Distribution, nature, and origin of Neogene–Quaternary magmatism in the northern Cordilleran volcanic province, Canada

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ABSTRACT

The northern Cordilleran volcanic province encompasses a broad area of Neogene to Quaternary volcanism in northwestern British Columbia, the Yukon Territory, and adjacent eastern Alaska. Volcanic rocks of the northern Cordilleran volcanic province range in age from 20 Ma to ca. 200 yr B.P. and are dominantly alkali olivine basalt and hawaiite. A variety of more strongly alkaline rock types not commonly found in the North American Cordillera are locally abundant in the northern Cordilleran volcanic province. These include nephelinite, basanite, and peralkaline phonolite, trachyte, and comendite. The most MgO-rich nephelinites, basanites, and alkaline basalts from throughout the northern Cordilleran volcanic province show trace element abundances and isotopic compositions that are consistent with an asthenospheric source region similar to that for average oceanic island basalt and for post-5 Ma alkaline basalts from the Basin and Range.

Our petrologic observations help constrain the origin of northern Cordilleran volcanic province magmatism as well as lithosphere changes between the four major basement terranes that underlie the province. Results from phase equilibria calculations and the spatial distributions of volcanic rock types and magmatic inclusions are more consistent with the existence of thicker lithosphere beneath Stikinia, which underlies the southern part of the northern Cordilleran volcanic province, than beneath the Cache Creek and Yukon-Tanana terranes, which underlie the northern part of the northern Cordilleran volcanic province. Our results support a model for initiation of northern Cordilleran volcanic province magmatism due to incipient rifting of the northern Cordillera, driven by changes in relative plate motion between the Pacific and North American plates ca. 15–10 Ma.

Keywords: alkaline basalt, Canada, Cordilleran, magmatism, Quaternary, volcanism.

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INTRODUCTION

Neogene to Quaternary magmatism in the Cordillera of North America is closely related to the current tectonic configuration between the North American, Pacific, and Juan de Fuca plates (Fig. 1). Where plate boundaries are convergent (e.g., Washington State), magmatism is dominated by calc-alkaline stratovolcanoes (e.g., CVA, Fig. 1). Where plate boundaries are dominantly extensional and/or transtensional (e.g., southeastern California), mafic alkaline magmatism dominates (e.g., BR and RG, Fig. 1).

The most recently defined volcanic province in the North American Cordillera is the northern Cordillera volcanic province (Edwards and Russell, 1999). The northern Cordilleran volcanic province comprises dominantly mafic, Neogene, alkaline volcanic rocks distributed across the northern Canadian Cordillera (Fig. 1). Edwards and Russell (1999) proposed that magmatism in the northern Cordilleran volcanic province is linked to changes in far-field forces between the Pacific and North American plates. They showed that the timing and volumetric rates of volcanism in the northern Cordilleran volcanic province correlate with changes in the relative motions between the Pacific and North American plates, from dominantly compressional to dominantly transtensional.

Our objectives are twofold. Much of what has been published on volcanism in the northern Cordilleran volcanic province derives from short scientific or technical reports found in government publications and unpublished theses. Therefore, our first aim is to compile these data and use the synthesis to map the distributions of these diverse volcanic rocks in space and time. We then use the compiled petrological and geochemical data to address the origins of this alkaline magmatism and the structure of the lithosphere beneath the northern Cordilleran volcanic province. Specifically, we determine the source region characteristics of northern Cordilleran volcanic province magmas using trace element and isotopic data, and we produce a petrological image of the lithosphere using phase equilibria calculations for lavas and mantle peridotite xenoliths. Results of this analysis provide a basis on which to amplify the tectonic model we have developed for the origins of northern Cordilleran volcanic province magmatism (Edwards and Russell, 1999).

GEOLOGIC SETTING

The northern Cordilleran volcanic province comprises more than 100 mapped occurrences of volcanic rocks within northwestern British Columbia, the Yukon, and easternmost Alaska (Fig. 1; north of lat 55°N and west of long 126°W). The northern Cordilleran volcanic province designation encompasses volcanic rocks that were previously referred to as the Stikine volcanic belt (e.g., Souther and Yorath, 1991). All volcanic centers are west of the Tintina fault system and east of the Denali-Coast fault system (Fig. 2). Both of these fault systems are major structural features in the northern Cordillera that have accommodated several hundred kilometers of mainly dextral strike-slip motion since the Cretaceous (cf. Gabrielse and Yorath, 1991). The Tintina-Northern Rocky Mountain Trench fault system separates autochthonous North American crust to the east from allochthonous terranes to the west. The Denali fault system extends almost 2000 km from central Alaska to northwestern British Columbia, where it merges with the Coast Range fault system (cf. Wheeler and McFeeley, 1991). The Denali-Coast fault system is an approximate boundary between more highly disrupted, allochthonous terranes to the west (e.g., Wrangellia)

GSA Bulletin; August 2000; v. 112; no. 8; p. 1280–1295; 11 figures; 2 tables.

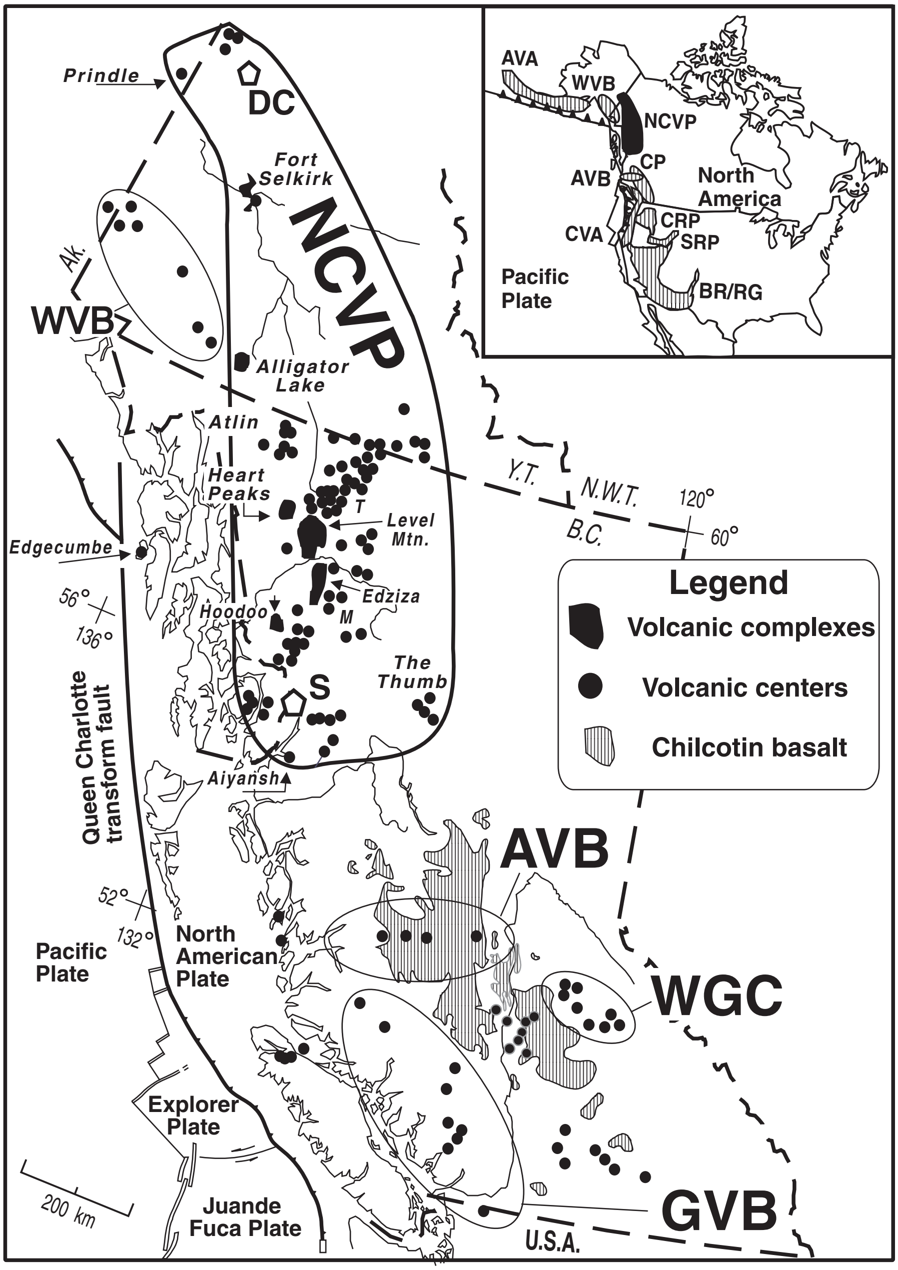

Figure 1. Distribution of Neogene and Quaternary volcanic rocks in the Canadian Cordillera, including: GVB—Garibaldi volcanic belt, WGC—Wells Gray-Clearwater volcanic field, AVB—Anaheim volcanic belt, WVB—Wrangell volcanic belt, and NCVP—the northern Cordilleran volcanic province (modified from Hickson, 1991). M—Locations of Maitland, and T—Tuya volcanic fields (Table 1) are also shown. The NCVP spans a region from DC—Dawson Creek, Yukon Territory, to S—Stewart, British Columbia. Inset shows the relationship of the NCVP to other volcanic regimes in western North America and includes: AVA—Aleutian volcanic arc, CVA—the Cascade volcanic arc, CP—Chilcotin plateau basalts; CRP—the Columbia River plateau basalt field, SRP—the Snake River Plain, and BR/RG—the Basin and Range-Rio Grande rift system.

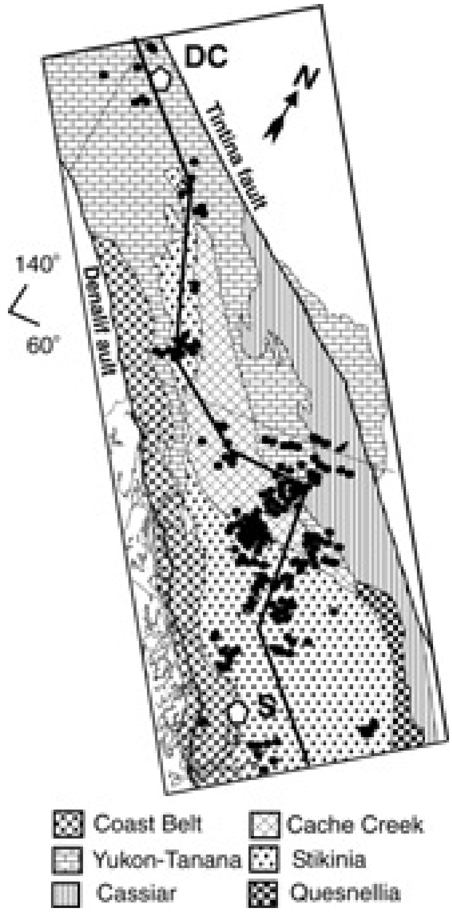

Figure 2. Distribution of volcanic centers in the northern Cordilleran volcanic province (NCVP) with respect to major tectonostratigraphic terrane boundaries and the Denali and Tintina fault systems (after Wheeler and McFeely, 1991). Line of section shown is that used in Figures 8, 9, and 10.

and larger, more coherent allochthonous terranes to the east (e.g., Stikinia) (cf. Wheeler and McFeely, 1991).

Northern Cordilleran volcanic province magmatism is spread across four major tectonostratigraphic terranes (Fig. 2), Stikinia, Cache Creek, Yukon-Tanana, and Cassiar. Stikinia is an allochthonous suite of late Paleozoic and Mesozoic volcanic, plutonic, and sedimentary rocks thought to have formed in an island-arc setting (Gabrielse and Yorath, 1991). The Cache Creek terrane, also allochthonous, is thought to have developed largely in an oceanic basin; it consists of late Paleozoic to Mesozoic oceanic melange and abyssal peridotites intruded by younger granitic plutons (cf. Gabrielse and Yorath, 1991). The Yukon-Tanana and Cassiar terranes comprise displaced, autochthonous sedimentary and metamorphic rocks derived from North America (Mortensen, 1992; Gabrielse and Yorath, 1991).

