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The Sedimentology, Petrology, and Tectonic Significance of the Middle Eocene Flattery Breccia, Lyre Formation, Northwestern Olympic Peninsula, Washington

Alice Benkovich Shilhanek

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THE SEDIMENTOLOGY, PETROLOGY, AND TECTONIC SIGNIFICANCE OF THE MIDDLE EOCENE FLATTERY BRECCIA, LYRE FORMATION, NORTHWESTERN OLYMPIC PENINSULA, WASHINGTON

By

Alice Benkovich Shilhanek

Accepted in Partial Completion of the Requirements for the Degree Master of Science

Dean of the Graduate School

Advisory Committee

Chair
THE SEDIMENTOLOGY, PETROLOGY, AND TECTONIC SIGNIFICANCE OF THE MIDDLE EOCENE FLATTERY BRECCIA, LYRE FORMATION, NORTHWESTERN OLYMPIC PENINSULA, WASHINGTON

A Thesis Presented to the Faculty of Western Washington University

In Partial Fulfillment of the Requirements for the Degree Master of Science

By

Alice Benkovich Shilhanek

May, 1992
MASTER’S THESIS

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Alice B. Shilhanek
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ABSTRACT

The Flattery breccia, an informally designated unit within the middle Eocene Lyre Formation, consists of sedimentary breccia and conglomerate exposed at Cape Flattery, located at the northwestern point of the Olympic Peninsula, Washington. The Flattery breccia was deposited during the late Narizian, approximately 44 to 42 Ma.

The boulder- through sand-size detritus of the Flattery breccia and western Lyre Formation, which changes in texture along strike, were deposited by sediment-gravity flows, such as surging high-density turbidity currents and sandy debris flows. Interfingering alluvial fan-deltas, interfingering lobes of coarse detritus on a submarine fan, or resedimented wedges of coarse-grained detritus deposited on slope or base of slope settings can be considered possible depositional environments for the Flattery breccia and western Lyre Formation.

The sandstones within the Flattery breccia are lithic arenites or lithic wackes, coarse-grained, angular to subangular, poorly sorted, with long and concavo-convex contacts, all of which indicate rapid sedimentation and burial from a nearby source. Petrologic trends along strike support the interfingering of two sources of detritus; petrologic data remain consistent, however, going up section into the overlying Hoko River Formation.

Vancouver Island is regarded as the major source of detritus to the Flattery breccia and western Lyre Formation due to matching lithologies, its close proximity, and its agreement with paleocurrent directions observed of flow to the south-southeast. Wrangellia, the Crescent terrane, and the Leech River Complex appear to comprise
variable portions of detritus to both the Flattery breccia and western Lyre Formation, while the Pacific Rim Complex and/or the Pandora Peak unit may be exclusive to the Flattery breccia source.

The Flattery breccia was deposited during the time of a major plate reorganization, which involved the demise of the Kula plate at 42 Ma. This plate reorganization probably caused regional uplift, perhaps including the Eocene rift basin basalts, as well as the initiation of Cascade arc volcanism and the metamorphism of the Leech River Complex. The Flattery breccia records evidence of regional uplift, such as the rapid unroofing of the Leech River Complex, as well as the existence of a dissected source terrane with a steep, rocky shoreline. Finally, the presence of an "exotic" source terrane to the west, possible based on the paleocurrent data observed, is not a necessity, because all clasts found in the Flattery breccia can be accounted for by lithologic units exposed on Vancouver Island.
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# TABLE OF CONTENTS

