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ORIGIN OF IGNEOUS ROCKS ASSOCIATED WITH MÉLANGES OF THE PACIFIC RIM COMPLEX, WESTERN VANCOUVER ISLAND, CANADA

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Abstract. The Pacific Rim Complex (PRC) has previously been interpreted as a late Mesozoic subduction complex that formed along the western margin of Vancouver Island. This paper examines a specific aspect of this interpretation: that igneous rocks within the PRC are fault slices derived from the footwall or hanging wall of a subduction thrust. The footwall would have been an oceanic plate, and the hanging wall, Wrangellia, a large coherent terrane that underlies most of Vancouver Island. New mapping has shown that the PRC comprises a lower Mesozoic volcanic unit, herein named the Ucluth Formation, and a superjacent sequence, more than 2 km thick, of Lower Cretaceous sediment-rich mélanges. Within the mélanges are large blocks of volcanic and plutonic rocks, most of which were derived from the underlying Ucluth Formation. A minor fraction of these blocks cannot be assigned to Ucluth; they consist of Upper Jurassic pillow basalt and rare ultramafite. Fossil ages and chemical data indicate that the bulk of the igneous rocks in the PRC, as represented by the Ucluth Formation and blocks derived from the Ucluth, could not have come from Wrangellia nor from a subducting oceanic plate. The blocks of Upper Jurassic pillow basalt do represent fragments of oceanic crust, but field relations indicate that they are not fault slices. The mudstone matrix surrounding the blocks contains interbeds of "green tuff" which are shown to be scree deposits derived from the Ucluth and the Upper Jurassic pillow basalts. My interpretation is that the PRC mélanges formed by surficial mass wasting, and not by faulting along a subduction thrust. Furthermore, regional geologic relations indicate that the present location of the PRC, outboard of Wrangellia, is a result of strike slip faulting during the latest Cretaceous or early Tertiary. This event postdates the formational age of the mélanges by at least 45 m.y.

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INTRODUCTION

The Mesozoic Pacific Rim Complex forms a narrow, fault-bounded terrane located along the west coast of Vancouver Island (Figure 1). Muller [1973, 1977a] and Page [1974] were first to identify and date this unit. They proposed that it was a Late Jurassic-Early Cretaceous subduction complex, formed by tectonic interleaving of trench sediments with igneous rocks derived from a subducting oceanic plate and an overriding continental plate. The continental plate in this interpretation would be Wrangellia, a coherent terrane that borders the Pacific Rim Complex to the northeast (Figure 1) and underlies most of Vancouver Island. The Pacific Rim Complex is generally considered to be part of a regionally extensive subduction complex that fringed western North America during the late Mesozoic, extending from California (Franciscan Complex) to southern Alaska (Chugach terrane) [Dickinson, 1976; Jones et al., 1978].

An important objective of my study [Brandon, 1984, 1985] was to critically examine the subduction complex interpretation. This paper focuses on one aspect of this interpretation: that igneous rocks in the Pacific Rim Complex were derived from the hanging wall or footwall of a subduction thrust. The data brought to bear on this question

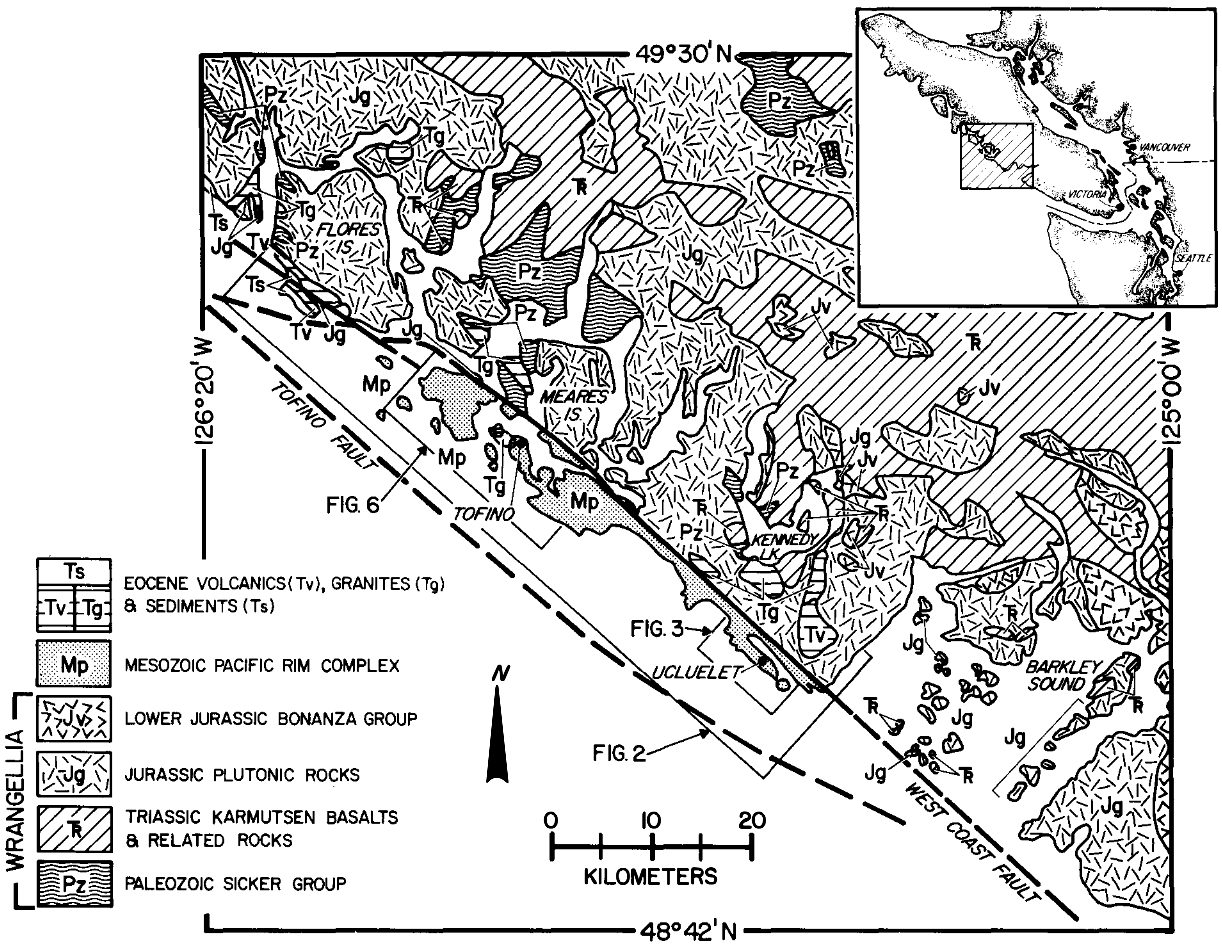

Fig. 1. Geologic map of western Vancouver Island [after Muller, 1977b]. Boxes outline the location of Figures 2, 3, and 6.

include stratigraphic observations, chemical analyses[1], and new paleontological ages (Table 1). An important conclusion is that the volcanic and plutonic rocks of the Pacific Rim Complex are unrelated to Wrangellia, and only a small fraction of these rocks could have been derived from typical oceanic crust.

GEOLOGIC OVERVIEW

The following overview provides a brief summary of the geology of the Pacific Rim Complex, based on Brandon [1989a]. The Pacific Rim Complex is divided into three units, which collectively form a crude stratigraphic sequence. This relationship is best demonstrated in a broad E-W trending anticline on the Ucluth Peninsula (Figures 2 and 3). The core of the Ucluth anticline exposes a Lower Mesozoic volcanic unit, herein called the Ucluth Formation. The flanks of the Ucluth anticline contain a thick sequence (> 2000 m) of Lower Cretaceous sediment-rich mélanges. Here and elsewhere in the Pacific Rim Complex the mélange sequence overlies the Ucluth Formation.

The Ucluth anticline is important because it exposes the largest extent of Ucluth Formation, consisting of about 4 km of uninterrupted coastal outcrop. The contact between the mélange sequence and the Ucluth Formation is best preserved in the south flank of the anticline (Big Beach, Figure 3). At this location the mélange sequence can be clearly shown to lie in depositional contact on the Ucluth Formation [Brandon, 1989a]. This contact is exposed for more than 100 m. Mudstone of the overlying mélange is unfoliated and contains numerous *Buchia* bivalves of Early Cretaceous (middle Valanginian) age. Thus the Ucluth Formation is considered to be basement to the mélange sequence.

[1] An appendix of chemical analyses, locality descriptions, sample petrography, analytical methods, and estimated accuracy is available with the entire article on microfiche. Order from American Geophysical Union, 2000 Florida Avenue, N.W., Washington, DC 20009. Document T89-004; $2.50. Payment must accompany order.

TABLE 1. Fossils From the Ucluth Formation and Pillow Basalt Blocks

Number	Geologic Setting and Location	Fossils	Age
	Ucluth Formation		
U1	limestone interbedded with volcanic breccia. Ucluth Peninsula (Figures 3-5).	conodonts	Late Triassic, late Early Norian
U2	limestone interbedded with volcanic rocks and intruded by diorite dike. Ucluth Peninsula (Figure 3).	(a) conodonts (b) ammonoids	Late Triassic, Carnian probably Late Triassic
U3	ribbon chert interbedded with pillow lava and tuff, tentatively assigned to the Ucluth Formation. Vargas Island (Figure 6).	radiolaria	Early Jurassic, middle or late Toarcian (or possibly earliest Middle Jurassic)
	Upper Jurassic Pillow Basalt Blocks		
JP1	red ribbon chert from pillow basalt block; ocean-floor chemistry (GJP2[a]). 5 km SE of Ucluelet.	radiolaria	Late Jurassic, late Kimmeridgian
JP2	ribbon chert interbedded with pillow basalt; ocean-floor chemistry (GJP8[a]). SE side of Ucluelet Inlet.	radiolaria	Late Jurassic, late Kimmeridgian to late Tithonian
JP3	ribbon chert interbedded with pillow basalt; ocean-floor chemistry (GJP7[a]). Francis Island, SE of Ucluelet (Figure 3).	radiolaria	Middle or Late Jurassic, Aalenian to early Tithonian

Paleontological reports and geologic descriptions for these localities are in Brandon [1989a].
[a] Numbers refer to chemical analyses of basalts from these localities (see appendix).

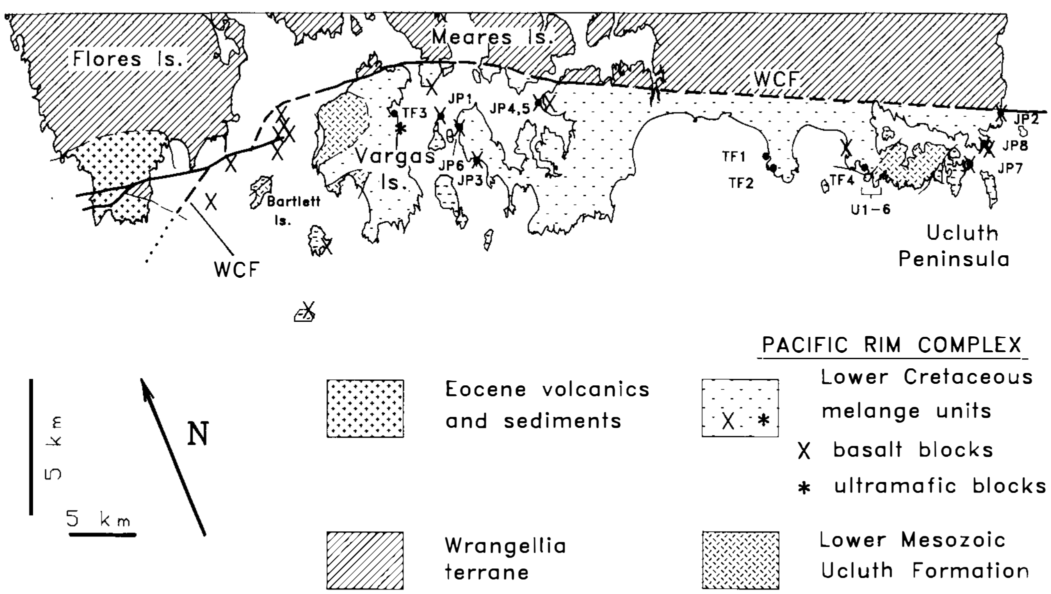

Fig. 2. Simplified geologic map of the Pacific Rim Complex. Sample localities for chemical analyses are shown with the following prefixes: U, Ucluth volcanic rock and diorite; JP, Upper Jurassic pillow basalt; TF, "green tuff". Note that the map scale is exaggerated by two in the north-northeast direction.

