MESOZOIC MELANGE OF THE PACIFIC RIM COMPLEX, WESTERN VANCOUVER ISLAND

TRIP 7

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PREFACE

This guidebook was prepared for a field trip to be held in conjunction with the 1985 meeting of the Geological Society of America, Cordilleran section. It is divided into two parts. The first part describes the geology of the Pacific Rim Complex, with a special emphasis on the origin of melanges in that unit; the second part describes the field stops for this three-day trip.

The first two days of the field trip consists of 10 stops that focus on the structural and stratigraphic relationships in the Pacific Rim Complex. Most of these stops are in rocky coastal areas and are therefore best exposed at low tides (below 1-1.5 m). Care must be taken to remain aware of waves and the occasional large swell. Most stops can only be reached by footpaths, and several require 20-30 minutes walking time, so plan accordingly. We will use a charter boat to get to the last stop on Day 1 (charter and rental arrangements can be made in Ucluelet).

The third day consists of four road stops as we cross the Island on our way back to Nanaimo. These stops provide a brief introduction to some of the stratigraphic units of Wrangellia, a large, relatively coherent terrane that underlies most of Vancouver Island. Most of the localities for this part of the trip were adapted from Muller's (1977) field guidebook (see list below).

PART I
THE ORIGIN OF THE PACIFIC RIM COMPLEX, A MESOZOIC MELANGE ALONG THE WESTERN MARGIN OF VANCOUVER ISLAND

ABSTRACT

The Pacific Rim Complex is exposed in a fault-bounded slice along the west coast of Vancouver Island. It is composed of a sequence of Lower Cretaceous melanges which depositionally overlie an older igneous basement. This basement unit, herein called the Ucluth Volcanics, is a lower Mesozoic calc-alkaline arc sequence composed of fragmental volcanic rocks with subordinate diorite intrusions and interbedded limestone. Based on age and composition, the Ucluth Volcanics are clearly not correlative with rocks of the Wrangellia terrane which underlie Vancouver Island to the east.

Melange deformation is restricted to Lower Cretaceous sedimentary rocks overlying this basement unit. The melanges are pervasively deformed and are characterized by a heterogeneous structural style, including pinch-and-swell, disharmonic folds, and thick overturned sequences of turbidite. Sediments in the melange were unlithified during deformation because large ductile strains were accommodated without the development of a penetrative cleavage or pervasive cataclasis.

Melange resting above the basal contact with the Ucluth Volcanics commonly contains large, slab-shaped igneous blocks identical to parts of the Ucluth unit. Field relationships indicate that these are slide blocks, probably derived by submarine rock falls from nearby fault scarps of Ucluth Volcanics.

Previous interpretations have considered the Pacific Rim to be a late Mesozoic accretionary wedge constructed against the west side of the Wrangellia terrane. A number of factors argue against a subduction-melange interpretation, such as: (1) the Pacific Rim melanges are underlain by an older, arc-related basement and not by oceanic crust, (2) exotic blocks are submarine slide blocks and not fault slices, and (3) the melanges show no evidence of thrust faults and imbricate fault zones, which are features commonly described in other ancient accretionary complexes. The heterogeneous structural style of the melanges is more compatiable with an origin by down-slope mass-movement processes, such as submarine slides, rocks falls, debris flows and in-situ liquefaction. Indirect evidence suggests that the extensive amount of mass-movement deformation recorded by the Pacific Rim melanges was due to frequent earthquakes and strong ground motion at a seismically active plate boundary.

Similarities in stratigraphy and metamorphism indicate that during the mid-Cretaceous the Pacific Rim Complex was in the vicinity of the San Juan Islands (northwestern Washington). During the latest Cretaceous or early Tertiary, the Wrangellia terrane of Vancouver Island was truncated on its western side by a major transcurrent fault, the West Coast fault. The Pacific Rim was moved into its present position along this truncated western edge by northward displacement on the West Coast fault.

INTRODUCTION

The Pacific Rim Complex is exposed in a narrow, fault-bounded slice along the west coast of Vancouver Island (Figure 1). The unit consists of a chaotic assemblage of Lower Cretaceous mudstone, sandstone and chert, which overlies an older volcanic arc complex. This paper focuses on the depositional and early deformational history of the Pacific Rim Complex, with an emphasis on the processes responsible for melange formation. The Complex contains some of the best preserved and exposed Mesozoic melanges* in western North America. Pleistocene glaciation and frequent Pacific storms have resulted in extensive tracts of fresh coastal outcrop. Fabrics and structures in the melange are generally not affected by younger superimposed deformation, and therefore can be interpreted with more confidence than is possible in many other melange terranes. Furthermore, the Complex contains a variety of melanges that appear to reflect a spectrum of deformation processes.

The origin of the Pacific Rim melanges has important tectonic implications. Previous workers (Muller, 1973, 1977a; Page, 1974) have argued that these melanges represent a tectonic assemblage formed within a late Mesozoic subduction complex. They have suggested, along with Dickinson (1976), that the Pacific Rim was coextensive with other coeval subduction complexes along the western margin of North America (e.g., Franciscan Complex of California, Chugach terrane of southern Alaska, etc.). Several large allochthonous terranes presently lie to the east of these subduction complexes. If this interpretation is correct, these terranes must have been sutured to North America prior to the proposed Late Jurassic inception of subduction. Most notable of these older terranes is the Wrangellia terrane (Jones, et al., 1977), which underlies most of Vancouver Island (Figure 1).

There are several reasons to question this interpretation. The Pacific Rim Complex is presently only 5 - 10 km wide in map view and lies fairly close to the modern subduction zone, 100 km to the southwest (Figure 1). If the Pacific Rim represents a major accretionary complex, either not much sediment was accreted, or large portions of this complex are missing. Elsewhere along the west coast of Vancouver Island, Pacific Rim rocks are generally absent, and instead older rocks of the Wrangellia terrane underlie the present continental margin. These relationships suggest that the tectonic history of the

* In this paper, melange is used as a nongenetic term to describe chaotically disrupted sedimentary rocks, commonly containing exotic blocks in a finer grained matrix. See Silver and Beutner (1980) for further discussion.

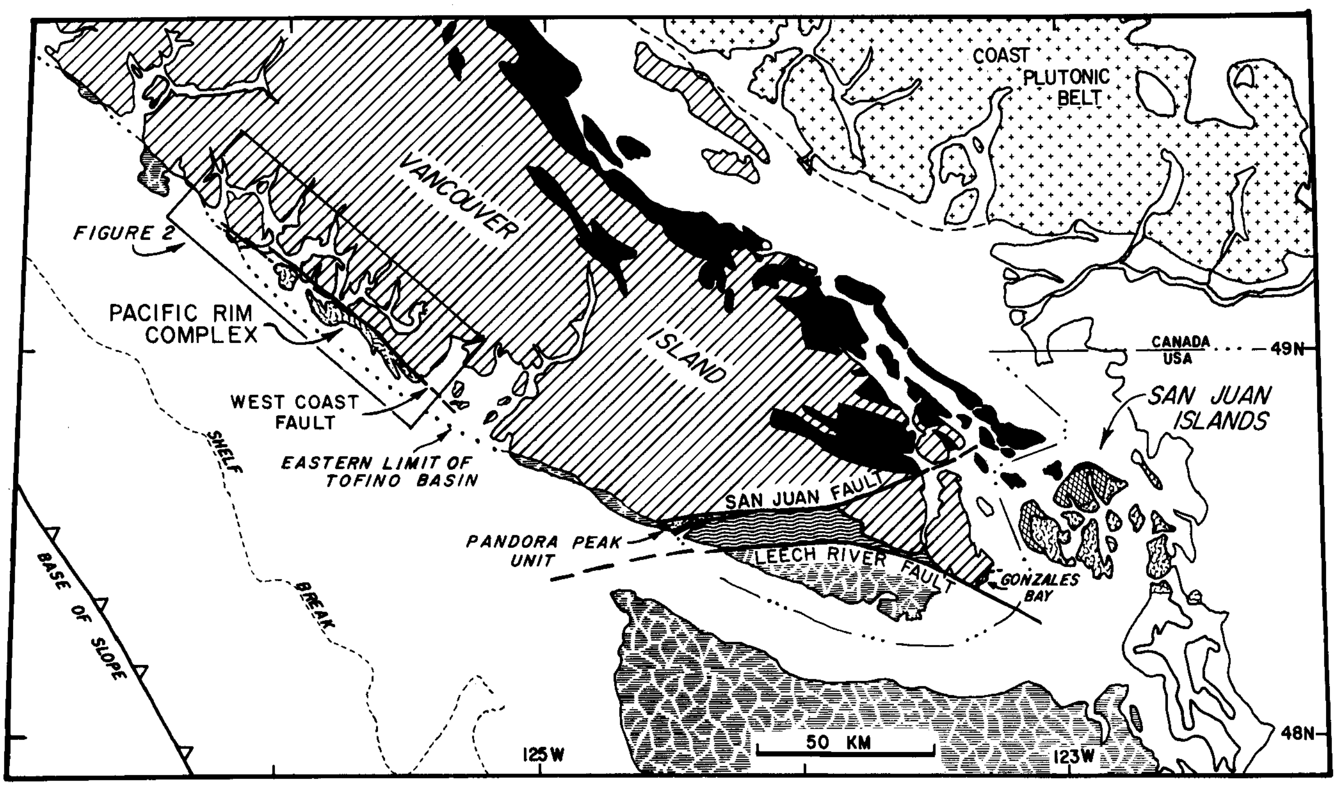

Figure 1. Generalized geologic map of Vancouver Island and surrounding area, modified from Roddick et al. (1979) to included more recent work on southern Vancouver Island (Muller, 1977b; Rusmore and Cowan, in press) and in the San Juan Islands (Brandon et al., in press). Quaternary sediments are not shown.

Lower Eocene and younger rocks. North of the Leech River fault: Upper Eocene and younger clastic rocks of the Carmanah Group (equivalent to strata of the offshore Tofino Basin).
South of the Leech River fault: Lower Eocene basalts and younger clastic rocks.

Nanaimo Group. Upper Cretaceous clastic rocks, mostly marine.

Leech River Complex. Mesozoic rocks that were regionally metamorphosed during the Late Eocene (Fairchild and Cowan, 1982).

Coast Plutonic Complex. Cretaceous and early Tertiary plutonic rocks; also includes minor pendants and screens of older rocks.

Pacific Rim Complex and other Mesozoic units. Generally consists of sandstone and mudstone with minor chert and basalt; locally includes older basement rocks. Other units are: Pandora Peak unit and rocks of Gonzales Bay on southern Vancouver Island; and Constitution formation, Lopez complex and Decatur terrane in the San Juan Islands.

Wrangellia terrane. Mesozoic and Paleozoic sequence that underlie most of Vancouver Island.

Paleozoic and lower Mesozoic rocks of the San Juan Islands.

Figure 1.

Vancouver Island margin is more complicated than previously appreciated.

A very different view of the tectonic evolution of this margin has emerged as the result of further field work in the Pacific Rim area and new fossil ages and radiometric dates. The Pacific Rim Complex represents a displaced fragment within a large transform fault system which truncated the west side of Vancouver Island during the latest Cretaceous or early Tertiary (Brandon and Cowan, 1983). This transform system has removed more westerly portions of the Wrangellia terrane and the Pacific Rim Complex, and has displaced them northward to southern Alaska. The Pacific Rim Complex has also been displaced with respect to Vancouver Island, but probably not more than 100 km. Similarities in stratigraphy and metamorphism indicate the Complex was originally coextensive with other Mesozoic rocks located around the southern end of Vancouver Island and in the San Juan Islands (Figure 1).

Therefore, the Pacific Rim Complex represents only a small portion of a once more extensive Mesozoic active-margin complex. The original tectonic setting of the Pacific Rim Complex is uncertain, but geologic relationships indicate that it does not represent an ancient accretionary wedge, that is, an imbricated complex of sediments and oceanic volcanic rocks formed by offscraping and accretion at an active subduction zone (Karig, 1983). Three lines of evidence have prompted this conclusion: (1) the Lower Cretaceous melange units depositionally overlie a regionally extensive lower Mesozoic volcanic arc complex and are not associated with normal oceanic crust; (2) chaotic disruption of the Lower Cretaceous melanges is not due to fault-zone deformation but instead occurred as a result of a variety of mass-movement processes, and (3) undisrupted portions of the melange matrix contain in-situ macrofossils indicating some of the sedimentary materials were originally deposited in relatively shallow depths and do not represent deeper water, trench-fill turbidites. These factors suggest that the melanges accumulated in small slope-basins within a morphologically complex active margin. If this margin included a coeval accretionary wedge, it was probably located seaward of the Pacific Rim Complex, and has since been removed by younger transcurrent faulting.

STRATIGRAPHIC FRAMEWORK

The Pacific Rim Complex can be divided into four major rock units. Based on geologic relationships exposed on the Ucluth Peninsula at the south end of the area (Figures 2 and 3), these units can be confidently placed into a general stratigraphic sequence, summarized in Figure 4. Age data for these units are shown in Figure 5.

The presence of a stratigraphic sequence is perhaps unexpected within a chaotic melange terrane, and therefore represents an important conclusion of my fieldwork. Previous workers (Muller, 1973, 1977a; Page, 1974) noted the prevalence of fault contacts within the Pacific Rim Complex and argued that these faults formed during subduction underthrusting. Most of the faults, however, are high-angle and appear to have only modest displacements. Furthermore, they commonly offset early Tertiary dikes and therefore are more likely related to younger deformation.