Abstract ......................................................................................................................................... iv  
Acknowledgements ..................................................................................................................... vi  
Table of Contents .......................................................................................................................... viii  
List of Tables ................................................................................................................................ x  
List of Figures ............................................................................................................................... xi  
Chapter 1: Introduction .................................................................................................................. 1  
  Purpose ..................................................................................................................................... 1  
  Age of Flattery breccia .............................................................................................................. 3  
  Previous work ........................................................................................................................... 3  
  Regional geologic and tectonic setting ....................................................................................... 5  
    Crescent terrane .................................................................................................................... 5  
    Olympic Core terrane ........................................................................................................... 9  
    Ozette terrane ..................................................................................................................... 10  
    Crescent terrane/mainland boundary .................................................................................. 11  
    Olympic Core/Crescent terrane boundary ......................................................................... 12  
Chapter 2: Sedimentology ............................................................................................................ 15  
  Introduction ............................................................................................................................ 15  
    Description of Flattery breccia/Lyre Formation ................................................................ 15  
    Conglomerate sedimentology ............................................................................................... 16  
    Methods ............................................................................................................................... 19  
  Facies descriptions and interpretations ................................................................................. 23  
    Cape Flattery quarry ............................................................................................................ 23  
      Facies sequence description ............................................................................................... 23  
      Facies sequence interpretation .......................................................................................... 26  
    Tatoosh Island ...................................................................................................................... 30  
      Facies sequence description ............................................................................................... 30  
      Facies sequence interpretation .......................................................................................... 37  
    Eastern outcrop summary ..................................................................................................... 38  
      Facies sequence description ............................................................................................... 38  
      Facies sequence interpretation .......................................................................................... 42  
  Discussion ................................................................................................................................. 43  
Chapter 3: Petrology ..................................................................................................................... 49  
  Methods ................................................................................................................................... 49  
  Descriptive petrography ......................................................................................................... 52
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sedimentary rock fragments</td>
<td>53</td>
</tr>
<tr>
<td>Igneous rock fragments</td>
<td>54</td>
</tr>
<tr>
<td>Metamorphic rock fragments</td>
<td>56</td>
</tr>
<tr>
<td>Other grain types</td>
<td>59</td>
</tr>
<tr>
<td>Petrologic trends</td>
<td>62</td>
</tr>
<tr>
<td>Discussion</td>
<td>68</td>
</tr>
<tr>
<td>Chapter 4: Provenance</td>
<td>70</td>
</tr>
<tr>
<td>Source areas for Flattery breccia</td>
<td>71</td>
</tr>
<tr>
<td>San Juan Islands</td>
<td>73</td>
</tr>
<tr>
<td>Olympic Peninsula</td>
<td>74</td>
</tr>
<tr>
<td>Olympic Core terrane</td>
<td>74</td>
</tr>
<tr>
<td>Ozette terrane: a comprehensive discussion</td>
<td>74</td>
</tr>
<tr>
<td>Crescent terrane</td>
<td>82</td>
</tr>
<tr>
<td>Vancouver Island</td>
<td>83</td>
</tr>
<tr>
<td>Wrangellia</td>
<td>84</td>
</tr>
<tr>
<td>Pacific Rim terrane</td>
<td>91</td>
</tr>
<tr>
<td>Crescent terrane</td>
<td>96</td>
</tr>
<tr>
<td>Paleocurrent analysis</td>
<td>98</td>
</tr>
<tr>
<td>Discussion</td>
<td>101</td>
</tr>
<tr>
<td>Chapter 5: Tectonic Significance of the Flattery breccia</td>
<td>108</td>
</tr>
<tr>
<td>Plate reorganization at 42 Ma</td>
<td>108</td>
</tr>
<tr>
<td>Effects on Flattery breccia</td>
<td>112</td>
</tr>
<tr>
<td>Further considerations</td>
<td>113</td>
</tr>
<tr>
<td>Chapter 6: Conclusions</td>
<td>116</td>
</tr>
<tr>
<td>References cited</td>
<td>119</td>
</tr>
<tr>
<td>Appendices:</td>
<td></td>
</tr>
<tr>
<td>Appendix 1: Point-count category definitions</td>
<td>127</td>
</tr>
<tr>
<td>Appendix 2: Point-count raw data</td>
<td>135</td>
</tr>
<tr>
<td>Appendix 3: Point-count rock fragment group data</td>
<td>138</td>
</tr>
</tbody>
</table>
LIST OF TABLES

Table 1. Sedimentary features of conglomerates .................................................... 21
Table 2. Coarse deposit classification ................................................................. 21
Table 3. Summary of sedimentation characteristics .............................................. 44
Table 4. Grain categories .................................................................................... 51
Table 5. Rock fragment categories ..................................................................... 63
Table 6. Vancouver Island source rocks .............................................................. 105
LIST OF FIGURES

Figure 1. Geologic map of study area ................................................................. 2
Figure 2. Generalized tectonic assemblage map of the Pacific Northwest ........ 6
Figure 3. Descriptive sedimentary features of conglomerates .......................... 17
Figure 4. Common associations of resedimented conglomerates ...................... 17
Figure 5. 4 models of resedimented conglomerates .......................................... 18
Figure 6. Complete deposit of high-density turbidity current ............................ 18
Figure 7. Classification scheme for deep-water sediments ............................... 22
Figure 8. Stratigraphic section at Cape Flattery quarry .................................. 24
Figure 9. Beds 1 & 2 at Cape Flattery quarry .................................................. 25
Figure 10. Bed 3 at Cape Flattery quarry ......................................................... 27
Figure 11. Portion of Bed 1 at Cape Flattery quarry ......................................... 28
Figure 12. Stratigraphic section on Tatoosh Island .......................................... 31
Figure 13. Beds 1 - 4 on Tatoosh Island .......................................................... 32
Figure 14. Lower portion of Bed 7 on Tatoosh Island ...................................... 34
Figure 15. Bed 8 on Tatoosh Island ................................................................. 35
Figure 16. Beds 6 & 7 on Tatoosh Island ....................................................... 36
Figure 17. Beds 4 - 7 on Tatoosh Island ......................................................... 39
Figure 18. Conglomerate bed at Tank quarry outcrop ...................................... 41
Figure 19. Area graphs of rock fragment percentages in Flattery breccia/Lyre
   Formation sandstones: up section ................................................................. 65
Figure 20. Area graphs of rock fragment percentages in Flattery breccia/Lyre
   Formation sandstones: along strike ............................................................ 66
Figure 21. Stacked bar graphs of rock fragment percentages of Tpac sandstones at Point of the Arches and Portage Head ........................................................... 77