The southern margin of the northern Cordilleran volcanic province coincides with southwestern Stikinia and is defined by isolated volcanic vents and eroded lava remnants south of the town of Stewart (Fig. 1). The southern limit of the northern Cordilleran volcanic province coincides with a gap in Neogene magmatism and the inferred northern

TABLE 1. SUMMARY OF LOCATIONS, AGES, VOLCANIC LANDFORMS, AND VOLUMES FOR NEOGENE TO QUATERNARY ALKALI BASALTIC CENTERS WITHIN THE NORTHERN CORDILLERAN VOLCANIC PROVINCE

Volcanic field or center	Location		Age† (Ma)	Volcanic landforms	Volume§ (km^3)	Rock types	Source#
	Lat (N)	Long (W)					
Eastern Alaska (1)							
Prindle	63.72°	141.62°	3.57 ± 0.14, 6.26 ± 0.15 or younger	Cone, flow	~0.1		19, 54, 59, 78
Western Yukon Territory (4)							
West Dawson							
Sixty Mile	64.05°	140.74°	17.2 ± 0.3 (*)	Unknown	<<0.001	Basanite	53
Clinton Creek	64.40°	140.63°	3.05 ± 0.22	Unknown	<<0.001		52, 53
Forty Mile	64.38°	140.50°	19.9 ± 0.5 (*)	Unknown	<<0.001		53
Moose Creek	64.16°	140.91°	Tertiary–Quaternary	Unknown	<<0.001		53
Central Yukon Territory (6)							
Fort Selkirk							
Volcano Mountain	62.94°	137.32°	<0.0075	Cone, flow	0.04	Nephelinite, basanite	7, 21, 22, 40, 75
Wootton's Cone or Ne Ch'e Ddhäwa	62.74°	137.24°	>0.038	Cone, flow	~0.5		7, 9, 22, 62
Fork Selkirk	62.78°	137.36°	1.08 ± 0.05	Cone, flow	<0.001		7, 9, 22, 55
Pelly Formation	62.8°	137.5°	1.28 ± 0.03, 1.6 to 0.89	Flow	~15		7, 9, 22, 55
Wolverine Formation	62.7°	137.4°	Pleistocene–Quaternary: 1.6 to 0.89	Flow	~23		7, 9, 22
Minto	62.6°	137.2°	Neogene	Flow	<0.001		7, 9
Southern Yukon Territory (25)							
Alligator Lake	60.42°	135.42°	3.3 ± 0.4, 3.12 ± 0.03	Cone, flow	~0.5	Basanite	9, 15, 16, 20, 32, 59, 77
Ibex Mountain	60.51°	135.50°	2.4 ± 0.2	Cone			15, 77
Miles Canyon	60.6°	135.0°	8.38 ± 0.12	Flow	<1		15, 32, 77
Southeast Yukon Territory (4)							
Watson Lake	60.0°	129.0°	4.3 ± 0.3, 0.765 ± 0.049, 0.604 ± 0.039, 0.545 ± 0.046, 0.232 ± 0.021	Cone, flow	<0.1		43, 46
Northwest British Columbia *Atlin* (11)							
Anderson Bay	59.30°	133.75°	27.5 ± 4.3 to 16.2 ± 2	Flow	<0.1		6, 8
Chikoida Mountain	59.20°	133.04°	Tertiary–Quaternary	Neck	<0.001		14
Cracker Creek	59.70°	133.29°	Late Quaternary	Cone, flow?	0.003		1, 14
Hirschfeld/Line Lake	59.53°	132.92°	Tertiary–Quaternary	Neck	<0.1	Nephelinite, basanite	1, 9, 23
Llangorse Mountain—North	59.37°	132.78°	Tertiary–Quaternary	Neck, flow	<0.1	Nephelinite	1, 9, 14
Llangorse Mountain—West	59.32°	132.90°		Flow	<0.001		
Llangorse Mountain—South	59.30°	132.78°		Flow	<0.001		
Mount Sanford	59.42°	132.75°	Tertiary–Quaternary	Neck, dike/sill	<0.001		37
Ruby Mountain	59.70°	133.38°	0.54 ± 0.2	Cone, flow	~1	Basanite	1, 14, 44, 57, 58
Volcanic Creek	59.77°	133.40°	Late Quaternary	Cone, flow	0.02		1, 14
Northern British Columbia *Tuya* (>50)							
Ash Mountain	59.28°	130.50°	Pleistocene–Quaternary: intraglacial	Subglacial, dike/sill	3.2	2, 3, 25, 48, 50, 76	
Kawdy Mountain	58.87°	131.25°	Pleistocene–Quaternary: intraglacial	Cone	~14		28, 36
Mathew's tuya	59.20°	130.43°	Pleistocene–Quaternary: intraglacial	Subglacial, dike/sill	~1		3, 25, 61, 76
Metah Mountain/Isspah Butte	59.10°	131.32°	Pleistocene–Quaternary: intraglacial	Flow, subglacial	~5		3, 25, 36
Mount Josephine	59.08°	130.71°	Pleistocene–Quaternary: intraglacial	Flow	~3		25, 36
South tuya	59.20°	130.50°	Pleistocene–Quaternary: intraglacial	Subglacial	1.6		3, 50
Tanzilla butte	59.20°	130.43°	Pleistocene–Quaternary: intraglacial	Cone, flow	~3		25, 36
Many Caribou tuya	59.23°	130.57°	Pleistocene–Quaternary: intraglacial	Subglacial	~0.5		3, 25
Tuya Butte	59.13°	130.57°	Pleistocene–Quaternary: intraglacial	Subglacial	2.6		2, 3, 25, 48, 50, 76
Northern British Columbia (24)							
Cry Lake	58.3°	129.3°	5.07 ± 0.39, 0.73 ± 0.03	Cone, flow, unknown			4, 26, 27

limit of Neogene subduction, marked by the eastward projection of the northern edge of the Juan de Fuca plate. These two features separate the northern Cordilleran volcanic province from Neogene magmatic provinces to the south, such as the Chilcotin plateau, the Anaheim belt, and Wells-Gray (Fig. 1). The eastern margin of the northern Cordilleran volcanic province is defined by a group of volcanic necks including the Thumb, in central British Columbia (Fig. 1). The northern and western boundaries are defined by Prindle volcano, in eastern Alaska, and by erosional remnants of lava flows that crop out immediately north and west of Dawson City (Fig. 1).

SPATIAL AND TEMPORAL DISTRIBUTION OF NORTHERN CORDILLERAN VOLCANIC PROVINCE CENTERS

The main attributes of individual volcanic centers within the northern Cordilleran volcanic

TABLE 1. (*Continued.*)

Volcanic field or center	Location Lat (N)	Long (W)	Age[†] (Ma)	Volcanic landforms	Volume[§] (km^3)	Rock types	Source[#]
Western British Columbia							
Heart Peaks	58.6°	131.9°	Neogene to Holocene (?)	Flow, subglacial	<160		10, 28, 68
Level Mountain	58.5°	131.3°	14.9 to Holocene (?)	Cone, flow, subglacial	~860 (total)	Ankaramite, hawaiite, phonolite, tristanite, comendite	28, 30, 31, 68
***Telegraph Creek* (>50)**							
Mount Edziza	57.5°	130.6°	7.4 to Holocene (?)	Shield, strato, caldera, cone, dome, neck, subglacial	~665 (total)	Ankaramite, hawaiite, phonolite, tristanite, comendite	63, 66, 67
***Klastline* (>4)**							
Castle Rock	57.8°	130.2°	Pleistocene–Quaternary: intraglacial	Cone, subglacial			45, 59, 60, 63
***Spatzizi* (>30)**							
Maitland Creek	57.4°	129.7°	4-5	Flow, neck	<0.001		17, 18, 64
Tumeka Lake	57.2°	129.5°	Tertiary–Quaternary	Unknown	<0.001		17, 18, 64
Griffith Creek	57.5°	128.5°	1.32 ± 0.03	Neck	<0.001	Nephelenite	17, 18, 64
Konigus Creek	57.0°	129.3°	Tertiary–Quaternary	Unknown	<0.001		17, 18
Upper Nass River	57.1°	129.0°	Pleistocene–Quaternary: intraglacial	Cone, subglacial	<0.1		17, 18
***Iskut* (10)**							
Cinder Mountain	56.58°	130.63°	0.033 ± 0.0024	Cone	<0.08	Hawaiite	5, 11, 29, 33, 34, 42, 58
Cone Glacier	56.57°	130.67°	Holocene	Cone, flow, subglacial	<0.09		5, 11, 29, 33, 34, 42, 58
Iskut River	56.73°	130.62°	0.07 ± 0.03 to 2555 ± 60 yr B.P.	Cone, flow	<8.6		5, 11, 29, 33, 34, 42, 57, 58
King Creek	56.48°	130.67°	Holocene	Subglacial	<0.07		5, 11, 29, 33, 34, 42, 57, 58
Lava Fork	56.42°	130.87°	360 ± 60 yr B.P. to ~150 yr B.P.	Cone, flow	<0.22		5, 11, 29, 33, 34, 42, 57, 58
Second Canyon	56.40°	130.71°	Holocene	Cone, flow	<0.13		5, 11, 29, 33, 34, 42, 57, 58
Snippaker Creek	56.63°	130.82°	Holocene	Cone, flow	<0.15		5, 11, 29, 33, 34, 42, 57, 58
Tom Mackay Creek	56.71°	130.55°	Holocene	Cone, flow	<0.012		5, 11, 29, 33, 34, 42, 57, 58
Hoodoo Mountain	56.77°	131.29°	0.11 to 0.02, 0.085 to 0.009*	Strato, cone, flow, subglacial, G, dome, neck, dike/sill	17.3	Phonolite	5, 12, 13, 42
Little Bear Mountain	56.82°	131.31°	0.235*	Cone, subglacial, dike/sill	1.8		12, 13
***Nass River* (20)**							
Alice Arm	55.4°	132.0°	Quaternary (?)	Flow	(?)		35
Bowser basin	56.9°	129.3°	1.6, Quaternary	Cone	(?)		29, 35
Widdzech Mountain	55.45°	129.33°	Pleistocene–Quaternary	Flow	(?)		17, 29
Hoan Creek	55.34°	129.28°	0.175 ± 0.05	Flow	(?)		17, 29, 49
Aiyansh River	55.1°	128.9°	250 ± 130 yr B.P., 625 ± 70 yr B.P.	Cone, flow	(?)		17, 29, 71, 72, 79
***McConnell Creek* (10)**							
The Thumb	56.16°	126.70°	Quaternary (?)	Subglacial, neck	(?)		47, 57

*Geographic specific designations are in italics, number of stratigraphic units within a geographic designation is shown in parentheses.

[†]All radiometric ages are K-Ar, except where (*) denotes Ar/Ar; Tertiary–Quaternary and Pleistocene–Quaternary are estimated ages.

[§]Volumes derive from literature or from calculations using mapped surface areas and reported estimates of thickness.