Perhaps the most compelling evidence for a stratigraphic interpretation is the presence of a regionally extensive basement unit beneath the Pacific Rim melanges. This previously unrecognized unit, which is herein named the Ucluth Volcanics, consists of calc-alkaline basalts with subordinate diorite intrusions and interbedded Upper Triassic limestone, plus a minor amount of Lower Jurassic pillow basalt and chert. The melange units overlie the Ucluth Volcanics, and consist of two basal mudstone-rich melanges, Units 1A and 1B, grading upward into a stratigraphically higher sandstone-rich melange, Unit 2. The basal melange units can locally be found in demonstrable depositional contact with the underlying volcanics. Elsewhere, they contain large diorite blocks, clearly derived from the Ucluth Volcanics.

These four units are described below, with special emphasis on features that might help to define how and where the Lower Cretaceous melange units were formed.

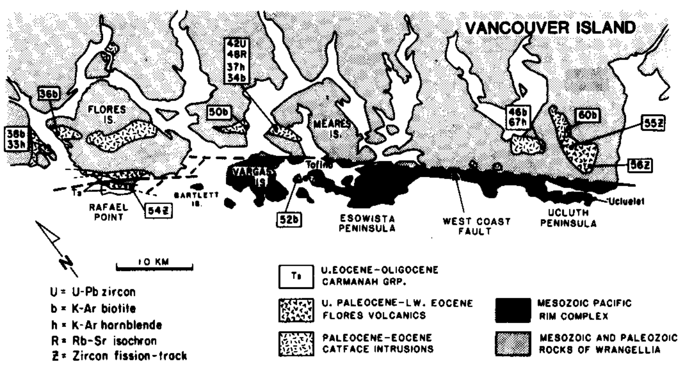

Figure 2. Geologic map of the Pacific Rim area, modified from Muller (1977b) to include my work. Radiometric dates are shown for early Tertiary volcanic and plutonic rocks. K-Ar dates are from Carson (1973) and Muller et al. (1981) and have been recalculated using new decay constants (Harland, et al., 1982). K-Ar, Rb-Sr and U-Pb dates for the pluton on Meares Island are from Isachsen (1984 and writ. comm., 1985). Zircon fission-track dates for the Flores volcanics (informal name) were determined by J. A. Vance, University of Washington.

LOWER MESOZOIC VOLCANIC BASEMENT

UCLUTH VOLCANICS

The Ucluth Volcanics represent a newly designated formation within the Pacific Rim Complex. This formation is named after the Ucluth Peninsula where it is well exposed in the core of an east-west trending anticline (Figure 3). Exposures on the west coast of the Peninsula are designated as the type area of the formation.

Lithology. The unit consists dominantly of green, aphanitic volcanic rocks, typically occurring as unstratified breccia with granule- to cobble-sized clasts, or less commonly as massive flow rocks. Locally the volcanics contain large (1-4 mm) dark green amygdales and sparse (less than 10%) plagioclase microphenocrysts. Pillowed flows and chert are rare, although they are present at one locality within the type area (at the end of the third access trail from the southeast as shown in Figure 3). A minor amount of thinly laminated, varegated tuff is also present and may represent waterlain tuff.

Irregular dikes and small stocks of diorite are ubiquitous throughout the unit and exhibit a range of textures from aphanitic to fine-grained allotriomorphic. In thin section, the diorite is composed mostly of plagioclase with minor quartz, biotite and hornblende. These intrusions are commonly difficult to distinguish from the surrounding volcanic rocks because of their fine grain-size, similar color and irregular intrusive contacts. Their fine-grained texture indicates that they are hypabyssal intrusions, probably related to Ucluth volcanism. This conclusion is supported by the geochemical similarity of the diorite intrusions and the volcanic rocks (data presented below).

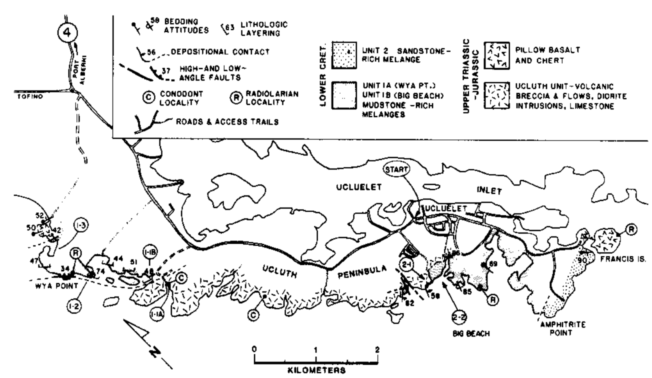

Figure 3. Geologic map of the Ucluth Peninsula showing the relationship between the Ucluth Volcanics and the overlying melange units. The numbers indicate field stops in this area.

Younger Tertiary dikes are also present throughout the Pacific Rim area, and can be easily confused with the older dikes which are restricted to the Ucluth Volcanics. The Tertiary dikes are distinguished by their more tabular form, fresher appearance and intermediate composition. Furthermore, they weather to a distinctive orangish color which contrasts with the surrounding green volcanics.

In contrast to the Tertiary dikes, the volcanic rocks and intrusions in the Ucluth unit display a patchy development of epidote-bearing metamorphic assemblages, probably a result of hydrothermal alteration. Locally, the volcanic rocks are converted to fine-grained amphibolite, apparently due to contact metamorphism by nearby diorite stocks. In thin section, these higher grade metamorphic assemblages are overprinted by minor amounts of prehnite, calcite and lawsonite. Lawsonite and prehnite are present throughout the Pacific Rim Complex; the significance of this very low-temperature, high-pressure metamorphic assemblage is discussed in the last section of this paper.

Irregular pods and lenses of light gray limestone are scattered throughout the unit and range up to 40 m in largest dimension. Bedding is locally apparent, especially where the limestone contains significant amounts of volcanic tuff. More typically, the limestone is fine-grained, massive and unfossiliferous, although rare fragments of crinoids and gastropods are present. In one locality, bedded tuffaceous limestone contains small unidentifiable ammonoids (southern conodont locality in Figure 3). Intercalation of limestone and volcanic rock is common and indicates that the limestone bodies are part of the Ucluth unit and are not exotic blocks.

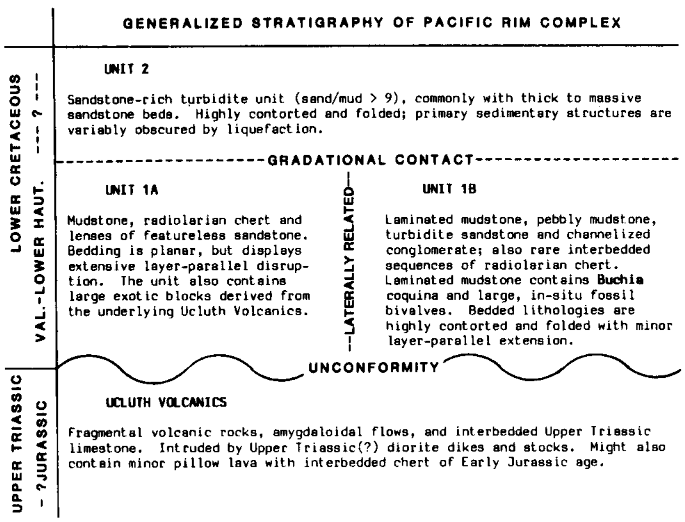

Figure 4. Generalized stratigraphic framework of the Pacific Rim Complex.

Age and Distribution. In the Ucluth Peninsula area, limestone from two localities have yielded Upper Triassic conodonts (Figure 3) with ages of: (1) Karnian (probably late Karnian) and (2) latest early Norian or earliest middle Norian (M. Orchard, pers. comm., 1983). The limestone at these particular localities are clearly interbedded with the volcanics. Furthermore, at the Norian locality, the dated limestone is cut by a small diorite dike.

The Ucluth Volcanics are also exposed in the northern part of the Pacific Rim Complex on the Vargas and Bartlett islands (Figure 2). Other isolated exposures of the unit occur on some of the small islets between Meares Island and the town of Tofino. Rocks in these areas consist of fragmental volcanic

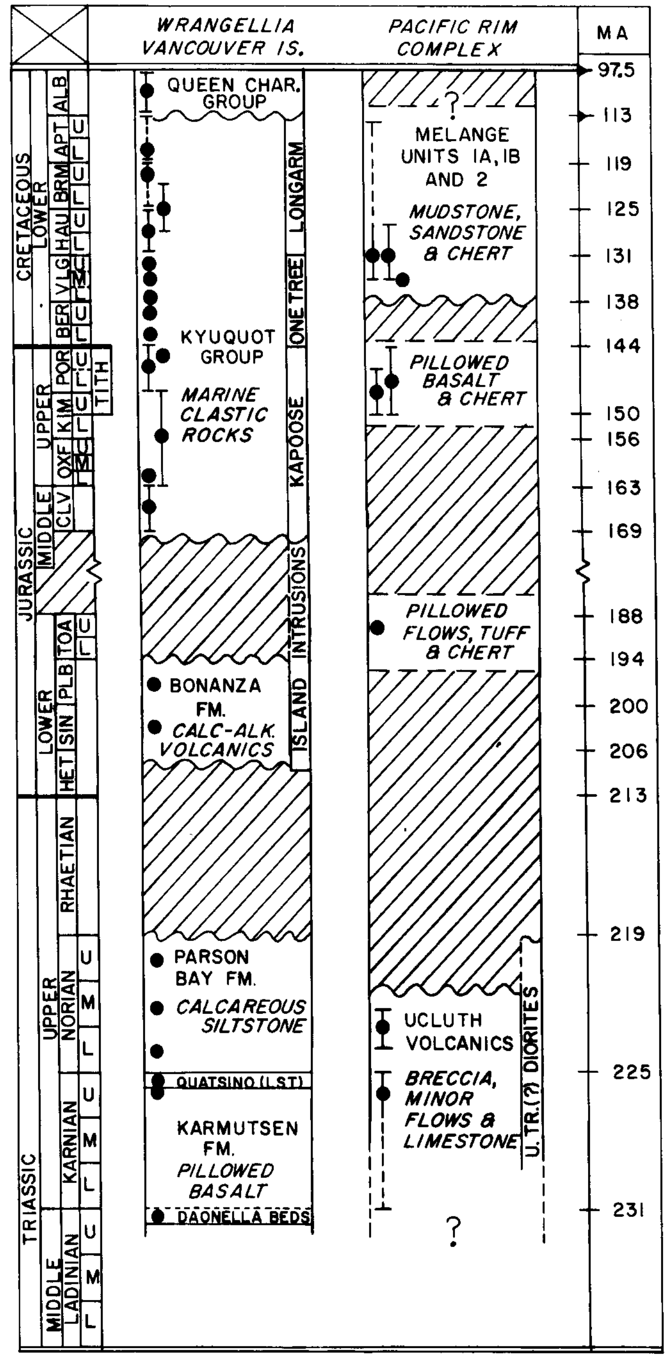

Figure 5. Stratigraphic comparison of the Pacific Rim Complex with Mesozoic units of the Wrangellia terrane, Vancouver Island. The ball-and-bracket symbols indicate the probable age and range of fossil ages from these units. Fossil ages for Wrangellia units are summarized from Muller et al. (1974, 1981) and other sources cited there, and those for the Pacific Rim Complex are from Brandon (1984). Recent changes in the zonation of Jurassic radiolaria (Baumgartner, 1984; Pessagno, pers. comm., 1984) indicate that the Upper Jurassic basalts in the Pacific Rim Complex could be as old as Callovian. The radiometric time scale shown on the right is from Harland et al. (1982).

rocks, limestone and cross-cutting diorite intrusions, and therefore are considered to be equivalent to the Ucluth unit in its type area.

Also exposed in the northern part of the Pacific Rim Complex is a poorly dated sequence of pillow lava, tuff and chert that may represent a younger part of the Ucluth Volcanics. This sequence, which would comprise only a minor part of the Ucluth unit, is exposed on Vargas Island, and on many of the small islands between Flores and Vargas islands (Figure 2). In these areas, it appears to be closely associated with the Triassic Ucluth rocks described above. The age of the sequence is probably Early Jurassic based on one radiolaria age from a chert interbed (late Toarcian -- E. A. Pessagno, writ. comm., 1983; Figure 6, west side of Vargas Island). Like the Triassic portion of the Ucluth, this Lower Jurassic sequence contains a large amount of fragmental volcanic rocks; limestone and diorite intrusions, however, are notably absent. These lithologic differences could be attributed to a difference in age and stratigraphic position. In this paper, the Lower Jurassic sequence is tentatively included with the Ucluth Volcanics; however, further work is need to confirm this stratigraphic relationship.

Geochemistry and Tectonic Setting. Five volcanic samples and two diorite samples from the Triassic portion of the Ucluth unit were analyzed for major and trace elements using a Kevex Energy Dispersive XRF at the University of California at Davis. Two of these samples were analyzed again on a Baird ICP (Induction-Coupled Plasma Spectrometer) operating at the University of Washington (see Brandon, 1984 for a description of the analytical procedure). These two techniques have yielded reasonably consistent results. An analysis of BCR-1, a USGS rock standard, done on the ICP compares quite well with published values (Table 1).

The ICP analyses, shown in Table 1, are representative of the suite. Silica content typically ranges from 47.9 to 53.4%, indicating that the volcanics and associated dikes are basaltic. One volcanic sample, however, is probably an andesite with silica of 59.6%. Metasomatic alteration has undoubtedly affected many of the major elements; most notable are the high NaO and low CaO contents. K_2O and Al_2O_3, however, are consistently high for all of the samples, especially when compared with basalts from modern ocean-floor settings (Hawkins, 1980; Table 2-1 in Hekinian, 1982) and from ancient ophiolites (Table 7 and Figure 29 in Coleman, 1977).

