Nixon, of the British Columbia Ministry of Energy and Mines Geological Survey Branch, were also beneficial for selecting optimal field areas. The selection of areas was based on accessibility, potential for exposure of thick stratigraphic sequences, and minimal faulting. The three areas chosen were Mount Arrowsmith on the central part of Vancouver Island, and east of Schoen Lake Provincial Park and west of the Karmutsen Range on the northern third of Vancouver Island (Fig. 2). With the exception of Mount Arrowsmith, these areas have not seen extensive sampling for geochemical studies.

Reconnaissance of these areas indicates that complete sections of the volcanic flood basalt sequences are not present in any one area. However, thick sections and isolated exposures of pillow lavas, pillow breccias and massive flows are well-exposed and accessible, primarily along logging roads. The degree of faulting, dense vegetation cover and the steep nature of the terrain made assessment of the stratigraphy difficult in particular areas. Fifty evenly distributed samples were collected for petrographic and geochemical analysis. Special care was taken to sample the freshest appearing basalts and cover the extent of the exposed Triassic stratigraphy.

Of the three study areas, exposures on Mount Arrowsmith preserve the most extensive stratigraphy. The thickness of the exposure (~3000 m) is approximately half that exposed at Buttle Lake (~6000 m), however, proportions of each of the members are comparable (Yorath *et al.*, 1985). The basal pillow lavas are easily distinguished by their globular form, selvage rims and interstitial filling (Photos 1 and 2). Pillow basalt is overlain by accumulations of broken pillow fragments (pillow breccia) with no easily-recognizable bedding (Photo 3). This unit is thick (~1000 m), widespread and fairly uniform in thickness in the area (Yorath *et al.*, 1985). The pillow breccia may have formed as the result of a varied eruptive stage where stacks of pillows emerging from young lava centres collapsed due to an increased level of magma flux or seismic activity (Yorath *et al.*, 1985).

Exposures of basalt in the area east of Schoen Lake Provincial Park are densely vegetated and difficult to access. This area was explored in detail by D. Carlisle (Carlisle, 1972), but has not been the focus of any geological investigation since. All three members of the Karmutsen are exposed in roadcuts in this area. On the west side of the Karmutsen Range, between Nimpkish Lake and Victoria Lake, the terrain is dissected by an extensive network of logging roads with exposures in roadcuts primarily preserving massive lava flows and isolated exposures of pillow basalt lower in the section.

Massive lava flows, exposed in each of the previously described areas, are generally 1 to 15 m thick and exhibit coarser grain size than the pillow basalt unit (Photo 4). Amygdules are prevalent thoughout individual flows, which commonly reveal uneven contacts with no discernible erosional surface, columnar jointing or substantial thickness of intercalated sediment. Comagmatic dikes or sills are rare in these areas and difficult to distinguish. The basalt flows are found to be rarely interbedded with thin, lenticular beds of both marine and non-marine sediments, however, most of the flows appear to have erupted subaerially or in shallow water, which precluded significant deposition (Carlisle and Suzuki, 1974).

MAGMATIC SULPHIDE DEPOSITS IN THE WRANGELLIA TERRANE OF BRITISH COLUMBIA?

The intrusive centres linked to the overlying Wrangellia flood basalts represent one of the largest belts of Ni-Cu-PGE–bearing mafic and ultramafic rocks in North America (Hulbert, 1997). Geochemical variations in the Wrangellia flood basalts preserve a record, as yet undeciphered, of the evolution of magmas within upper crustal magma chambers or sills and interactions with local contaminants and deep crustal contaminants during ascent. At Noril'sk, the geochemistry of the flood basalts has been used as an indication of the likelihood that complementary intrusive rocks contain Ni-Cu-PGE deposits (*e.g.*, Naldrett and Lightfoot, 1993) and the geochemistry of the intrusive rocks has been successfully used to constrain the role of staging chambers for crustal contamination and sulphide segregation within magmas prior to eruption (*e.g.*, Arndt *et al.*, 2003). In contrast, there has been limited geochemical examination of the intrusive complexes of the Wrangellia Terrane, other than the Kluane Mafic-Ultramafic Belt (Hulbert, 1997). More importantly, in proportion to their vast aerial exposure,

Photo 1. Cross-section of a stack of closely packed, asymmetric basalt pillows with what were originally glassy pillow rinds west of the Karmutsen Range (626835 E, 5586081 N). The pillows have features indicating formerly chilled rims and more massive interiors. These features indicate eruption in a relatively deep marine setting. Geologic hammer (~80 cm) for scale.

Photo 2. Close-up of Photo 1, showing pillow basalt with areas of concentrations of vesicles. Geologic hammer (~80 cm) for scale.

Photo 3. Pillow breccia with angular, blocky clasts in a fine-grained matrix east of Schoen Lake (709745 E, 5567557 N). Geologic hammer (~40 cm) for scale.

Photo 4. Massive basalt flows near Keogh Lake, west of the Karmutsen Range (627605 E, 5595029 N). Arrows (~2 m) indicate possible contacts between flows. Most flows have concentrations of amygdules (~5-15% volume) filled with chlorite, quartz and calcite. Flow tops do not appear brecciated.

minimal attention has been given to the thick sequences of flood basalts (*e.g.*, Barker *et al.*, 1989; Lassiter *et al.*, 1995).

