Flood basalts of the Wrangellia Terrane, southwest Yukon: Implications for the formation of oceanic plateaus, continental crust and Ni-Cu-PGE mineralization

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ABSTRACT

The Wrangellia Terrane along the northwest margin of North America is an extensive accreted oceanic plateau. These volcanic sequences erupted onto an extinct island arc in less than 5 million years at ca. 230 Ma. Triassic Wrangellia basalts and intrusions form a 1 to 10 km-wide linear belt of mafic and ultramafic rocks extending 300 km across southwest Yukon. A total of 85 samples were collected for geochemical and isotopic analysis from 10 widespread areas along the entire length of the linear belt. Field observations during the summer of 2004, and a synthesis of previous research for the Yukon portion of Wrangellia, are part of a larger research project involving Wrangellia basalts extending from Vancouver Island to central Alaska. The Wrangellia volcanic sequences represent one of the finest examples of an accreted oceanic plateau worldwide. They provide an excellent opportunity to gain a better understanding of the mantle source of oceanic plateaus and to assess the role of accretion of oceanic plateaus in continental growth.

RÉSUMÉ

La Wrangellie est un vaste terrane constitué d'un plateau océanique accrété le long de la marge nord-ouest de l'Amérique du Nord. Ces séquences volcaniques se sont formées sur un arc insulaire éteint en moins de 5 millions d'années vers 230 Ma. Les basaltes et intrusions triasiques de la Wrangellie forment une zone linéaire de roches mafiques et ultramafiques de un à dix kilomètres de largeur qui s'allonge sur 300 km dans le sud-ouest du Yukon. Au total, 85 échantillons ont été recueillis pour des analyses géochimiques et isotopiques dans dix régions réparties sur toute la longueur de la zone linéaire. Les observations de terrain faites à l'été 2004 et la synthèse des recherches antérieures dans la partie de la Wrangellie située au Yukon s'inscrivent dans le cadre d'un vaste projet de recherche portant sur les basaltes de la Wrangellie qui s'étendent de l'île de Vancouver jusqu'au centre de l'Alaska. Les séquences volcaniques de la Wrangellie, qui constituent un des meilleurs exemples de plateau océanique accrété au monde, offrent une excellente occasion de mieux comprendre la source mantellique des plateaux océaniques et d'évaluer le rôle de l'accrétion de ces plateaux dans l'expansion des continents.

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INTRODUCTION

A large part of the Wrangellia Terrane consists of an oceanic plateau, a vast outpouring of basalt and more Mg-rich magma that erupted onto the ocean floor, which was then subsequently accreted to the western margin of the North American plate. Wrangellia flood basalts exposed in southwest Yukon are believed to have originated by melting in a mantle plume and they constitute the oceanic variety of a Large Igneous Province (LIP) that erupted onto the extinct Pennsylvanian and Permian Sicker-Skolai island arc.

Oceanic plateaus represent the largest known magmatic events on Earth. Enormous volumes of magma erupt in ocean basins over geologically short time intervals (several million years), and are suspected to have catastrophic effects on the climate and biosphere (Wignall, 2001). Throughout Earth's history, the formation and accretion of oceanic plateaus may have significantly contributed to the growth of continents (Kroenke, 1974; Ben-Avraham et al., 1981; Nur and Ben-Avraham, 1982; Schubert and Sandwell, 1989; Abouchami et al., 1990; Richards et al., 1991; Boher et al., 1992; Abbott and Mooney, 1995; Kimura and Ludden, 1995; Saunders et al., 1996; Stein and Goldstein, 1996; Albarède, 1998; Kerr et al., 2000; Kerr, 2003). However, accreted oceanic plateaus can be difficult to distinguish in the geological record, and well-preserved examples are rare. Exposures of Triassic Wrangellia flood-volcanic sequences represent one of the finest examples of an accreted oceanic plateau worldwide and offer an exceptional opportunity to closely examine the on-land remains of such a phenomenon.

The present overview is a preliminary report of fieldwork within the Kluane Ranges of southwest Yukon and a summary of previous research on the Wrangellia Terrane. This paper represents one component of a larger research project on Wrangellia flood basalts extending from Vancouver Island to central Alaska. The principal objectives of this project are to gain a better understanding of the mantle source of oceanic plateaus and to determine the role of accretion of oceanic plateaus in the growth of continental crust. Ultimately, the goal of the ongoing larger study is to characterize the composition of the Wrangellia oceanic plateau. Then, using this constrained elemental reservoir, we aim to model the effect of adding oceanic plateaus to continental crust.