Figure 22. Point of the Arches outcrop: debris flow deposit ................................. 79

Figure 23. Estimates of paleocurrent direction in the Flattery breccia ......... 100

Figure 24. Paleomagnetic reconstruction of the west end of the Olympic Peninsula (from Moyer, 1985) ................................................................. 102

Figure 25. Early Eocene plate geometry in the Pacific Northwest ................. 109

Figure 26. Plate motion polygons from 59 - 36 Ma for a position near present-day Olympic Peninsula ........................................................................ 111
CHAPTER 1: INTRODUCTION

Purpose

The breccia and conglomerate of Cape Flattery is an informal unit within the middle Eocene Lyre Formation, part of a package of north-dipping Tertiary volcanic and sedimentary rocks located on the northern rim of Washington's Olympic Peninsula. The sedimentary breccia unit is approximately 600 meters thick and crops out on the northwesternmost tip of the Peninsula at Cape Flattery, for which it has been named (Snavely, 1983; Figure 1). It is a distinctive, coarse facies of the Lyre Formation. In the following pages, I will refer to this unit as the Flattery breccia, after Snavely (1983).

The purpose of this research was to record the sedimentological characteristics and the petrology of both the Flattery breccia and the westernmost portion of the Lyre Formation proper in the Cape Flattery area and to interpret the depositional setting and provenance of the Flattery breccia. Reasons for undertaking this project were to study the sedimentology and petrology of the Flattery breccia in more detail and to investigate its significance with regard to the middle Eocene tectonic setting of the Pacific Northwest. Howell and von Huene (1981) noted that breccia wedges commonly occur along basin-margin fault scarps. Because the Flattery breccia occurs at the furthest northwest end of the Tertiary basinal sequence on the Peninsula, it may represent a paleoboundary with an ancient landform that has been translated northward. In light of recent studies that indicate many Alaskan terranes were once in more southerly latitudes, a closer study of this unit seemed important, as detritus from such an exotic terrane may have been preserved in the breccia.
EXPLANATION

TI  Lyre Formation
T1f  Flattery breccia
T1fbc  Tertiary Point of the Arches conglomerate (TPac)
Aldwell Formation
Crescent Formation
Hoko River Formation
Terrane south of the Crescent thrust fault and north of the Calawah fault

Cf  Crescent thrust fault
Cf  Calawah fault
Of  Ozette fault

Sample locations/sample #
1 Cape Flattery quarry/1-19a, 10-2a
2 Archewat Peak/17-3b
3 Borrow pit/15-3a
4 Mushroom rock/9-1a
5 Tatooch Island/24-1a, 27-2a
6 MSR/12
7 CFT/61
8 Section 16/14-3a
9 Wastch prairie/13-2b
10 Wastch quarry/11-3b
11 Wastch Peak/10-1b
12 Cheeka Peak/12-1c
13 Tank quarry/12-2b
14 Portage Head(FORT)/19-6a
15 Point of the Arches(POTA)/19-4b
16 Bear Creek/2-1a

Figure 1. Map showing the location and geology of study area (mapping after Shavelly and others, 1986b; Shavelly, 1987).
Age of Flattery breccia

Determining the age of the Flattery breccia is difficult due to the scarcity of fossils, but benthic foraminifera of Narizian age have been found within siltstone interbeds (Snavely and others, 1986a). Difficulty remains, however, in that discrepancies exist with respect to the accepted absolute ages of the benthic foram stages (i.e. Narizian, Refugian, etc.) as well as accepted absolute ages of epochs (i.e. Eocene; middle/late boundary). Recent correlation charts have placed the Lyre Formation’s approximate age at 45-43 Ma (Armentrout and others, 1983); 41.5-40.5 Ma (Snavely, 1987); and 44-42(?) Ma (Heller and others, 1987). This study uses 44-42 Ma following the correlation chart of Heller and others (1987), which used the time scale of Palmer (1983) and benthic foram stages based on Armentrout and others (1983) and Rau (1981).