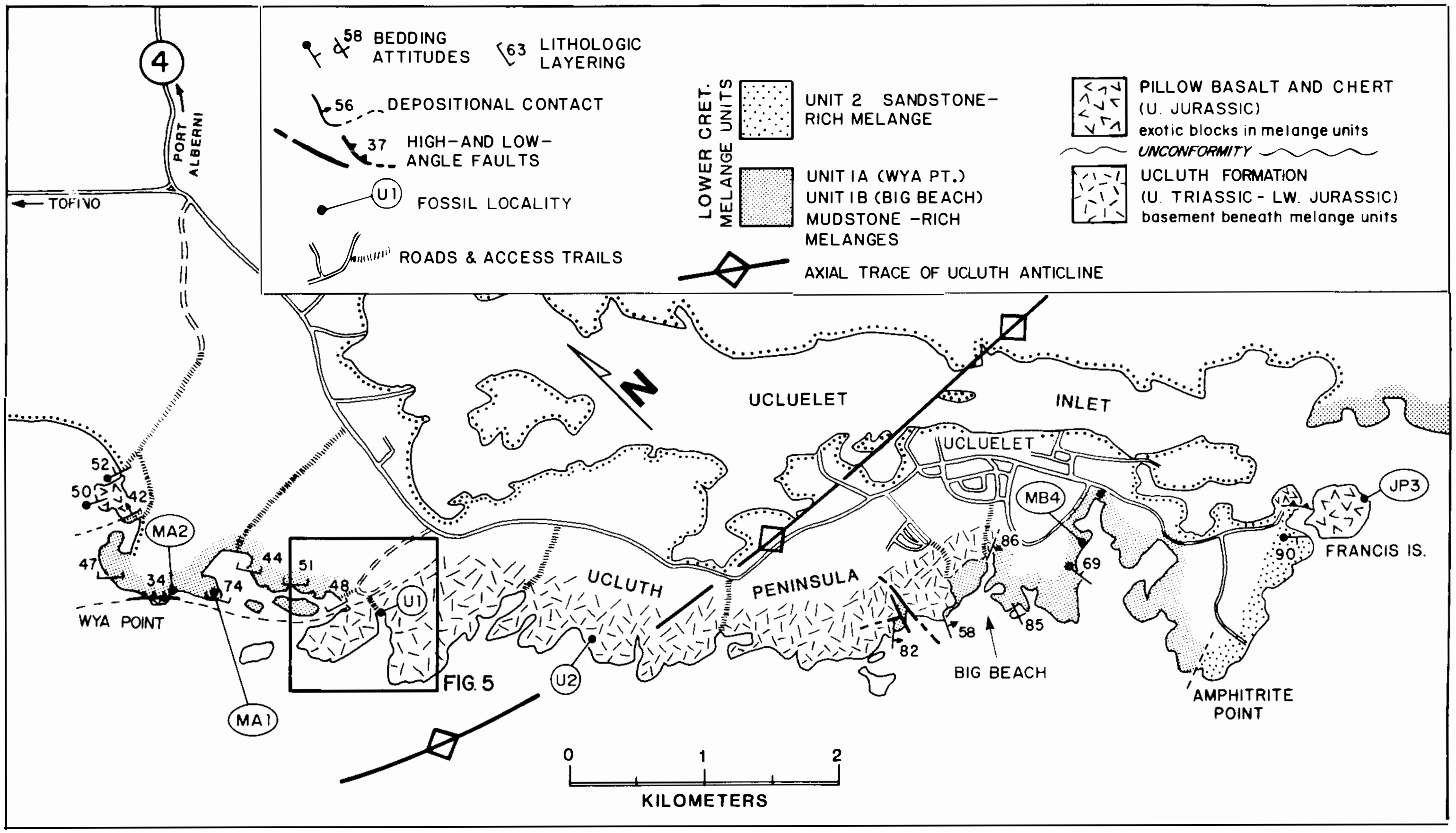

Fig. 3. Geologic map of the Ucluth Peninsula, located at the southeast end of the Pacific Rim Complex (Figure 1). The heavy line marks the trace of the Ucluth anticline. The anticline exposes the Ucluth Formation in its core and the mélange sequence (units 1 and 2) in its flanks. Fossil localities U1, U2, and JP3 are described in Table 1. The remaining localities (MA1, MA2, and MB4) mark Early Cretaceous fossils from matrix sediments of the Unit 1 mélange [Brandon, 1989a]. Boxes outline the location of Figure 5.

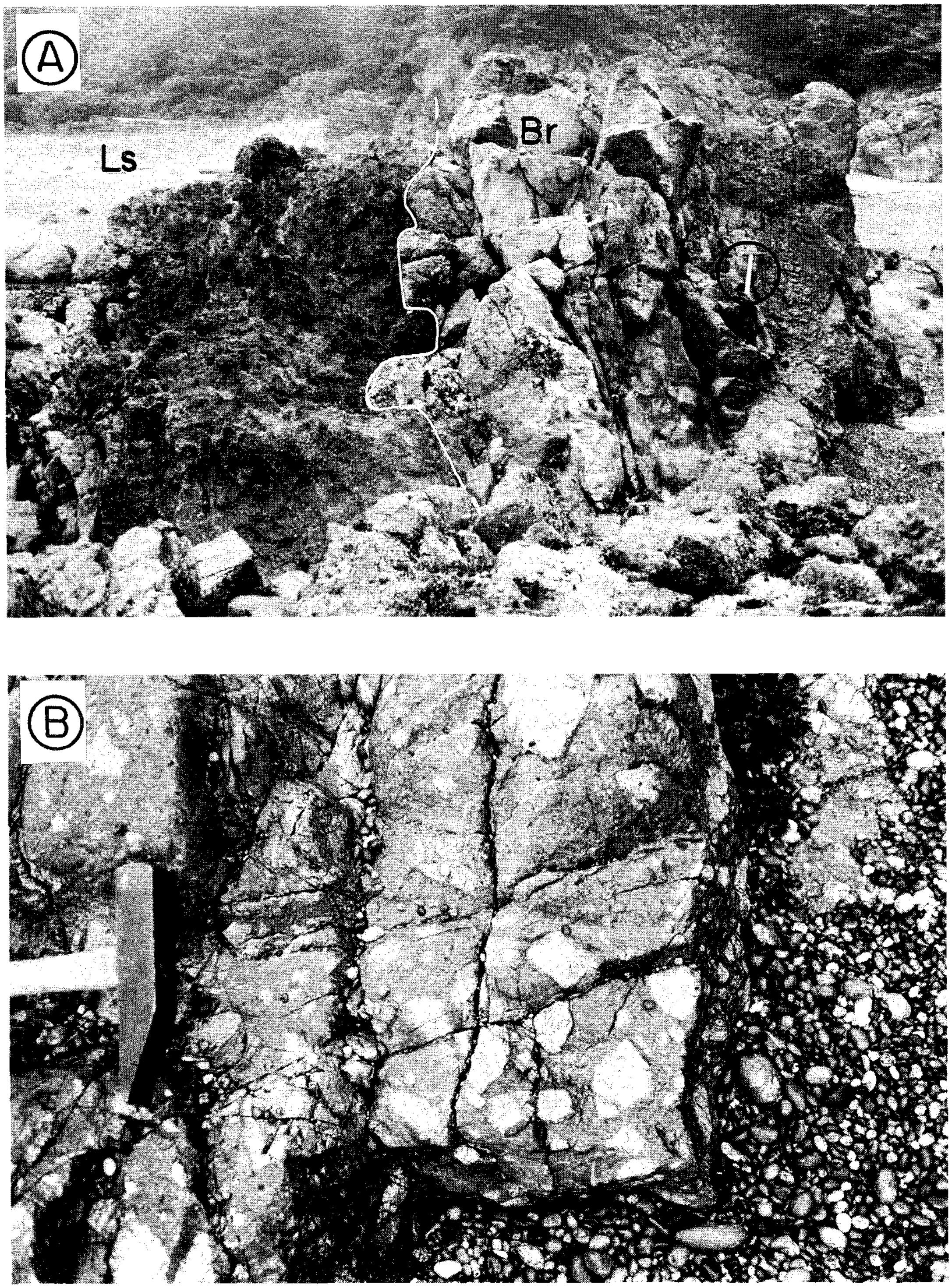

Fig. 4. Photographs of rocks in the Ucluth Formation. (a) Interbedded limestone (Ls) and volcanic breccia (Br) at Fletcher Beach (see Figure 5). Angular, cobble-sized clasts in the breccia are visible on the right side of the outcrop. Conodonts from this limestone indicate a Late Triassic age (U1 in Table 1). Note hammer (circled) for scale. (**b**) Close-up of angular clasts in volcanic breccia (from the outcrop shown above). (**c**) Diorite dike cutting volcanic breccia (western Vargas Island, opposite Hobbs Islet). Intrusion measures about 2 m across.

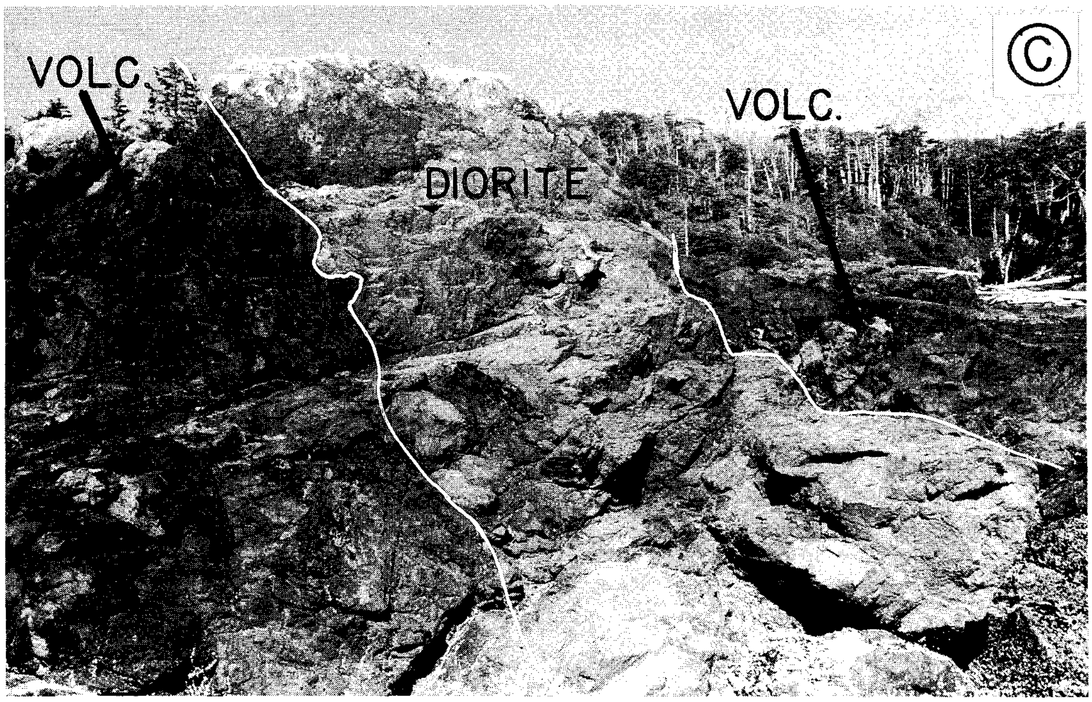

Fig. 4. (continued)

Island (localities B and C in Figure 6) and Bartlett Island (Figure 2). A few isolated outcrops are located on some of the islets northeast of the town of Tofino. All of these areas display a typical suite of Ucluth rocks (volcanic breccia, limestone, and diorite intrusions) and thus are easily correlated with the Ucluth in its type area.