Intrusive complexes within the Wrangellia Terrane have distinct similarities to intrusions related to some of the world's richest ore deposits. For example, intrusions related to the Siberian LIP, the continental equivalent of an oceanic plateau, host the Noril'sk deposit in Siberia, which is arguably the richest ore deposit in the world. To date, no large economically exploitable copper-nickel-PGE (platinum group elements) deposits have been discovered in the Yukon segment of the Wrangellia Terrane despite the fact that mineralization in the intrusive complexes resembles that at Noril'sk (Hulbert, 1997). This is surprising, because the essential conditions required to form a Noril'sk-type deposit, specifically the emplacement of hot, Ni- and PGE-rich picritic magmas into S-bearing sediments, appear to be present in the Wrangellia Terrane. In this respect, this project will provide information to allow better evaluation of the potential for magmatic Ni-Cu-PGE mineralization in the Wrangellia Terrane.

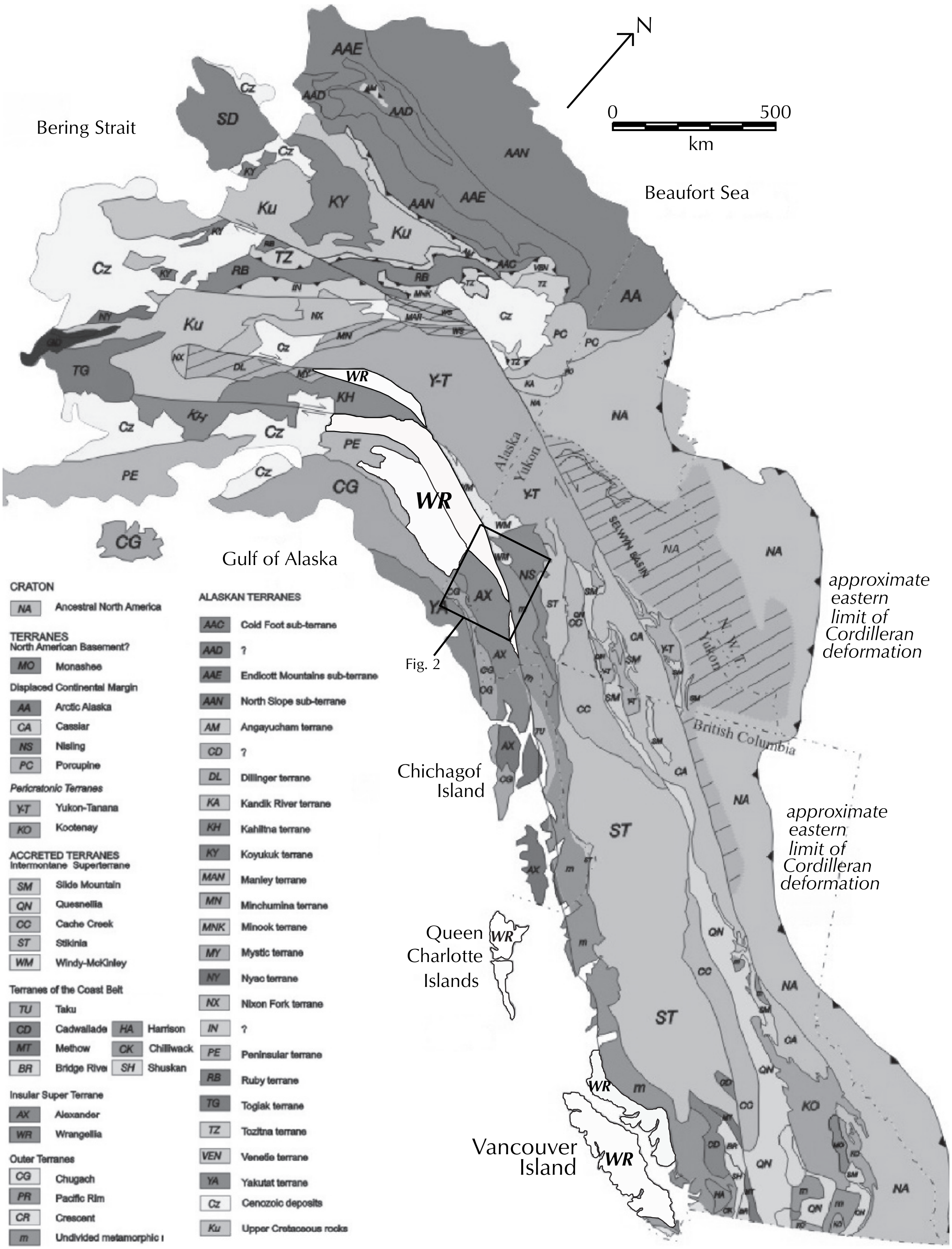
TECTONIC SETTING OF THE WRANGELLIA TERRANE