Immobile trace elements also indicate that the Ucluth Volcanics are different from ocean-floor tholeiites. The Y/Nb ratio is greater than 2.6 for all of the samples, which rules out an alkalic association (Pearce and Cann, 1973). The calc-alkaline character of these rocks is quite clearly demonstrated by the lack of any increase in TiO_2 with increasing Zr (Figure 7); almost all samples plot within the calc-alkaline basalt field using a TiO_2-Zr discriminant diagram (Pearce and Cann, 1973; Garcia, 1978). Calc-alkaline basalts are typical of modern volcanic arcs such as Japan, Java and Lesser Antilles (Pearce and Cann, 1973). The prevalence of fragmental volcanic rocks in the Ucluth Volcanics is also a common feature of modern volcanic arcs and is not typical of ocean-floor and oceanic-island volcanic settings (Garcia, 1978).

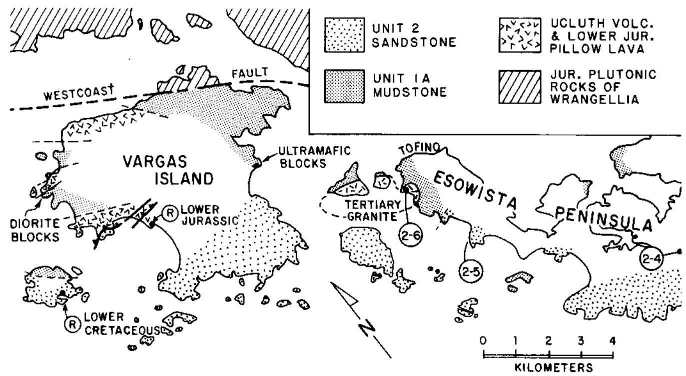

Figure 6. Geologic map of the Esowista Peninsula - Vargas Island area, located at the north end of the Pacific Rim area. Sandstone-rich melange of Unit 2 is extensively exposed in this area and appears to overlie older units; contact relationships, however, are not exposed. Other features include: rare ultramafic blocks in Unit 1A melange on eastern Vargas Island and Lower Jurassic pillow lava and chert on western Vargas Island. Numbers refer to field stops in this area.

LOWER CRETACEOUS MELANGE UNITS

The Pacific Rim melanges comprise almost all of the sedimentary rocks of the Complex. Where best exposed on the Ucluth Peninsula (Figure 3), these melanges preserve a crude stratigraphic succession consisting of two basal mudstone-rich melanges, Units 1A and 1B, grading upward into a sandstone-rich melange, Unit 2 (Figure 4). Units 1A and 1B occur on opposite sides of the large east-west trending anticline on the Peninsula, and unconformably overlie the Ucluth Volcanics, exposed in the core of the anticline. These two units are nowhere exposed together; however, similarities in age and stratigraphic position, together with the prevalence of black mudstone in each, indicate that they are probably laterally equivalent. There are differences in lithology and style of disruption. Unit 1A contains a greater proportion of chert and is characterized by a planar fabric, whereas Unit 1B is more highly contorted and contains graded turbidite sandstone, conglomerate and pebbly mudstone.

Sandstone in all three of these melange units contain minor amounts of prehnite, lawsonite and calcite. This assemblage is also locally present in chert of these melanges. The significance of this high pressure metamorphic assemblage is discussed below in the last section.

UNIT 1A: MUDSTONE-RICH MELANGE

Lithology, age, and distribution. Unit 1A is best exposed at Wya Point on the north side of the anticline (Figure 3). In that area, the melange is at least 400 m thick, not including the large block of pillow basalt on the north side of the Point. The unit consists of fragments and lenses of chert, sandstone and minor green basaltic tuff, organized into a planar fabric and surrounded by black mudstone (Figures 8 and 9). Unit 1A has yielded three Early Cretaceous radiolarian chert localities (late Valanginian to late Aptian -- Pessagno, writ. comm., 1983). These dated cherts are clearly interbedded with the matrix of the melange, and therefore indicate an Early Cretaceous age for the matrix as well. The melange also contains numerous exotic blocks of igneous rock (Figures 9 and 10), most of which were derived from the underlying Ucluth Volcanics.

Unit 1A is considered to rest unconformably on the Ucluth volcanics; however, unlike Unit 1B, there is no direct evidence of this relationship in the Ucluth Peninsula area. The basal contact of Unit 1A is locally exposed at Wya Point (Figure 3), but younger faulting has obscured primary contact relationships. A stratigraphic contact cannot be proven, but is suggested by: (1) the presence in the melange of blocks derived from the Ucluth Volcanics, (2) a younger-over-older relationship with Lower Cretaceous melange on lower Mesozoic volcanics, and (3) the concordance of the melange fabric with the underlying contact. This interpretation is also supported by the presence of an exposed basal

Table 1. Major and trace element data for selected volcanic rocks.

	UCLUTH VOLCANICS		UPPER JURASSIC(?) BASALTS		KARMUTSEN	USGS STANDARD BCR-1	
WT. %	VOLCANIC FLOW*	FINE-GRAINED DIORITE†	PILLOW BASALT§	SHEET FLOW**	AVERAGE OF 75 SAMPLES††	ICP ANALYSIS	PUBLISHED VALUES§§
SiO_2	53.55	49.91	53.86	48.76	47.58	55.01	54.85
Al_2O_3	16.37	18.02	16.84	13.44	14.81	13.80	13.68
Fe_2O_3 (total)	10.26	9.98	7.75	12.46	12.69	13.09	13.54
MgO	5.50	5.40	5.88	7.21	6.79	3.64	3.49
CaO	3.43	6.29	7.05	9.88	10.85	6.95	6.98
Na_2O	5.50	5.28	6.09	4.01	2.45	3.35	3.29
K_2O	1.87	1.89	0.0	0.25	0.24	1.56	1.68
MnO	0.16	0.12	0.13	0.16	0.19	0.15	0.19
P_2O_5	0.30	0.35	0.22	0.23	---	0.35	0.33
TiO_2	0.92	0.81	1.05	1.96	1.76	2.15	2.22
TOTAL	97.86	98.05	98.87	98.36	97.36	100.05	100.25
(WT. ppm)							
Zr	97	58	81	111		185	185
Nb	6	7	9	7		12	14
Sr	220	280	330	145		280	330
Y	23	18	17	36		30	37?
Ba	1230	805	130	93		600	680
Sc	28	18	31	36		27	34
Co	42	41	53	46		41	37
Cr	37	3	325	115		14	16
V	235	240	240	365		385	410
La	8	8	5	3		21	25
Zn	91	49	64	86		115	120
Cu	85	145	35	57		22	19

NOTE: Unless noted otherwise, the analyses were done on a Baird ICP at University of Washington (C. Cool, Analyst). Relative error for SiO_2: <2%; other major elements: <5%; trace elements: <10%. Detection limits are <2 ppm.

* 811013-2 NW side of Ucluth Peninsula. † 811016-5 NW side of Ucluth Peninsula.

§ 81728-2 NE side of Stubbs Island. ** 80922-6 At West Coast fault, E of Uclulet Inlet.

†† From Muller, et al. (1981). H_2O = 2.57% giving a total of 99.93%. P_2O_5 was not reported.

§§ From Abbey, 1977.

Table 1. Major and trace element data for volcanic rocks in the Pacific Rim Complex.

unconformity beneath the Unit 1B melange (discussed below).

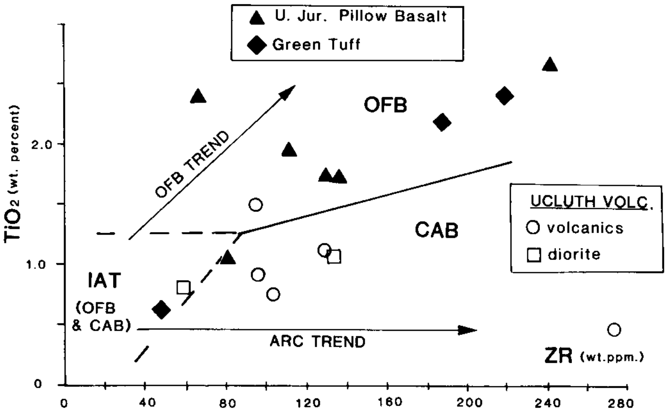

Figure 7. TiO_2-Zr relationships for the Ucluth Volcanics and the Upper Jurassic basalts and for green tuff from Unit 1A melange. Discriminant fields are from Pearce and Cann (1978) and Garcia (1978): OFB = ocean-floor basalt, CAB = calc-alkaline basalt, IAT = island-arc tholeiite. Trends for ocean-floor basalts and island-arc volcanics are from Garcia (1978). Relative errors for TiO_2 and Zr are less than 15% and 20% respectively. All samples plotted are basaltic with SiO_2 less than 54%, except for the Ucluth sample with the highest Zr value which has SiO_2 = 59.6%.

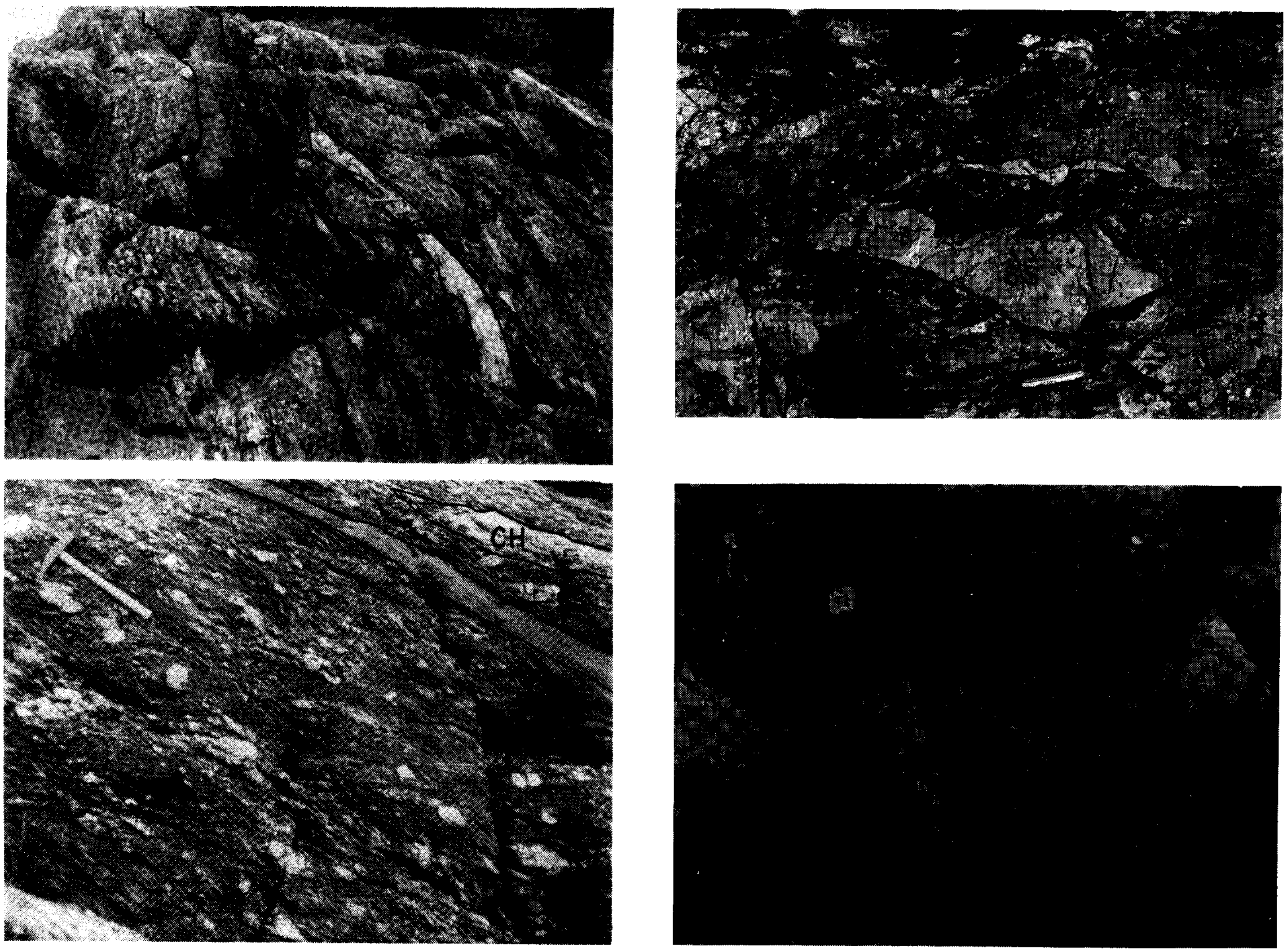

Figure 8. Photographs of various structures in Unit 1A melange. Figure 8a shows a typical example of the planar fabric of the melange, defined by tabular layers of sandstone (ss) and ribbon chert (ch), and also by aligned fragments of chert and sandstone. The surrounding matrix consists of black mudstone. The top of the mealnge is to the right (northeast). Figure 8b is a close-up of part of the view shown in Figure 8a (upper right corner). The ellipsoidal and spheroidal fragments consist mostly of chert (rock hammer shown for scale). Figures 8c and 8d are typical of some of the irregular pods of sandstone present in the melange. The tail-like feature in Figure 8c represents an injection of sand into the surrounding mudstone (note the knife and Brunton compass shown for scale).

Internal Structure. Unit 1A is characterized by a well layered but highly disrupted fabric. This fabric is dominated by oblate- and spheroidal-shaped fragments of chert and sandstone which range considerably in size and aspect ratio (Figures 8 and 9). In some respects, these fragments resemble boudins, but instead of the "sausage-like" shapes typical of boundinage (Ramsey, 1967), beds of sandstone and chert have been deformed into pancake-shape fragments, as if they were extended in all directions parallel to layering (cf. Cowan, 1982b). Evidence is given below (see ORIGIN OF MELANGE STRUCTURE) that, instead of layer-parallel extension, these boudin-like fragments were formed by a non-extensional process involving lateral flowage and thickening.