Tentatively included in the Ucluth Formation is a group of volcanic rocks exposed in scattered outcrops along the west side of Vargas Island (locality A in Figure 6) and on many of the small islands to the west of Vargas. These rocks consist of fragmental tuff, chert, and minor pillow lava; limestone and diorite intrusions are notably absent. Radiolaria from interbedded chert (U3 in Figure 6 and Table 1) indicate an Early Jurassic age, which makes these rocks younger than the type Ucluth. The main reason for including them is that the tuff has an andesitic texture in thin section (porphyritic with phenocrysts of plagioclase and hornblende), similar to volcanic rocks of the type Ucluth. In addition, these Lower Jurassic rocks lie near volcanic and plutonic rocks that can be confidently assigned to the Ucluth (localities B and C in Figure 6). The main effect of this decision is that it extends the age of Ucluth into the Early Jurassic.

Chemical Analyses

Five volcanic samples and two diorite samples were analyzed for major and trace elements in order to assist the comparison of the Ucluth Formation with other coeval volcanic units and also to help establish its petrotectonic origin. The analyses are summarized in Table 2, and the results of various discriminant plots are shown in Table 3. Samples were collected from the type area (Figures 2 and 5) and are considered to be representative of the Upper Triassic part of the Ucluth. In the field these samples displayed relatively fresh igneous textures. Thin sections of two samples, a volcanic rock and a diorite, indicate less than 4% secondary mineralization (epidote, chlorite, minor calcite and white mica; see petrographic descriptions in appendix).

The analyses support a calc-alkaline arc volcanic origin for the Ucluth Formation. Silica varies from 52 to 65%, indicating a wide compositional range, from basalt to dacite (Figure 7a), a feature typical of arc volcanic rocks. Potassium increases with increasing silica with a moderate-potassium trend (Figure 7a), a feature associated with some calc-alkaline series volcanic rocks. Silica versus FeO*/MgO also indicates a calc-alkaline affinity (Figure 7b). The effect of hydrothermal alteration on these major element data was checked by plotting SiO_2, FeO*/MgO, and K_2O against Zr (see appendix), an immobile trace element commonly used as a differentiation index. An unaltered suite of analyses should preserve a well-correlated positive trend, whereas an altered suite typically shows a scattered pattern [Pearce, 1989]. SiO_2 and FeO*/MgO show good trends (Figures A1 and A2 in appendix), indicating that these values have not been significantly affected by alteration. On the other hand, K_2O does not correlate with Zr (Figure A3 in appendix), indicating that it was relatively mobile during alteration. This lack of correlation is probably due to variable amounts of potassium loss, because the alteration assemblage is potassium-poor (<1% white mica; Table A1 in appendix).

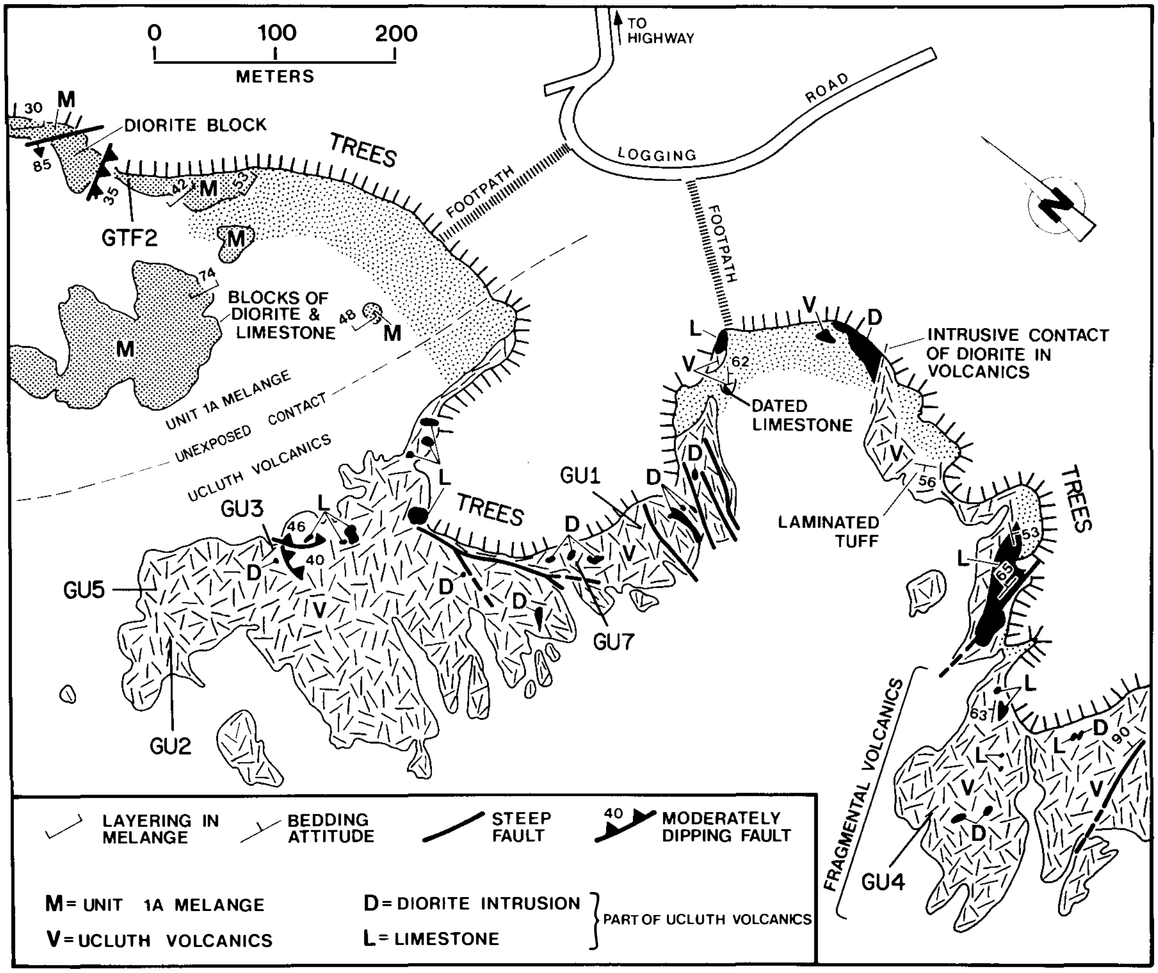

Fig. 5. Outcrop map of Ucluth Formation, as exposed at Fletcher Beach on the Ucluth Peninsula (location shown in Figure 3). The map illustrates the distribution of limestone and diorite bodies in the Ucluth volcanic sequence (shown as small black spots labeled "L" and "D"). The outcrop marked "dated limestone" is shown in Figure 4a and corresponds to fossil locality U1 (Table 1). Numbered localities refer to chemistry samples: GTF2 is "green tuff" from the unit 1A mélange, and GU1 to GU7 are Ucluth volcanic rock and diorite (GU6 lies just beyond the right side of the map).

Note that the introduction of 1% K_2O during alteration would require a modal increase of about 8% potassium-rich mica or clay. Thus the more potassium-rich analyses are considered to be a reasonable estimate of the original potassium content of the Ucluth.

Immobile trace elements are preferred for interpreting altered volcanic rocks. Most discriminant diagrams, however, are designed solely for basaltic rocks (Table 3) and thus are not applicable for the Ucluth analyses. One exception is the Ti-V diagram of Shervais [1982], which yields an ambiguous interpretation: either volcanic arc or ocean floor. The TiO_2-Zr diagram of Pearce and Cann [1973] can be used to discriminate between these two settings. For the Ucluth, TiO_2 remains nearly constant with increasing Zr (Figure 7c), which is a trend characteristic of calc-alkaline rocks [Pearce and Norry, 1979].

Two other observations support the volcanic arc option. First, ocean floor volcanic rocks from modern spreading centers [Hawkins, 1980; Hekinian, 1982, Table 21] do not exhibit the wide silica range and moderate potassium content found in the Ucluth volcanic rocks. This statement is also true for altered volcanic rocks from ancient ophiolites [Coleman, 1977, Table 7, Figure 29]. Second, the predominance of fragmental volcanic rocks in the Ucluth is atypical of ocean floor spreading centers. Garcia [1978] notes that ocean floor volcanic settings are dominated by flow rocks, with less than 6% fragmental volcanic rock, whereas modern volcanic arc settings typically contain more than 80% fragmental rocks.

Comparisons With Upper Triassic Rocks of Wrangellia

On the basis of their subduction complex interpretation, Muller [1973, 1977a] and Page [1974] argued that volcanic

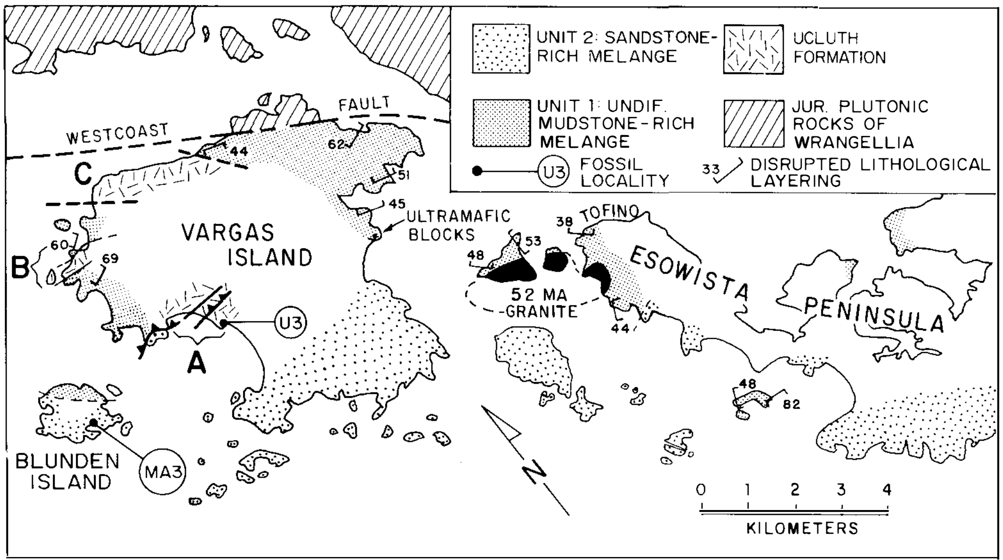

Fig. 6. Geologic map of Vargas Island and Tofino area, located at the northwest end of the Pacific Rim Complex (Figure 1). Fossil locality U3 from the Ucluth Formation is described in Table 1. Locality MA3 marks the location of an Early Cretaceous fossil from a small exposure of unit 1 mélange [see Brandon, 1989a].

rocks in the Pacific Rim Complex were fault slices derived from subducting oceanic crust or from the overriding Wrangellia terrane. The second option was particularly attractive because Wrangellia contains an Upper Triassic sequence, composed of Karmutsen basalt and Quatsino limestone (Figure 8), which could account for the association of limestone with volcanic rocks in the Pacific Rim.

Neither of these options can account for the Ucluth Formation. The first option, derivation from subducting oceanic crust, is ruled out by the arc volcanic character of the Ucluth. The second option is rejected because of fundamental differences in stratigraphy (Figure 8) and composition (Table 2) between the Ucluth Formation and the Karmutsen-Quatsino sequence. The Karmutsen consists of a 6-km-thick sequence of pillow basalt with subordinate breccia and tuff [Muller et al., 1981], whereas the Ucluth is dominated by volcanic breccia and contains only rare pillow lava. The Karmutsen does contain thick sections of breccia, but the breccia fragments are composed almost entirely of pillow fragments [Carlisle, 1963; Carlisle and Susuki, 1974]. Volcanic breccia in the Ucluth consists of angular fragments, cobble-sized and smaller, with no evidence of original pillow shapes. Fossils from the Ucluth indicate that volcanism extended into the Norian, whereas for the Karmutsen it is well established that volcanism ceased before the end of the Carnian (Figure 8). The age and stratigraphy of the Karmutsen is well known over most of the area of Vancouver Island, including the Kennedy Lake area [Eastwood, 1968], which lies less than 10 km to the northeast of the Pacific Rim Complex (Figure 1).

The third and last difference is composition. Tables 2 and 4 summarize 85 analyses of relatively unaltered flow rocks from the Karmutsen. The reason for including Table 4 is to show the remarkable uniformity of the Karmutsen, especially in light of the comprehensive sampling that this unit has received, both stratigraphically [Kuniyoshi, 1972] and regionally [Muller, 1971; Kuniyoshi, 1972; Scheffler, 1983] (also see Barker et al., [1985]). The Karmutsen consists of a restricted suite of low-potassium tholeiitic basalts and basaltic andesites (Figure 7, Tables 2 and 3). These features are in marked contrast to the wider compositional range, moderate-potassium content, calc-alkaline affinity of the Ucluth. Thus the Ucluth Formation is neither oceanic crust nor a piece of Wrangellia but rather an isolated fragment of a Lower Mesozoic volcanic arc.