Previous work

Weaver (1916) was one of the first to study the geology of the Olympic Peninsula in his descriptions of the Tertiary rocks of western Washington. He later went on to name and describe the Lyre Formation as a sequence of conglomerate, sandstone, and siltstone exposed along the Lyre River (Weaver, 1937). This definition was later modified by Brown and others (1956), who moved the upper contact to a distinct horizon between the underlying conglomerates and overlying finer-grained rocks. This change essentially split out the overlying Twin River Group from the Lyre Formation. Brown and others (1956), working near Lake Crescent, also subdivided the Lyre
Formation into a lower sandstone facies and an upper conglomeratic facies. Brown continued to work on the Lyre Formation while mapping the Port Angeles-Lake Crescent area (Brown and others, 1960). Ansfield (1972) studied the petrology and sedimentology of the Lyre Formation and mapped the western portion, in which he mapped lower and upper "members", following the informal usage of Brown and others (1960). Pisciotto (1972) completed a petrographic study of the entire Lyre Formation, while Pearl (1977) focused on the petrology of the Tertiary sediments in the northwestermost part of the Olympic Peninsula, including the Lyre Formation. In their geologic map of the Olympic Peninsula, Tabor and Cady (1978a) separated the Lyre Formation into four mapable units, one of those being the breccia and conglomerate that crops out on Cape Flattery (Tlb). Tabor and Cady (1978a) reassigned Ansfield’s (1972) lower member rocks along the southern part of Cape Flattery to the Tertiary unnamed sedimentary rocks (Tusb) unit. Tabor and Cady (1978a) also assigned Ansfield’s (1972) upper member rocks located farther south along the Pacific coast at Portage Head and Point of the Arches to the breccia and conglomerate unit of the Lyre Formation (Tlb). Snavely (1983) informally referred outcrops of breccia and conglomerate north of the Calawah fault to the "Flattery breccia". Spencer (1984) studied the Lyre Formation as part of his dissertation, focusing on the lower Tertiary biostratigraphy and paleoecology in the Quilcene-Discovery Bay area. In a recent map of the Cape Flattery 15 minute quadrangle, Snavely and others (1986b) mapped an interfingering contact between the Lyre Formation proper (TI) and the breccia and conglomerate of Cape Flattery (Tlfb).
Snavely and others (1986b) also reassigned Tabor and Cady’s (1978a) Tlb outcrops at Portage Head and Point of the Arches to the Tertiary Point of the Arches conglomerate and sandstone (Tpac), which is a unit within the Sooes terrane (Figure 1).

**Regional geologic and tectonic setting**

Silberling and Jones (1984) divided the Olympic Peninsula into lithotectonic terranes, three of those being the Crescent, the Olympic Core, and the Ozette terranes (Figure 2). In the following paragraphs I will briefly describe these rock units, their equivalent units on southern and western Vancouver Island, and associated faults.

**Crescent terrane**

The Crescent terrane, also referred to as the "peripheral rocks" by Tabor and Cady (1978a), crops out in a distinctive horseshoe open to the west as it rims the north, east, and southeastern sides of the Olympic Peninsula (Figure 2). It is composed of the lower to middle Eocene Crescent Formation, which consists predominantly of a thick section of tholeiitic pillowed to massive submarine flows and massive to columnar-jointed shallow water and subaerial basalt flows (Babcock and others, 1992a). The Crescent Formation also includes the volcaniclastic Blue Mountain unit, which underlies and interfingers with the Crescent basalts (Babcock and others, in press, 1992a). The Crescent Formation is directly correlated to the
Figure 2. Generalized regional geology of the Pacific Northwest (modified from Brown, 1987).

CR = Crescent terrane
Cb = Crescent basalts
M = Metchosin Igneous Complex
P = Prometheus magnetic anomaly
OC = Olympic Core terrane
e = east, w = west
OZ = Ozette terrane
CZ = Cenozoic sediments
TC = Carmanah Group
LRC = Leech River Complex
PP = Pandora Peak Unit
PR = Pacific Rim Complex
CPC = Coast Plutonic Complex
WR = Wrangellia terrane
HRF = Hurricane Ridge fault
CF = Calawah fault
CTF = Crescent thrust fault
OF = Ozette fault
LRF = Leech River fault
TF = Tofino fault
Metchosin Igneous Complex of Massey (1986), formerly known as the Metchosin Volcanics and the Sooke Gabbro of Clapp and Cooke (1917), located at the southern tip of Vancouver Island (Figure 2; Muller, 1980a). Also correlative are the Eocene basalts that form the Prometheus magnetic anomaly, which is located offshore along western Vancouver Island (Figure 2; Brandon, 1985). Clowes and others (1987) correlated the Crescent, the Metchosin, and the Prometheus volcanics on the basis of age, geochemistry and stratigraphy.