[#]Sources include: 1—Aitken (1959); 2—Allen (1991); 3—Allen et al. (1982); 4—Anderson (GSC 92-16) in Hunt and Roddick (1992); 5—BC Hydro (1985); 6—Bloodgood and Bellefontaine (1990); 7—Bostock (1936); 8—Bultman (1979); 9—Carignan et al. (1994); 10—Casey (1980); 11—Cousens and Bevier (1995); 12—Edwards (1997); 13—Edwards et al. (1995); 14—Edwards et al. (1996); 15—Eiché (1986); 16—Eiché et al. (1987); 17—Evenchick (1995, personal commun.); 18—Evenchick and Thorkelson (1993); 19—Foster et al. (1966); 20—Francis (1987); 21—Francis (1991); 22—Francis and Ludden (1990); 23—Francis and Ludden (1995); 24—Gabrielse (1963); 25—Gabrielse (1968); 26—Gabrielse (1978); 27—Gabrielse (GSC 92-24) in Hunt and Roddick (1992); 28—Gabrielse et al. (1962); 29—Grove (1986); 30—Hamilton (1981); 31—Hamilton (1991); 32—Hart and Villeneuve (1999); 33—Hauksdóttir (1994); 34—Hauksdóttir et al. (1994); 35—Hickson (1991); 36—Hickson (1995, personal commun.); 37—Higgins and Allen (1984); 38—Jackson (1989); 39—Jackson (GSC 92-43) in Hunt and Roddick (1992); 40—Jackson and Stevens (1992); 41—Jackson et al. (1996); 42—Kerr (1948); 43—Klassen (1987); 44—Levson (1992); 45—Littlejohn and Greenwood (1974); 46—Lord (1944); 47—Lord (1948); 48—Mathews (1947); 49—V. McNicoll (unpublished, 1997); 50—Moore et al. (1995); 51—Mortensen (GSC 92-29) in Hunt and Roddick (1992); 52—Mortensen (GSC 92-50) in Hunt and Roddick (1992); 53—Mortensen and Roddick (1989); 54—Mortensen and Wirth (GSC 92-97, 92-98) in Hunt and Roddick (1992); 55—Naeser et al. (1982); 56—Nelson (GSC 92-25) in Hunt and Roddick (1992); 57—Nicholls and Stout (1996); 58—Nicholls et al. (1982); 59—Prescott (1983); 60—Ross (1983); 61—Simpson (1996); 62—Sinclair et al. (1978); 63—Souther (1971); 64—Souther (1991a); 65—Souther (1991b); 66—Souther (1992); 67—Souther and Hickson (1984); 68—Souther and Yorath (1991); 69—Souther et al. (1984); 70—Stasiuk and Russell (1989); 71—Sutherland Brown (1969); 72—Symons (1975); 73—Thorkelson (GSC 92-23) in Hunt and Roddick (1992); 74—Thorkelson (1992); 75—Trupia and Nicholls (1996); 76—Watson and Mathews (1944); 77—Wheeler (1961); 78—Wirth (1991); 79—Wuorinen (1978).

province are summarized in Table 1, including location, age, volcanic landforms, estimates of volume, and rock types. Pertinent references are also listed. Three main types of volcanic centers dominate the northern Cordilleran volcanic province: (1) areally extensive, long-lived (>5 m.y.) volcanic plateaus with associated felsic domes and subvolcanic intrusions (e.g., Edziza), (2) areally restricted, polygenetic volcanic complexes (e.g., Hoodoo), and (3) areally restricted, monogenetic volcanoes, cinder cones, and isolated lava flows (e.g., Aiyansh). Volcanic deposits include lava flows, welded and nonwelded pyroclastic deposits, hydroclastic deposits, and other ice-contact volcanic deposits. The diversity of deposit types, in part, reflects the changes in eruption environments from dominantly subaerial to largely subglacial (e.g., Souther, 1992) during the formation of the northern Cordilleran volcanic province.

Types of Volcanic Centers

Broad plateaus of coalesced, basaltic shield volcanoes are the most voluminous volcanic deposits in the northern Cordilleran volcanic province. They are found only in the central part of the province and include the Level Mountain, Mount Edziza, Heart Peaks, and Maitland volcanic complexes (Fig. 1). At Level Mountain and Mount Edziza, the plateaus form a base for subsequent felsic lava domes and mafic and felsic lava flows (Hamilton, 1981; Souther, 1992). Level Mountain, the largest of the volcanic plateaus, comprises more than 860 km^3 of flat-lying mafic lava flows, felsic lava flows, and felsic domes covering an area of ~1800 km^2 (Hamilton, 1981). The Mount Edziza volcanic complex is the second largest and one of the best-studied centers in the northern Cordilleran volcanic province. Souther (1992) recognized five magmatic cycles at Mount Edziza, each of which began with dominantly basaltic magmatism and ended with eruption of peralkaline, felsic lava. The total volume of volcanic rocks erupted at Mount Edziza is ~670 km^3 and the total surface area covered is ~1000 km^2 (Souther, 1992). Heart Peaks, the third largest center in the northern Cordilleran volcanic province, is immediately west of Level Mountain. It is made up of mafic lava flows with a composite thickness up to 430 m, which cover an area of ~275 km^2 (Souther and Yorath, 1991). The Maitland volcanic complex is situated 50 km east of Mount Edziza (Fig. 1) and includes numerous isolated lava flows and volcanic necks that have been interpreted as the remnants of a shield volcano originally covering more than 900 km^2 (Souther, 1991).

The Fort Selkirk, Alligator Lake, and Hoodoo Mountain volcanic complexes are intermediate in size between the large shield volcanoes and smaller, monogenetic centers. Fort Selkirk, in the north-central Yukon Territory, includes two sequences of valley-filling basaltic lava flows and three basaltic to nephelinitic volcanic centers (Table 1). The Alligator Lake volcanic complex, in the south-central Yukon Territory, is represented by remnants of five different sequences of basaltic lava flows and two younger cinder cones (Eiché et al., 1987). The Hoodoo Mountain volcanic complex, in west-central British Columbia, is a large phonolitic and trachytic volcano with a smaller satellite basaltic volcano (Edwards, 1997). The complex is similar in size to Fort Selkirk and Alligator Lake but has a stronger chemical affinity to Level Mountain and Mount Edziza because of its bimodal character.

Smaller, valley-filling lava flows and cinder cones are numerous throughout the northern Cordilleran volcanic province and mainly have been identified by regional-scale geologic mapping (e.g., Gabrielse et al., 1962; Gabrielse, 1968; Evenchick and Thorkelson, 1993). Some lava flows and associated vents (e.g., cinder cones) are still preserved (e.g., Aiyansh; Sutherland Brown, 1969). However, in the northern half of the northern Cordilleran volcanic province many of the lava flows have been heavily eroded and the locations of the corresponding vents are unknown (e.g., West Dawson; Mortensen and Roddick, 1989).

Neogene subvolcanic intrusions are exposed in areas of high relief. For example, volcanic necks or plugs have been described at Mount Edziza, Level Mountain, Hoodoo Mountain, and the Thumb and from the Atlin and Maitland areas (Table 1). Many of the isolated necks in the Atlin and Maitland areas are olivine nephelinite or basanite (cf. Table 1 for references). Small plugs of gabbro and alkali granite that are spatially and temporally associated with volcanic stratigraphy are described from Mount Edziza and Level Mountain (Table 1).

The northern Cordilleran volcanic province hosts numerous subglacial and/or subaqueous volcanic deposits (Table 1). For example, the type locality for tuyas (Mathews, 1947) is the central part of the northern Cordilleran volcanic province. The abundance of subglacial volcanic deposits in the northern Cordilleran volcanic province reflects the common coincidence of volcanoes and glaciers in the northern Cordillera during the late Pliocene and Quaternary.

Temporal Distribution of Magmatism

Volcanism in the northern Cordilleran volcanic province ranges in age from Neogene (20 Ma) to Quaternary (Table 1). However, early Neogene (>14 Ma) alkali-olivine basalt is found only in the northern half of the northern Cordilleran volcanic province (Fig. 3A) and mid-Neogene (9-4 Ma) volcanic deposits are found mainly in the central part of the northern Cordilleran volcanic province (Fig. 3A). The two largest volcanic centers in the northern Cordilleran volcanic province (Level Mountain and Mount Edziza) have extended magmatic histories; these centers were intermittently active from the late Neogene through to the Quaternary. Pleistocene-Quaternary volcanism (3.5 Ma to 10 ka) was distributed throughout the length of the northern Cordilleran volcanic province and included activity at large volcanic centers (e.g., Level Mountain) and at many smaller, isolated centers (Fig. 3A). Several of these isolated volcanic centers occur in the central part of the northern Cordilleran volcanic province and are indirectly dated as Pliocene and/or Pleistocene, on the basis of the presence of subglacial and/or intraglacial deposits (Table 1). Holocene eruptions have been reported from at least four different areas within the northern Cordilleran volcanic province, including Volcano Mountain, Mount Edziza, and Hoodoo Mountain (Fig. 3A; Table 1). Some lava flows may be as young as 200 yr B.P. and constitute the youngest volcanic activity in Canada (e.g., Lava Fork and Aiyansh; Table 1).

Rates of Magmatism

Within the northern Cordilleran volcanic province, the number of active centers and the volumetric eruption rate have varied with time (Edwards and Russell, 1999). Over the past 20 m.y., the number of active centers in the northern Cordilleran volcanic province has averaged <5 centers per million years (e.g., 5 c/m.y.; Edwards and Russell, 1999). In contrast, from 2 Ma to the present the number ranged from 25 centers/m.y. (2-1 Ma) to 11 centers/m.y. (1 Ma to present).

Figure 4 shows the cumulative volume of erupted material versus time for the northern Cordilleran volcanic province; the slope is a qualitative measure of the overall rate of magmatism (km^3/m.y.). Although the rate of magmatism has varied substantially through time, there is no correlation between the rate of magma production and the number of active centers during any interval of time (Edwards and Russell, 1999). Initially (20 Ma) volcanism was sporadic, producing small volumes of material. The eruption rate increased markedly (e.g., ~10^{-4} km^3 yr^{-1}) when volcanism began at Level Mountain at 15 Ma. When Mount Edziza began to erupt (ca. 7 Ma), rates of magmatism for the northern Cordilleran volcanic province increased to ~3×10^{-4} km^3 yr^{-1} (Fig. 4). Between ca. 4 and 3 Ma a magmatic lull appears to have ensued; subsequently rates of magmatism have remained relatively constant at 10^{-4} km^3 yr^{-1}. Current rates of magmatism for the northern Cordilleran volcanic province are