UNIT 1B: MUDSTONE-RICH MELANGE

Unit 1B is best exposed in the Big Beach area, on the south side of the Ucluth anticline (Figure 3). In comparison with Unit 1A, this melange contains a greater diversity of clastic rocks and is more highly contorted and internally folded. The unit is dominated by massive and laminated mudstone, with subordinate sandstone turbidite, channelized conglomerate, pebbly mudstone and ribbon chert. Exotic blocks of fragmental volcanic rocks are present, but are confined to pebbly mudstone.

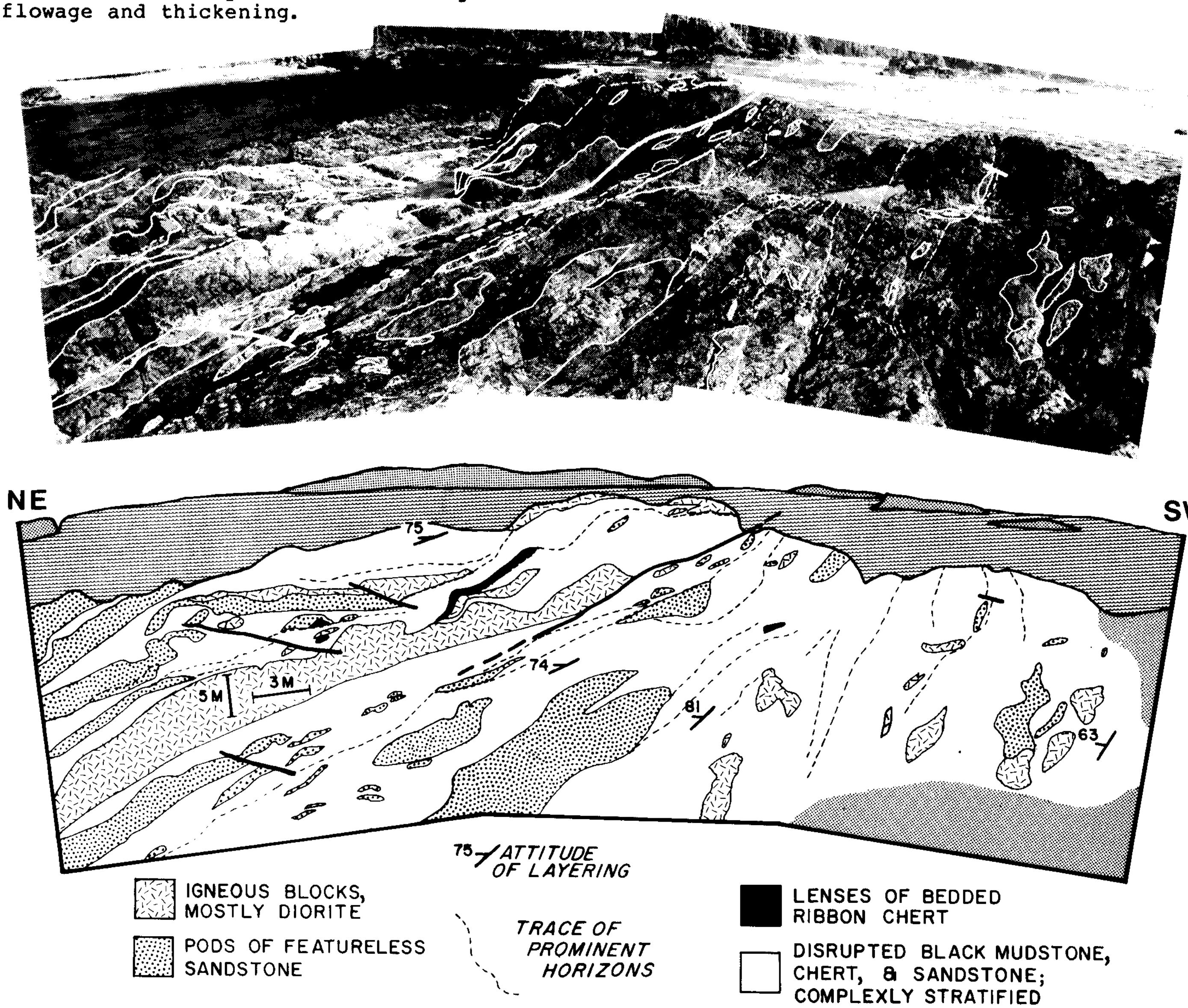

Figure 9. Detailed map of melange fabric in Unit 1A. The oblique photo in the top of the figure was used as a base map; photo and map face to the southeast. The contact of Unit 1A with the underlying Ucluth Volcanics lies about 50 m of the right (southwest) side of the map. The prominent chert lens in the center of the map has yielded Early Cretaceous (late Valanginian to late Aptian) radiolaria. The large diorite block shown on the left side of the map is 45 m long and 6 m wide.

Age. Fossils from Unit 1B indicate an Early Cretaceous age. Buchia of early or middle Valanginian age (J.A. Jeletzky, writ. comm., 1983; Muller et al., 1981) are present at a number of localities in mudstone of the melange. Most typically they occur in rare interbeds composed entirely of reworked shells. Three radiolarian localities from ribbon chert have yielded nearly identical ages (late Valanginian to early Hauterivian -- Pessagno, writ. comm., 1983), thus confirming the Early Cretaceous age of the unit. A number of large bivalves are also present in laminated mudstone and in mudstone interbeds of the turbidite sequences (localities labeled as Inoceramus? in Figures 12 and 13). These bivalves are not age diagnostic, but they occur in growth position and therefore can be used to constrain the original depositional setting of some of the sediments now incorporated in the melange.

Figure 10. Photograph of a large diorite block in Unit 1A melange. The block is about 4.5 m thick and extends for more than 35 m along strike. Contacts with the surrounding melange are irregular and unfaulted. The top of the melange is to the right (northeast).

Basal Contact. Unit 1B melange rests unconformably on Ucluth Volcanics. This unconformity is exposed north of Big Beach and can be traced eastward, based on isolated exposures of Ucluth Volcanics in the Big Beach area (Figure 3). Figure 12 shows a detailed map of part of this unconformity. The contact dips moderately to the south and east, and has been offset and repeated by a number of high-angle faults with both right-lateral and left-lateral separation. This situation illustrates how younger faults in the Pacific Rim area have obscured primary contact relationships, especially in areas with limited exposure. At the contact, Buchia-bearing mudstone rests in clear depositional contact directly above Upper Triassic limestone and volcanic rocks of the Ucluth unit. The mudstone directly above the contact appears to be a debris flow with randomly oriented Buchia surrounded and supported by a homogeneous mudstone matrix.

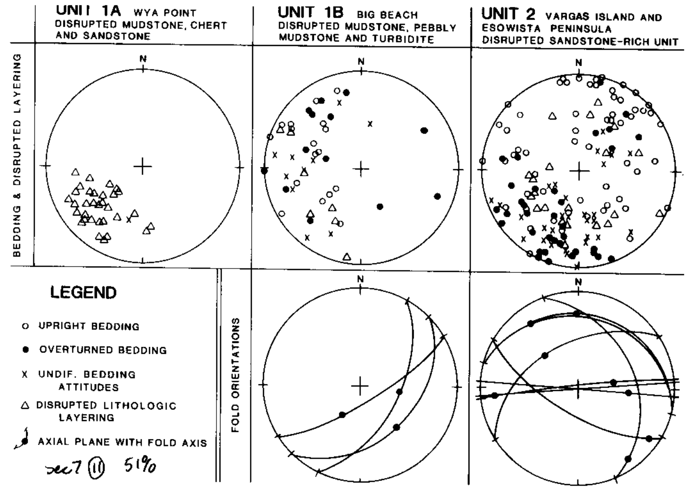

Figure 11. Stereonet plots of structural features in the melange units (equal-area projection). These stereonets show the contrast between the planar fabric of Unit 1A and the chaotic and folded fabric of Units 1B and 2.

Lithology. A detailed map of the Big Beach area, shown in Figure 13, displays typical map-scale relationships between the lithologic components of the Unit 1B melange. At this scale, the melange appears to a highly disorganized assemblage; at outcrop scale, however, bedding features and sedimentary structures are commonly well preserved.

Mudstone in the melange is either massive or, more commonly, bedded with thin silty laminae and rare sandstone interbeds. Trace fossils and other evidence of infauna are rare. Calcareous concretions are commonly present in the mudstone. These features are typical of mudstone deposited under restricted oxygen conditions (Johnson, 1978).

Sequences of coarser clastic rocks are composed of sandstone turbidites with interbedded mudstone and channelized conglomerate bodies. The sandstones range in bedding thickness but are generally medium to thickly bedded with sandstone/mudstone ratios of 3 to 6. Thicker sequences of massive sandstone are exposed on the southeast side of the map area and probably represent amalgamated turbidite beds. Interbedded conglomerate lenses are composed of well rounded, granule- to pebble-sized clasts, consisting predominantly of radiolarian chert (green, gray and white) with minor shale, sandstone and intermediate plutonic rock. These conglomerates are clast-supported with a sandy matrix and are typically well organized and locally graded.

Pebbly mudstone is exposed on the southwest side of the map area (Figure 13) and consists of black mudstone with well-rounded green volcanic clasts (Figure 14a). Clast size generally ranges from granule to small boulder, but larger blocks, up to about 4 m across, are locally present (Figure 14d).

Clasts are all volcanic, predominantly tuff and tuff breccia with minor flow rocks. The volcanic clasts are similar to parts of the Ucluth Volcanics and were probably derived from that unit. The pebbly mudstone is matrix-supported and generally lacks an organized fabric. Locally, it has a layered appearance defined by the preferred orientation of elongate clasts and variations in the relative proportions of clasts.

Chert is rare within Unit 1B, but a seven-meter-thick sequence of ribbon chert is exposed on the southwest side of the Big Beach map area (Figure 13) and is clearly interbedded with mudstone and sandstone of the melange. The sequence consists mostly of gray-green radiolarian ribbon chert with subordinate sandy ribbon chert. These cherts together with a small chert lens in massive sandstone have yielded the Early Cretaceous radiolaria described above.

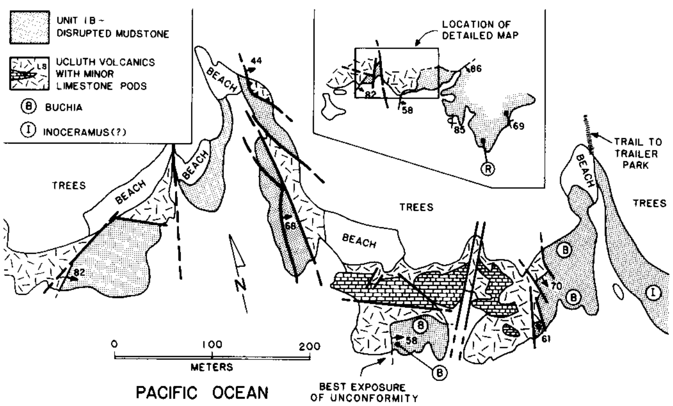

Figure 12. Outcrop map showing the basal unconformity of Unit 1B on the Ucluth Volcanics. The inset is from Figure 3 and shows the location of the detailed map. The basal contact is offset and repeated by a number of steep faults; therefore, it helps to refer to the schematic version of the contact shown in the inset. The unconformity is fairly irregular on a small scale, suggesting that the surface had some local relief. Note that in the center of the map, Lower Cretaceous Buchia-bearing mudstone directly overlie the Ucluth Volcanics.

Internal Structure. Rotated and overturned strata are the most visible effects of melange deformation in Unit 1B. When plotted as S-poles on a stereonet, bedding attitudes from the Big Beach areas form a crude girdle pattern with a moderately plunging, east-trending axis (Figure 11). Despite this girdle pattern, conventional fold geometries and large-scale fold closures are commonly not observed. Locally strata are contorted into irregularly shaped folds, but more typically, thick concordant sequences of upright or overturned strata appear to be bounded by discrete slip surfaces. Some rotation could have occurred on listric-shaped slip surfaces, but overturned strata are difficult to explain by this process alone. More likely, these slip surfaces have dismembered larger-scale overturned folds.

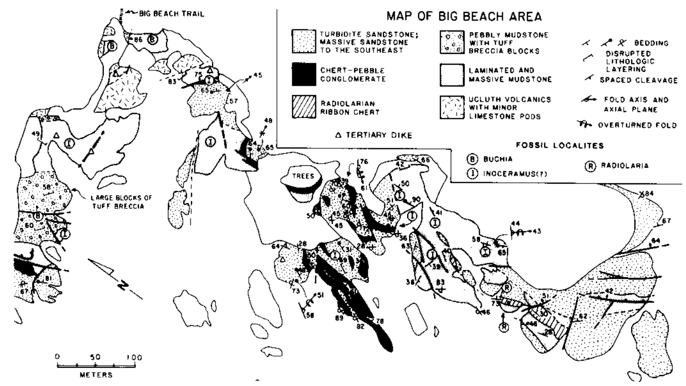

Figure 13. Detailed map of the Big Beach area showing the deformational style of Unit 1B. Melange deformation has resulted in a chaotic arrangement of upright and overturned strata. Exotic blocks are confined to pebbly mudstone. Buchia and radiolaria are Early Cretaceous in age. Unidentifiable bivalves (Inoceramus?) are also common in this area.