UPPER JURASSIC OPHIOLITIC ROCKS

The unit 1A mélange contains about twenty blocks of pillow basalt and two closely spaced blocks of ultramafite (locations shown in Figure 2). These ophiolitic blocks represent only a small fraction of the blocks in unit 1A. They do, however, form some of the largest blocks in this mélange. They measure from 50 m to more than 300 m across, whereas blocks composed of Ucluth lithologies vary from 1 to 60 m across [Brandon, 1989a].

The basalt blocks consist mainly of pillowed flows (Figure 9a) with subordinate interbedded red and green ribbon chert (Figure 9b). Radiolaria from three localities give Late, and possibly Middle, Jurassic ages (Table 1), with the most precise determination: middle Late Jurassic (late Kimmeridgian). Other types of volcanic rock, such as sheet flows or volcanic breccia, are uncommon. Internal deformation in the blocks is limited to widely spaced faults, generally with minor slip. The basalts themselves are relatively fresh. In many cases, individual pillows still retain

TABLE 2. Summary of Chemical Analyses From the Pacific Rim Complex (PRC) and From Coeval Rocks in the Surrounding Area

	Ucluth Formation[a] Lower Mesozoic Basement Beneath PRC Mélange			Karmutsen Formation[b] Triassic Basalts of the Wrangellia Terrane			Upper Jurassic Pillow Basalt[a] Exotic Blocks in Unit 1A Mélange			"Green Tuff"[a] Interbeds in Unit 1A Matrix			
										basaltic		andestic	
	mean	range	n	mean	range	n	mean	range	n	GFT1	GFT3	GFT2	GFT4
Major Elements (oxide weight percent)													
SiO_2	56.83	(51.5 -64.5)	7	50.19	(44.8 -55.6)	85	51.43	(49.5 -54.8)	8	50.24	52.74	56.11	60.30
TiO_2	0.91	(0.35- 1.6)	7	1.84	(1.2 - 2.7)	85	2.05	(1.2 - 2.7)	8	2.28	2.50	0.59	0.55
Al_2O_3	17.21	(14.3 -18.6)	7	15.25	(12.4 -19.3)	85	14.46	(13.1 -17.3)	8	15.52	17.54	17.73	16.79
Fe_2O_3	0.84	(0.37- 1.1)	7	1.30	(1.0 - 1.9)	85	1.23	(0.79- 1.4)	8	1.19	1.05	0.84	0.84
FeO	6.84	(3.0 - 8.6)	7	10.57	(8.1 -15.5)	85	9.96	(6.4 -11.3)	8	9.66	8.48	6.79	6.83
MnO	0.15	(0.07- 0.20)	7	0.04	(0.0 - 0.24)	85	0.26	(0.15- 0.54)	8	0.19	0.19	0.17	0.19
MgO	4.20	(1.2 - 5.8)	7	6.84	(4.4 -11.1)	85	6.72	(6.0 - 7.6)	8	7.59	5.36	3.67	4.45
CaO	5.13	(3.2 - 9.9)	7	11.10	(6.7 -16.4)	85	8.63	(6.1 -11.7)	8	8.04	7.71	9.82	4.55
Na_2O	6.02	(4.2 - 7.6)	7	2.58	(1.0 - 4.4)	85	4.46	(3.2 - 6.2)	8	4.43	2.98	3.84	4.83
K_2O	1.62	(0.82- 2.5)	7	0.23	(0.0 - 0.91)	85	0.57	(0.13- 0.98)	8	0.57	1.02	0.29	0.57
P_2O_5	0.25	(0.12- 0.33)	7	0.05	(0.0 - 0.42)	85	0.24	(0.17- 0.42)	8	0.29	0.42	0.15	0.11
Trace Elements (element weight, parts per million)													
Ba	725	(100 -1440)	7	32	(12 - 48)	6	178	(70 - 500)	8	200	300	100	200
Cr	62	(3 - 310)	7	114	(42 - 249)	6	165	(87 - 353)	8	260	260	23	46
Nb[c]	~8	(6 - 14)	7	---	---------	--	~8	(5 - 18)	7	14	21	~4	~3
Ni	9	(4 - 14)	2	72	(43 - 118)	6	103	(79 - 133)	3	--	--	--	--
Rb[c]	~20	(7 - 35)	5	6	(0 - 15)	14	~4	(0 - 8)	7	~0	11	~0	~3
Sr	317	(230 - 420)	7	227	(88 - 664)	20	230	(85 - 381)	8	290	250	300	290
V	241	(235 - 246)	2	570	(450 - 680)	6	309	(220 - 400)	4	--	--	--	--
Y	24	(17 - 33)	7	---	---------	--	42	(17 - 54)	8	34	33	17	13
Zr	123	(65 - 300)	7	111	(67 - 142)	6	127	(58 - 220)	8	170	200	45	52
FeO*/MgO	1.96	(1.5 - 2.8)	7	1.77	(1.1 - 3.0)	85	1.64	(1.2 - 1.9)	8	1.41	1.76	2.06	1.71
Ti/V	24	(22 - 26)	2	22	(17 - 27)	6	37	(28 - 51)	4	--	--	--	--
Y/Nb[c]	~3	(2.3 - 4.7)	7	---	---------	--	~6	(1.9 - 9.0)	8	2.4	1.6	~4	~4

Major elements are recalculated to a volatile-free basis and an assumed ferrous-ferric ratio of FeO=0.9(total FeO). Trace elements were analyzed on a volatile-free basis. For FeO*/MgO, Fe* is total iron expressed as FeO.

[a] Most analyses were done by the Analytical Chemistry Section of the Geological Survey of Canada using ICP and XRF methods; 4 analyses, including one replicate, were done on the University of Washington ICP. See appendix for details.

[b] From Table 4.

[c] Mean values are shown as approximate where Nb and Rb are below the 10 parts per million detection limit.

TABLE 3. Discriminant Plots for Volcanic Rocks in the Pacific Rim Complex and Karmutsen Formation

Discriminant Diagrams[a]	Ucluth Formation	Karmutsen Formation	Upper Jurassic Pillow Basalts	"Green Tuff"
SiO_2 - K_2O (1; no restrictions)	moderate- to high-K calc-alkaline field	low-K field	low-K field	low-K and moderate-K fields
SiO_2 - FeO*/MgO (2; no restrictions)	calc-alkaline field	tholeiitic field	tholeiitic field	both calc-alkaline and tholeiitic fields
Y/Nb ratio (3; only basalts)	not alkaline	not alkaline	not alkaline	not alkaline
TiO_2-Zr-Y (3; only non-alkaline basalts)	NA	----------	ocean floor basalt field	NA
TiO_2-MnO-P_2O_5 (4; basalts and basaltic andesites)	NA	ocean floor basalt field	ocean floor basalt field	NA
Ti - V (5; no restrictions)	overlap region between arc and ocean floor fields	both ocean floor and arc basalt fields	ocean floor basalt field	---------
TiO_2 - Zr (3, 6, 8; only arc and ocean floor volcanic rocks)	calc-alkaline field	ocean floor basalt field	ocean floor basalt field	both calc-alkaline and tholeiitic fields
TiO_2 - Cr (6, 7; only arc and ocean floor basalts)	NA	ocean floor basalt field	ocean floor basalt field	NA
Interpreted Tectonic Setting	calc-alkaline volcanic arc	intra plate rift?	mid-oceanic ridge or back arc basin	detrital material from igneous blocks in mélange

Based on analyses summarized in Table 2; Y/Nb ratio for Karmutsen Formation is from Barker et al. [1985]. NA indicates that the diagram is not applicable because analyses do not meet the restrictions for that diagram (see first column for restrictions). Dashes indicate that the necessary chemical data were not available for that unit.
[a]References: 1, Wilson and Davidson [1984]; 2, Gill [1981]; 3, Pearce and Cann [1973]; 4, Mullen [1983]; 5, Shervais [1982]; 6, Garcia [1978]; 7, Pearce [1975]; 8, Pearce and Norry [1979].

a well defined rind composed of partially altered glass and numerous microspherules.

The ultramafic blocks are restricted to a single locality on eastern Vargas Island (Figure 6). According to Page [1974], they are composed primarily of serpentinized clinopyroxenite. These blocks are tabular in cross section, with an average thickness and length of 8 m and 70 m, respectively. These blocks may have been derived from the same ophiolitic terrane as the pillow basalts, a point that is discussed further below.

Chemical Analyses of the Pillow Basalts

Eight basalt samples were collected for chemical analysis (Figure 2; Table A1 in the appendix). Results are summarized in Tables 2 and 3. Most of the analyzed samples came from the central, more holocrystalline part of the basalt flows to avoid problems with alteration. Petrographic observations (Table A2 in appendix) show that the samples are fine grained (0.02 to 0.5 mm), with an intergranular texture of plagioclase (~70%), clinopyroxene (~20%), and minor Fe-Ti oxides (3-5%). Alteration consists of veins (1-3%) of chlorite ± calcite ± quartz and rare chlorite-filled amygdules.

Discriminant plots of the analyses indicate an ocean floor petrotectonic setting, either at a mid-oceanic ridge or a back arc basin. Major element diagrams (Figures 10a and 10b) classify the basalts as low-potassium tholeiites. The analyses consistently fall in the ocean floor field for all of the relevant discriminant diagrams listed in Table 3. Geologic evidence, such as the predominance of pillowed flows, the paucity of fragmental rocks, and the association of radiolarian chert, further support an ocean floor origin for these rocks.