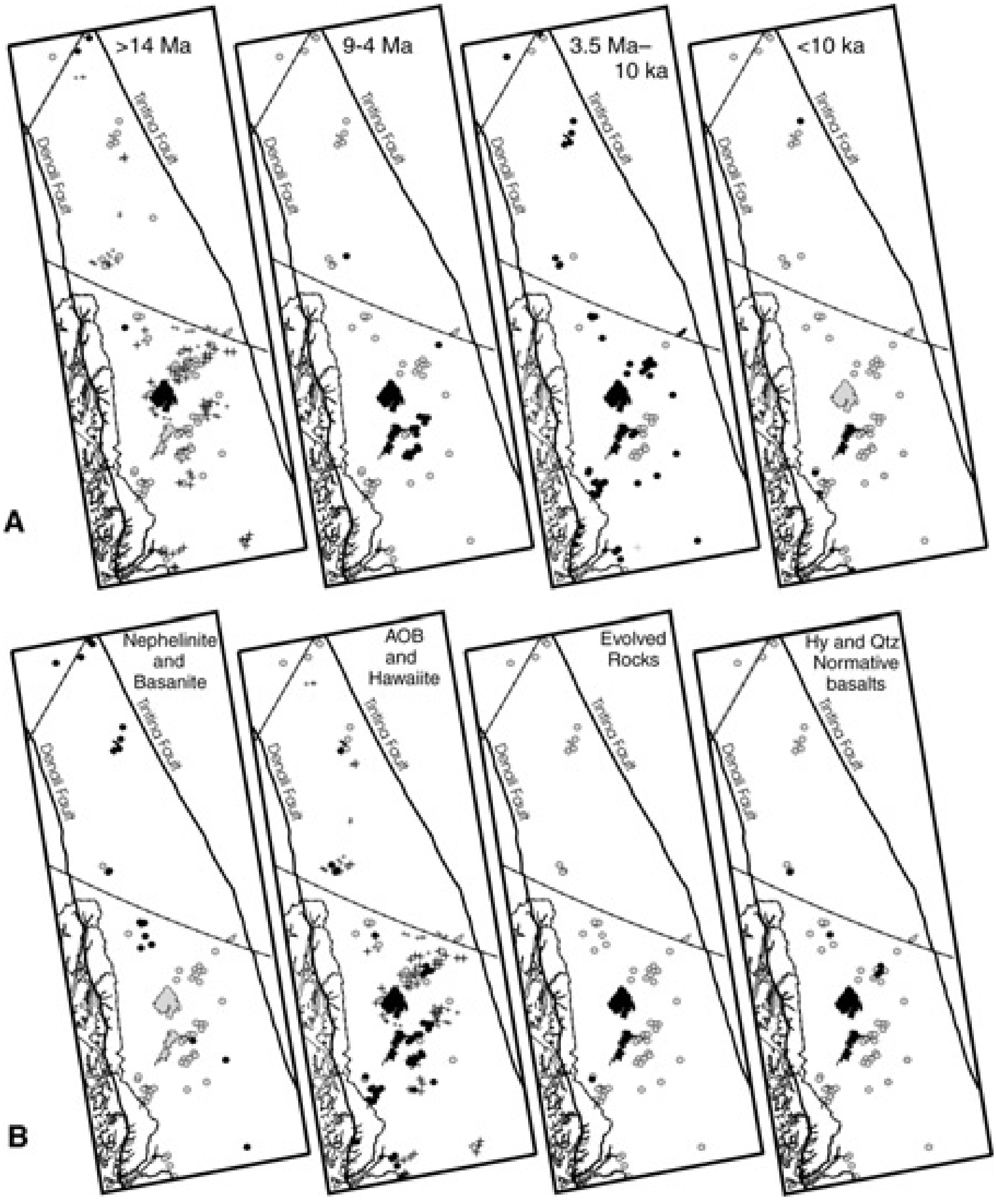

Figure 3. Distribution of northern Cordilleran volcanic province volcanic rocks are shown for: (A) specific age intervals: >14 Ma, 9–4 Ma, 3.5 Ma to 10 ka, and <10 ka, and (B) specific rock types: basanite and olivine nephelinite, AOB (alkali olivine basalt) and hawaiite, evolved rocks (e.g., phonolite, trachyte, peralkaline rhyolite), and hypersthene- and quartz-normative basalt. Centers that include rocks of the specific age or rock type are shown in black; all others are shown in gray. Dark crosses denote either (A) localities with no radiometric or geologic age constraints or (B) localities reported only as olivine basalt.

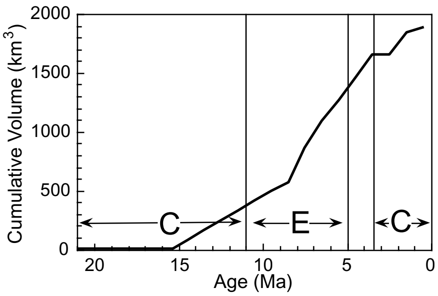

Figure 4. Variations in intensity of magmatism are plotted as cumulative volume of magmatism as function of time. Vertical lines denote changes in relative motions of Pacific and North American plates from compression (C) to extension (E) (see text for explanation).

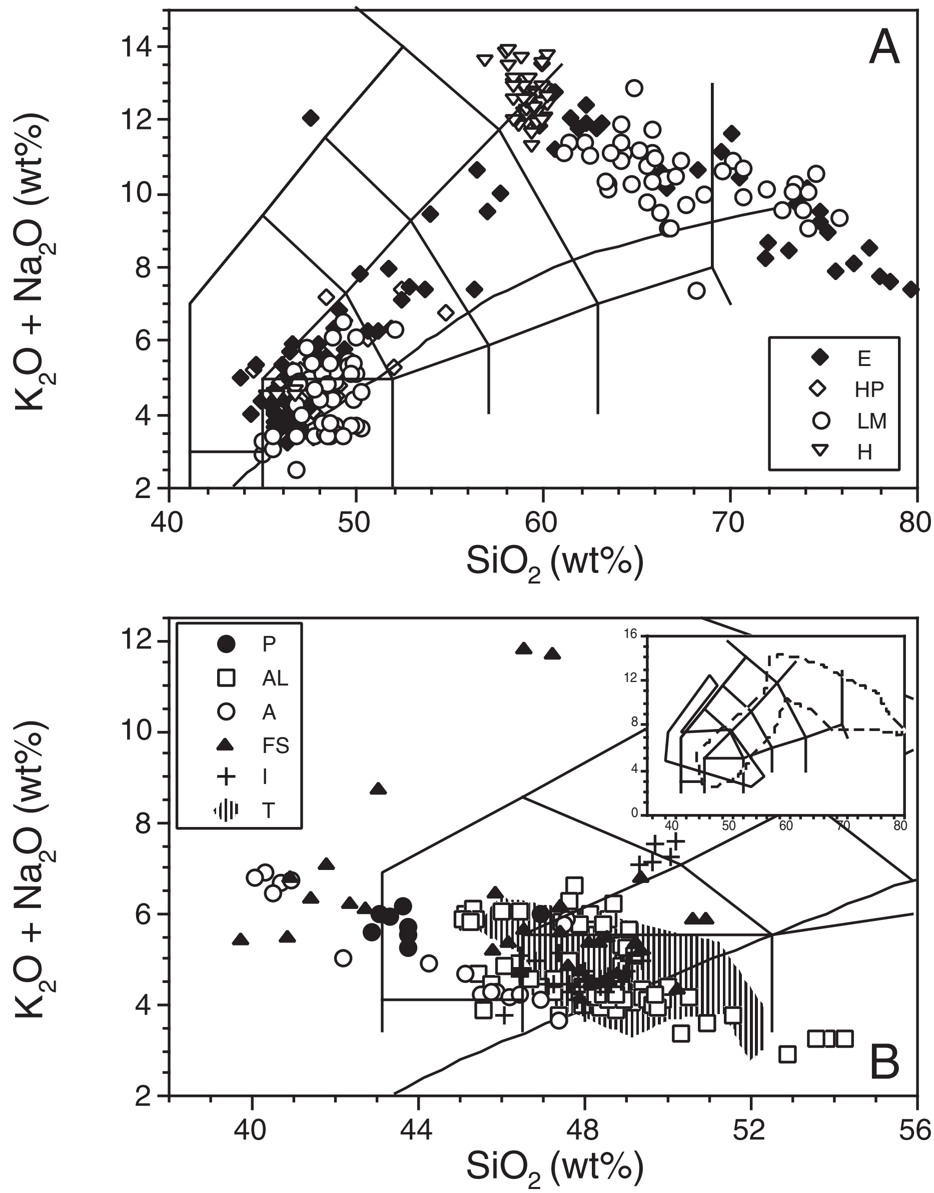

Figure 5. Rock compositions plotted as $K_2O + Na_2O$ vs. SiO_2 (LeBas et al., 1986) for (A) volcanic complexes with evolved rocks including E—Edziza, HP—Heart Peaks, LM—Level Mountain, and H—Hoodoo, and (B) other centers within the NCVP including P—Prindle, AL—Alligator Lake, A—Atlin, FS—Fort Selkirk, I—Iskut, and T—Tuya. Inset figure (B) compares fields for both data sets.

much less than those estimated for Hawaii (10^{-1}–10^{-3} km^3 yr^{-1}; Shaw, 1987) or the Cascade volcanic arc (0.2–6 km^3 yr^{-1}; Sherrod and Smith, 1990). However, the temporal patterns emerging for northern Cordilleran volcanic province volcanism must be treated cautiously. The older volcanic centers have been eroded by Pleistocene glaciers and many of the centers have not yet been directly dated or have not been dated in sufficient detail to recognize more discrete temporal patterns (e.g., Hildreth and Lanphere, 1994).

PETROLOGY

Volcanic Rocks

The northern Cordilleran volcanic province is dominated by mafic, alkaline volcanic rocks (Table 1). Alkali olivine basalt and hawaiite occur throughout the length of the northern Cordilleran volcanic province and are volumetrically the most abundant rock types (Fig. 3B). Basanite and olivine nephelinite are less common and are most abundant from Atlin northward (Fig. 3B); however, isolated occurrences of basanite occur throughout the northern Cordilleran volcanic province. Locally, tristanite, mugearite, picritic basalt, ankaramite, and minor amounts of hypersthene- and quartz-normative basalt have also been reported (Fig. 3; Table 1).

More evolved alkaline rock types such as phonolite, trachyte, and comendite are limited to the southern half of the northern Cordilleran volcanic province and are only associated with the larger volcanic centers (Fig. 3B). At Mount Edziza, comendite and pantellerite compose ~50% by volume of the complex (Souther, 1992). At Hoodoo Mountain, phonolite and trachyte make up >90% by volume of the exposed volcanic pile.

The alkaline signature is pervasive throughout the northern Cordilleran volcanic province. Mineralogically, the mafic rocks contain groundmass olivine and titanaugite and lack Ca-poor pyroxene. Whole-rock compositions generally plot in the alkaline field (Irvine and Baragar, 1971; Le Bas et al., 1986) (Fig. 5). Evolved rock types (SiO_2 > 56 wt%) include silica-undersaturated, nepheline-bearing phonolite and silica-saturated, peralkaline (molar Na + K > Al) trachyte, comendite, and pantellerite containing aegirine-augite, arfvedsonite, and/or aenigmatite (Table 1). Collectively, the rocks form a sodic, alkaline province (Fig. 5).

Lithospheric Xenoliths and Magmatic Inclusions

Lithospheric xenoliths derived from the mantle and crust, megacrysts of ubiquitous origins, and cognate inclusions are common throughout the northern Cordilleran volcanic province (Edwards, 1997; Table 2). Crust-derived xenoliths include high-grade metamorphic rocks and felsic plutonic rocks (Table 2). Granulite facies xenoliths are reported only from Prindle, Fort Selkirk, Castle Rock, and Iskut River (Table 2); granulite fa-