The Wrangellia Terrane is a complex and variable terrane that extends from Vancouver Island to central Alaska (Fig. 1). The northernmost part of Wrangellia, which underlies large areas of east-central Alaska, is divided into two narrow linear belts to the south, which are separated by the Alexander Terrane. In the Yukon, the eastern belt is the narrowest section of Wrangellia rocks currently exposed.

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 Island and the 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-central Alaska (Nikolai formation). The flood basalt sequences in this belt have distinct similarities and are recognized as a once-contiguous terrane (Jones et al., 1977).

Wrangellia has a long and diverse geologic history that spans much of the Phanerozoic. In Yukon, Wrangellia lies on the west side of the Denali Fault, where Nikolai basalt

Figure 1 (facing page). *Terrane map of western Canada and Alaska (modified after Wheeler et al., 1991) showing the distribution of the Wrangellia Terrane (WR; in white) in B.C., the Yukon and Alaska.*


N
0 500
km
Bering Strait
Beaufort Sea
Gulf of Alaska
Fig. 2
Chichagof Island
Queen Charlotte Islands
Vancouver Island
Alaska
Yukon
N.W.T.
Yukon
British Columbia
Selwyn Basin
approximate eastern limit of Cordilleran deformation
approximate eastern limit of Cordilleran deformation
CRATON
NA Ancestral North America
TERRANES
North American Basement?
MO Monashee
Displaced Continental Margin
AA Arctic Alaska
CA Cassiar
NS Nisling
PC Porcupine
Pericratonic Terranes
Y-T Yukon-Tanana
KO Kootenay
ACCRETED TERRANES
Intermontane Superterrane
SM Slide Mountain
QN Quesnellia
CC Cache Creek
ST Stikinia
WM Windy-McKinley
Terranes of the Coast Belt
TU Taku
CD Cadwallade
HA Harrison
MT Methow
CK Chilliwack
BR Bridge Rive
SH Shuskan
Insular Super Terrane
AX Alexander
WR Wrangellia
Outer Terranes
CG Chugach
PR Pacific Rim
CR Crescent
m Undivided metamorphic
ALASKAN TERRANES
AAC Cold Foot sub-terrane
AAD ?
AAE Endicott Mountains sub-terrane
AAN North Slope sub-terrane
AM Angayucham terrane
CD ?
DL Dillinger terrane
KA Kandik River terrane
KH Kahiltna terrane
KY Koyukuk terrane
MAN Manley terrane
MN Minchumina terrane
MNK Minook terrane
MY Mystic terrane
NY Nyac terrane
NX Nixon Fork terrane
IN ?
PE Peninsular terrane
RB Ruby terrane
TG Togiak terrane
TZ Tozitna terrane
VEN Venetie terrane
YA Yakutat terrane
Cz Cenozoic deposits
Ku Upper Cretaceous rocks

overlies Pennsylvanian to Permian marine sediments and arc sequences of the Hasen Creek and Station Creek formations (Read and Monger, 1976; Campbell, 1981). In the Late Triassic, rapid uplift associated with a rising plume head led 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, represented by the Upper Triassic to Lower Jurassic Chitistone and Nizina limestones and McCarthy Formation (Armstrong et al., 1969; MacKevett, 1970a, 1970b, 1971, 1972; Armstrong and MacKevett, 1977; MacKevett, 1978; Armstrong and MacKevett, 1982). Thick, deep marine fan deposits of the Dezadeash Formation overlap the Alexander and Wrangellia terranes (Smith and MacKevett, 1970; MacKevett, 1971; Read and Monger, 1976).

The enormous exposures of the Nikolai appear to represent a single flood basalt event (Richards et al., 1991). 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 1×10^6 km^3 (Panuska, 1990) within a maximum of 5 million years (Carlisle and Suzuki, 1974).