The Crescent Formation basalts are part of a larger collection of Paleocene to middle Eocene basalts that crop out from southern Oregon to southern Vancouver Island (Wells and others, 1984). This basaltic basement has several names: the Oregon-Washington Coast Range (OWCR), the Coast Range volcanic province (CRVP), the Coast Range basalts, the Crescent terrane, the Late Eocene basalts, etc. While most workers agree that these lower Eocene basalts were emplaced against the North American continent in the mid-Eocene (Clowes and others, 1987; Yorath and Davis, 1988; Snavely, 1983; and Wells and others, 1984), several theories exist as to the origin of the basalts. One theory proposed that the Crescent Formation and its equivalents were generally oceanic tholeiites with stratigraphy suggesting a gradation from ocean crust to emergent seamounts, with subsequent accretion at the continental convergent margin after mid-Eocene (Duncan, 1982; Snavely, 1983). However, the geochemical signature of these basalts plots across several fields including mid-ocean ridge, oceanic island, as well as an intra-arc setting (Tabor and Cady, 1978a). Also, the seamount model doesn’t account for the great thickness of basalt (up to 15 km
along Hood Canal) that overlies and interfingers with the continentally-derived Blue Mountain unit (Cady, 1975). Wells and others (1984), Brandon and Massey (1985), and Snavely (1987) have suggested that the basalts were erupted in a marginal basin that developed within the continent’s margin in response to a transcurrent fault regime, possibly analogous to the Gulf of California. This model supports Johnson’s (1984) suggestion that transcurrent faults, active during the late Cretaceous/early Eocene, truncated much of western Washington and southern Vancouver Island. Recent detailed work by Clark (1989) and Babcock and others (in press, 1992a & b) supports the marginal rift-basin theory, suggesting that rifting was initiated by any one or a combination of the following: the increase in the velocity and obliquity of Kula plate convergence, the increase in development of slab window and slab traction, and the effects of an approaching Yellowstone hotspot in the early Eocene.

Also part of the Crescent terrane is a 6000 meter sequence of mostly marine middle Eocene to middle Miocene sedimentary rocks that overlie the Crescent Formation (Snavely, 1983). These rocks, which include the Flattery breccia, consist of siltstones, sandstones, pebbly mudstones, and conglomerates that range from deep water turbidites to coal-bearing shallow deposits (MacLeod and others, 1977). Along with the Crescent Formation, they have been folded and faulted, but are generally stratigraphically continuous (Tabor and Cady, 1978b). This sedimentary sequence may be equivalent in part to the Carmanah Group, a thinner package of Eocene to Oligocene sedimentary rocks that crop out in coastal exposures along southern and western Vancouver Island (Figure 2; Muller, 1983a). Snavely and others (1980)
proposed that these sediments were deposited in the Tofino-Fuca basin, a deep linear
trough that extended along the west coast of Vancouver Island southwest into the
western half of the Strait of Juan de Fuca during most of the Tertiary. Heller and
others (1987) have regarded these rocks as forearc sediments that accumulated on the
Crescent basaltic basement along the Cascadia convergent margin.

Olympic Core terrane

Inside the horseshoe of the Crescent terrane lies the Olympic Core terrane, a
tectonically thickened assemblage of variously metamorphosed turbidites, shales, and
basalts (Figure 2; Silberling and Jones, 1984). These rocks are approximately coeval
with, but in fault contact with, the rocks of the Crescent terrane (Tabor, 1983). The
Eocene to early Oligocene eastern core rocks have been metamorphosed to slates,
phyllites, and semischists of the prehnite-pumpellyite to greenschist facies of regional
metamorphism (Tabor, 1983). They have been pervasively sheared and in places
resemble the melanges in the Franciscan rocks of California, although there have been
no exotic blocks of eclogite or blueschist recognized in the core rocks (Tabor and
Cady, 1978b). The western core rocks, predominantly sedimentary rocks of Eocene to
Miocene age, are nonslaty and locally stratigraphically continuous, but contain
complex folds and faults to the degree of resembling a broken formation (Tabor and
Cady, 1978b). However, recent work by Brandon and Calderwood (1990) revealed a
high pressure assemblage in some sandstones close to the western core rocks
suggesting that those rocks were more deeply buried than Tabor and Cady (1978b) recognized.

The rocks of the Olympic Core terrane were interpreted as a Cenozoic accretionary prism complex by Tabor and Cady (1978b). Long, arcuate packets of rocks have been recognized on the basis of gross lithology and are separated by wide shear zones (Tabor, 1983). These imbricate packets represent packages of ocean-floor sediment that were thrust under the Crescent Formation as the offshore oceanic plate descended beneath North America (Tabor, 1983). With continuing subduction, this thickened assemblage was eventually uplifted into the Olympic Mountains against the backstop of the Crescent basalts, with some packets being overturned in the east (Tabor and Cady, 1978b). This theory may be in question, however, due in part to the modification of the metamorphic zonation suggested by Brandon and Calderwood (1990). The new metamorphic data ties in with Brandon and Vance (in press), who used fission-track dating methods to better constrain the age of the central and eastern parts of the Core units, as well as the timing of metamorphism. Brandon and Vance (in press) also propose that the Olympic Core represents a subduction complex; however, the Olympic Mountains consist of a dome, exposing the youngest and the most deeply exhumed units in the central portion of the Peninsula.