TABLE 2. DISTRIBUTION OF XENOLITHS WITHIN THE NORTHERN CORDILLERAN VOLCANIC PROVINCE

Terranes or centers	Types of xenoliths and inclusions				
	Peridotite	Granulite	Crustal	Megacrysts	Xenocrysts
Yukon-Tanana					
Clinton Creek	Lherzolite, harzburgite, wehrlite, or websterite	Mafic, felsic	Granite, gneiss, schist	Clinopyroxene	
40 Mile	Lherzolite, harzburgite, wehrlite, or websterite	Mafic, felsic	Granite, gneiss, schist	Clinopyroxene	
60 Mile	Lherzolite, harzburgite, wehrlite, or websterite	Mafic, felsic	Granite, gneiss, schist	Clinopyroxene	
Prindle	Lherzolite, harzburgite, wehrlite, or websterite	Mafic, felsic	Granite, gneiss, schist	Clinopyroxene	
Yukon Tanana–Stikinia					
Volcano Mountain	Lherzolite, dunite, wehrlite, or websterite		Granite, schist		Quartz, K-feldspar
Pelly Formation	Lherzolite, dunite, wehrlite, or websterite		Granite, schist		Quartz, K-feldspar
Fort Selkirk	Lherzolite, dunite, wehrlite, or websterite		Granite, schist		Quartz, K-feldspar
Wootton's Cone	Lherzolite, dunite, wehrlite, or websterite		Granite, schist		Quartz, K-feldspar
Wolverine Formation	Lherzolite, dunite, wehrlite, or websterite		Granite, schist		Quartz, K-feldspar
Coast Plutonic Complex					
Alligator Lake	Lherzolite, harzburgite		Granite		
Cache Creek					
Ruby Mountain	Lherzolite, harzburgite, dunite, wehrlite, or websterite			Granite, gabbro	Clinopyroxene
Cracker Creek	Lherzolite, dunite		Granite		
Volcano Creek	Lherzolite, dunite, wehrlite, or websterite		Granite	Clinopyroxene	
Chikoida Mountain	Lherzolite, dunite		Granite	Clinopyroxene	
Hirschfeld orLine Lake	Lherzolite, harzburgite, dunite, wehrlite, or websterite			Granite, gabbro	Clinopyroxene
Llangorse Mountain	Lherzolite, harzburgite, dunite, wehrlite, or websterite			Granite gabbro	Clinopyroxene
Kawdy Mtn.	Lherzolite		Granite		
Cassiar					
Ash Mountian			Granite, gabbro		
3 Caribou			Granite		
South tuya			Granite		
Stikinia (N)					
Heart Peaks					Quartz, K-feldspar
Level Mountain	Lherzolite, wehrlite, or websterite		Gabbro, gneiss, schist	Clinopyroxene	
Castle Rock	Lherzolite, dunite	Mafic	Granite, gabbro		
Edziza	Lherzolite		Granite, gabbro		
Maitland Creek	Lherzolite		Granite		
Kunigus Creek	Lherzolite		Granite		
Tumeka Lake	Lherzolite		Granite		
Griffith Creek	Lherzolite		Granite		
Stikinia (NW)					
Hoodoo Mountain			Granite, gabbro		
Little Bear Mountain			Granite, gabbro	Clinopyroxene	
Iskut River			Granite, gabbro	Plagioclase, clinopyroxene	
Snippaker Creek			Granite		
Cone Glacier			Granite		
King Creek			Granite		
Lava Fork			Gneiss schist	Plagioclase	
Stikinia (W) Aiyansh			Granite	Plagioclase	
Stikinia (E) The Thumb			Gabbro		

cies basement rocks are not exposed adjacent to any of these centers. Felsic plutonic xenoliths are much more widespread (Table 2) and commonly derived from locally exposed granite and granodiorite bodies. For example, Eiché et al. (1987) found granitic xenoliths at Alligator Lake that match nearby Coast Belt intrusions.

Cognate inclusions include troctolite, gabbro, syenite, and a suite of plagioclase-dominated inclusions (Table 2). The cognate inclusions are most common in lavas from the central part of the northern Cordilleran volcanic province, including the Tuya area, Level Mountain, Mount Edziza, and Hoodoo Mountain (Table 2). The latter three centers represent long-lived volcanoes that contain chemically evolved volcanic rocks and are underlain by Stikinia. The predominance of cognate inclusions as well as the presence of evolved rock types in centers underlain by Stikinia are consistent with the lithosphere beneath Stikinia being either thicker than that beneath the other basement terranes to the northern Cordilleran volcanic province or having structural characteristics conducive to the formation of lithospheric magma chambers.

Megacrysts found in northern Cordilleran volcanic province lava flows compose three distinct groups (Table 2): kaersutitic amphibole, clinopyroxene, and plagioclase. The kaersutite megacrysts have been reported from a single locality, Llangorse Mountain (Higgins and Allen, 1984). Glassy, black clinopyroxene megacrysts occur across the entire northern Cordilleran volcanic province (e.g., from Prindle volcano to the Iskut area). We interpret this as indicating that their formation is independent of lithospheric structure. Conversely, clear, glassy plagioclase megacrysts are found mainly in the southern part of the northern Cordilleran volcanic province (e.g., Iskut area, Mount Edziza, and Aiyansh) and mainly within the boundaries of Stikinia (Table 2). We interpret this restricted distribution as indicating an origin that is sensitive to the lithospheric structure and composition (e.g., contamination or magma ponding). Plagioclase and clinopyroxene megacrysts locally display obvious signs of reaction with the host magma, including sieve-textured cores and irregular, resorbed and embayed outer margins everywhere they are found.

At least 15 volcanic centers covering more than two-thirds of the length of the northern Cordilleran volcanic province contain mantle-derived xenoliths (Table 2). Their distribution is skewed toward the northern half of the northern Cordilleran volcanic province and toward the Yukon-Tanana and Cache Creek terranes (Fig. 2). Mantle-derived xenoliths are found in most of the centers situated in Yukon-Tanana, in approximately one-half of the centers in Cache Creek, and in several centers within Stikinia; they have not been reported from the Cassiar terrane (D. Francis, 1996, personal commun.).

Mantle xenoliths include dunite, lherzolite, harzburgite, websterite, wehrlite, and garnet pyroxenite (Table 2). Previous geochemical studies have shown both depleted and undepleted ultramafic xenolith populations at Fort Selkirk (Prescott, 1983; Ross, 1983), Alligator Lake (Francis, 1987), and Castle Rock (Prescott, 1983; Ross, 1983). Shi et al. (1998) suggested that northern Cordilleran volcanic province volcanic centers carry two distinct suites of xenoliths: unimodal and bimodal. The unimodal suite is dominated by lherzolite and occurs in centers situated either north of Alligator Lake or south of Atlin. The bimodal suite comprises harzburgite and lherzolite and is found only in the Atlin area and at Alligator Lake.

We have summarized data on xenoliths in a schematic, north-south-oriented cross section through the northern Cordilleran volcanic province (Fig. 6). The line of section follows that shown in Figure 2. Positions of volcanic centers have been projected into the cross section at the correct latitudinal positions against the backdrop of the major terrane boundaries. The orientations of the terrane boundaries in the subsurface are largely undetermined, but are a focus of the ongoing Lithoprobe (Snorcle transect) and Accrete seismic studies. The middle portion of Figure 6 summarizes the types of xenoliths found at each center. Upper crustal xenoliths occur throughout the length and breadth of the northern Cordilleran volcanic province, whereas lower crustal xenoliths are less common. Similarly, mantle xenoliths occur in volcanoes overlying all of the different terranes, but are less common south of 57°N.

Calculated equilibrium temperatures from two-pyroxene thermometry (Wells, 1977) applied to mantle and lower crust xenoliths are shown in the lower panel of Figure 6. The data derive mainly from Prescott (1983), Francis (1987), Nicholls et al. (1982), and Edwards and Russell (unpublished data). Maximum and minimum temperatures recorded by mantle xenoliths increase to the south. A Prindle xenolith records the lowest temperature (860 °C) and temperatures from Fort Selkirk xenoliths show the smallest range (960–1050 °C). Xenoliths from Castle Rock record the highest temperatures (1260 °C) and the largest range in temperatures (1000–1260 °C). Also shown in Figure 6 are temperatures for two felsic granulites from Prindle (open circles; 930–960 °C).

GEOCHEMICAL CHARACTER OF NORTHERN CORDILLERAN VOLCANIC PROVINCE SOURCE REGIONS

Several workers have attempted to characterize geochemical variations in the source regions of the northern Cordilleran volcanic province magmas using major and trace element geochemistry and radiogenic isotopes (e.g., Carignan et al., 1994; Francis and Ludden, 1990, 1995; Cousens and Bevier, 1995; Moore et al., 1995). Moore et al. (1995) argued that magmas in the Tuya area (Fig. 1) derived from two different mantle sources: one giving rise to hypersthene normative (tholeiitic) basalt and another producing nepheline normative (alkali olivine) basalt. In contrast, Francis and Ludden (1990, 1995) identified three mafic magma series in the Atlin and central Yukon areas based on major and trace element characteristics: olivine nephelinite, basanite, and alkali olivine to transitional basalt. They proposed that these series represented at least two different mantle sources. In contrast to Moore et al. (1995), they suggested that nepheline normative and hypersthene normative basalt are cogenetic. Carignan et al. (1994) suggested that volcanic rocks from the northern Cordilleran volcanic province required at least three distinct isotopic reservoirs: (1) a nonradiogenic source for olivine nephelinites at Fort Selkirk and Atlin, (2) a somewhat more radiogenic source for alkali olivine basalts from Fort Selkirk; and (3) a source with radiogenic Pb but nonradiogenic Sr for alkali olivine basalts from Mount Edziza.

Our analysis of the source region variations to the northern Cordilleran volcanic province magmatism is based on trace and isotopic data compiled from the literature (Figs. 7 and 8). Trace element compositions of the most primitive rock types throughout the northern Cordilleran volcanic province (e.g., nephelinites, basanites, and high-MgO basalts) are plotted normalized to primitive mantle values in Figure 7. The patterns for all the volcanic rocks are broadly similar, showing overall enrichments of as much as 100× primitive mantle for incompatible elements and 10× primitive mantle for the more compatible elements. Nephelinite rocks are the most enriched, followed by basanite and then by basalt. Within-group variations for the three rock types are slight; samples show similar degrees of enrichment and parallel patterns, suggesting a common origin for each rock type.

Mafic volcanic rocks are very similar in trace element abundance patterns to the average composition of oceanic island basalt (OIB, Fig. 7). Thus we infer that nephelinite, basanite, and alkali olivine basalt from the northern Cordilleran volcanic province are derived from source regions having trace element distributions similar to those of average OIB mantle sources (Fig. 7).

Isotopic data on volcanic rocks from the northern Cordilleran volcanic province are limited (Fig. 8). Most samples have values of ε_{Nd} greater than +5 and values of $^{87}Sr/^{86}Sr < 0.705$. All northern Cordilleran volcanic province volcanic rocks have isotopic compositions that plot in the OIB field or overlap the most radiogenic end of the mid-ocean ridge basalt field. In this regard, the isotopic data corroborate the trace element data (Fig. 7); both data sets illustrate the geochemical similarity between northern Cordilleran volcanic province and OIB source regions.

Also shown in Figure 8 is the field for Stikinia, which serves as basement to many northern Cordilleran volcanic province volcanic centers (cf. Fig. 2). Samples from Stikinia with $^{87}Sr/^{86}Sr < 0.707$ tend to be isotopically indistinguishable from northern Cordilleran volcanic province volcanic rocks and modern-day OIB. This observation underscores the challenge of using isotopic data for detecting the effects of crustal contamination in the northern Cordillera.

Figure 9 shows geochemical characteristics for mafic rocks from the northern Cordilleran volcanic province having MgO contents >6 wt% plotted against position along the line of section (Fig. 2). Included are calculated Mg#s and selected isotopic ratios. Values of Mg# for the most primitive samples (Fig. 9A) are slightly lower than the field for primary mantle melts as defined in the BVSP (Basaltic Volcanism Study Project) (BVSP, 1981), although the differences are small enough to be attributed to small amounts of olivine fractionation. The lack of high Mg# rocks also underscores the fact that northern Cordilleran volcanic province rocks tend to be Fe rich (e.g., Nicholls et al., 1982; Francis and Ludden, 1995). Even northern Cordilleran volcanic province volcanic rocks containing high MgO (e.g., >12 wt%) tend to show high values of FeO_{total} (e.g., ≅13 wt%). Overall the highest value of Mg# found at each center decreases south of Level Mountain (Fig. 9A).