UNIT 2: SANDSTONE-RICH MELANGE

Lithology, age, and distribution. The sandstone-rich melange of Unit 2 appears to overlie Units 1A and 1B with a gradational contact. This relationship is best preserved at the south end of the Ucluth Peninsula (Figure 3) where the transition from Unit 1B to Unit 2 is marked by a gradual increase in the amount of sandstone. To the north on the Esowista Peninsula (Figures 2 and 6), Unit 2 appears to overlie Unit 1A melange, but contact relationships are not exposed. The age of Unit 2 is not known, but based on its similarity with Unit 1B, an Early Cretaceous age is inferred (Hauterivian or younger -- Figure 4).

Unit 2 is composed almost entirely of sandstone (less than 10% mudstone) and most commonly occurs in massive exposures with little evidence of internal bedding and structure. Thick- to medium-bedded turbidites are locally interbedded with the massive sandstone. Minor interbeds of clast-supported conglomerate are also present and typically consist of well-rounded clasts ranging from granule to cobble size. Most clasts are composed of intermediate and silicic volcanic rocks, with minor calcareous sandstone, diorite and shale.

Internal Structure. The deformational style of Unit 2 is very similar to Unit 1B. Stereonets in Figure 11 show bedding and fold orientations for sandstone-rich melange exposed in the Vargas Island-Esowista Peninsula area (Figures 2 and 6). Bedding attitudes and fold orientations are highly variable; upright and overturned beds occur without any systematic pattern. Folds in Unit 2 tend to be more coherent than in Unit 1B. They have amplitudes of 1 - 3 m and are generally isoclinal or tight. In some places, overturned strata occur in coherent slab-like sequences, ranging up to 375 m thick. These sequences are similar to overturned slabs in Apennine olistostromes (Hsu, 1967). If these sequences in Unit 2 were overturned by folding, their dimensions indicate fold amplitudes greater than 500 m.

In contrast to the other melanges, extensional features are not common. Discrete slip surfaces are present, and locally can be observed to juxtapose folded and unfolded strata. In general, however, folding and failure in Unit 2 has occurred in a relatively cohesive and plastic fashion, similar to Unit 1B. In well-bedded sandstones, there is some evidence for local liquefaction within small regions (less than a meter) where sedimentary structures have been variably distorted or obliderated. The absence of sedimentary structures in massive sandstone may also be due to postdepositional liquefaction, or instead may merely reflect the original depositional process.

ORIGIN OF MELANGES

EVIDENCE FOR MASS-MOVEMENT DEFORMATION

Previous workers (Muller, 1973, 1977a; Page,1974) suggested that the Pacific Rim melanges formed within a subduction complex, assembled by accretion of abyssal sediments and ocean-floor basalts from the down-going plate, and by tectonic erosion of older rocks from an overriding plate represented by the Wrangellia terrane of Vancouver Island. The following results of my study argue against a subduction-zone interpretation: (1) The melanges are underlain depositionally by an older basement composed of arc volcanic rocks and not by oceanic crust. Furthermore, peb-

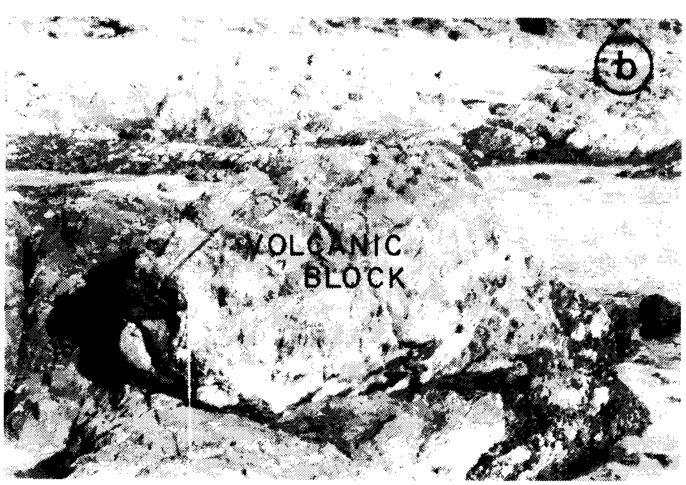

Figure 14. Photographs of pebbly mudstone and boudinage sandstone in Unit 1B melange. Figure 14a shows a typical pebbly mudstone with large clasts of volcanic rock. The presence of rounded clasts and their lithologic similarity with parts of the Ucluth Volcanics suggests that they were derived from a subaerially exposed portion of the Ucluth unit. Figure 14b shows one of the largest clasts in the pebbly mudstone; this clast is about 4 m across and consists of volcanic tuff breccia. Figure 14c shows an example of layer-parallel extension in turbidite beds of Unit 1B (staff on right side of photo is 1.5 m long). The beds have extended mostly by shear failure along small normal faults, resulting in a series of rotated blocks.

bly mudstones contain rounded cobbles that were derived from this basement, indicating that it was subaerially exposed prior to Early Cretaceous melange formation. (2) Exotic blocks do not represent fault slices, but instead appear to have been introduced into the melange by submarine rock falls and by muddy debris flows. (3) The Complex does not display any significant evidence of thrust imbrication, fault-zone deformation or older-over-younger relationships, all features that characterize well-documented ancient subduction complexes (see Moore and Karig, 1980; Moore and Allwardt, 1980; Leggett, et al., 1982). (4) The large bivalves in Unit 1B indicate that at least some of the sediments in the melange were initially deposited at relatively shallow depths, and therefore do not represent trench-fill turbidites. (5) The Lower Cretaceous ribbon cherts in the melange are unlike abyssal siliceous oozes and therefore were not accreted from a subducting oceanic plate. They are clearly interbedded with mudstone and sandstone of the melange, indicating deposition in a continental-margin setting.

My interpretation is that chaotic deformation occurred during surficial mass movement of unconsolidated sediments. The Pacific Rim melanges have a number of features similar to other well-established sequences of mass-movement deposits (Helwig, 1970; Hoedmaker, 1973; Woodcock, 1979), which include: (1) diversity of structural styles, (2) variability in form and geometry of folds, (3) development of isoclinal folds and boudinage without associated cleavage or cataclasis, and (4) chaotic arrangement of upright and overturned strata. This deformational style is quite unlike that produced during conventional folding and thrust faulting, even in areas where on-land thrust systems have overridden and imbricated unconsolidated foreland basin sequences (e.g., Figure 6 in Price, 1981). Admittedly, there is no consensus as to how unconsolidated sediments deform within subduction zones (Bachman, 1978; Cloos, 1982; Karig, 1983; Brandon, 1984; Byrne, in press; Cowan, in press). However, a less chaotic structural style should be expected within more deeply seated deformational settings, because the deforming mass is confined on all sides and therefore must deform in a relatively coherent fashion. The structural variability that appears to typify mass-movement deformation reflects, in part, the relatively unconfined, near-surface deformational environment. In this setting, deformation is probably more highly influenced by local variations in slope angle and in physical properties of the deforming sediments (for discussion, see Helwig, 1970). Another factor that also contributed to this structural variability is that the unit is formed by the sequential emplacement of a series of mass-movement deposits, each of which has moved and/or flowed independently of the others.

ORIGIN OF MELANGE STRUCTURE

At this point it is possible to consider in more detail the origin of structures within the melange. The structural styles of Unit 2 and 1B suggest that shear failure and extensive slumping and sliding were the primary means of mass transport. While there is evidence of local liquefaction, sedimentary structures and bedding features are usually well preserved. Thick sections of overturned strata suggest long transport distances during sliding and the presence of at least a small slope gradient. The extensive involvement of basinal strata might be due to retrogressive enlargement of one or more submarine slides. In a retrogressive slide, the headwall scarp keeps moving rearward so that the size of the slide increases over a period of time. This process can happen slowly over a period of years or quickly as it did in the submarine slide at Valdez during the 1964 Alaska earthquake (Seed, 1968).

The origin of structures within Unit 1A is more problematic. The consistent planar geometry of the unit argues against an origin by rotational slumping and sliding, or by remobilized debris flows. All of the sandstones in this unit appear to have been thoroughly liquefied and remobilized so that they now lack any evidence of primary sedimentary structures. The low permeability of the surrounding mud must certainly have enhanced the tendency for these sands to have liquefied. The presence of small sandstone dikes (e.g., Figure 8c) indicates that large pore-pressure gradients were locally developed between the sand and mud, directly analogous to the pore pressure gradients used to propagate tensile fractures during hydrofracture experiments (Lockner and Byerlee, 1977). As discussed above, sands have a greater pore-pressure potential during cyclic loading which would allow them to rapidly develop higher pore pressures than the surrounding muds. Furthermore, the chert was probably just as prone to liquefaction as the sand, because prior to lithification it was a fine-grained radiolarian sand.

In contrast to the other melanges, Unit 1A probably formed in a level-ground setting. There is little evidence of non-coaxial deformation or brittle shear surfaces that would be expected to form during down-slope movement. Furthermore, the extensive amount of liquefaction indicates a setting with low initial shear stresses, such as a level-ground setting (Seed, 1976). The main problem with this interpretation is that pinch-and-swell structures in the melange appear to indicate fairly large extensional strains in all directions parallel to layering (Figure 15a). Cowan (1982b) was first to call attention to this unusual structural style. Based on his study of a melange in the Franciscan Complex, he suggested that axial-symmetric layer-parallel extension occurred during lat-

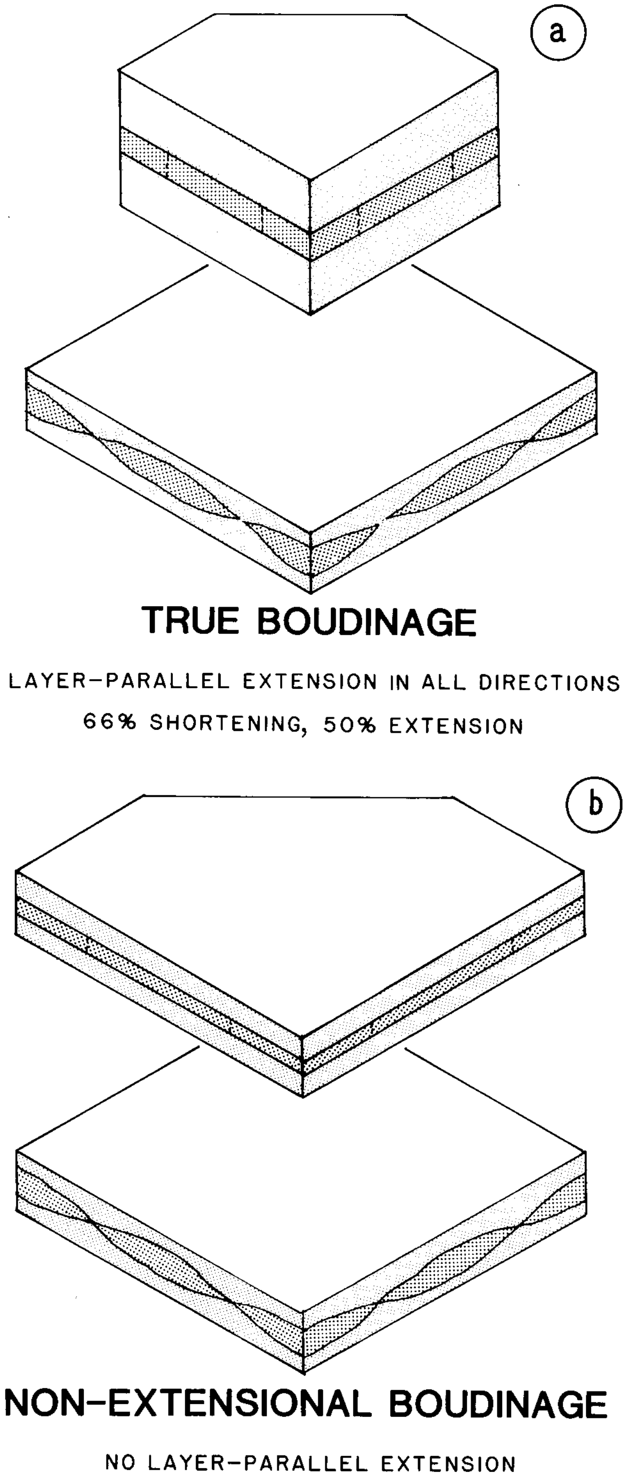

Figure 15. Two processes that can produce boudin-like structures, such as those observed in Unit 1A. Figure 15a shows a typical example of extensional boudinage; note, however, that extension occurs in all directions parallel to layering. Non-extensional boudinage, shown in Figure 15b, represents an alternative possibility. In this case, "boudinage" occurs by lateral flowage and swelling of the sand layer, without any layer-parallel extension. It is important to note that, unlike these idealized examples, the boudin-like structures in Unit 1A are highly irregular in shape and in spacing (e.g., Figures 8d and 9).

eral spreading of an unconfined lobate mass of muddy sediments.

There are indications that pinch-and-swell structure in the Unit 1A melange might not have formed by layer-parallel extension. The alternative is that the boudin-shapes formed by flowage during liquefaction. In the extreme, this flowage might result in what I call non-extensional boudinage (Figure 15b) where a layer contracts and swells into boudin-like shapes, but without any layer-parallel extension. In proposing this term, I am attempting to distinguish this idealized situation from true boudinage which involves layer-parallel extension (Ramsay, 1967). The following features are offered as evidence that the boudin-like structures in Unit 1A have formed by a non-extensional process: (1) If the boudins formed by layer-parallel extension then apparently there are abrupt changes and anomalously wide variations in the amount of extensional strain. For instance, an undeformed tabular bed of sandstone or chert commonly occurs directly adjacent to a horizon where chert and sandstone are extensively "boudinaged" (e.g., see Figure 8a). (2) Spheroidal boudins tend to be more widely separated than ellipsoidal boudins which suggests that apparent extension is controlled by the amount of thickening of individual boudins. (3) Unlike true boudinage (Ramsay, 1967), the boudin-like shapes in Unit 1A are very irregular in shape, in size and in spacing (e.g., see Figures 8 and 9). Theoretical analyses of the necking instability in true boudinage indicates that the boudins produced by this process should be relatively regular in shape and in spacing (see Smith, 1977); this conclusion is in accord with natural occurrences of true boudinage (Ramsay, 1967). (4) Irregular bulbous protrusions are present on the upper and lower sides of some sandstone boudins (e.g., Figure 8d) and provide at least some direct evidence of thickening. Cowan (1982b) has noted similar features associated with pinch-and-swell structures in Franciscan melange.