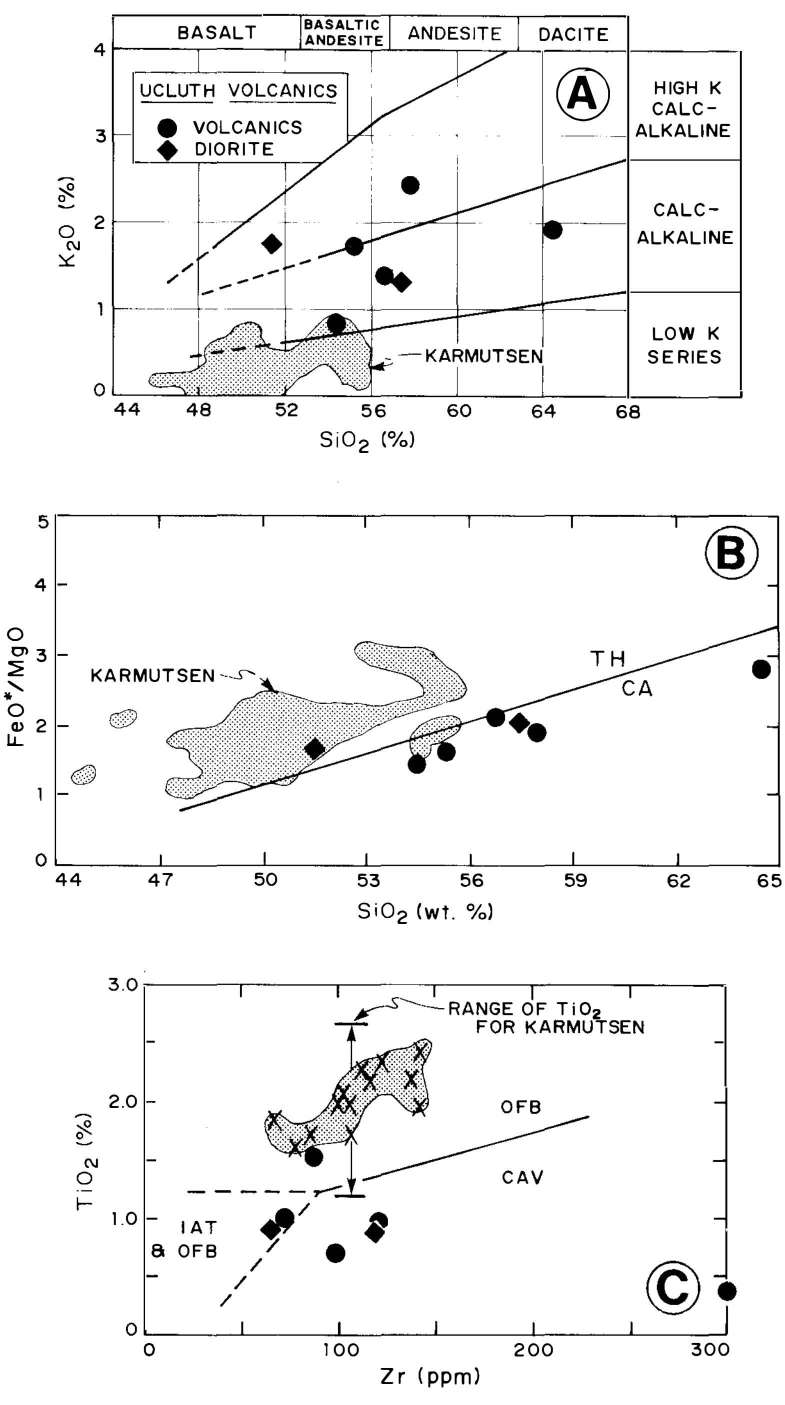

Fig. 7. Discriminant diagrams for the Ucluth and Karmutsen Formations. (a) SiO_2-K_2O diagram of Wilson and Davidson [1984]. Volcanic rock and diorite of the Ucluth Formation show a wide range in silica and potassium, suggesting a moderate-K calc-alkaline association. In contrast, the Karmutsen basalts (85 analyses) show a restricted range in silica and potassium and are classed as low-K basalts. (b) FeO*/MgO-SiO_2 diagram of Gill [1981], used to separate calc-alkaline and tholeiitic volcanic rocks (FeO* is total iron as FeO). The Karmutsen (85 analyses) plots in the tholeiitic field, whereas the Ucluth plots in the calc-alkaline field. (c) TiO_2-Zr diagram of Pearce and Cann [1973], used to discriminate between ocean floor basalts (OFB) and calc-alkaline volcanic rocks (CAV). The Karmutsen plots in the ocean floor basalt field and the Ucluth Formation plots in the calc-alkaline field.

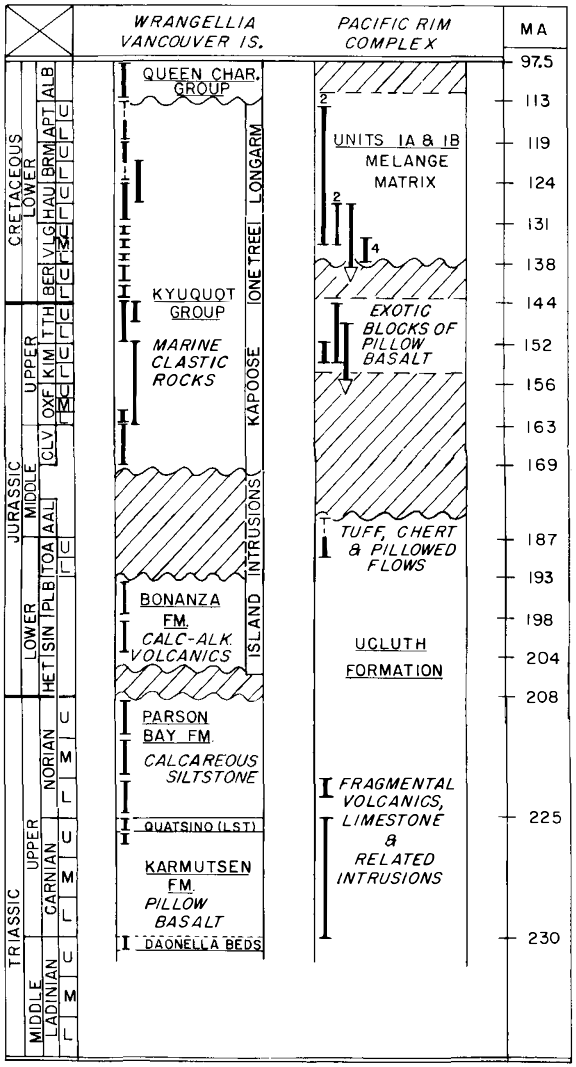

Fig. 8. Stratigraphic comparison of the Pacific Rim Complex with Mesozoic units of the Wrangellia terrane, Vancouver Island. The bracketed lines refer to the age range of fossils from these units. For the Pacific Rim Complex a number is shown where there is more than one locality of that age. Paleontological ages for Wrangellia are summarized from Muller et al. [1974, 1981] and sources cited there. Those for the Pacific Rim Complex are from Table 1 and Brandon [1989a]. The absolute time scale shown on the right is from Kent and Gradstein [1985].

Comparisons With Adjacent Rock Units

An important conclusion is that the Upper Jurassic pillow basalts are not related to Wrangellia or to other rocks units in the Pacific Rim Complex. These pillow basalts are chemically similar to the Karmutsen Formation (Table 2), but they are some 65 m.y. younger. The Upper Jurassic of Wrangellia consists solely of marine clastic strata of the Kyuquot Group [Muller et al., 1981]; volcanic rocks are absent. The Ucluth Formation is both older and compositionally quite distinct (Table 2) from the pillow basalt blocks. Thus the source of these blocks remains cryptic.

"GREEN TUFF" IN UNIT 1A MÉLANGE

Green tuffaceous sediment is a common component of many mudstone-rich mélanges [see Cowan, 1985]. In the field this sediment is frequently described as a green basaltic tuff, but there has been little petrographic work to substantiate this designation. In the Pacific Rim Complex, "green tuff" is restricted to unit 1A where it forms a minor (~5%) component of the matrix [Brandon, 1989a]. The tuff is clearly interbedded with the matrix sediments and commonly forms wispy lenses and thin irregular beds (Figure 11). It is fine to medium-grained but locally contains pebble- and cobble-sized clasts. The "tuff" beds share the same Early Cretaceous age determined for the matrix sediments of unit 1A. It is interesting to note that all of the volcanic rocks so far identified in the Pacific Rim are at least 15 to 20 m.y. older.

Petrographic observations (Table A2 in appendix) indicate that the "tuff" is not a pyroclastic deposit but rather a poorly sorted detrital sediment composed of fragments of metavolcanic and metaplutonic rocks. While a misnomer in this case, I continue to use the term "green tuff" because it has become such a widely used field term for this distinctive green sediment in mudstone-rich mélanges. Three types of tuff are recognized in the Pacific Rim Complex, each distinguished by a unique source rock: (1) microcrystalline basalt altered to chlorite, (2) plagphyric andesite with plagioclase partially altered to chlorite, and (3) medium-grained diorite with minor epidote. Chlorite and epidote alteration assemblages appear to predate deposition of the "tuff", as indicated by monomineralic clasts of epidote and by lithic clasts with boundaries that truncate alteration assemblages.

Four chemical analyses (Tables 2 and 3) indicate that the "tuff" is chemically similar to the igneous blocks in unit 1A. Two analyses are identical to the pillow basalt blocks, whereas the other two, which include a sample with grains of metadiorite, closely match the composition of volcanic and plutonic rocks in the Ucluth Formation.

Brandon [1989a] argues that the igneous blocks in unit 1A were emplaced by submarine rock falls from nearby basement scarps underlain by the Ucluth Formation and a cryptic Upper Jurassic ophiolitic terrane. The rock falls are considered to have been emplaced in a mud-rich basin adjacent to the basement scarps. The preferred alignment and tabular shapes of the blocks suggest that the blocks may have glided for some distance across the muddy seafloor surface before coming to rest [Brandon, 1989a]. Glide blocks are a recognized feature in both modern [Prior et al., 1984) and ancient [Ineson, 1985] rock fall deposits. In this context the "green tuff" is interpreted as a scree deposit derived from the blocks and possibly from the basement scarps as well. This interpretation is consistent with the composition of the "tuff", the fact that the "tuff" is restricted to those mélanges with igneous blocks, and the absence of any evidence for a contemporaneous volcanic source for the "tuff".

TABLE 4. Summary of Chemical Analyses From Basalt Flows in the Upper Triassic Karmutsen Formation

	Kuniyoshi [1972]														
	Kelsey Member			Hkusam Member			Menzies Member			Scheffler [1983]			Muller [1971]		
	mean	range	n	mean	range	n	mean	range	n	mean	range	n	mean	range	n
Major Elements (oxide weight percent)															
SiO_2	49.23	(46.0 -51.2)	19	52.46	(49.3 -55.6)	9	49.56	(44.8 -54.6)	37	51.79	(49.7 -55.4)	14	49.95	(49.1 -50.5)	6
TiO_2	1.92	(1.6 - 2.4)	19	1.60	(1.35- 2.22)	9	1.80	(1.20- 2.65)	37	1.97	(1.30- 2.42)	14	1.89	(1.26- 2.47)	6
Al_2O_3	15.70	(13.3 -17.3)	19	13.89	(12.4 -15.2)	9	15.33	(12.9 -17.3)	37	15.50	(14.0 -19.3)	14	14.78	(13.3 -17.5)	6
Fe_2O_3	1.38	(1.2 - 1.9)	19	1.13	(1.04- 1.39)	9	1.30	(1.10- 1.52)	37	1.30	(1.11- 1.46)	14	1.34	(1.00- 1.56)	6
FeO	11.21	(9.9 -15.5)	19	9.16	(8.45-11.2)	9	10.55	(8.90-12.4)	37	10.53	(8.99-11.8)	14	10.84	(8.13-12.6)	6
MnO	---	-------------		---	-------------		---	-------------		0.19	(0.15- 0.23)	14	0.19	(0.14- 0.24)	6
MgO	6.55	(5.4 - 8.3)	19	5.97	(4.72- 7.69)	9	7.65	(5.28-11.1)	37	5.66	(4.35- 7.92)	14	6.85	(5.51- 8.12)	6
CaO	11.56	(9.8 -12.6)	19	12.78	(10.6 -16.4)	9	11.07	(9.62-14.9)	37	9.45	(6.67-11.6)	14	11.11	(9.66-13.4)	6
Na_2O	2.26	(1.4 - 3.2)	19	2.64	(1.92- 3.88)	9	2.50	(0.98- 3.45)	37	3.15	(2.07- 4.39)	14	2.67	(1.77- 3.69)	6
K_2O	0.20	(0.06- 0.51)	19	0.37	(0.04- 0.91)	9	0.23	(0.01- 0.91)	37	0.22	(0.01- 0.82)	14	0.22	(0.0 - 0.56)	6
P_2O_5	---	-------------		---	-------------		---	-------------		0.23	(0.18- 0.42)	14	0.16	(0.11- 0.22)	6
Trace Elements (element weight, parts per million)															
Ba	33	(22 - 43)	3	12	-----------	1	40	(31 - 48)	2	---	--------------		---	--------------	
Cr	95	(42 - 54)	3	45	-----------	1	45	(37 - 52)	2	---	--------------		---	--------------	
Nb	---	-------------		---	-------------		---	-------------		---	--------------		---	--------------	
Ni	---	-------------		---	-------------		---	-------------		---	--------------		---	--------------	
Rb	75	(58 - 86)	3	45	-----------	1	81	(43 - 118)	2	6	(0 - 15)	14	---	--------------	
Sr	196	(158 - 220)	3	190	-----------	1	180	(170 - 190)	2	---	--------------		---	--------------	
V	587	(450 - 680)	3	600	-----------	1	530	(460 - 600)	2	243	(88 - 644)	14	---	--------------	
Y	---	-------------		---	-------------		---	-------------		---	--------------		---	--------------	
Zr	---	-------------		---	-------------		---	-------------		111	(67 - 142)	14	---	--------------	
FeO*/MgO	1.91	(1.7 - 2.3)	3	1.73	(1.3 - 2.0)	9	1.57	(1.1 - 2.1)	37	2.13	(1.3 - 3.0)	14	1.77	(1.3 - 2.1)	6
Ti/V	21	(17 - 25)	3	22	-----------	1	23	(19 - 27)	2	---	--------------		---	--------------	

Compilation is limited to least altered flow rocks, as noted by each author. Tuff, breccia, and dike rock were not included. Major elements are recalculated to a volatile-free basis and an assumed ferrous-ferric ratio of FeO=0.9(total FeO). For FeO*/MgO, FeO* is total iron expressed as FeO.