Figure 9 (B, C, and D) shows isotopic data compiled for mafic rocks along the same line of section. For comparative purposes we include the range of values found in alkaline basalts from the Basin and Range province (Kempton et al., 1991; Lum et al., 1989). Values of $^{87}Sr/^{86}Sr$ vary from as high as 0.7040 at Alligator Lake to values <0.7028 at Edziza (Fig. 9B). Values of ε_{Nd} for northern Cordilleran volcanic province rocks are as high as +9.4 epsilon units at Fort Selkirk and as low as +4.4 in the Iskut area (Fig. 9C). Samples from Prindle and Fort Selkirk have high ε_{Nd} values relative to average values for volcanic rocks from both the northern Cordilleran volcanic province and the Basin and Range province. Northern Cordilleran volcanic province samples show an increase in $^{206}Pb/^{204}Pb$ from 18.7 at Prindle to a high of 19.4 in the Iskut area (Fig. 9D).

The isotopic data shown in Figures 8 and 9 (B-D) have three main features. First, the northern Cordilleran volcanic province volcanic rocks have isotopic compositions that are entirely consistent with an asthenospheric source region. Second, isotopic values for $^{143}Nd/^{144}Nd$ and $^{206}Pb/^{204}Pb$ generally overlap with values established for asthenospherically derived magmas

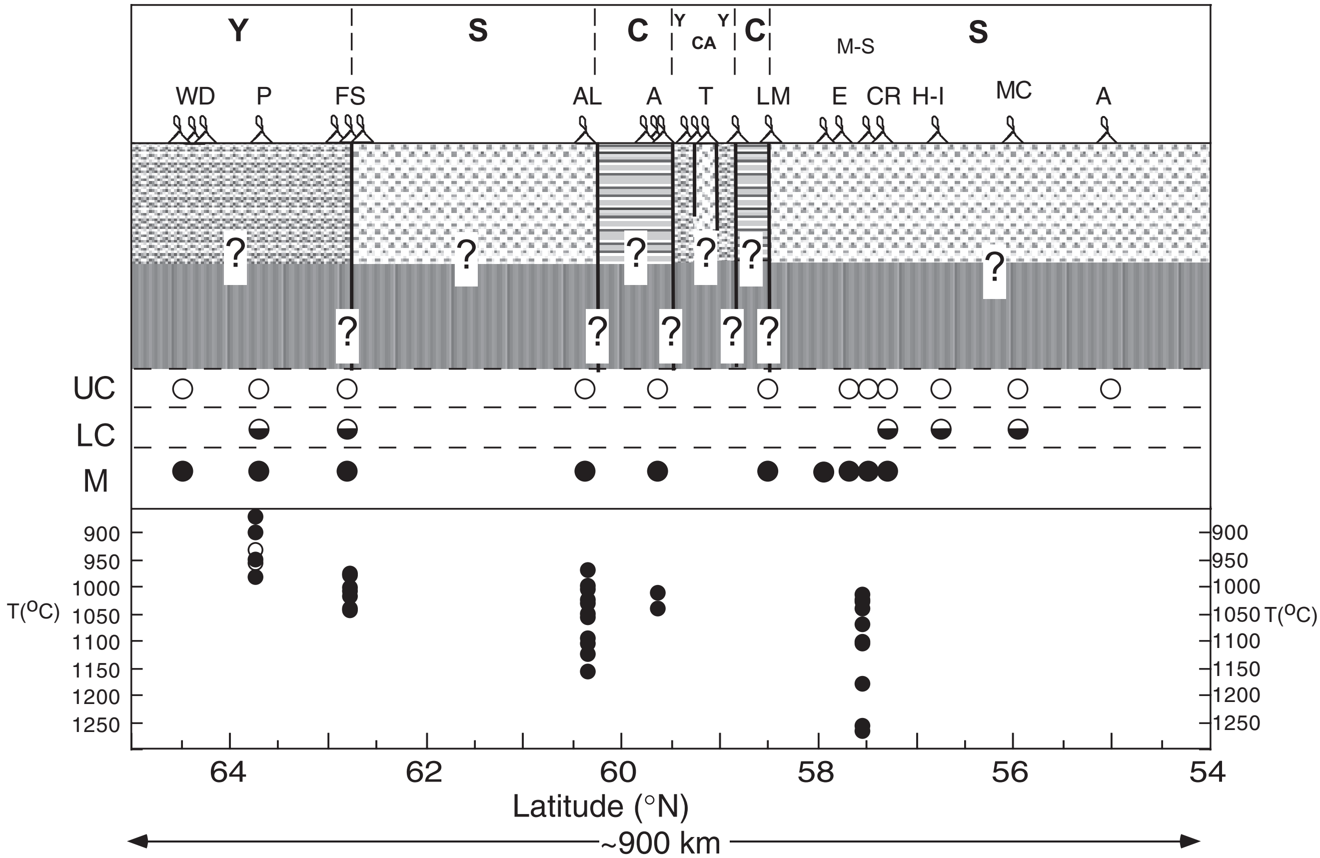

Figure 6. Schematic cross section of the lithosphere to the northern Cordillera showing the distribution of northern Cordilleran volcanic province volcanic centers across major terrane boundaries. The line of section is shown in Figure 2. Centers include: WD—West Dawson, P—Prindle, FS—Fork Selkirk, AL—Alligator Lake, A—Atlin, T—Tuya, LM—Level Mountain, M-S—Spatzizi, E—Edziza, CR—Castle Rock, H-I—Iskut, MC—McConnel Creek, and Ai—Aiyansh. Terrane abbreviations are: Y—Yukon-Tanana, S—Stikine, C—Cache Creek, and CA—Cassiar. Patterned areas are unique for the lithosphere beneath each of the different terranes. The vertical striped pattern denotes asthenosphere. Types of xenoliths from each center include upper crustal (UC—open circles), lower crustal (LC—half-filled circles), and mantle (M—filled circles). Lower panel of figure shows two pyroxene temperature estimates for xenoliths.

from the Basin and Range province (Kempton et al., 1991; Lum et al., 1989). Third, values of $^{87}Sr/^{86}Sr$ are lower, and hence represent a source that is slightly less radiogenic than the source for Basin and Range magmas.

None of the isotopic ratios correlate strongly with changes in the basement geology across terrane boundaries from north to south. We interpret this as indicating that northern Cordilleran volcanic province magmas largely record isotopic compositions that are characteristic of their source regions and that this source region is isotopically homogeneous over a length of >1200 km. Because we view the lithosphere that underlies the northern Cordilleran volcanic province as highly heterogeneous, we favor an asthenospheric source for the mafic northern Cordilleran volcanic province magmas. We also recognize that, on the basis of available trace element and isotopic data, the asthenospheric source for northern Cordilleran volcanic province magmas is similar in character to the source region for post-5 Ma alkaline basaltic magmas from the Basin and Range province. For both provinces, this source region has characteristics similar to average OIB.

PETROLOGICAL IMAGING OF THE CORDILLERAN LITHOSPHERE

We have drawn some inferences concerning the configuration of the mantle underlying the northern Cordilleran volcanic province on the basis of petrographic observations and thermodynamic calculations using the MELTS software (Ghiorso and Sack, 1995). Figure 10 is a summary of calculated pressure-temperature formation conditions for high-MgO lavas and xenoliths. We use the following thermodynamic calculations as a means of showing potential relative differences between samples and not necessarily as a tool for establishing accurate formation conditions.

Figure 10A shows the calculated stability fields for the liquidus phases of the most Mg-rich lavas for each volcanic center as a function of pressure (depth). At shallow depths all rock compositions have olivine (Ol) as the liquidus phase; mafic rocks of the northern Cordilleran volcanic province usually show Ol as the earliest crystallizing silicate (e.g., Francis and Ludden, 1990, 1995; Hauksdóttir, 1994). These calculations show that lavas from north of Atlin could maintain Ol as the liquidus phase over a much larger depth interval (to 75 km) than could lavas to the south (<25 km). These calculations may limit the depth intervals of crystallization for these magmas during ascent. The petrography of mafic lavas from the north (e.g., Fort Selkirk) would permit crystallization at depths of >70 km. In contrast, lavas to the south (e.g., Aiyansh) are

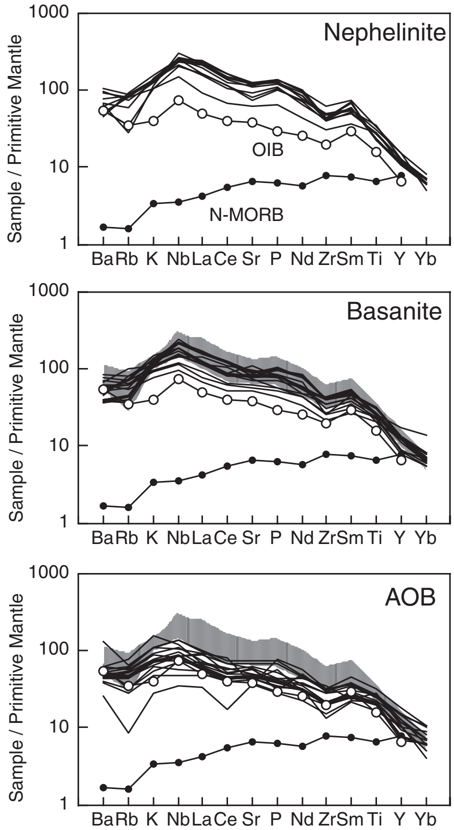

Figure 7. Normalized trace element plot for high-MgO lavas from the northern Cordilleran volcanic province (NCVP). Data are from Francis and Ludden (1990, 1995), Wirth (1991), Cousens and Bevier (1995), and Edwards (1997). Data from the NCVP are compared to oceanic-island basalt (OIB; open circles) and normal mid-ocean ridge basalt (N-MORB; closed circles). The shaded area in the bottom two diagrams is the range of compositions for nephelinite from the NCVP. Values for trace elements are normalized to values of primitive mantle (Sun and McDonough, 1989).

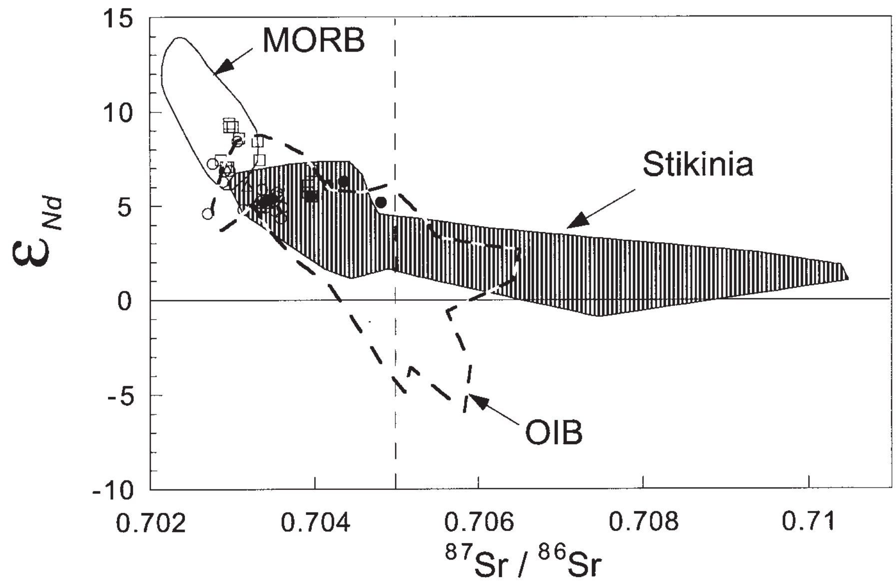

Figure 8. The ε_{Nd} vs. $^{87}Sr/^{86}Sr$ values for volcanic rocks from the northern Cordilleran volcanic province (NCVP) and Stikinia. Data for NCVP samples (see Fig. 5 for symbols) are from Cousens and Bevier (1995), Carignan et al. (1994), M.L. Bevier (1997, personal commun.), R. Theriault (1995, personal commun.), and Wirth (1991). Values for mid-ocean ridge basalt (MORB) and oceanic-island basalt (OIB) are after Cohen et al. (1980), Cohen and O'Nions (1982), and White and Hoffman (1982). Values for Stikinia field are from Samson et al. (1989).

olivine porphyritic; this restricts crystallization to depths above 20 km.