The boudins in Unit 1A bear some resemblance to sedimentary load structures, such as ball-and-pillow structure (Allen, 1982). However, unlike load structures, the boudins appear to have grown in a relatively symmetric fashion and show no evidence of having sunk downward into the underlying mud (cf. p. 360 in Allen, 1982). Furthermore, chert load structures would be unexpected because siliceous sediments typically have lower densities than clay-rich muds (Hamilton, 1976).

While these relationships do not prove a non-extensional origin for the boudin-like structures in Unit 1A, they do argue strongly against an origin by conventional boudinage. It is not clear how non-extensional boudinage occurs, although in the case of Unit 1A, the liquefaction phenomenon appears to be involved. The fact that these boudin-like shapes have formed exclusively by ductile flowage, with no evidence of tensile or shear failure, supports this contention. As part of a follow-up study, we hope to test this interpretation by using a large shaker-table to subject an interlayered sequence of mud and sand to earthquake-like ground motion.

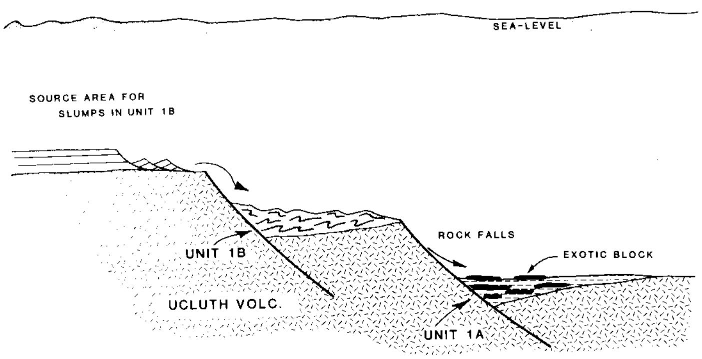

Figure 16. A schematic cross-section depicting an early stage in the evolution of the Pacific Rim melanges. Melange formation began with the development of small, structurally controlled basins. Initially, basin-margin faults tended to isolate the melanges from coarse clastic sedimentation. Contorted strata of Unit 1B were derived by retrogressive slumping of a turbidite fan sequence located up-slope. Unit 1A was located in a more "distal" setting which was dominated by deposition of mud, chert and subordinate sand. Rockfalls originating from local fault scarps introduced exotic blocks of Ucluth Volcanics into Unit 1A.

TECTONIC INTERPRETATIONS

ORIGINAL TECTONIC SETTING

The Pacific Rim melanges appear to record the Early Cretaceous formation (about 135 Ma) of a structurally controlled basin. A stage in the evolution of this basin is schematically illustrated in Figure 16, and represents the time of formation for Units 1A and 1B, which are coeval units (Figure 4). This interpretation is supported by the following observations: (1) The unconformity beneath the Lower Cretaceous melanges, together with the presence of rounded clasts of Ucluth Volcanics in pebbly mudstone of Unit 1B, indicates that the initiation of the basin was associated with the regional subsidence of the Ucluth Volcanics. (2) The presence of large diorite slabs in Unit 1A indicates the local presence of submarine fault scarps underlain by Ucluth Volcanics. (3) The difference in lithofacies between coeval units -- mudstone and ribbon chert in Unit 1A, and turbidite and mudstone in Unit 1B -- suggest a morphologically complex setting, perhaps dissected by large faults. (4) The indirect evidence for seismically induced liquefaction suggests a seismically active setting.

For these reasons, the inception of deposition and melange formation are envisioned to be the result of large dip-slip displacements on basin-margin faults. Naylor (1982) has suggested a similar tectonic setting for the formation of an olistostromal melange in the northern Apennines. These basin-margin faults exposed large scarps of basement rock and, at least in part, were probably responsible for the subsidence of the Ucluth unit. Furthermore, these faults probably disrupted sediment transport patterns resulting in initial deposition of mud-rich facies. Contorted strata of Unit 1B were derived by retrogressive slumping of a turbidite fan sequence located upslope. Unit 1A was located in a more "distal" setting which was dominated by deposition of mud, chert and minor sand. Unlike Unit 1B, the disruption of Unit 1A is envisioned to have occurred by in-situ liquefaction; exotic blocks, however, were introduced by locally derived rock falls. A later stage, not shown in Figure 16, involves the transition into a more widespread, sand-rich melange, Unit 2. This transition is envisioned to be the result of: (1) an increase in the proportion of sand-rich facies in the source area for the submarine slumps, and (2) a gradual "progradation" of mass-movement deposits across this morphologically complex margin.

REGIONAL TECTONIC IMPLICATIONS

The Pacific Rim melanges were probably originally coextensive with other similar upper Mesozoic units exposed on southern Vancouver Island (Figure 1; Pandora Peak unit and rocks of Gonzales Bay -- Rusmore and Cowan, in press) and in the San Juan Islands (Constitution formation and Lopez complex -- Brandon, et al., in press). Brandon et al. (in press) collectively refer to these units, including the Pacific Rim melanges, as the western facies of upper Mesozoic rocks in the Pacific Northwest. The western facies is characterized by a chaotic assemblages of mudstone, sandstone, chert and green tuff with a variety of exotic blocks. In addition to stratigraphic similarities, western facies rocks, including the Pacific Rim Complex, have experienced a distinctive high pressure-very low temperature metamorphism characterized by the assemblage: lawsonite + prehnite + quartz ± aragonite (Brandon et al., in press; Rusmore and Cowan, in press). (As indicated, aragonite is only sporatically present and has not been found in the Pacific Rim Complex and in the Pandora Peak unit.)

This metamorphic assemblage is apparently unique to the Pacific Northwest. Brandon et al. (in press) present evidence that metamorphism in the San Juan Islands happened as a direct result of rapid structural loading during the emplacement of a thick thrust sequence, which occurred during a short-lived mid-Cretaceous event, between 99 and 83 Ma. Furthermore, the presence of cobbles of metamorphosed Constitution sandstone in the Upper Cretaceous Nanaimo Group (Figure 1) indicates that, at the end of this thrusting event, the western facies rocks were in close proximity to the Wrangellia terrane (Brandon et al., in press).

My work in the Pacific Rim area indicates that prehnite-lawsonite assemblages, which are widespread in the Pacific Rim Complex, are not present in adjacent rocks of the Wrangellia terrane to the east. While there is no direct evidence of thrust sheets that might have once overlain the Pacific Rim Complex, the presence of lawsonite + quartz indicates structural burial and metamorphism at depths in excess of about 11 km (Liou, 1976). Based on these relations, I propose that the Pacific Rim Complex was also involved in San Juan thrusting and metamorphism, and was subsequently displaced northward to its present position on western Vancouver Island.

As shown in Figure 17, truncation of Vancouver Island and northward displacement of the Pacific Rim Complex were completed by 55 Ma. Radiometric dates and geochemistry indicate that Tertiary volcanic and plutonic rocks in the Pacific Rim area are part of a suite of intermediate to silicic calc-alkaline rocks that were erupted and intruded during Late Paleocene to Early Eocene time (radiometric dates summarized in Figure 2; geochemistry from Carson, 1973 and Brandon, unpublished data). This volcanic-plutonic suite occurs on both sides of the West Coast fault (Figure 2), and therefore appears to postdate major movement on this fault.

The Pacific Rim is bounded on its west side by another major fault. In the offshore region to the west of the Pacific Rim area, drilling and exploration by Shell Canada has identified a regionally extensive sequence of Eocene(?) basalts (Shouldice, 1971). MacLeod et al. (1977) have correlated these rocks with Eocene tholeiitic basalts of the Crescent and Metchosin Formations, located to the southeast (Figure 1). Geochemical analyses and petrographic study of drilling samples provided by Shell Canada confirm this correlation (Brandon, unpublished data). Aeromagnetic maps in this area (Shell Canada, unpublished data) indicate a northwest-trending contact between the Eocene(?) basalts and rocks of the Pacific Rim area. The dissimilarity between coeval volcanic rocks -- tholeiitic basalt to the west and calc-alkaline dacite to the east -- indicates that this contact is an important fault, which I call the Tofino fault.

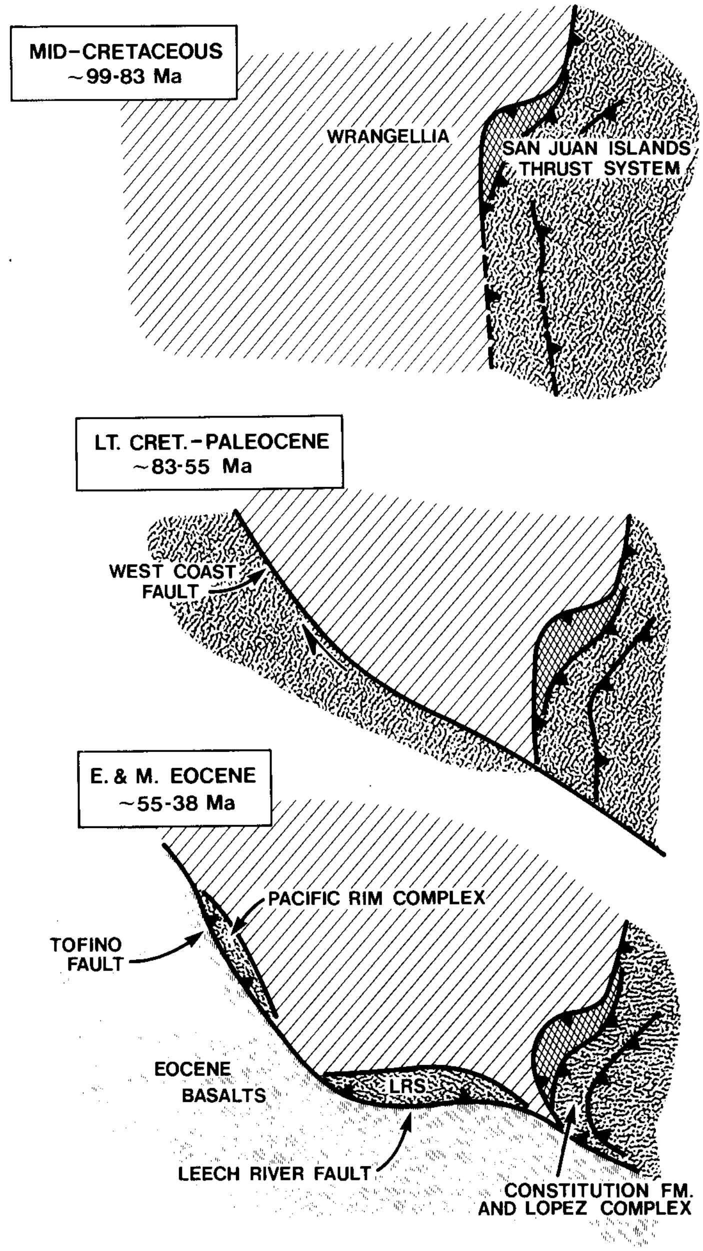

Figure 17. A schematic model for the offset of the Pacific Rim Complex and the truncation of Vancouver Island. In this model, the Pacific Rim is shown as part of the San Juan thrust system at mid-Cretaceous time. During the latest Cretaceous or earliest Tertiary, the Pacific Rim Complex was displaced northward on the West Coast fault to its present position on western Vancouver Island. Subsequently, the Pacific Rim was underthrust on its west side by a thick sequence of Eocene(?) basalt, probably due to Eocene initiation of the modern subduction regime.

Presently, the Tofino fault appears to be a northeast-dipping thrust fault. This conclusion is based on a recent seismic reflection study across Vancouver Island (Yorath et al., 1985), which indicates that the offshore basaltic unit extends at least 35 km northeastward beneath the Island. Major movement on this fault must post-date Early Eocene volcanism and pre-date Late Eocene and younger strata of the Tofino Basin which overlie both volcanic units (Figure 1; shown as the Carmanah Group in Figure 2). This thrust fault is probably associated with the Eocene initiation of the present subduction regime which was developed against the truncated edge of Vancouver Island.

A number of authors have suggested a more southerly location for portions of southern Alaska during the early Tertiary (eg., Stone and Packer, 1979; Cowan, 1982a; Moore, et al., 1983). For instance, Cowan (1982a) has argued that rocks presently exposed on Baranof Island in southeast Alaska were offset by Eocene transcurrent faulting from the Leech River Complex on southern Vancouver Island. My work in the Pacific Rim area indicates that western Vancouver Island preserves a record of this northward-directed traffic and probably represents an important source area for offset terranes in southern Alaska.

ACKNOWLEDGMENTS

This paper reports on research done at the University of Washington as part of my Ph.D. degree. I thank the members of my committee: J. Bourgeois, W. Bruner, P. Misch and J. Vance, and especially my adviser, D.S. Cowan; their comments and criticisms were of great assistance throughout this project. Futhermore, they, as well as S. Monsen, provided extensive comments on an initial version of this manuscript. M. Rusmore shared preliminary results of her work on the Pandora Peak unit, which helped me to place the Pacific Rim Complex into a more regional context. J. Muller of the Geological Survey of Canada graciously related his knowledge of Pacific Rim geology and also provided maps and thin sections. Paul Brandon, Bev Brashen, Jill Karsten, Carol Levine, Amy Ng, and Kathyrn Willis all provided able assistance in the field. Shell Canada kindly provided aeromagnetic maps and drilling samples from the offshore area to the west of the Pacific Rim. C. Cool and T. Tingle supplied geochemical analyses. J. Hedges provided analyses for organic carbon. E. A. Pessagno, Jr., E. Kauffman and J. A. Jeletzky kindly identified fossils for me. I gratefully acknowledge funding support from Sigma Xi, the Geological Society of America, the Department of Geological Sciences Corporation Fund and the National Science Foundation (grant EAR-8107654 to Dr. Cowan).