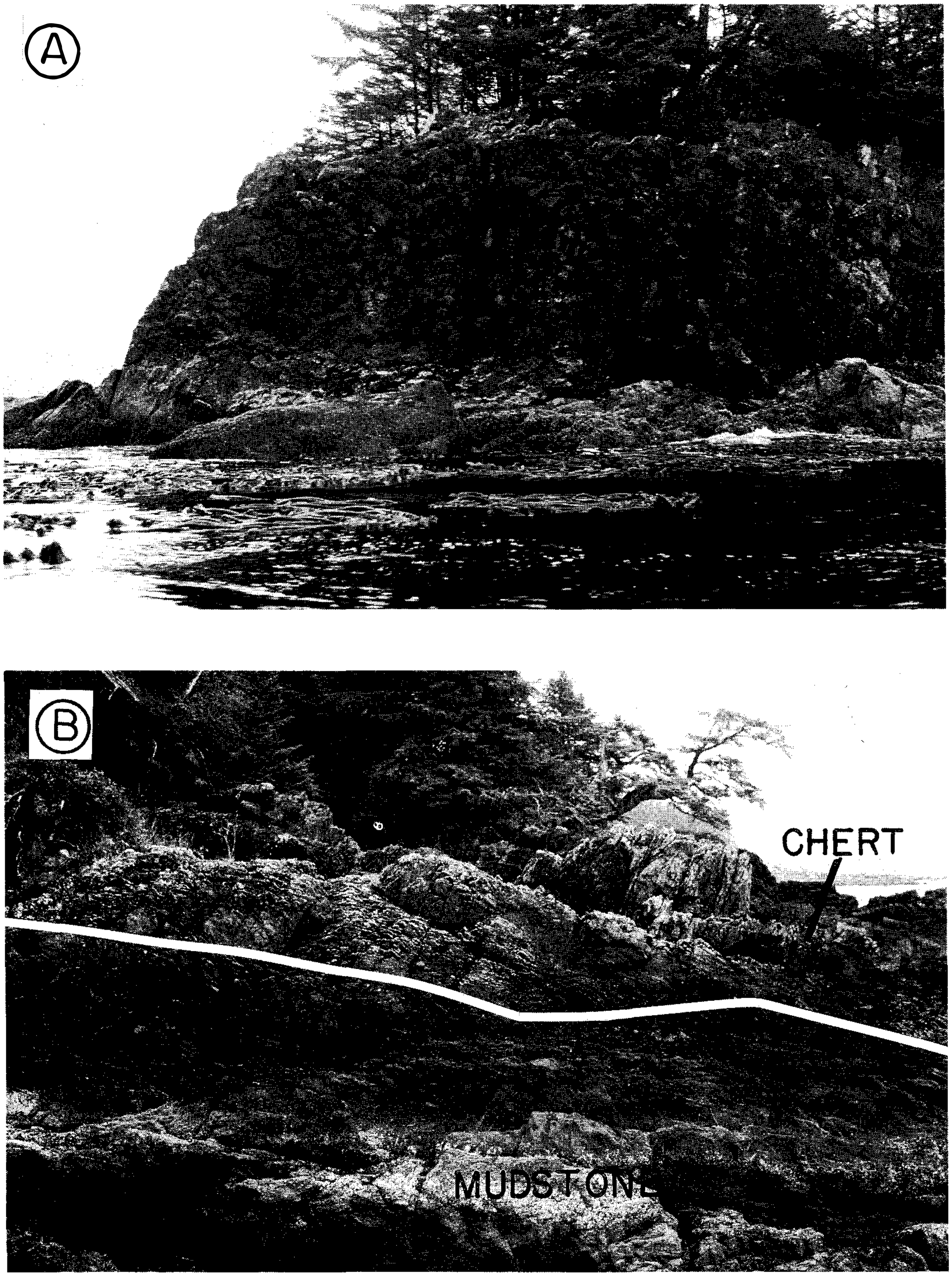

Fig. 9. Photographs of the Upper Jurassic pillow basalts. (a) A large pillow basalt block that underlies a group of islets (Beg Islands) west of the Ucluth Peninsula. Individual pillows are about 0.6 to 1 m across. (b) The lower contact of a chert-basalt block surrounded by mudstone-matrix mélange. Ribbon chert lies in the foreground, and associated basalt flows lie in the background. Radiolaria from this locality are Late Jurassic in age (JP1 in Table 1). An analysis of the associated basalt (GJP2 in the appendix) indicates an ocean floor type chemistry. The block is located about 5 km southeast of the town of Ucluelet.

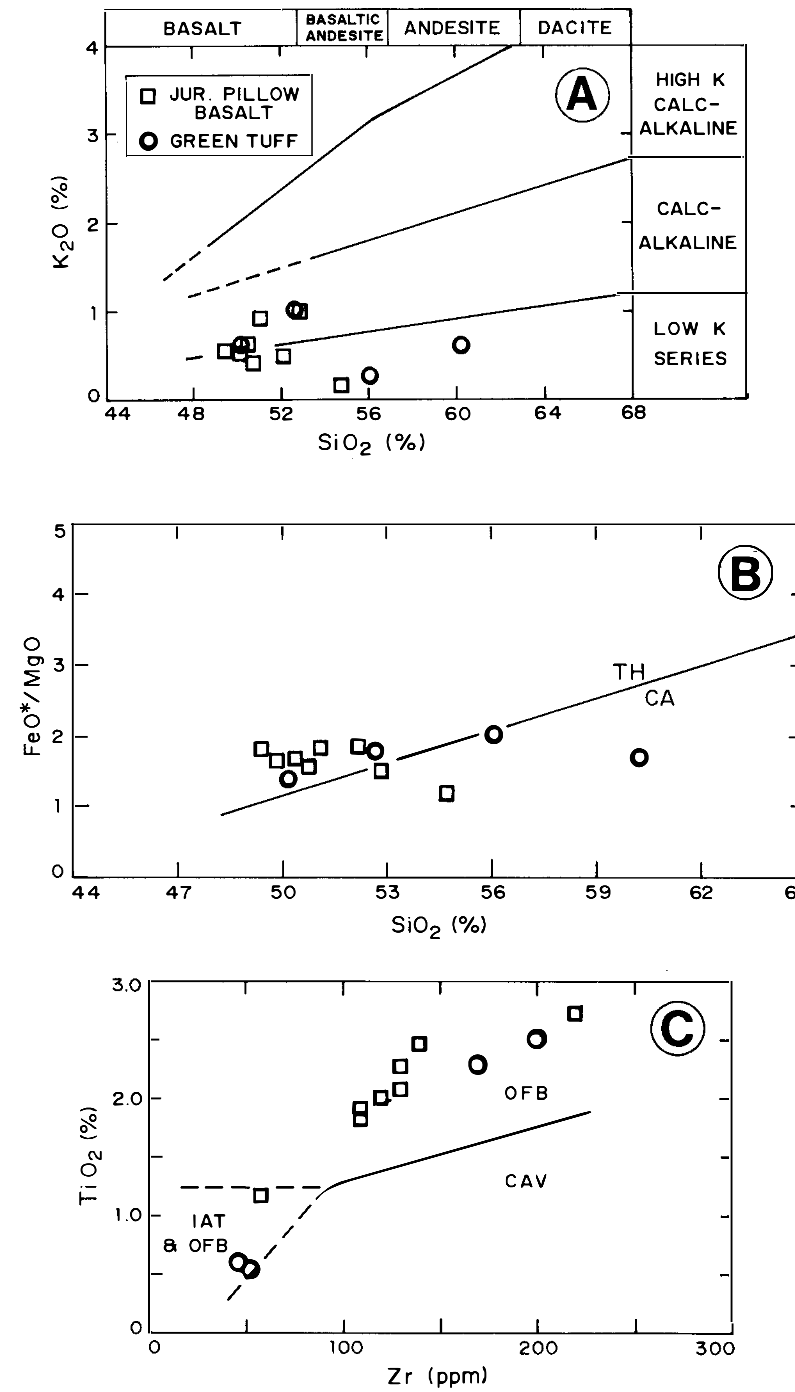

Fig. 10. Discriminant diagrams for the Upper Jurassic pillow basalts and the "green tuff". (a) SiO_2-K_2O diagram of Wilson and Davidson [1984]. The Upper Jurassic pillow basalts are low in silica and potassium. The "green tuff" shows low potassium values and a large range in silica. (b) FeO*/MgO-SiO_2 diagram of Gill [1981], used to separate calc-alkaline and tholeiitic volcanic rocks (FeO* is total iron as FeO). The pillow basalts generally plot in the tholeiitic field, whereas the "green tuff" plots in both fields. (c) TiO_2-Zr diagram of Pearce and Cann [1973], used to discriminate between ocean floor basalts (OFB) and calc-alkaline volcanic rocks (CAV). The pillow basalts generally lie in the ocean floor field, although one analysis is in an overlap region that includes both island arc tholeiites (IAT) and ocean floor basalts. The "green tuff" analyses plot in both fields.

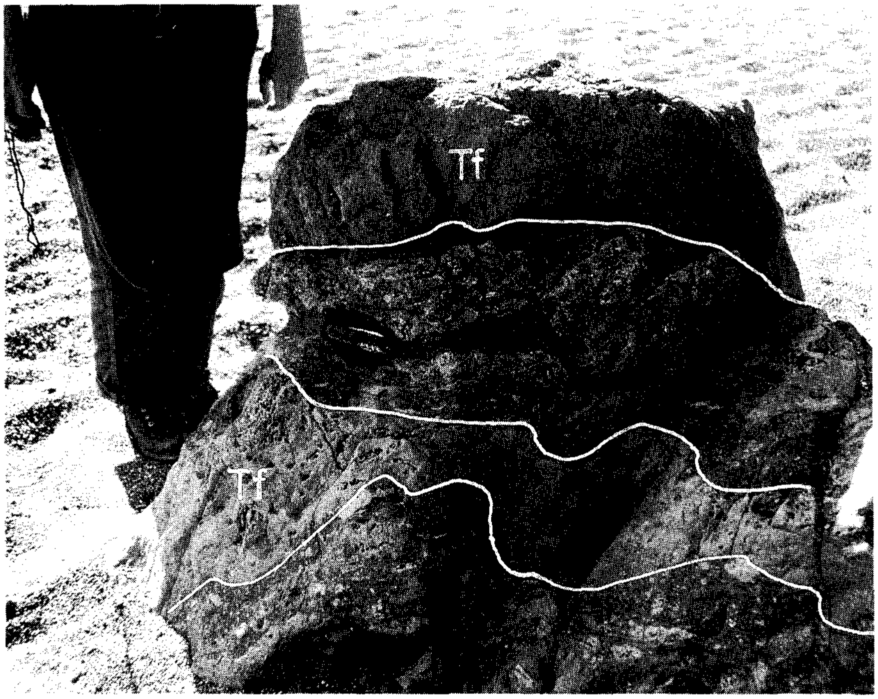

Fig. 11. Interstratified "green tuff" and mudstone in unit 1A, located about 4 km north of the Ucluth Peninsula (Quisitis Point). The lower mudstone horizon is a pebbly mudstone containing volcanic and limestone clasts; whereas the upper mudstone horizon consists of black mudstone, clay-rich ribbon chert, and small (1-2 cm) lenses of "tuff". Note the pocket knife for scale.

As mentioned above, "green tuff" is a common constituent in other mudstone-rich mélanges in the western Cordillera (Franciscan Complex [Aalto, 1986], Kelp Bay Group of the Chugach terrane [Johnson and Karl, 1985], and Ghost Rocks Formation [Byrne, 1984]; for other examples, see Cowan, [1985]). In these cases the presence of "tuff" is usually cited as evidence of near-trench volcanism [e.g., Aalto, 1986], perhaps related to subduction of a ridge crest or a leaky transform fault. In some cases there is further supporting evidence, such as coeval volcanic rocks or crosscutting dikes. It interesting to note, however, that "green tuff" is usually found only in mélanges with igneous blocks. Where I have observed these mélanges the "tuff" appears much like the "green tuff" in the Pacific Rim mélanges.