Ozette terrane

Located in the northwestern portion of the Olympic Peninsula, the Ozette terrane is bounded on the north by the Calawah fault, on the south by the Ozette fault,
and on the east by the convergence of the two faults (Figure 2; Silberling and Jones, 1984). This terrane corresponds roughly to the Sooes terrane of Snavely and others (1986b; Figure 1). Of particular interest is a gneissic and uralitized quartz diorite and gabbro body with a K-Ar hornblende age of 144 Ma, located at the Point of the Arches headland (Snavely and others, 1971). The gabbro body is overlain by Cretaceous sandstone, argillite, chert, and pillow basalt, which in turn is in fault contact with a Tertiary/Cretaceous (?) melange zone of sheared siltstone with angular polished blocks of pre-Tertiary rocks (Snavely and others, 1986b). A lower Eocene (K-Ar hornblende age of 59 +/- 3 m.y.) dacite sill intrudes the Cretaceous rocks (Snavely and others, 1986b). The whole Ozette assemblage is overlain unconformably by lower Eocene pillow basalt and middle Eocene sediments, sediments that Tabor and Cady (1978a) mapped as the Flattery breccia.

The origin of these pre-Tertiary rocks is an enigma, as this small fragment is the only known pre-Tertiary rock unit west of the Cascades between the Klamath Mountains and Vancouver Island (MacLeod and others, 1977). Snavely (1983) considered the complex to be an olistostromal block derived from Vancouver Island. More recently, Snavely (1987) accounted for the entire Ozette terrane as having been an (exotic) terrane fragment obducted onto the northwest end of the Peninsula in the late middle Miocene due to northeastward convergence of oceanic plates.
Crescent terrane/mainland boundary

The most obvious boundary between the early Eocene basalts and North America is on Vancouver Island, marked by the Leech River fault (Figure 2). This fault separates the Metchosin Igneous Complex, which is equivalent to the Crescent Formation, from the Leech River Complex, a Mesozoic assemblage of metamorphosed pelitic rocks (Fairchild and Cowan, 1982). Correlative to and probably coextensive with the Leech River fault is the Tofino fault, which is located further north along the west coast of Vancouver Island (Figure 2; Brandon, 1985; Clowes and others, 1987; and Yorath and Davis, 1988). The Tofino fault juxtaposes the offshore Prometheus volcanics, equivalent to the Metchosin Complex, against the Pacific Rim Complex, which has been correlated with the Leech River Complex (Brandon, 1985).

To the south the eastern boundary of the Crescent terrane is cryptic. Johnson (1984), Clowes and others (1987), and Roberts (1991) placed this contact in the Puget Lowlands (Figure 2). This interpretation is substantiated by a large gravity anomaly that represents the contact of the basalts at depth (Johnson, 1984; Roberts, 1991).

Olympic Core terrane/Crescent terrane boundary

There is much debate over which fault on the Olympic Peninsula marks the boundary between the Olympic Core terrane and the Crescent terrane. This is due to the imbricate nature of the fault boundary and the different theories held regarding the origin of the Crescent basalts, as well as the rugged terrain and poor exposure common to the Olympic Peninsula. Tabor (1983), who suggested that the Crescent
basalts were erupted out onto and interfingered with the continentally-derived Blue Mountain Unit, considered the boundary in the eastern half of the Peninsula to lie along the Hurricane Ridge fault (Figure 2). This fault separates the volcanic sandstone and argillite of the Blue Mountain unit of the Crescent terrane from the highly sheared micaceous sandstone and slate of the eastern Olympic Core terrane (Tabor, 1983).

Following the Hurricane Ridge fault to the west along the northern rim of the Peninsula, Tabor (1983) suggested that the Hurricane Ridge fault eventually merges into the left-lateral Calawah fault, which extends northwestward to the Pacific coast just south of Cape Flattery (Figure 2). The wide shear zone of the Calawah fault separates both the western Olympic Core terrane and the Ozette terrane from the Crescent terrane to the north (Tabor and Cady, 1978a). The distinction between the mid-Eocene units within these terranes is less clear than in the eastern Peninsula, although the sedimentary rocks of the western Olympic Core and Ozette terrane differ in structural competency and provenance from those of the Crescent terrane (MacLeod and others, 1977).

In another interpretation, however, Snavely (1983) proposed that the Crescent fault marks the boundary between the Crescent terrane and the Olympic Core terrane. The Crescent fault is an extensive thrust fault that lies at the base of the Crescent basalts, which Snavely (1983) mapped from near Port Angeles west to Cape Flattery (Figure 2). It dips northward, ranging from vertical to flat-lying, is locally folded and often imbricated (Snavely, 1983). Snavely’s interpretation, that the Crescent fault marks the boundary between the Crescent terrane and the Olympic Core terrane,
differs from that of Tabor (1983) and Tabor and Cady (1978a&b) in that it implies that the Blue Mountain unit is part of the Olympic Core terrane, instead of the Crescent terrane.