PART II

ROADLOG FOR 3-DAY FIELD TRIP TO THE PACIFIC RIM COMPLEX AND ADJACENT AREAS

This field trip is primarily designed to examine the melanges of the Pacific Rim Complex and to illustrate structural and stratigraphic relationships that bear on their origin and tectonic significance. The field trip starts at Ucluelet, a small town located at the south end of the Pacific Rim area on the west coast of Vancouver Island (Figure 18). The first day we will look at: (1) the Ucluth Volcanics, an arc-volcanic unit that underlies the melanges; and (2) Unit 1A, a highly disrupted mudstone-rich melange with large exotic diorite blocks. For the last "stop" of the day, we will take a charter boat to visit the West Coast fault, a high-angle fault that separates the Pacific Rim Complex from the Wrangellia terrane to the east. The second day will be spent examining Unit 1B, a mudstone-turbidite melange, and Unit 2, a sandstone-rich melange. In addition, we will look at the basal depositional contact of the Unit 1B melange on the underlying Ucluth volcanics. The last stop will be at the Tofino pluton, an Eocene granitic stock that intrudes the Pacific Rim Complex. The third day will involve a series of road stops to looking at various units within the Wrangellia terrane of Vancouver Island. We will return to Vancouver by way of the B.C. ferry which leaves from Nanaimo.

DAY 1

0.0 mi/ 0.0 km Mileage for the road log begins at the corner of Hemlock St. and Peninsula Rd., on the north side of Ucluelet (Figure 3). Refer to Figure 3 for a map of today's stops and the major connecting roads on the Ucluth Peninsula. For Stop 1-1, drive north towards Tofino on Peninsula Rd. which turns into the Tofino-Ucluelet highway.

2.6 mi/ 4.2 km **Stop 1-1A and 1-1B: Ucluth Volcanics at Fletcher Beach.**

Park near the logging road and old clear-cut on the west side of the highway (across from the house at 2335 Tofino-Ucluelet highway). Follow the logging road to the large loop near its west end. The two beaches can be reached by following footpaths through the wooded areas. A detailed map of this area is provide in Figure 19. Allow about 2 hours for this stop, which includes about 20 minutes walking time each way. A low tide is preferred but not required.

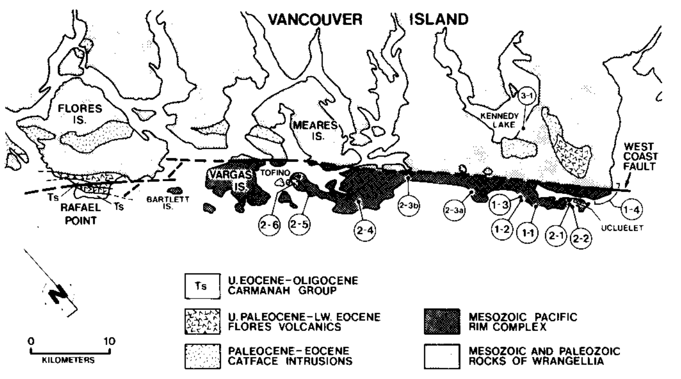

Figure 18. Geologic map for stops in the Pacific Rim area.

The first part of this stop (1-1A) is at the smaller, more southerly beach (Figure 19) which offers some representative exposures of the lower Mesozoic Ucluth volcanics. This unit is dominated by fragmental volcanic rocks with subordinate limestone and diorite intrusions. Limestone on the north side of the beach has yielded Late Triassic (Norian) conodonts, which indicates that the Ucluth limestones are younger than Triassic limestone of the Wrangellia terrane (Figure 5). Small irregular intrusions of diorite are ubiquitous in this area (Figure 19), especially on the north side of the beach. These intrusions are compositionally similar to the volcanics (Table 1) and are restricted to the Ucluth unit. The overlying Unit 1A melange contains exotic blocks of Ucluth diorite, which we will examine at Stop 1-2.

The second part of this stop (1-1B) is at the more northerly beach. The contact between the Unit 1A melange and the Ucluth volcanics lies unexposed beneath the beach and strikes to the northwest. The volcanics are exposed south of the beach, and the melange crops out on the beach and north of it. Layering in the melange dips moderately to the northeast and strikes parallel to the basal contact. We will examine the melange more extensively at the next stop.

Proceed north a short distance on the Tofino-Ucluelet highway. Drive past Lee St. and park near the second house on the west side of the highway.

3.0 mi/ 4.8 km **Stop 1-2: Unit 1A melange at Wya Point.**

The footpath to the beach south of Wya Point starts from behind the house (an A-frame house). Ask the owner of the house for permission to cross their property to get to the path. This stop will take about 4 hours including 30 minutes walking time each way and a lunch stop on the beach. Low tide is suggested but not necessary. See Figure 20 for an outcrop map of the Wya Point area.

The melange is well exposed north of the beach. Numerous blocks of diorite are present in this melange. The fabric of the melange and the relations between blocks and melange matrix are illustrated in Figures 8, 9 and 10. The locations of these figures are shown in the outcrop map in Figure 20.

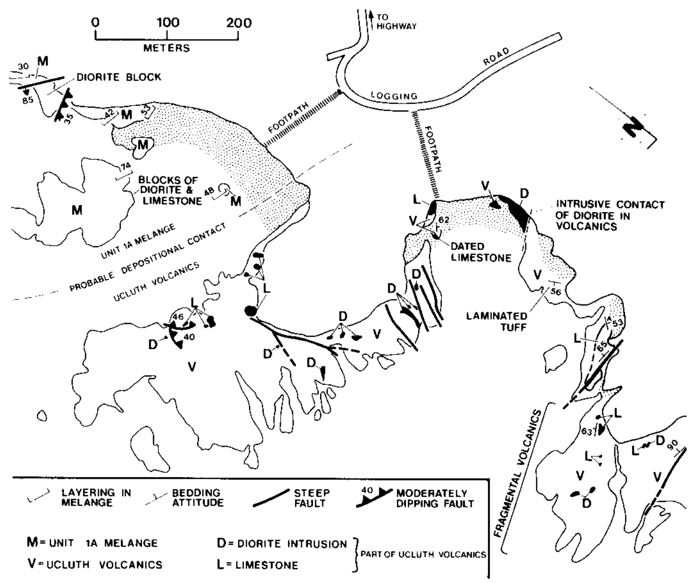

Figure 19. Outcrop map of Ucluth Volcanics at Fletcher Beach (Stop 1-1).

3.4 mi/ 5.5 km **Stop 1-3 (optional): Block of pillow basalt in melange north of Wya Point.**

This optional stop is provided in case we cannot get a charter boat for Stop 1-4. Proceed north on the Tofino-Ucluelet highway. At 3.3 mi/ 5.3 km, turn left onto the unmarked road across from Willowbrae Rd. and proceed to the end of the road where there is a good boardwalk trail to the northern part of Wya Point. This part of Wya Point lies inside the Pacific Rim National Park. Take the left fork of the trail to get to Stop 1-3 (Figure 3). Allow about 1 1/2 hours including 30 minute walking time each way.

On the north side of the beach is a large, upright block of pillow basalt, probably Late Jurassic in age. Structural relationships are shown in Figure 3 and in the outcrop map in Figure 20. At low tide, the basal contact of the block with the underlying melange is exposed on the north side of the beach. Sediments directly beneath this contact are highly deformed, probably due to the emplacement of this block, which is more than 220 m thick. Deformation appears to have occurred while the sediments were still unlithified; brittle-style faults are not present. Geochemical data for similar blocks of pillow basalts elsewhere in the melange indicate that they were erupted in an ocean-floor setting (Figure 7). The source of these blocks is nowhere exposed in the Pacific Rim area.

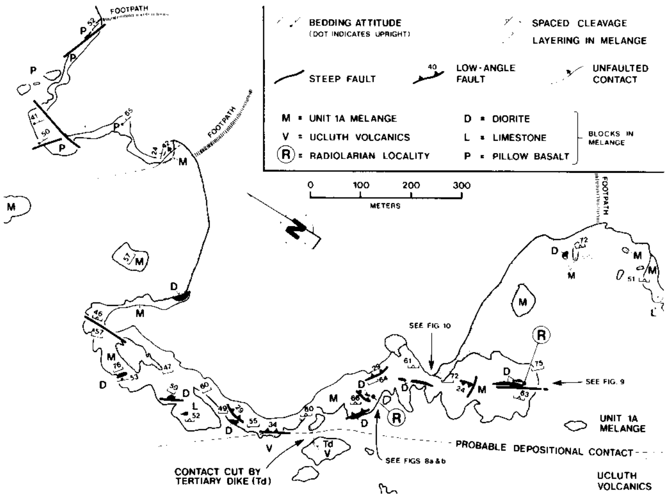

Figure 20. Outcrop map of Unit 1A melange at Wya Point (Stops 1-2 and 1-3).

(BY BOAT) **Stop 1-4: West Coast fault east of Ucluelet Inlet.**

The charter boat will follow the east side of Ucluelet Inlet (Figure 18). While heading southeast along the coast, the first exposure will be disrupted mudstone melange with pods of sandstone. Next, we will pass by a prominent group of islands (Beg Islands) composed of pillow basalt with interbedded ribbon chert. Similar ribbon cherts have yielded Late Jurassic radiolarian ages (Figure 5). As we approach the West Coast fault, another large block of basalt and chert is exposed and is underlain along an unfaulted contact by mudstone and chert of Unit 1A melange.

Continuing east along the coast, we will see the the West Coast fault which separates the Pacific Rim Complex from Jurassic plutonic rocks of the West Coast Complex. At this location, the fault appears to be steep and is confined to a narrow zone, no wider than a couple of meters. For about 40 m east of the fault, plutonic rocks of the West Coast Complex are highly deformed and altered. Outside of this zone, the West Coast Complex consists of undeformed quartz diorite with numerous mafic xenoliths. This location is the most southern exposure of the West Coast fault. To the south it apparently strikes into the offshore area west of Barkeley Sound.

DAY 2

0.0 mi/ 0.0 km Mileage for today's road log begins at the same place as for Day 1. See Figure 18 for today's stops. The first two stops are in the Big Beach area west of Ucluelet. Refer to Figure 3 for the location of these stops.

Drive north on the Tofino-Ucluelet highway. Turn left onto Norah Rd. (0.2 mi/ 0.3 km) and then right onto Pacific Crescent. Park in front of the Whispering Pine Mobile Home Park located on the left side of the road.

0.4 mi/ 0.6 km **Stop 2-1: Basal contact of Unit 1B melange, north of Big Beach.**

The footpath to this outcrop starts at the southeast rear corner of the trailer park (behind trailer #63). Please respect the privacy and property of the people living there. The footpath ends at a narrow inlet on the coast. Refer to Figure 12 for an outcrop map of this field stop. Allow about 1 hour for this stop including 15 minutes walking time each way. The unconformity is best exposed at low tide (less than 4 ft/ 1.2 m), so plan accordingly.

At this stop, the Unit 1B melange rests unconformably on the Ucluth volcanics. This contact is offset by a number of high-angle faults (Figure 12), but overall it dips moderately to the south. The Ucluth unit underlies the next 4 km of coastline to the north of this contact, indicating that the volcanics are not just a block in the melange. The mudstone above the contact is probably a mass-flow deposit. It contains numerous Buchia which have been identified as Early Cretaceous (early or middle Valanginian) in age. Large Inoceramus-like bivalves are also present (Figure 12). In some areas, the Buchia are dispersed throughout the mudstone and in others they are densily packed into thin beds which are now folded and contorted, presumably as a result of down-slope mass-movement. This basal contact strikes eastward into the Big Beach area which is the location of the next stop.

After this stop, return to the Tofino-Ucluelet highway (Peninsula St.) and head south into Ucluelet. Turn right onto Bay St. (0.9 mi/ 1.4 km) and continue until you see the sign for the Big Beach trail on the right side of the road.

1.1 mi/ 1.8 km **Stop 2-2: Unit 1B melange at Big Beach.**

Follow the boardwalk trail to the beach. This stop will be about 2 hours including 15 minutes walking time each way. A low tide is prefered but not required. Refer to Figure 13 for an outcrop map of this area.

The Big Beach area offers some good representative exposures of the Unit 1B melange. The basal contact of the melange is poorly exposed amongst the low outcrops at the foot of the trail. In particular note the Buchia-bearing mudstone to the south of the trail.

In this melange unit, exotic blocks are confined to debris flow deposits or pebbly mudstones (Figure 14a). These pebbly mudstones are best exposed north of the beach where they typically contain volcanic clasts, some of which range up to 4 m across (Figure 14b).

The low, rocky area south of the beach is underlain by a disrupted turbidite-conglomerate sequence which in many places is overturned (Figure 13; also see stereonets in Figure 11). This disruption is attributed to submarine slumping. The paucity of fold hinges suggests that the upright and overturned sequences represent detached pieces of large slump folds. Large fossil bivalves, locally preserved in growth position, occur in mudstone interbeds in the turbidites. Based on their morphological similarities with Cretaceous Inoceramus, these fossils suggest that the turbidites were originally deposited in upper bathyal or neritic environments (less than 2000 m water depth). They were subsequently carried into deeper water by down-slope movement.