We have also calculated the 10^4 Pa liquidus temperatures for the highest MgO lavas from northern Cordilleran volcanic province centers (Fig. 10B). These temperatures represent the minimum temperature of formation for the samples, assuming that the samples are representative of liquid compositions (e.g., Francis and Ludden, 1990). Although most of the samples used for the calculations had olivine-phenocrysts, we attempted to select samples for the liquidus calculations that would most closely approximate liquid compositions. The highest liquidus temperatures are for samples from Fort Selkirk and Alligator Lake (both ~1380 °C). To the south liquidus temperatures decrease from ~1380 °C at Alligator Lake to ~1320 °C at Atlin. South of Atlin estimated liquidus temperatures decrease to a low of ~1130 °C at Aiyansh. These differences cannot be attributed to the effects of fractionation alone because the Mg#s of these lavas decrease only slightly from north to south (e.g., Fig. 9A). We suggest that magmas in the northern part of the northern Cordilleran volcanic province derive from a hotter and/or deeper part of the asthenosphere than magmas in the southern part of the northern Cordilleran volcanic province. Evidence that may support this idea derives from seismic studies by Frederiksen et al. (1997), which identified an area of anomalously hot asthenosphere beneath the northern part of the northern Cordilleran volcanic province.

Figure 10C is our petrological interpretation of the lithosphere underlying the northern Cordillera. Following Griffith and O'Reilly (1985), we interpret the lowest temperatures recorded by spinel lherzolite xenoliths as giving the minimum temperature of the petrological transition at the crust-mantle boundary (Moho). The range in equilibrium temperatures for a given suite of xenoliths is taken as an estimate of the thickness of the lithosphere for a particular area. These interpretations depend on two things. First, we assume that magmas are unbiased samplers of the lithosphere. This is consistent with the relatively continuous range of temperatures recorded by mantle xenoliths shown in Figure 10C. Second, our interpretation assumes a more or less uniform geothermal gradient throughout the lithosphere of the northern Cordilleran volcanic province. This assumption is supported by the work of Hyndman and Lewis (1999) that shows the northern Cordillera to have uniformly high heat flow (80–100 m Wm^{-3}). We acknowledge that this assumption may be less valid near the lithosphere-asthenosphere boundary given the anomaly identified by Frederiksen et al. (1997).

The Prindle and Fort Selkirk xenolith suites record the lowest xenolith temperatures, suggesting that the Moho is shallowest under the northern end of the northern Cordilleran volcanic province. Likewise, the range of temperatures for the northernmost xenolith suites is approximately one-half the temperature range found in southern xenoliths. The differences in the ranges of temperatures suggest that a thin lithosphere is beneath the terranes underlying the northern part of the northern Cordilleran volcanic province and a thicker lithosphere is beneath the central part of the Stikinia terrane, which underlies most of the southern part of the northern Cordilleran volcanic province. This suggestion is strengthened if the geothermal gradient within the lithosphere beneath the northern part of the northern Cordilleran volcanic province is higher than that in the southern part of the northern

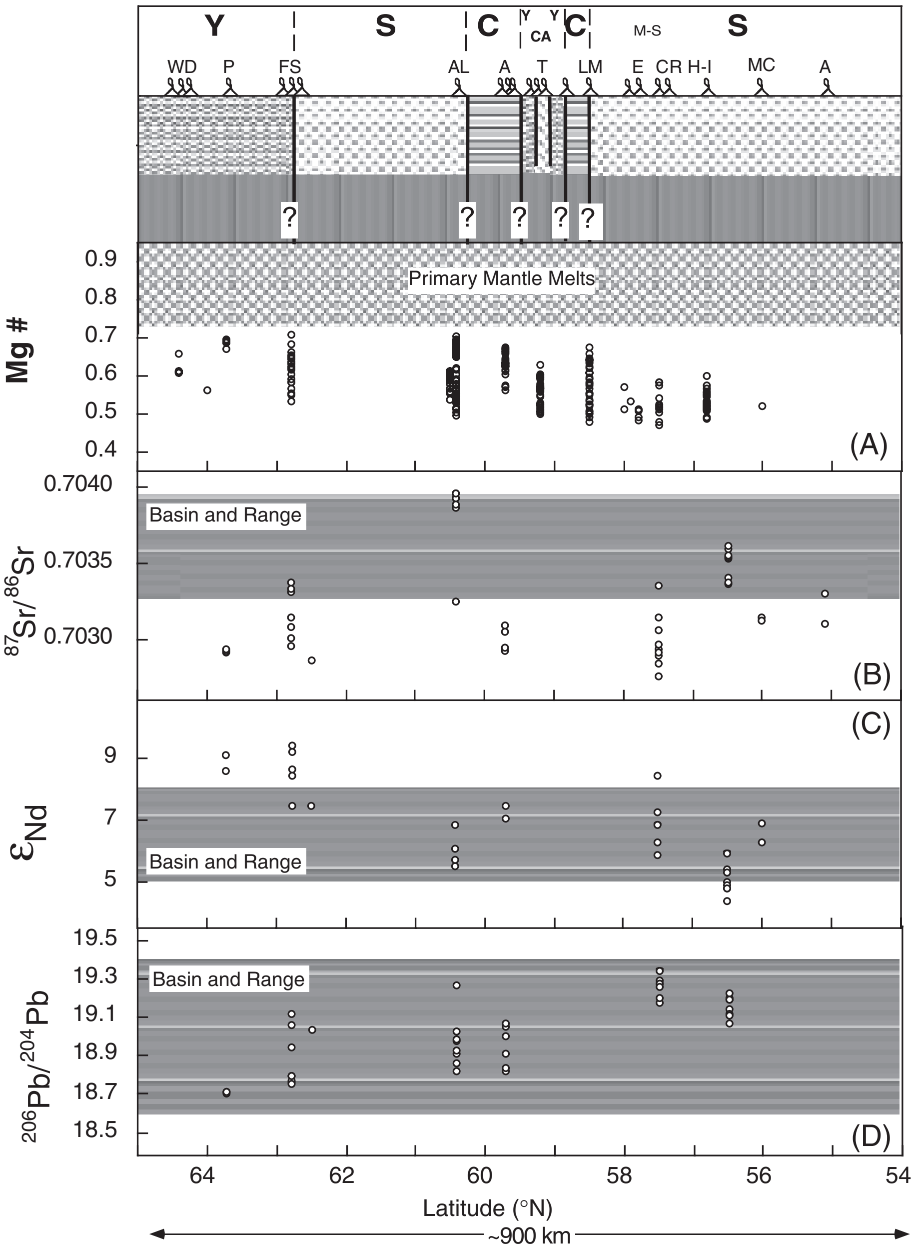

Figure 9. Geochemical characteristics of northern Cordilleran volcanic province volcanic rocks containing >6 wt% MgO projected onto the cross section shown in Figure 2. The field for primary mantle melts is defined as Mg# > 0.72 (BVSP, 1981). Calculated Mg# assumes FeO = 0.9 * $FeO_{(total\ Fe)}$. Shaded regions denote the range of isotopic values for Basin and Range province lavas (Kempton et al., 1991; Lum et al., 1989). See Figure 6 for abbreviations.

Cordilleran volcanic province, as implied by the results of Frederiksen et al. (1997). A higher geothermal gradient would mean that a xenolith recording a temperature of 900 °C was derived from a shallower depth than one from an area with a lower geothermal gradient that also records a temperature of 900 °C. Other evidence in support of lithospheric thickening under central Stikinia includes: (1) the increased abundance of cognate inclusions and plagioclase megacrysts in rocks from the southern part of the northern Cordilleran volcanic province, which may be indicative of ponding and crystallization of magma in the lithosphere; and (2) the exclusive presence of petrologically evolved rock types in the southern half of the northern Cordilleran volcanic province. Whether the evolved magmas originate from fractionation of mafic magmas, fractionation accompanied by lithospheric contamination, or solely from lithospheric melting, their presence supports the model of thicker lithosphere underlying the southern part of the northern Cordilleran volcanic province. Interpretations of recent seismic data in the southwestern part of the northern Cordilleran volcanic province (Hammer et al., 2000) show that the crust beneath Stikinia, which forms the basement to most of the volcanic rocks in the southern part of the northern Cordilleran volcanic province, is thicker than that beneath the adjacent Coast Plutonic complex.

The liquidus temperatures for northern Cordilleran volcanic province magmas discussed here are projected in Figure 10C. These temperatures, which we assume are the minimum temperatures of formation for the northern Cordilleran volcanic province magmas, are generally higher than the equilibrium temperatures recorded by spinel lherzolite xenoliths. We take these calculated liquidus temperatures as further evidence that the northern Cordilleran volcanic province magmas originated in the asthenosphere. The samples from the southern part of the northern Cordilleran volcanic province have minimum liquidus temperatures that are similar to the maximum spinel lherzolite temperatures. This may indicate that magmas in the southern part of the northern Cordilleran volcanic province ponded at the base of the lithosphere prior to erupting at the surface.

RIFTING IN THE NORTHERN CORDILLERA

At least four different mechanisms for triggering magmatism within the northern Cordillera have been suggested, including slab windows, mantle plumes, deglaciation, and crustal extension (Edwards and Russell, 1999). We favor a model of northern Cordilleran volcanic province magmatism driven by incipient rifting of the North America plate caused by crustal extension, based on the following evidence: (1) northern Cordilleran volcanic province magmatism is dominantly alkaline and includes highly alkaline and peralkaline rock types (Table 1); (2) the dominant spatial-temporal pattern of magmatism is initiation in the central part of the province, followed by migration to the north, south, and possibly northeast (Fig. 3A); (3) heat flow in the northern Cordillera is high (80–100 m Wm^{-2}; Hyndman and Lewis, unpublished data); (4) seismicity is distinctly absent across the northern Cordilleran volcanic province; and (5) the most voluminous period of northern Cordilleran volcanic province magmatism correlates with an interval of net extension between the Pacific and North American plates (Edwards and Russell, 1999).