The Olympic Core/Crescent terrane boundary becomes more complex in the northwestern portion of the Olympic Peninsula where the unnamed sedimentary unit (Tusb) is sandwiched between the Crescent basalts (and Crescent fault) and the Calawah fault (Tabor and Cady, 1978a), a structural position similar to that of the Blue Mountain unit. Unlike the Blue Mountain unit, however, the unnamed sedimentary unit (Tusb) is slightly younger than the Crescent Formation. Nonetheless, Tabor (1983) regarded it as part of the Crescent terrane, while Snavely (1983) assigned it to part of the Olympic Core terrane. More recently, Snavely and others (1986b) designated these rocks as "the terrane south of the Crescent thrust fault and north of the Calawah fault". This difference in the literature regarding the boundary between the Olympic Core and Crescent terranes has obvious tectonic implications with respect to our understanding of the origin of the Blue Mountain unit and the Tertiary unnamed sedimentary rocks (Tusb). It also affects their genetic and tectonic relationship to adjacent units, one being the Flattery breccia and western Lyre Formation, which unconformably overlies or is in fault contact with this unnamed sedimentary unit (Tusb) of Tabor and Cady (1978a). Although this study does not address whether the unnamed sedimentary rocks (Tusb) should or should not be part of the Crescent terrane, this ambiguity seemed worth mentioning as it emphasizes the tectonic and structural complexity in the northwestern part of the Peninsula.
CHAPTER 2: SEDIMENTOLOGY

Introduction

Description of the Flattery breccia and western Lyre Formation

The study area, located near the town of Neah Bay on the Makah Indian Reservation, is outlined in Figure 1. The Flattery breccia consists of poorly sorted, massive, sedimentary breccia and conglomerate, interbedded with massive sandstone and minor siltstone (Snavely and others, 1986b). The Flattery breccia interfingers with the Lyre Formation proper to the east along strike, where the latter is composed of channeled pebble to boulder conglomerate and pebbly sandstone interbedded with thick-bedded sandstone and minor thin-bedded sandstone and siltstone (Snavely and others, 1986b).

Ansfield (1972) concluded that the Lyre Formation at Cape Flattery represented a proximal depositional setting on a submarine cone-fan. He suggested that material was shed from northern tectonic highlands and accumulated at bathyal depths on a series of submarine fans. Snavely (1983) observed that debris from Vancouver Island was transported southward into the Tofino-Fuca deep marginal basin, forming the clastic wedges and channel deposits of the Flattery breccia and Hoko River Formation. However, using the hypothesis that the Flattery breccia may represent a breccia wedge that marks a paleoboundary against an ancient landform that has since been faulted away, the possibility remains that the gravels were deposited in a shallower environment. Wescott and Ethridge (1980) noted that the reexamination of several ancient coarse-grained clastic wedges, previously interpreted as submarine fans or
alluvial fans, revealed them to be deposits of fan deltas. Simply put, a fan delta is a variety of delta built by an alluvial fan (Nemec, 1990). The aim of this portion of this study was to focus in more detail on the sedimentology of the Flattery breccia and western Lyre Formation, particularly sedimentation features common to thick sequences of gravels.

**Conglomerate sedimentology**

Most depositional-process models (Lowe, 1982; Massari, 1984) and conglomerate-facies models (Walker 1975a,b; 1977; 1978) revolve around four main descriptive features common to thick sequences of gravels: sorting and size distribution, fabric, stratification, and grading (Figure 3). Common associations of these sedimentary features can then be used as signals of conglomerate depositional settings (Figure 4; Walker, 1975b). Using the resedimented deep-water conglomerates as an example, Walker (1975a,b; 1977; 1978) used common associations of these main sedimentary features to develop four facies models that reflect the maturity of a turbidity current and the corresponding depositional slope (Figure 5). Similarly, Massari’s (1984) model of a gravelly high-density turbidity-current deposit shows these same sedimentary features in a particular vertical sequence (Figure 6). The individual parts of the sequence (i.e. R1, R2, S2, etc.) represent deposits containing particular sedimentation features (such as grading, imbrication, and stratification) which result from the various grain-support mechanisms (i.e. fluid turbulence, dispersive pressure, matrix strength, etc.) and sedimentation mechanisms (traction,
Figure 3. Descriptive features for conglomerate. Under fabric, the coding a(p)a(i) means a-axis parallel to flow and imbricated; a(t)b(i) means a-axis transverse to flow with b-axis imbricated (from Walker, 1975b).

Figure 4. Common associations of features in conglomerate. The diagram is not intended to show all possible types but rather those that are abundant (from Walker, 1975b).
Figure 5. Four models for resembed (deepwater) conglomerates, shown in their inferred downcurrent positions (from Walker, 1984a).