In this ongoing study, detailed geochemical (major and trace elements, PGE) and isotopic studies (Pb-Sr-Nd-Hf) of the Wrangellia flood basalts on Vancouver Island will be used to critically test the relative importance of different components on the formation of magmatic sulphide deposits (*e.g.*, magma composition, nature and relative age of wallrock, extent of contamination, prior sulphide segregation, tectonic setting). Hulbert (1997) stated the possibility that olivine-rich basalt flows (picritic basalts) and mafic and ultramafic intrusions may be restricted to the Yukon segment of Wrangellia as a result of their formation in proximity to the hotter axial "jet" of the mantle plume. However, this aspect of the Wrangellia flood basalt province is poorly understood due to the lack of comparative studies. To assess the significance of primitive S-undersaturated magmas, crustal contamination, and high-level magmatic processes, it is important to understand the relative contributions to the magmas from the plume source and the lithosphere (Lightfoot and Hawkesworth, 1997). This, in turn, will provide insight into the potential for Ni-Cu-PGE mineralization in the British Columbia part of the Wrangellia Terrane.

The nature of the basement rock is likely crucial to the formation of magmatic Ni-Cu-PGE deposits in flood basalt provinces. Late Paleozoic sediments underlie Wrangellia flood basalts on Vancouver Island, as well as in the Kluane Ranges and Wrangell Mountains (Muller, 1967; Jones *et al.*, 1977). Zoned, sill-like mafic and ultramafic bodies, representing subvolcanic magma chambers for the overlying Triassic flood basalts, appear to preferentially intrude particular sequences of Late Paleozoic sediments within the Kluane Ranges (Hulbert, 1997). These relationships indicate that S- and Ba-rich sediments may have been integral to contaminating magmas and initiating sulphide immiscibility (Hulbert, 1997). Is this the case for flood basalts and intrusive sills within the Wrangellia Terrane in British Columbia? What does the geochemistry of the Wrangellia flood basalts and intrusions in British Columbia tell us about the likelihood of Ni-Cu-PGE deposits in this part of the terrane? And on a regional scale, what is the relationship between magma composition, wallrock, age and tectonic setting throughout the entire Wrangellia Terrane?

ONGOING AND PLANNED RESEARCH

We are presently preparing 50 samples for high-precision analytical work to help answer these questions. Presently, samples are being prepared for analysis of major and trace elements, and radiogenic isotopes at the Pacific Centre for Isotopic and Geochemical Research (PCIGR) at the University of British Columbia (UBC). Careful procedures are being used to avoid any contamination of samples during crushing. Petrographic thin-sections for all the samples are also currently being analyzed for their mineralogy and texture.

We plan a thorough evaluation of the petrology, geochronology and geochemistry of flood basalts in the Wrangellia Terrane. Particular emphasis will be placed on determining the extent of crustal contamination in the Wrangellia magmatic suite by local sedimentary sources and/or by lower crustal material. Due to the lack of a comprehensive geochemical database for Wrangellia, especially for the British Columbia portion, this requires the acquisition of a large, internally consistent geochemical database with element concentrations and isotopic ratios measured in the same laboratory. Ratios of low-abundance trace elements are very sensitive to differences in sources and contaminants (*e.g.*, Nb/La, La/Sm, Ba/Th, Sr/Nd, Pb/Nd), while combining different radiogenic isotopic systems (*e.g.*, Pb-Pb, Rb-Sr, Sm-Nd, Lu-Hf) with different geochemical behaviours and relative ratios for the parent and daughter isotopes can precisely fingerprint source components (*e.g.*, enriched mantle, depleted mantle, arc crust, sediments). Select samples will be precisely dated (Ar-Ar) to provide absolute time constraints on magmatism in the Wrangellia Terrane of British Columbia. It will also be essential to evaluate relative PGE enrichment-depletion in the basalts and intrusions. Finally, the Ni contents of olivine will be systematically determined in all olivine-bearing lavas and intrusions to monitor the effects of sulphide segregation in this large magmatic system.

We plan to complete the compilation of geological information for the entire Wrangellia Terrane (British Columbia, Yukon and Alaska). The major goal of the compilation work is to constrain the location, areal significance and stratigraphic location of intrusions and sedimentary sequences. Additional field studies planned in the Yukon and Alaska during the summer of 2005 will be beneficial to the work on Vancouver Island. Insights gained here, in regions of relatively minor faulting, will be applied to Wrangellia exposures in British Columbia where structural complexity is more evident.

The ultimate goal of this project is the establishment of criteria for evaluating the Ni-Cu-PGE mineralization potential of the Wrangellia Terrane in British Columbia. This will be accomplished through integration of field, petrologic, geochemical and geochronologic constraints of volcanic sequences. The criteria for magmatic Ni-Cu-PGE sulphide mineralization in the Wrangellia Terrane established in this project should help to attract mineral exploration programs in British Columbia and aid mineral exploration companies in refining their existing exploration models.

ACKNOWLEDGMENTS

Funding for this project has been generously provided by the Rocks to Riches Program administered by

the British Columbia and Yukon Chamber of Mines. We would also like to thank Nick Massey and Graham Nixon, of the British Columbia Ministry of Energy and Mines Geological Survey Branch, for their insightful discussions and Nick Arndt for helping to initiate the mineralization potential study.

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