During the approximately 80 million years 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 or been in close proximity (stratigraphic continuity) with the Alexander Terrane (Gardner et al., 1988; Yorath et al., 1999). 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 that 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 NIKOLAI FORMATION

Flood basalts of the Nikolai formation are preserved in a discontinuous, southeast-trending linear belt 30-60 km wide, extending over 300 km in the southwest corner of Yukon (Fig. 2). Marine sedimentary rocks of the Paleozoic Station Creek Formation and island arc rocks of the Hasen Creek Formation and Nikolai formation are intruded by mafic-ultramafic sills considered to be associated with eruption of the flood basalts. The Nikolai formation is commonly intercalated with thin, discontinuous lenses of marine sedimentary rocks and is capped by shallow-water limestone (Armstrong et al., 1969; Read and Monger, 1976).

The earliest geological mapping of the Kluane Ranges was done by McConnell (1905). Reconnaissance mapping was done periodically in the early 1900s until prospecting and exploration increased in the 1950s as the result of several discoveries (Hulbert, 1997). For the northern segment of Wrangellia, mapping was primarily accomplished by MacKevett (1970, 1970, 1971, 1972, 1978) in Alaska and J.E. Muller, P.B. Read, and R.B. Campbell (Muller, 1967; Read and Monger, 1976; Campbell and Dodds, 1982, 1985) in southwest Yukon. This initial work established the location, characteristics and depositional history of the Triassic volcanic sequences. Muller (1967) produced the first regional geologic map of the Kluane Ranges at 1:250 000 scale and proposed the correlation between the flood basalts in Yukon and those underlying extensive areas of east-central Alaska. Numerous exploration companies have since investigated the mineralization potential of mafic-ultramafic intrusions in the Kluane Ranges, and some of this work is reviewed in Hulbert (1997) and Carne (2003). Hulbert (1997) studied the intrusive complexes in the Yukon segment of the Wrangellia Terrane and refers to these bodies as the Kluane Mafic-Ultramafic Belt. The most recent summary of the geology of the Kluane Ranges is by Gordey and Makepeace (2000). The Yukon Geological Survey recently initiated a bedrock mapping project in the Kluane Ranges, the preliminary results of which are summarized by Israel and Van Zeyl (this volume).

The Nikolai formation in southwest Yukon is preserved in thin flood-volcanic sequences with minimal lithologic variation. The extrusive marine sequences locally exceed 1000 m in thickness. Extensive faulting and folding throughout the Yukon segment of Wrangellia, however, makes reconstruction of the stratigraphic thickness

Figure 2. *Geologic map of southwest Yukon showing exposures of flood basalt from the Triassic Nikolai formation (dark shading). This map was modified from Israel (2004).*

challenging. The basalts preserve both a submarine and subaerial history of eruption for the oceanic plateau. In the Kluane Ranges, the base of the volcanic section is a thin zone of volcanic breccia, pillow lava and conglomerate that is typically less than 100 m thick (Fig. 3). The remaining sequences of flood basalt are almost exclusively massive flows with undulating contacts and abundant amygdules. The concordant subaerial flows preserve minimal evidence of erosional surfaces between them and lack significantly thick or laterally continuous intravolcanic sedimentary rocks (Read and Monger, 1976). 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.

There are distinct differences between the nature of the flood basalt sequences in Yukon and those in the southern portion of the Wrangellia Terrane in British Columbia. The correlative Karmutsen Formation on Vancouver Island contains a much larger proportion of submarine basalts than the predominantly subaerial Nikolai. However, there are subaerial flows in the uppermost sequences of the Karmutsen and submarine basalts near the base of the Nikolai formation (Muller et al., 1974; Read and Monger, 1976; Jones et al., 1977). On Vancouver Island, Wrangellia flood basalts reach thicknesses of nearly 6000 m, whereas in the Yukon the total thickness is ~1000 m. On Vancouver Island, the Karmutsen volcanics are commonly distinguished by (1) a lower member of exclusively pillow lava (2500 ± 150 m) (2) a middle member of pillow breccia and aquagene tuff (600 to 1100 m) and (3) an upper member of massive basalt flows (2600 ± 150 m; Carlisle and Suzuki, 1974). With the exception of a thin zone of submarine basalt near the base, the Nikolai formation consists primarily of subaerial lava flows.