DISCUSSION

The subduction complex interpretation of Muller [1973, 1977a] and Page [1974] postulates that igneous rocks in the Pacific Rim Complex were derived by tectonic interleaving of fault slices from the Wrangellia terrane or from a subducting oceanic plate. The evidence presented above indicates that the Ucluth Formation, which comprises the bulk of these igneous rocks, could not have been derived from either of these sources. The Upper Jurassic pillow basalts, and perhaps the ultramafic blocks as well, do represent pieces of oceanic lithosphere, but they form only a small fraction lithosphere, but they form only a small fraction (< 5%) of the igneous rocks in the Pacific Rim. Furthermore, they only occur as blocks in the unit 1A mélange. The "green tuff" interbedded with the matrix sediments of unit 1A suggests that the blocks in unit 1A were emplaced in a near-surface setting, perhaps by submarine rocks falls [Brandon, 1989a].

The Pacific Rim Complex is commonly compared to other late Mesozoic subduction complexes of western North America, such as the Franciscan Complex of California and the Chugach terrane of Alaska [Dickinson, 1976; Muller, 1977a]. It is important to note, however, that the Pacific Rim Complex is much smaller. A few sporadic outcrops of Pacific Rim-like rocks have been identified elsewhere along the western coast of Vancouver Island [Muller et al., 1974; Rusmore and Cowan, 1985; Smyth, 1985], but the main extent of the unit is confined to the 65-km-strip of coastal outcrop in the Tofino-Ucluelet area (Figures 1 and 12). In this area the Pacific Rim lies wedged between Wrangellia to the northeast and a thick, coherent terrane of Eocene basalts that underlies the offshore area to the southwest of the Tofino fault [Clowes et al., 1987]. The bounding faults, the West Coast and Tofino faults (Figures 1 and 12), lie no more than 15 km apart. For comparison, the Franciscan Complex extends as a nearly continuous belt for 1000 km with an outcrop width of 50 to 100 km.

The interpretation I favor is that the Pacific Rim Complex is a displaced terrane, offset during the latest Cretaceous or early Tertiary from an original position to the southeast well. The West Coast fault is considered to be latest Cretaceous or younger (< 84 Ma), based on contrasts in the metamorphic histories of the Pacific Rim Complex and Wrangellia (discussed below). Thus the faults that bound the Pandora Peak and Pacific Rim are at least 45 m.y. younger than the Early Cretaceous (130 Ma) formational age of the mélanges.

Much of the evidence for the offset interpretation rests on the equivalence of the Pacific Rim Complex, Pandora Peak unit, and the Constitution Formation. All three units are composed mainly of sandstone- and mudstone-rich mélanges. The mudstone-rich mélanges contain interstratified "green tuff" and exotic blocks of (1) pillow basalt and ribbon chert, (2) limestone, (3) intermediate volcanic rocks, and (4) fine-grained diorite. The first two types of blocks are described by Rusmore and Cowan [1985] for the Pandora Peak unit and by Brandon et al. [1988] for the Constitution Formation. The last two types of blocks have not been recognized in the Constitution Formation, but they are present in the eastern part of the Pandora Peak unit (Harling Point and west side of Finlayson Arm, near Victoria (Brandon, unpublished field notes, 1986). Table 5 shows that the pillow basalt blocks in these units have a very consistent and similar composition. Trace element discriminant diagrams indicate that they are ocean floor type basalts (Constitution Formation [Brandon et al., 1988]; see appendix for Pandora Peak data).

Paleontologic ages indicate that the three units are coeval, although ages from the Constitution Formation and Pandora Peak unit are sparse and of low precision. The Pandora Peak unit has a single fossil age: Late Jurassic or Cretaceous radiolaria from ribbon chert interbedded in a pillow basalt block (Gonzales Bay locality of Rusmore and Cowan [1985]). The Constitution Formation has two radiolarian ages, both Late Jurassic or Early Cretaceous, from ribbon cherts interbedded with mudstone and sandstone [Brandon et al., 1988, p. 27]. Fault slices of probable Constitution Formation in the Lopez Structural Complex have yielded three additional fossil ages [Brandon et al., 1988, p. 30]: (1) Jurassic or Cretaceous radiolaria from chert in a sandstone unit, (2) Jurassic radiolaria from a block of pillow basalt and chert, and (3) Valanginian *Buchia* from a chaotic mudstone mélange. Identical *Buchia* are found in several localities in Unit 1B of the Pacific Rim Complex [Brandon, 1989a].

The most important similarity is that these units were all affected by a distinctive high-pressure metamorphism, which resulted in the characteristic assemblage: prehnite ± lawsonite ± aragonite/calcite. Except for the Pacific Rim Complex and Pandora Peak unit, this unusual assemblage is only found in the Late Cretaceous nappes of the San Juan Islands and northwestern Cascade Mountains [Brown et al., 1987; Brandon et al., 1988]. Rocks of the Wrangellia terrane, which lie to the west of nappes, show no evidence of this high pressure metamorphism. The San Juan-Cascade nappes are interpreted to have formed along the inboard or eastern side of Wrangellia when it collided with North America during the Late Cretaceous [Monger et al., 1982; Brandon and Cowan, 1985; Brandon, 1989b]. In the San Juan Islands it has been well established that metamorphism occurred as a direct result of thrust-related structural burial and that thrusting and metamorphism were short lived, confined to the interval 100 to 84 Ma [Brandon et al., 1988]. Thus the Pacific Rim Complex and Pandora Peak unit are viewed as offset pieces of the San Juan-Cascades nappes. If correct, then we might expect to find the Upper Jurassic ophiolitic terrane and the Ucluth Formation among these nappes.

The San Juan nappes do contain a clear candidate for the Upper Jurassic ophiolitic terrane: the Fidalgo Igneous Complex [Gusey and Brown, 1987; Brandon et al., 1988]. This unit includes Middle and Upper Jurassic pillow basalts with interbedded ribbon chert. Chemical analyses of these basalts (Table 5) are identical with those of the pillow basalt blocks in the Pacific Rim Complex, Pandora Peak unit, and Constitution Formation.

Candidates for the Ucluth Formation are two Triassic arc volcanic units (Figure 12): the Haro Formation of the San Juan Islands [Brandon et al., 1988] and the Cultus Formation in the northwestern Cascade Mountains [Monger, 1970; Brown et al., 1987]. Both units are composed of well-bedded volcaniclastic and pyroclastic sediments, argillaceous limestone, and cherty argillite. Fossils from the Cultus are Middle Triassic, Late Triassic, and Early Jurassic [Monger, 1970; Arthur, 1986], and fossils from the Haro are Late Triassic [Brandon et al., 1988]. The Haro and Cultus lack the coarse fragmental deposits and diorite intrusions that characterize the Ucluth, but these differences might be expected within a large volcanic arc terrane. Thus the evidence is compatible with, but not strongly supportive of, a Ucluth-Haro-Cultus correlation.

The tectonic setting associated with the Pacific Rim mélanges remains a mystery. The mélanges formed about 30 m.y. before the earliest evidence for the beginning of Wrangellia collision. The mélanges may have been related to some subduction zone located between Wrangellia and North America. The difficulty with this interpretation is that the North American margin shows a near absence of arc magmatism at 155 to 125 Ma [Armstrong, 1988], when the Pacific Rim, Pandora Peak, and Constitution mélanges were presumably forming. Another alternative is that the mélanges may have formed in a continental transform zone, perhaps like the southern California borderlands [Brandon, 1989a]. Perhaps the most important thing to stress is that the early history of these late Mesozoic mélange terranes has been largely obscured by younger events.

CONCLUSIONS

This paper has examined the origin of igneous rocks in the Pacific Rim Complex. These rocks are found in two distinct settings: as a basement unit, herein named the Ucluth Formation, that underlies the Pacific Rim mélanges and as large blocks in some of the mélanges. Most blocks are directly related to rocks within the basement unit. A small fraction (~20%), however, were derived from a cryptic Upper Jurassic ophiolitic terrane which is nowhere exposed in the present vicinity of the Pacific Rim Complex. The blocks were apparently emplaced by submarine rock falls from uplifted basement highs. Green tuff in the mudstone matrix of the mélange is shown to be a scree-like sediment derived from these igneous blocks or possibly from nearby basement

TABLE 5. Comparison of Jurassic Pillow Basalts From the Pacific Rim Complex and the San Juan Islands

	Pacific Rim Complex[a] Pillow Basalt Blocks in Mélange			Pandora Peak Unit[b] Pillow Basalt Blocks in Mélange		San Juan Islands[c]					
						Pillow Basalt Blocks in the Constitution and Lopez Units			In-situ Pillow Basalts of the Fidalgo Ophiolite		
	mean	range	n	GPP1	GPP2	mean	range	n	mean	range	n
Major Elements (oxide weight percent)											
SiO_2	51.43	(49.5 - 54.8)	8	48.42	49.09	51.74	(47.1 - 54.4)	8	50.17	(47.3 - 52.5)	5
TiO_2	2.05	(1.2 - 2.7)	8	1.24	1.88	1.43	(1.1 - 1.8)	8	1.38	(1.1 - 1.7)	5
Al_2O_3	14.46	(13.1 - 17.3)	8	15.26	14.07	15.40	(13.3 - 18.4)	8	17.19	(14.1 - 20.3)	5
Fe_2O_3	1.23	(0.79- 1.4)	8	0.94	1.18	1.02	(0.82- 1.3)	8	0.97	(0.79- 1.1)	5
FeO	9.96	(6.4 - 11.3)	8	7.64	9.56	8.30	(6.7 - 10.4)	8	7.88	(6.4 - 8.7)	5
MnO	0.26	(0.15- 0.54)	8	0.18	0.20	0.18	(0.15- 0.22)	8	0.17	(0.12- 0.28)	5
MgO	6.72	(6.0 - 7.6)	8	6.46	6.27	6.65	(4.4 - 8.2)	8	5.26	(3.3 - 7.3)	5
CaO	8.63	(6.1 - 11.7)	8	16.64	13.97	11.39	(8.1 - 13.4)	8	12.89	(10.4 - 15.3)	5
Na_2O	4.46	(3.2 - 6.2)	8	2.95	3.41	3.52	(2.0 - 4.4)	8	3.32	(2.7 - 4.3)	5
K_2O	0.57	(0.13- 0.98)	8	0.18	0.15	0.21	(0.09- 0.43)	8	0.62	(0.10- 1.4)	5
P_2O_5	0.24	(0.17- 0.42)	8	0.10	0.21	0.15	(0.11- 0.20)	8	0.13	(0.10- 0.16)	5
Trace Elements (element weight, parts per million)											
Ba	78	(70 - 500)	8	40	100	72	(30 - 100)	5	156	(155 - 157)	2
Cr	165	(87 - 353)	8	270	210	230	(110 - 515)	9	210	(142 - 346)	6
Nb[d]	~8	(5 - 18)	7	~4	~8	~5	(1 - 13)	4	4	---------	1
Ni	103	(79 - 133)	3	49	68	83	(49 - 175)	8	17	---------	1
Rb[d]	~4	(0 - 8)	7	~0	~0	~3	(1 - 5)	2	22	(19 - 25)	2
Sr	230	(85 - 381)	8	170	320	211	(108 - 420)	6	59	---------	1
V	309	(220 - 400)	4	240	300	272	(240 - 310)	5	--	---------	--
Y	42	(17 - 54)	8	26	40	26	(18 - 32)	6	32	---------	1
Zr	127	(58 - 220)	8	69	120	85	(60 - 120)	6	92	---------	1
FeO*/MgO	1.64	(1.2 - 1.9)	8	1.31	1.69	1.43	(1.2 - 2.1)	8	1.80	(1.3 - 2.8)	5
Ti/V	3	(28 - 51)	4	31	38	32	(39 - 25)	5	--	---------	--
Y/Nb[d]	~6	(1.9 - 9.0)	8	~1.7	~5	~14	(2 - 34)	4	~9	---------	1

Major elements are recalculated to a volatile-free basis and an assumed ferrous-ferric ratio of FeO=0.9(total FeO). Trace elements were analyzed on a volatile-free basis. For FeO*/MgO, FeO* is total iron expressed as FeO.

[a]From Table 2.

[b]See appendix.

[c][Brandon and others, 1988].

[d]Mean values are shown as approximate where Nb and Rb are below the 10 parts per million detection limit.

scarps. This distinctive green sediment certainly deserves further scrutiny for it may provide diagnostic evidence of how exotic blocks are introduced into sediment-rich mélanges.