The data summarized in this paper strengthen the possible links between extension and magma

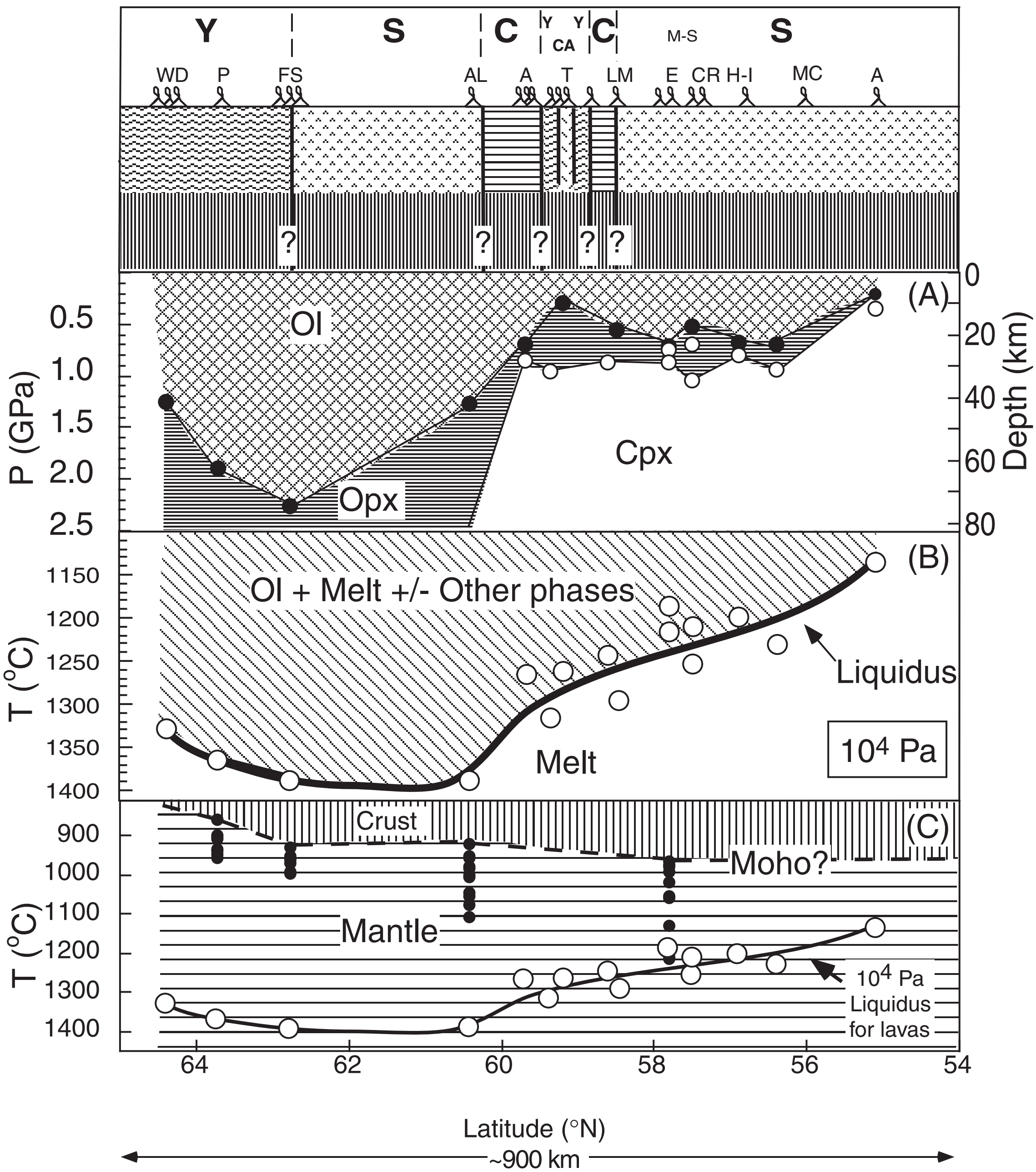

Figure 10. Phase equilibria characteristics of northern Cordilleran volcanic province volcanic rocks containing >6 wt% MgO are summarized on the cross section shown in Figure 2. (A) Calculated liquidus mineralogy as a function of pressure (depth), (B) calculated liquidus temperatures at 10^4 Pa, and (C) estimates of equilibration temperatures for mantle-derived xenoliths compared to 10^4 Pa liquidus temperatures. Crust-mantle boundary is inferred to coincide with the lowest calculated temperature associated with spinel lherzolite xenoliths (Griffith and O'Reilly, 1985). Source regions must lie between the highest temperature peridotite and 10^4 Pa liquidus temperatures for the volcanic rocks. See Figure 6 for abbreviations. Ol—olivine; Opx—orthopyroxene; Cpx—clinopyroxene.

generation within the northern Cordilleran volcanic province. Trace element, isotopic, and phase equilibria data from the northern Cordilleran volcanic province are consistent with derivation from an asthenospheric mantle source (Fig. 9) that is chemically similar to sources for OIB and for post-5 Ma alkaline basalts in the Basin and Range (Fitton et al., 1991; Fig. 8). One possible explanation for OIB-like asthenosphere beneath the northern Cordilleran volcanic province is the presence of a slab window, the existence of which was suggested by Thorkelson and Taylor (1989). However, little direct physical evidence linking the production of asthenospherically derived magmas in the northern Cordilleran volcanic province to an extensional tectonic regime has been previously reported (e.g., Edwards and Russell, 1999). The Mess Lake fault, along the west side of Mount Edziza (Souther, 1992), is usually cited as the main structural evidence for Neogene extension in the northwestern Cordillera (Fig. 11). However, new

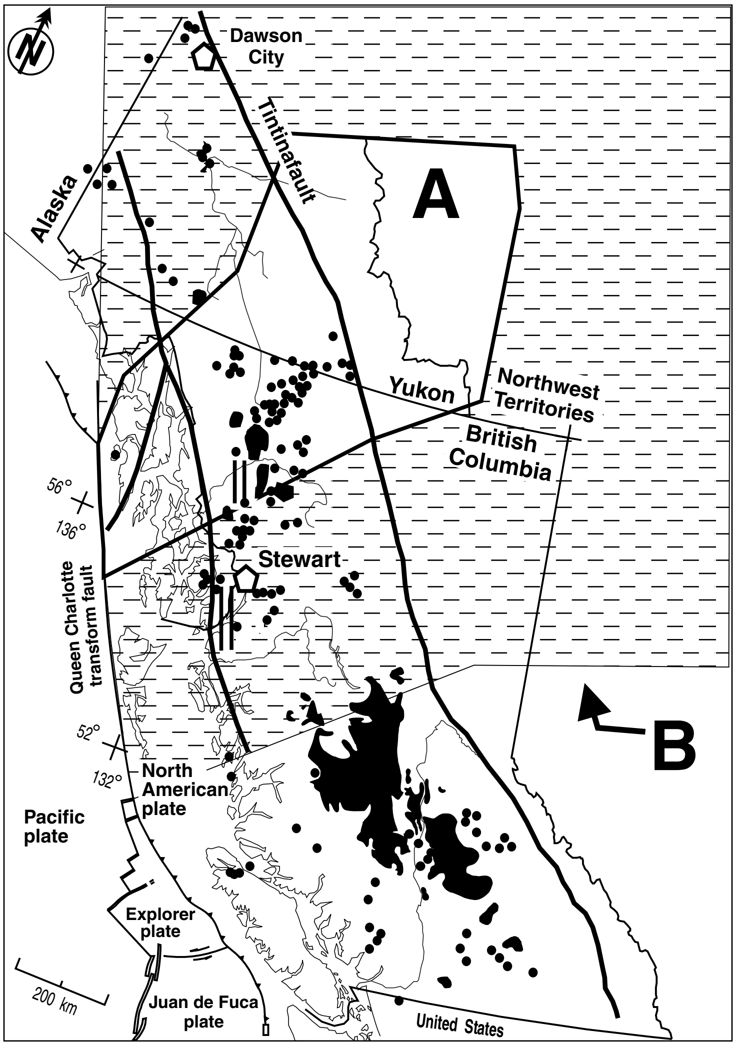

Figure 11. Distribution of Neogene volcanism in Canadian Cordillera is compared to projected area of slab window at 20 Ma (A) and projected area of current slab window (B) (e.g., Edwards and Russell, 1999). Also shown (parallel liines) are locations of Neogene or younger extensional faults at Mess Creek (Souther, 1992) and southwest of Aiyansh (Evenchick et al., 1999).

structural mapping (Rohr and Currie, 1997; Evenchick et al., 1999) and seismic studies of the Coast Belt (e.g., Accrete project: Hollister and Adronicos, 1997; Lithoprobe: Hammer et al., 2000) have documented the presence of brittle, extensional faults southwest of Stewart (Fig. 11). Rohr and Currie (1997) argued that the faults recognized by the Accrete project were last active between 20 and 5 Ma. Evenchick et al. (1999) mapped a series of north-trending faults that appear to represent young, extensional tectonic events along the southwestern margins of the northern Cordilleran volcanic province (Fig. 11). These extensional fault zones may have been active as recently as 5 Ma (Evenchick et al., 1999). Evenchick et al. (1999) speculated that these brittle faults zones may be associated with local Miocene and younger volcanism in the southern part of the northern Cordilleran volcanic province. Furthermore, brittle fault zones with similar north-trending orientations may extend as far north as the Mess Lake fault, in the central part of the northern Cordilleran volcanic province (Fig. 11; C.A. Evenchick, 1999, personal commun.).

We suggest that the following sequence of plate tectonic events supported development of the northern Cordilleran volcanic province. Cessation of subduction along the western margin of the northern Cordillera at 43-40 Ma (cf. Hyndman and Hamilton, 1993) eventually led to the development of a slab window beneath the northern Cordillera by 10 Ma (Thorkelson and Taylor, 1989), providing access to relatively undepleted asthenosphere (Fig. 11). Changes in relative plate motions between the Pacific and North American plates ca. 10 Ma generated extensional stresses across the northern Cordillera (e.g., Stock and Molnar, 1988), resulting in lithospheric thinning and decompression melting of OIB-like mantle to produce alkaline Neogene magmatism. Most plate motion models suggest a return to net compression across the Pacific-North American plate boundaries sometime after ca. 4 Ma (e.g., Pollitz, 1988; Harbert and Cox, 1989). Magmatism in the northern Cordilleran volcanic province through the Quaternary and Holocene most likely results from a continuation of asthenospheric upwelling and local transtension along the Pacific-North American plate boundary, accommodated in part by abundant east-west faults that are present throughout the northern Cordilleran volcanic province.

SUMMARY

The northern Cordilleran volcanic province constitutes an igneous province that is characterized by spatially and temporally related alkaline volcanic rocks. The northern Cordilleran volcanic province represents a minimum of 100 volcanic centers that encompass a broad range of volcanic styles, including large volcanic plateaus with mafic and felsic eruption products, isolated volcanic cones and lava flows, and subglacial eruption products. The oldest volcanic rocks within the northern Cordilleran volcanic province are ca. 20 Ma and the youngest are 300-200 yr B.P. The peak of northern Cordilleran volcanic province magmatism occurred between 9 and 7 Ma and coincides with a period of net extension along the Pacific-North American plate margin. Over the past 4 m.y. rates of magmatism have remained relatively constant at about 10^{-4} km^3 yr^{-1}. Alkali olivine basalt and hawaiite are the dominant rock types, but basanite and nephelinite are also common. More evolved rock types such as phonolite, trachyte, and comendite are associated only with a few larger, longer lived volcanic centers.

Phase equilibria calculations based on lava compositions and geothermometry of mantle-derived xenoliths allow construction of a north-south cross section for the petrological lithosphere to the northern Cordillera, which shows that the crust and the lithosphere beneath the northern Cordilleran volcanic province thicken from the north to the south. However, values of $^{87}Sr/^{86}Sr$, ε_{Nd}, and $^{206}Pb/^{204}Pb$ do not vary systematically from north to south across terrane boundaries. Trace element abundances and isotopic ratios for mafic rocks from the northern Cordilleran volcanic province suggest that they are derived from an asthenospheric source similar to that for average OIB and for asthenospheric-derived magmas from the Basin and Range (e.g., Kempton et al., 1991). Our compilation and analysis of petrological data provide further support for the incipient rifting model used by Edwards and Russell (1999) to explain the origins of northern Cordilleran volcanic province magmatism.

ACKNOWLEDGMENTS

This research has been supported by NSERC Lithoprobe during the period 1994-1997 as part of the University Supporting Geoscience Program for the SNORCLE Transect. We have benefited from discussions with D. Francis, J. Nicholls, R. Anderson, C. Evenchick, C. Hart, T. Hamilton, C. Hickson, M. Kopylova, J. Mortensen, and D. Thorkelson. We also thank M. Bevier and R. Theriault for sharing unpublished isotopic data. The manuscript was improved substantially by reviews from N. Green and M. Reid. The comments of G. Mahood were especially helpful for clarifying our presentation. However, the views we express and any residual inconsistencies remain solely our responsibility. This publication is LITHOPROBE contribution 956.

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MANUSCRIPT RECEIVED BY THE SOCIETY NOVEMBER 25, 1997
REVISED MANUSCRIPT RECEIVED JULY 23, 1999
MANUSCRIPT ACCEPTED NOVEMBER 17, 1999

Printed in USA