Farther south there is a sequence of ribbon chert interbedded with sandstone and mudstone of the melange. This relationship is important because ribbon cherts in other melange units are commonly thought to be exotic blocks. Radiolaria from these cherts give a late Valanginian or early Hauterivian age, which is nearly identical to the age of the Buchia-bearing mudstone in this melange.

After this stop, go back to the Tofino-Ucluelet highway and proceed north towards Tofino. (The mileage at the junction with Highway 4 is 6.0 mi/ 9.7 km). We will stop for lunch at either Stop 2-3a or 2-3b. Stop 2-3b offers better outcrop and scenery. In the event of poor weather, however, we will go to Stop 2-3a where those less hardy souls will be able to find some shelter at the Wickaninnish Inn.

------------ **Stop 2-3a: Unit 1A melange at the Wickaninnish Inn.**

Turn left off the highway at the sign for Wickaninnish beach (9.0 mi/ 14.5 km). Follow the road to the beach, then bear left and park near the Wickaninnish Inn. The "Wick" use to be an old beach resort which has since been converted by Parks Canada into a restaurant and a visitor's center.

Outcrops to the south of the Inn consist of Unit 1A melange. In this area, pods of sandstone locally display some small injection features (Figure 8c).

The mileage to Stop 2-3a is not include in the subsequent log, so remember to resume your mileage when you return to the junction with the highway.

----------- **Stop 2-3b: Unit 1A melange at the north end of Long Beach.**

Go past the sign for Long Beach and take the second left (16.1 mi/ 25.9 km) into the more northerly parking lot at the beach.

The low outcrops on the north side of the beach consist of Unit 1A melange and display good examples of progressive stratal disruption of chert beds in the melange. Farther north, the beach surrounds some small rocky islands which are underlain by radiolarian ribbon chert. Locally these cherts contain interstratal folds, that is, highly folded horizons bounded by unfolded chert beds. These folds apparently pre-dated lithification of the chert since they formed without the development of a cleavage.

After Stop 2-3a or 2-3b, return to the highway and continue north towards Tofino. Turn left at the sign for Radar Hill (19.9 mi/ 32.0 km) and continue to the top of the hill.

20.8 mi/ 33.6 km **Stop 2-4: Regional overview from Radar Hill.**

Follow the footpath to the observation platform at the top of the hill. Use the map displayed there in conjunction with Figures 2 and 6 to pick out the main geologic features.

The West Coast fault is generally located along the the eastern edge of the broad coastal plain. The last exposure of the Pacific Rim Complex occur just off of the south tip of Flores Island. North of there, the West Coast fault strikes into the offshore area.

The offshore area to the west is underlain by Eocene and younger strata of the Tofino basin. Drilling and exploration by Shell Canada during the 1960's established the fact that this basin is underlain by a basement of Eocene(?) basalts, probably correlative with the Coast Range basalts of southern Vancouver Island, Washington and Oregon (Metchosin, Crescent and Siletz volcanics). The Prometheus well, which was one of two wells that drilled into this basaltic basement, was located about 25 km offshore to the southwest. This offshore basaltic unit is separated from the Pacific

Rim Complex by the Tofino fault (Figure 17), which, based on a recent seismic reflection profile across Vancouver Island, appears to be a major northeast-dipping thrust.

Radar Hill and the coastline to the west of the hill are underlain by Unit 2, a sandstone-rich melange. We will examine this unit more closely at the next stop.

Return to the highway and continue north towards Tofino. Turn left at the sign for the MacKenzie Beach resort (26.3 mi/ 42.4 km). Be sure to ask the proprietors of the resort for permission to park and to access the beach through their property.

26.7 mi/ 43.0 km Stop 2-5: Unit 2 melange at MacKenzie Beach.

Walk to the rocky headland at the south end of MacKenzie Beach. An outcrop map of this area is provided in Figure 21.

The Unit 2 melange consists of disrupted sand-rich turbidites and massive sandstones. In this area, melange deformation has resulted in a thick overturned sequence of turbidites. The fold associated with this overturned sequence must have had an amplitude in excess of 500 m, as shown in the true profile cross-section in Figure 21. As is commonly the case, the hinge of this fold is not preserved. In this area and elsewhere in Unit 2, bedding attitudes and small-scale folds lack a well-organized structural geometry (Figure 11), which is attributed to deformation in a near-surface setting. A spaced cleavage is locally present and appears to have postdated folding since it is oblique to the axial planes of small-scale folds (Figure 21).

After this stop, return to the highway and continue north to Tofino. Turn left onto First St. and then bear right at the small quarry located at 29.4 mi/ 47.3 km. Outcrops on the left are Pacific Rim mudstone and sandstone that have been hornfelsed by the Tofino pluton. Turn onto the dirt road at the sign for Tonquin park (29.5 mi/ 47.5 km), and follow that road to the trailhead for the park.

29.7 mi/ 47.8 km Stop 2-6: Tofino pluton at Tonquin Park.

Follow the footpath to the beach. Allow 45 minutes for this stop, including 10 minutes walking time each way.

The Pacific Rim Complex is intruded by numerous dikes and several small stocks which appear to be related to the Lower Eocene Flores volcanics, exposed east of Ucluelet and to the north on Flores Island (Figure 2). One of these stocks, the Tofino pluton, is exposed on the north and south ends of this beach. A K-Ar biotite date of 52 Ma from Stubbs Island (one of the small islands to the north of the beach) indicates an Early Eocene age for this pluton. An intrusive contact of the pluton with the surrounding melange is exposed along the coast a short distance north of the beach.

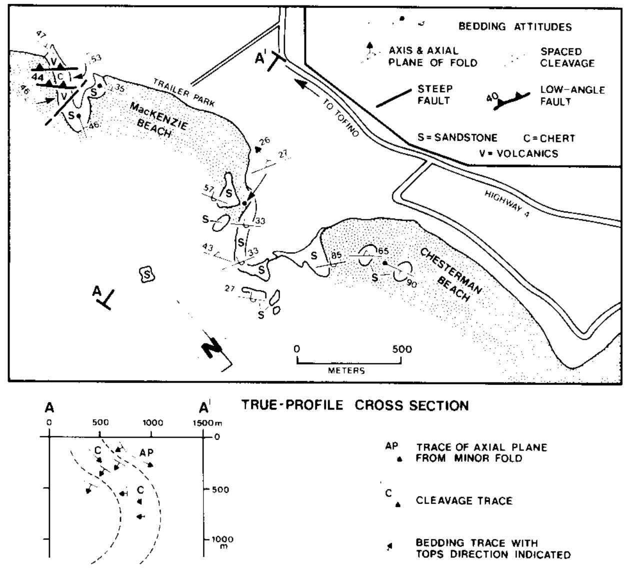

Figure 21. Outcrop map of Unit 2 melange at MacKenzie Beach (Stop 2-5). Based on bedding attitudes and a minor fold, the large fold plunges at about 25° to the north. The cross-section dips 65° to the south in order to present a true-profile view of the structure.

DAY 3

0.0 mi/ 0.0 km The road log begins at the same place as Day 1. Today's stops, which are shown in Figure 22, will concentrate on some of the major rock units of the Wrangellia terrane. In addition to the four stops for today, the log also describes some geologic sights along the way. Drive north on the Tofino-Ucluelet highway and head east on Highway 4 towards Port Alberni (junction at 4.5 mi/ 7.3 km).

A short distance beyond the junction with Highway 4, the road makes a sharp bend. Exposed there in a large road-cut on the right is another Tertiary pluton. While this intrusion has given somewhat discordant K-Ar dates (biotite - 46 Ma; hornblende - 67 Ma), it is thought to be early Tertiary in age. This and other Tertiary plutons in this area are probably subvolcanic intrusions related to the dacite volcanics exposed on the mountain tops to the east of here (Flores volcanics, Figure 2).

Outcrops of Quatsino limestone are visible on the right side of the road starting at 9.6 mi/ 15.4 km. The next stop is located at one of these outcrop, just beyond the point where Kennedy Lake becomes visible from the road.

11.4 mi/ 18.3 km Stop 3-1: Quatsino limestone at Kennedy Lake.

Exposed here are typical outcrops of Quatsino limestone, a dense gray limestone about 400 m thick that overlies the Karmutsen basalts. This outcrop consists of massive and laminated limestone which is locally recrystallized to marble. It is cut in several places by granitic dikes which could be either early Tertiary or Jurassic in age. Late Triassic Halobia were found at a nearby locality to the east of here. Elsewhere, fossils indicate a more precise late Karnian age for the Quatsino (Figure 5).

Continue east on Highway 4. Starting at the long, uphill grade (13.1 mi/ 21.1), there are exposures of probably Karmutsen basalt. This unit, which typically weathers to a dark reddish brown, comprises most of the outcrop across the central part of the island (Figure 22). In the mountains to the north of the highway you might occasionally notice small, whitish outcrops of Quatsino limestone.

27.6 mi/ 44.5 km Stop 3-2: Bonanza volcanics in the Kennedy River.

Glaciated outcrops of Bonanza volcanics are exposed here in the Kennedy River (assuming that the water level is not too high). These outcrops consist of amygdaloidal volcanics with small clusters of plagioclase phenocrysts, and numerous leucocratic dikes. The age of the Bonanza on the south part of the island is poorly known, but based on fossils from the north, it is thought to be restricted to the Early Jurassic (Figure 5).

Continue east on the highway. At Sproat Lake, the road passes a number of reddish brown outcrops of Karmutsen basalts (starting at 37.2 mi/ 59.9 km).

44.6 mi/ 71.8 km Stop 3-3: Pillow basalts of the Karmutsen Formation at Sproat Lake.

Park at the pullout on the right side of the road just before the beginning of the concrete barrier along the right side of the road. The outcrops of interest are those along the road for the next 200 m to the east of the pullout. Please be cautious of cars since traffic moves along this road at relatively high speeds.

Exposed here are relatively fresh amygdaloidal basalts of the Karmutsen Formation with good pillow flows locally present.

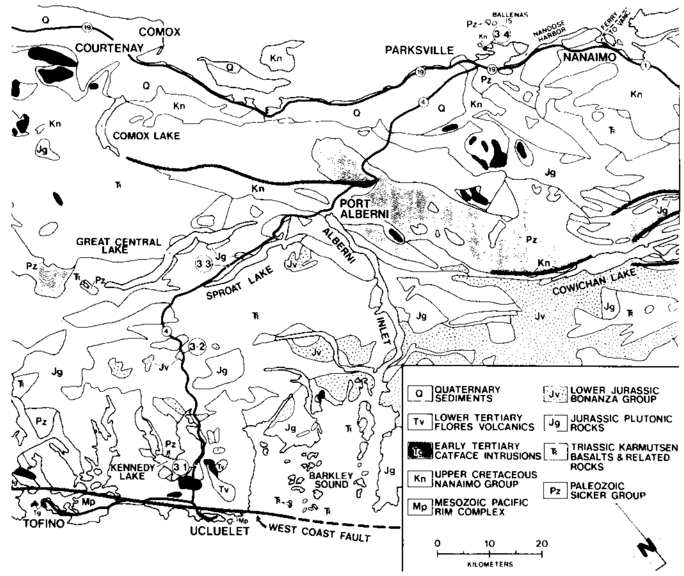

Figure 22. Geologic map of central Vancouver Island for stops on Day 3 (adapted from Muller, 1977b with minor modifications).

Continue east on Highway 4. A rest-stop area is located at 45.4 mi/ 73.1 km. Starting at about 52.7 mi/ 84.8 km, there are exposures on the left side of the road of Jurassic granodiorite. This pluton belongs to the Island Intrusions which are generally thought to be the intrusive equivalent of the Bonanza volcanics; radiometric dates, however, indicate that they might span a wider interval of time, from Early to Late Jurassic.

Continue east to Port Alberni. (At 56.1 mi/ 90.3 km, you should cross the bridge over Sproat River.) The Alberni valley is underlain by Upper Cretaceous strata of the Nanaimo Group. East of Port Alberni, the highway starts to climb up the west side of the Beaufort Range. The road-cut on the left at 66.1 mi/ 106.3 km contains a steep reverse fault that places Paleozoic rocks of the Sicker Group westward over Nanaimo Group. This fault is one of several faults that bound the west flank of the Beaufort Range and account, in part, for the uplift of Triassic and Paleozoic rocks exposed in the core of the range. In this area, the Sicker Group consists of green schistose volcanic rocks, clasts of which are present in basal conglomerates and breccia of the Nanaimo Group locally exposed along the highway.

Continue on Highway 4. (At 67.3 mi/ 108.4 km, you should pass the turnoff for Mt. Arrowsmith Ski Area.) At the junction with the Highway 19 bypass, head south towards

Nanaimo. At Nanoose Bay (96.4 mi/ 155.2 km), turn left on Northwest Bay Rd. (Canadian Forces Maritime Testing Facility) and then turn right (98.5 mi/ 158.6 km) onto Claudet Rd. Follow this road, which turns into Marina Way, until you get to Beachcomber Park, located at the tip of Cottam Point.

100.7 mi/ 162.1 km **Stop 3-4: Nanaimo unconformity on Sicker Group at Cottam Point.**

At the park, follow the path down to the beach. This park is privately owned; contact the Beachcomber Park Association (604 468-7679) for access permission.

Exposed here is a spectacular angular unconformity of Nanaimo Group on Paleozoic sandstone and mudstone of the Sicker Group. The basal Upper Cretaceous conglomerate was depositied across a surface of considerable relief and contains large angular blocks of the underlying Sicker Group. This conglomerate is overlain by sandstone with fossil fragments; locally you might find the outlines of large Inoceramus shells. (Note that the Sicker Group is well exposed at Clayton's Beach to the south.)

Return to Highway 19 and proceed to Nanaimo where the ferry departs for Vancouver.

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