The timing of the eruption of Wrangellia flood basalts is poorly constrained. The age of Wrangellia flood basalts is bracketed by fossils in the underlying and overlying sedimentary units and corroborated with several radiometric dates (Fig. 3). The entire eruption and deposition of Wrangellia flood basalts on Vancouver Island possibly occurred within 2.5 to 3.5 million years (early Upper Ladinian to early Upper Carnian-middle Triassic; Carlisle and Suzuki, 1974). Zircon ages for related intrusive units on Vancouver Island corroborate bracketing ages of 217 to 222 Ma (Isachsen et al., 1985) and 227 ± 3 Ma (Parrish and McNicoll, 1992). In Yukon,

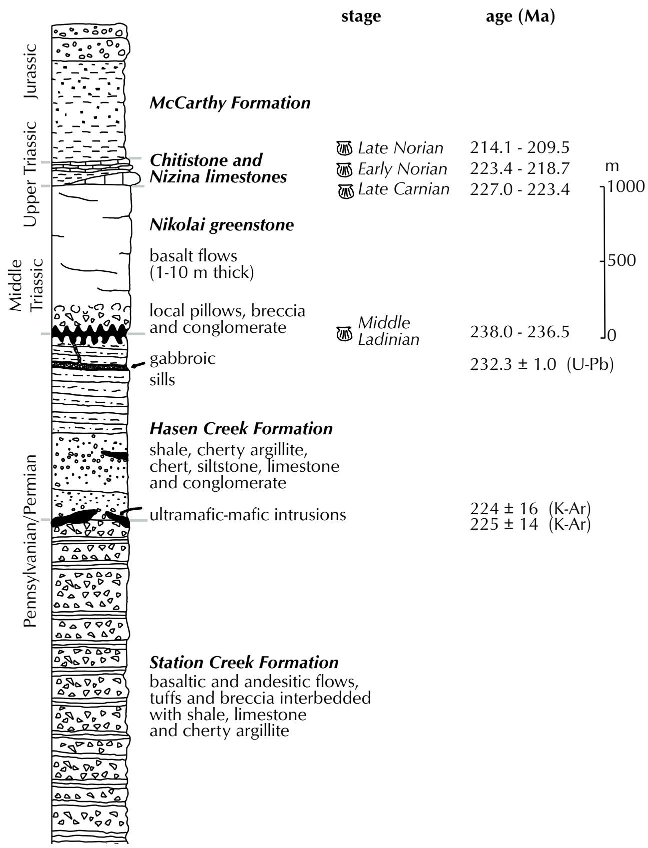


Figure 3. *Composite stratigraphic column depicting flood basalt sequences of the Nikolai formation and other major sedimentary sequences in the Kluane Ranges in southwest Yukon. Modified after Read and Monger (1976) and Hulbert (1997).*

K-Ar ages for phlogopite in peridotite from two intrusive complexes yield ages of 224 ± 16 Ma and 225 ± 14 Ma (Campbell, 1981). A U-Pb age for zircon from a gabbro sill contemporaneous with eruption of the Nikolai volcanics yielded an age of 232.2 ± 1.0 Ma (Mortensen and Hulbert, 1991). Conodonts from the Nikolai volcanics in Alaska also indicate a latest Carnian to earliest Norian age (Plafker et al., 1989).

DESCRIPTION OF THE STUDY AREA

Field studies were undertaken in August, 2004 to investigate Wrangellia flood basalts in southwest Yukon. Published literature and maps were evaluated for the selection of target areas prior to commencing fieldwork. Field areas were selected based on accessibility, potential for exposure of thick stratigraphic sequences, and an even distribution throughout the linear belt of exposures.