Several factors indicate that the Pacific Rim Complex did not originate in its present position along the western perimeter of the Wrangellia terrane. The Ucluth Formation and the Upper Jurassic ophiolitic blocks are unlike coeval rocks of Wrangellia. The faults that bound the Pacific Rim are probably latest Cretaceous or younger, which is at least 45 m.y. younger than the formational age of the Pacific Rim mélanges. The Pacific Rim Complex shares some important similarities in stratigraphy and metamorphism with the Constitution Formation, which forms one of the Late Cretaceous nappes in the San Juan Islands. It is suggested that the Pacific Rim was offset from there, during the latest Cretaceous or early Tertiary. Late Cretaceous thrust nappes in the San Juan Islands include a Middle to Upper Jurassic ophiolite that could have been the source for the ophiolitic blocks in the Pacific Rim mélanges. Lower Mesozoic arc volcanic rocks (Haro and Cultus Formation) are also present and may represent the arc volcanic terrane from which the Ucluth Formation was offset.

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REFERENCES

Aalto, K.R., Depositional sequence of argillite, diamictite, hyaloclastite, and lava flows within the Franciscan Complex, northern California, *J. Geol.*, *94*, 744-752, 1986.

Armstrong, R.L., Mesozoic and early Cenozoic magmatic evolution of the Canadian Cordillera, *Spec. Pap. Geol. Soc. Am.*, *218*, 55-91, 1988.

Arthur, A., Stratigraphy along the west side of Harrison Lake, southwestern British Columbia, *Pap. Geol. Surv. Can. 86-1B*, 715-720, 1986.

Barker, F., G. Plafker, and A. Sutherland Brown, Karmutsen Formation, Queen Charlotte Is. and Vancouver Is.: An arc-rift ferrotholeiite of Wrangellia (abstract), *Geol. Soc. of Am., Abstr. Programs*, *17*, 340, 1985.

Brandon, M.T., Deformational processes affecting unlithified sediments at active margins: A field study and a structural model, Ph.D. thesis, 160 pp., Univ. of Wash., Seattle, 1984.

Brandon, M.T., Mesozoic mélange of the Pacific Rim Complex, western Vancouver Island, in *Field Guides to Geology and Mineral Deposits in the Southern Canadian Cordillera (Geological Society of America Cordilleran Section Meeting): Vancouver, British Columbia*, edited by D. Tempelman-Kluit, pp. 7.1-7.28, Geological Survey of Canada, Ottawa, 1985.

Brandon, M.T., Deformational styles in a sequence of olistostromal mélanges, Pacific Rim Complex, western Vancouver Island, Canada, *Geol. Soc. Am. Bull.*, in press, 1989a.

Brandon, M.T., Geology of the San Juan-Cascade nappes, Northwestern Cascade Range and San Juan Islands, in *Geologic Guidebook for Washington and Adjacent Areas*, Information Circular 86, edited by N. L. Joseph et al., pp. 137-162, Washington Division of Geology and Earth Resources, Olympia, 1989b.

Brandon, M.T., and D.S. Cowan, The Late Cretaceous San Juan Islands-Northwestern Cascades Thrust System (abstract), *Geol. Soc. Am. Abstr. Programs*, *17*, 343, 1985.

Brandon, M.T., D.S. Cowan, and J.A. Vance, The Late Cretaceous San Juan thrust system, San Juan Islands, Washington, *Spec. Pap. Geol. Soc. Am.*, *221*, 81 pp., 1988.

Brown, E.H., M.L. Bernardi, B.W. Christenson, J.R. Cruver, R.A. Haugerud, P.M. Rady, and J. N. Sondergaard, Metamorphic facies and tectonics in part of the Cascade Range and Puget Lowland, northwestern Washington, *Geol. Soc. Am. Bull.*, *92*, 170-178, 1981.

Brown, E.H., et al., Geologic map of the northwest Cascades, Washington, *Map and Chart Ser.*, MC-61, scale 1:100,000, Geol. Soc. of Am., Boulder, Colo., 1987.

Byrne, T., Early deformation in mélange terranes of the Ghost Rocks Formation, Kodiak Islands, Alaska: *Spec. Pap. Geol. Soc. Am.*, *198*, 21- 52, 1984.

Carlisle, D., Pillow breccias and their aquagene tuffs, Quadra Island, British Columbia, *J. Geol.*, *71*, 48-71, 1963.

Carlisle, D., and T. Susuki, Emergent basalt and submergent carbonate-clastic sequences including the Upper Triassic Dilleri and Welleri Zones on Vancouver Island, *Can. J. of Earth Sci.*, *11*, 254-279, 1974.

Clowes, R.M., M.T. Brandon, A.G. Green, C.J. Yorath, A. Sutherland Brown, E.R. Kanasewich and C. Spencer, LITHOPROBE -southern Vancouver Island: Cenozoic subduction complex imaged by deep seismic reflections, *Can. J. Earth Sci.*, *24*, 31-51, 1987.

Coleman, R.G., *Ophiolites*, 229 pp., Springer-Verlag, New York, 1977.

Cowan, D.S., Structural styles in Mesozoic and Cenozoic mélanges in the western Cordillera of North America, *Geol. Soc. Am. Bull.*, *96*, 451-462, 1985.

Danner, W.R., Stratigraphic reconnaissance in the northwestern Cascade Mountains and San Juan Islands of Washington State, Ph.D. thesis, Univ. of Wash., 562 pp., Seattle, 1957.

Dickinson, W.R., Sedimentary basins developed during the evolution of Mesozoic-Cenozoic arc-trench system in western North America, *Can. J. Earth Sci.*, *13*, 1268-1287, 1976.

Eastwood, G.E.P., Geology of the Kennedy Lake area, Vancouver Island, British Columbia, British Columbia

Department of Mines and Petroleum Resources, *Bull. 55*, 63 pp., Victoria, 1968.

Fairchild, L.H., and D.S. Cowan, Structure, petrology, and tectonic history of the Leech River complex northwest of Victoria, Vancouver Island, *Can. J. Earth Sci.*, *19*, 1817-1835, 1982.

Garcia, M.O., Criteria for the identification of ancient volcanic arcs, *Earth Sci. Rev.*, 14, 147-165, 1978.

Gill, J.B., *Orogenic Andesites and Plate Tectonics*, 390 pp., Springer-Verlag, New York, 1981.

Gusey, D.L., and E.H. Brown, The Fidalgo Ophiolite, in *Centennial Field Guide*, volume 1, edited by M. L. Hill, pp. 389-392, Geological Society of America, Boulder, 1987.

Hawkins, J.W., Petrology of back-arc basins and island arcs: Their possible role in the origin of ophiolites, in *Ophiolites, Proceedings of the International Ophiolite Symposium*, pp. 244-254, Cyprus Geological Survey Department, Nicosia, 1980.

Hekinian, R., *Petrology of the Ocean Floor*, 393 pp., Elsevier, New York, 1982.

Ineson, J.R., Submarine glide blocks from the Lower Cretaceous of the Antarctic Peninsula, *Sedimentology*, *32*, 659-670, 1985.

Johnson, B.R., and S.M. Karl, Geologic map of western Chichagof and Yakobi Islands, southeastern Alaska, 15 pp., scale 1:125,000, *U. S. Geol. Surv. Misc. Invest. Ser. Map 1506*, 1985.

Jones, D.L., M.C. Blake Jr., E.H. Bailey, and R.J. McLaughlin, Distribution and character of upper Mesozoic subduction complexes along the west coast of North America, *Tectonophysics*, *47*, 207-222, 1978.

Kent, D.V., and F.M. Gradstein, A Cretaceous and Jurassic geochronology, *Geol. Soc. Am. Bull.*, *96*, 1419-1427, 1985.

Kuniyoshi, S., Petrology of the Karmutsen Group, northeastern Vancouver Island, British Columbia, Ph.D. thesis, 252 pp., Univ. of Calif., Los Angeles, 1972.

Monger, J.W.H., Hope map-area, west half, British Columbia: *Pap. Geol. Sur. Can.*, *69-47*, 75 pp., 1970.

Monger, J.W.H., R.A. Price, D.J. Tempelman-Kluit, Tectonic accretion and the origin of two major metamorphic and plutonic welts in the Canadian Cordillera, *Geology*, *10*, 70-75, 1982.

Mullen, E.D., $MnO/TiO_2/P_2O_5$: A minor element discriminant for basaltic rocks of oceanic environments and its implications for petrogenesis, *Earth Planet. Sci. Lett.*, *62*, 53-62, 1983.

Muller, J.E., Chemistry and petrology of some Mesozoic volcanic rocks of Vancouver Island, British Columbia, *Pap. Geol. Sur. Can.*, *71-1B*, 5-10, 1971.

Muller, J.E., Geology of Pacific Rim National Park, *Pap. Geol. Sur. Can.*, *73-1A*, 29-37, 1973.

Muller, J.E., Evolution of the Pacific Margin, Vancouver Island, and adjacent regions, *Can. J. Earth Sci.*, *14*, 2062-2085, 1977a.

Muller, J.E., Geology of Vancouver Island, scale 1:250,000, *Geol. Sur. Can. Open File Map 463*, 1977b.

Muller, J.E., K.E. Northcote, and D. Carlisle, Geology and mineral deposits of Alert-Cape Scott map-area, Vancouver Island, British Columbia, *Pap. Geol. Sur. Can.*, *74-8*, 77 pp., 1974.

Muller, J.E., B.E.B. Cameron, and K.E. Northcote, Geology and mineral deposits of Nootka Sound map-area, Vancouver Island, British Columbia, *Pap. Geol. Sur. of Can.*, *80-16*, 53 pp., 1981.

Page, R.J., Sedimentology and tectonic history of the Esowista and Ucluth Peninsulas, west coast, Vancouver Island, British Columbia, Ph.D. thesis, 72 pp., Univ. of Wash., Seattle, 1974.

Pearce, J.A., Basalt geochemistry used to investigate past tectonic environments on Cyprus, *Tectonophysics*, 25, 41-67, 1975.

Pearce, J.A., A "user guide" to basalt discrimation diagrams, in *The Geochemistry of Oceanic Basalts*, edited by J. Tarney, Wiley and Sons, New York, in press 1989.

Pearce, J.A., and J.R. Cann, Tectonic setting of basic volcanic rocks determined using trace element analyses, *Earth Planet. Sci. Lett.*, *19*, 290-300, 1973.

Pearce, J.A., and M.J. Norry, Petrogenetic implications of Ti, Zr, Y, and Nb variations in volcanic rocks, *Contrib. Mineral Petrol.*, *69*, 33-47, 1979.

Prior, D.B., B.D. Bornold, and M.W. Johns, Depositional characteristics of a submarine debris flow, *J. Geol.*, *92*, 707-727, 1984.

Rusmore, M.E., and D.S. Cowan, Jurassic-Cretaceous rock units along the southern edge of the Wrangellia terrane on Vancouver Island, *Can. J. Earth Sci.*, *22*, 1223-1232, 1985.

Scheffler, J.M., A petrologic and tectonic comparison of the Hell's Canyon area, Oregon-Idaho, and Vancouver Island, British Columbia, M.S. thesis, 98 pp., Wash. State Univ., Pullman, 1983.

Shervais, J.W., Ti-V plots and the petrogenesis of modern and ophiolitic lavas, *Earth Planet. Sci. Lett.*, *59*, 101-118, 1982.

Smyth, W.R., Geology of the Brooks Peninsula, Vancouver Island, *Preliminary Reports of Activities*, pp. 161-170, Brit. Colombia Minist. of Energy, Mines, and Pet. Resour., Victoria, 1985.

Wells, R.E., D.C. Engebretson, P.D. Snavely, Jr., and R.S. Coe, Cenozoic plate motions and the volcano-tectonic evolution of western Oregon and Washington, *Tectonics*, *3*, 275-294, 1984.

Whetten, J.T., H.D. Gower, P.R. Carroll, and E.H. Brown, Bedrock geologic map of the Port Townsend quadrangle, Washington, scale 1:100,000, *U. S. Geol. Surv. Misc. Invest. Ser. Map I-1198G, 1989.*

Wilson, M., and J.P. Davidson, The relative roles of crust and upper mantle in the generation of oceanic island arc magmas, *Philos. Trans. R. Soc. London, Ser. A*, *310*, 667-674, 1984.

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