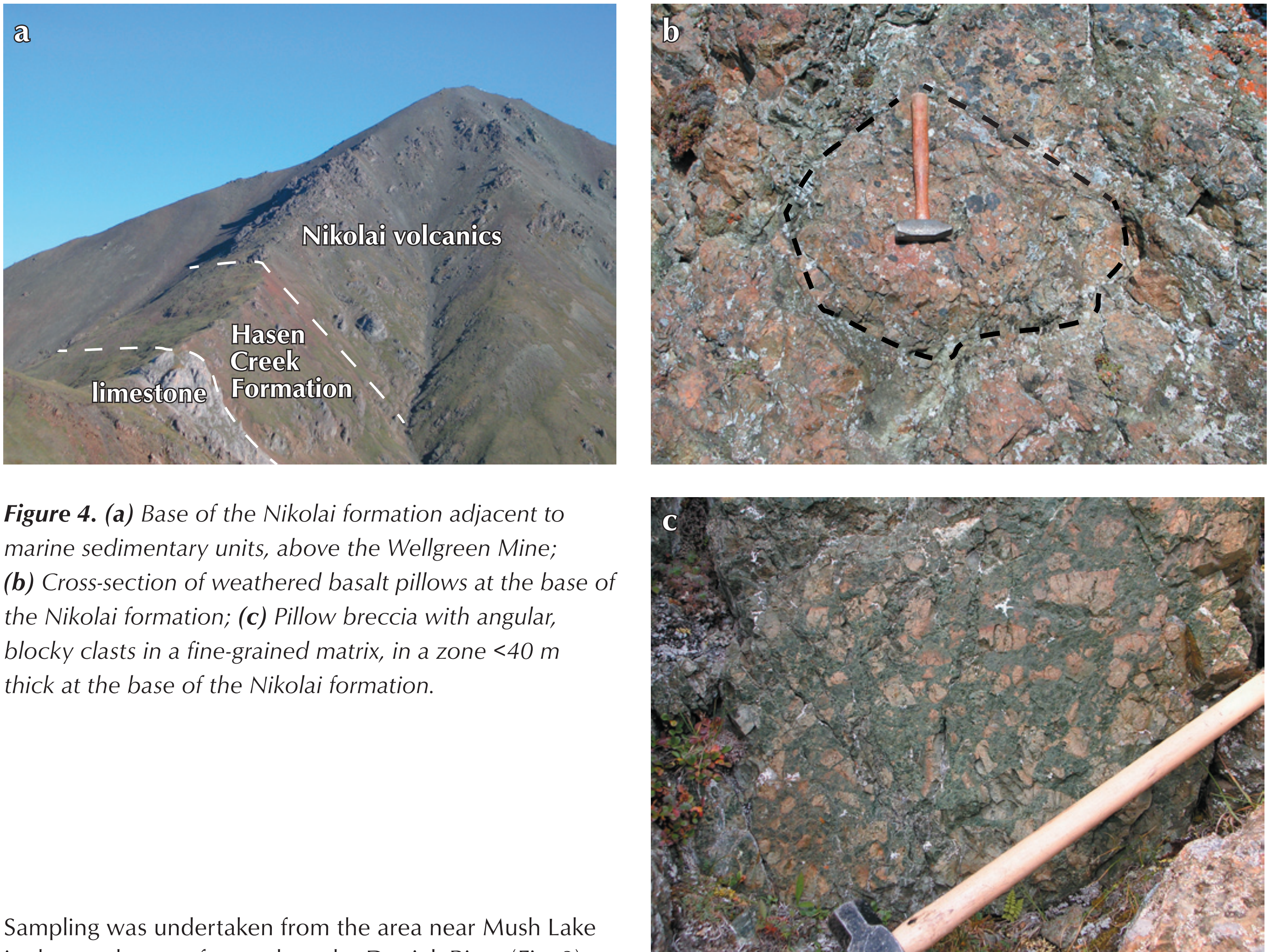


***Figure 4. (a)** Base of the Nikolai formation adjacent to marine sedimentary units, above the Wellgreen Mine; **(b)** Cross-section of weathered basalt pillows at the base of the Nikolai formation; **(c)** Pillow breccia with angular, blocky clasts in a fine-grained matrix, in a zone <40 m thick at the base of the Nikolai formation.*

Sampling was undertaken from the area near Mush Lake in the south, to as far north as the Donjek River (Fig. 2).

Reconnaissance of these areas revealed that complete sections of the volcanic flood basalt sequences are not present in any one area. Small sequences of pillow lavas and breccia underlying more extensive sequences of massive flows, however, are well-exposed and easily accessible. The degree of faulting made assessment of the stratigraphy difficult in most areas. Eighty-five evenly-distributed samples were collected for petrographic and geochemical analysis. Special care was taken to sample the freshest-appearing basalts and to cover the extent of the exposed Triassic stratigraphy.

Of the ten areas investigated, nearly half of the time was spent between Burwash Creek and the Donjek River. In several areas where the base of the Nikolai formation is exposed adjacent to Middle Triassic marine sediments, it is marked by a thin zone, commonly <40 m thick, of breccia or conglomerate with angular volcanic clasts (Read and Monger, 1976; Fig. 4). Pillow lavas near the base of the Nikolai formation are difficult to distinguish and are closely associated with this thin zone of breccia, which preserves no easily-recognizable bedding (Fig. 4a). The pillow breccia may have formed as the result of a varied eruptive stage where stacks of pillows emerging from young lava centers collapsed due to an increased level of magma flux or seismic activity (Yorath et al., 1999).

The exposed thickness of the Nikolai formation varies throughout the linear belt. Massive lava flows in each of the investigated areas are generally 1 to 15 m thick (Fig. 5a). Amygdules are prevalent throughout individual flows, which commonly reveal uneven contacts with no discernible erosional surface or columnar jointing. Phenocrysts are common throughout many of the flows. The basalt flows are rarely interbedded with thin, lenticular beds of marine sediments (Fig. 5b). Most of the flows appear to have erupted subaerially or in shallow water, which likely precluded significant deposition of sedimentary rocks (Carlisle and Suzuki, 1974).

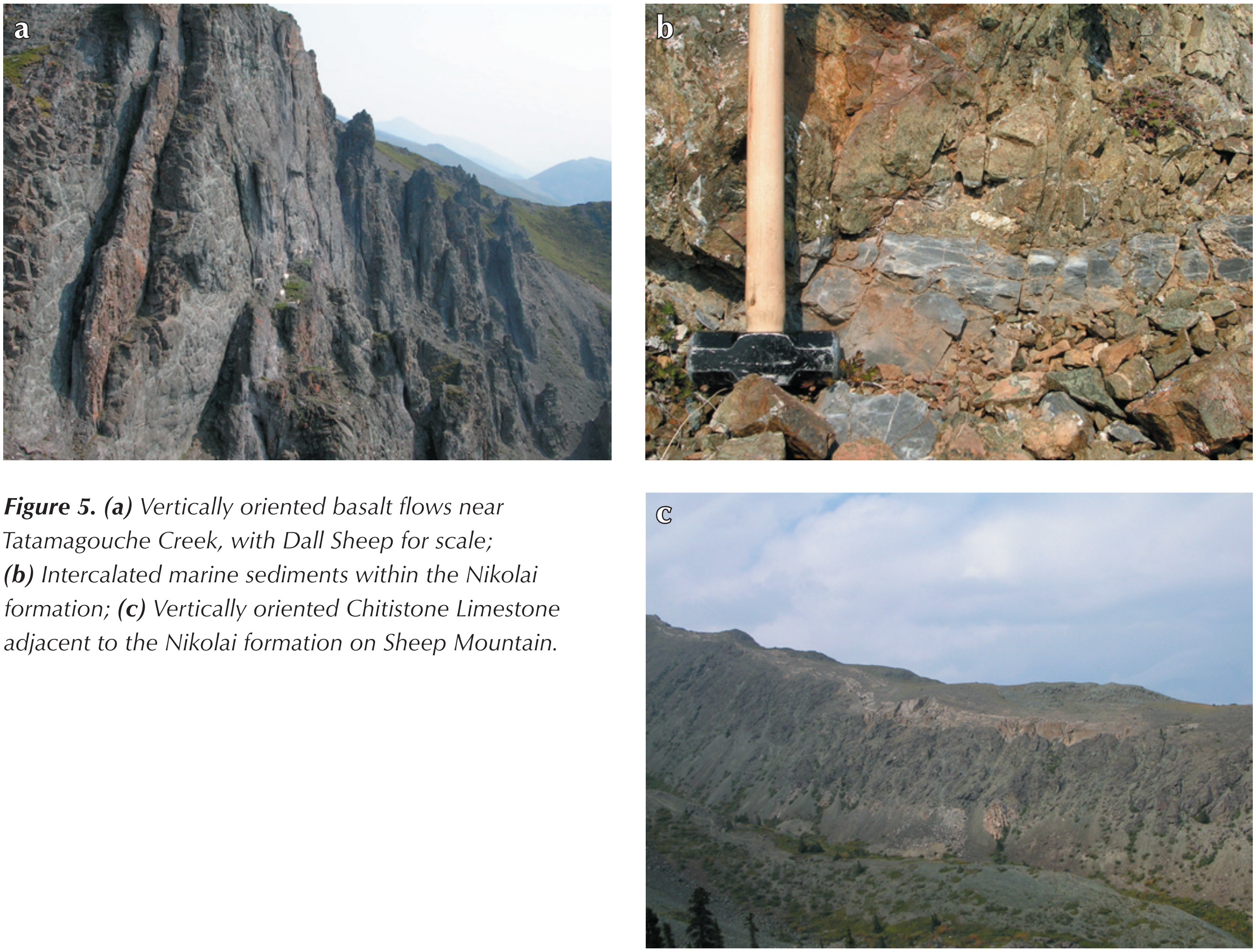


Figure 5. (a) *Vertically oriented basalt flows near Tatamagouche Creek, with Dall Sheep for scale;* ***(b)*** *Intercalated marine sediments within the Nikolai formation;* ***(c)*** *Vertically oriented Chitistone Limestone adjacent to the Nikolai formation on Sheep Mountain.*

MAGMATIC SULPHIDE DEPOSITS IN THE WRANGELLIA TERRANE IN YUKON?

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). Numerous deposits and occurrences in Yukon and adjacent parts of Alaska have seen considerable attention (e.g., Wellgreen, Yukon MINFILE 115G 024; Canalask, Yukon MINFILE 115F 045) and the characteristics of some of these are summarized by 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 their interaction 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 (Arndt et al., 2003). These studies concluded that the assimilation of S-bearing sedimentary rocks by picritic (high-MgO) magma led to the segregation of Ni- and PGE-rich magmatic sulphides.

In this ongoing study, detailed geochemical and isotopic studies of the Wrangellia flood basalts may provide insight into the relative importance of different components on the formation of magmatic sulphide deposits. These components include magma composition, nature and relative age of wallrock, extent of contamination, prior sulphide segregation and tectonic setting. Hulbert (1997) suggested 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).

The nature of the basement rock is likely crucial to the formation of magmatic Ni-Cu-PGE deposits in flood basalt provinces. Late Paleozoic marine sediments and arc volcanics underlie Wrangellia flood basalts in the Kluane Ranges and throughout most of the Wrangellia Terrane (Muller, 1967; Read and Monger, 1976; Jones et al., 1977; Campbell, 1981). Zoned, sill-like mafic and ultramafic bodies, representing subvolcanic magma chambers for the overlying Triassic flood basalts, appear to preferentially intrude at or near the contact between the Hasen and Station Creek Formations in the Kluane Ranges. Many of these mafic and ultramafic sills have anomalous magmatic sulphide concentrations (Hulbert, 1997). These relationships indicate that S- and Ba-rich sediments may have been integral to contaminating magmas and initiating sulphide immiscibility (Hulbert, 1997). One of the aims of this study is to determine what the geochemistry of the Wrangellia flood basalts can tell us about the likelihood of discovering additional Ni-Cu-PGE deposits in this part of the terrane.

ONGOING AND PLANNED RESEARCH

We are presently preparing 85 samples of flood basalt and basement rock from the Wrangellia Terrane in Yukon for high-precision geochemical and isotopic analytical work at the Pacific Centre for Isotopic and Geochemical Research (PCIGR) at the University of British Columbia (UBC). Additionally, we are preparing 50 samples from Vancouver Island for analysis. 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. Due to the lack of a comprehensive published geochemical database for Wrangellia, this evaluation will require the acquisition of a large, internally consistent database with element concentrations and isotopic ratios measured in the same lab. Ratios of low-abundance trace elements, such as Nb/La, La/Sm, Ba/Th, Sr/Nd and Pb/Nd, are very sensitive to differences in sources and contaminants, and are therefore used to determine the extent of crustal contamination. Furthermore, combinations of different radiogenic isotopic systems such as Pb-Pb, Rb-Sr, Sm-Nd and Lu-Hf with different geochemical behaviours and relative ratios for the parent and daughter isotopes can precisely fingerprint potential source components (e.g., enriched mantle, depleted mantle, arc crust, sedimentary rocks). Select samples will be precisely dated by Ar-Ar methods to provide absolute time constraints on magmatism in the Wrangellia Terrane. Particular emphasis will be placed on determining the extent of crustal contamination in the Wrangellia magmatic suite by local sedimentary rock sources and/or by lower crustal material. Geochemical modeling will help to elucidate trends in compositional evolution and will determine whether arc assimilation may have given the Wrangellia flood basalts their distinct geochemical signature.

We plan to complete the compilation of geological information for the entire Wrangellia Terrane in B.C., Yukon and Alaska. The major goal of the compilation work is to constrain the location, aerial significance, and stratigraphic location of intrusions and sedimentary sequences. Additional field studies planned in Alaska during the summer of 2005 will supplement the work in Yukon. Ultimately, the goal of this project is to characterize the chemical composition of Wrangellia flood basalts in order to better understand the origin and evolution of oceanic plateaus, from their initiation at the mantle source to their accretion in the continental graveyard.

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