Figure 6. Ideal deposit of a coarse-grained high-density turbidity current (after Massari, 1984).
frictional freezing, suspension sedimentation, etc.) that operate as a flow decelerates (Lowe, 1982, Middleton and Hampton, 1973). Ultimately, however, sediment gravity flows such as turbidity currents, debris flows, fluidized flows, and grain flows (Middleton and Hampton, 1973) operate in both the subaqueous portions of fan deltas and on submarine fans, thereby resulting in the same sedimentation features in both environments. Surlyk (1984, pg. 381) recognized this problem and concluded that with coarse deposits "the interpretation of the depositional environment has to be based on the sum of tectonic setting, overall geometry of the deposit, spatial distribution of facies association, large- and small-scale cyclicity, small-scale paleotopography, paleocurrents, and fossil content". These factors are taken into account in analyzing the deposits of the Flattery breccia and western Lyre Formation.

**Methods**

Using the geologic map of Tabor and Cady (1978a), eleven outcrops were studied, spaced vertically through the Flattery breccia and laterally into the western Lyre Formation, as well as two outcrops south of the Calawah fault that were previously mapped as the Flattery breccia (Figure 1). Although the Lyre Formation is generally a ridge-former, outcrops inland were limited to logging road-cuts due to dense vegetation. The Flattery breccia is best exposed in a continuous section in the steep sea cliffs on the northwest side of Cape Flattery that was not studied due to inaccessibility. I was able, however, to visit Tatoosh Island and described an
accessible sea cliff there. Sedimentary features listed in Table 1 were recorded at each outcrop.

The gravels and sands of the Flattery breccia and western Lyre Formation are described in this study using the deep water facies classification of Pickering and others (1986; Figure 7). This classification closely follows the submarine fan facies classification of Walker and Mutti (1973). In both classifications, Facies A, which consists of coarse gravels and pebbly sands, is subdivided according to the presence (organized) or absence (disorganized) of stratification, grading, and fabric. In describing the Flattery breccia, the use of Pickering and others’ (1986) detailed expansion of Facies A (Table 2) enables the recognition of vertical sequences that can then be compared with Walker’s (1975a,b; 1977, 1978) facies models or Lowe (1982) or Massari’s (1984) depositional models of high-density sediment gravity flows. This classification was chosen in part for its detail, but, as mentioned earlier, since sediment gravity flows in both shallow and deep environments result in the same sedimentation features, no oversight should have resulted in using this deep-water classification system on a potentially shallow deposit. Through the descriptions that follow, I have used "unstratified" to mean "lacking internal stratification", as used by Walker (1975a,b; 1984).

In the following pages, three representative outcrops of the Flattery breccia and western Lyre Formation will be described with regard to the particular facies sequences observed, followed by an interpretation of the depositional processes required to produce those facies sequences. Those outcrops include: Cape
Table 1

Sedimentary features observed for field description of conglomerates and breccias

External aspects
1. bed thickness
2. underlying contact: sharp, gradational, scoured
3. bed geometry: flat sheetlike, lensoid, composite (amalgamated)

Internal aspects
5. stratification: unstratified, horizontal, inclined
6. grading: inverse, normal, ungraded
7. fabric: long axis orientation, imbrication
8. clast-matrix proportion
9. modality
10. degree of clast and matrix sorting
11. clast shape
12. mean pebble size (MPS; mean of 10 largest clasts)
13. sedimentary structures: fossils, bioturbation, coaly debris, concretions, cementation, rip-ups, flames, dish structures, outsized clasts, tool marks, etc.

Table 2

Coarse deposit classifications

<table>
<thead>
<tr>
<th>Walker and Mutti, 1973</th>
<th>Pickering and others, 1986</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1: disorganized conglomerate</td>
<td>A1.1: disorganized gravels</td>
</tr>
<tr>
<td></td>
<td>A1.2: disorganized muddy gravels</td>
</tr>
<tr>
<td>A3: disorganized pebbly sands</td>
<td>A1.3: disorganized gravelly muds</td>
</tr>
<tr>
<td></td>
<td>A1.4: disorganized pebbly sands</td>
</tr>
<tr>
<td>A2: organized conglomerate</td>
<td>A2.1: stratified gravels</td>
</tr>
<tr>
<td></td>
<td>A2.2: inversely graded gravels</td>
</tr>
<tr>
<td></td>
<td>A2.3: normally graded gravels</td>
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<tr>
<td></td>
<td>A2.4: graded stratified gravels</td>
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<td>A4: organized pebbly sands</td>
<td>A2.5: stratified pebbly sands</td>
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<tr>
<td></td>
<td>A2.6: inversely graded pebbly sands</td>
</tr>
<tr>
<td></td>
<td>A2.7: normally graded pebbly sands</td>
</tr>
<tr>
<td></td>
<td>A2.8: graded stratified pebbly sands</td>
</tr>
<tr>
<td>CLASS</td>
<td>GROUP</td>
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<td>------------------------------</td>
<td>-------</td>
</tr>
<tr>
<td>A GRAVELS, MUDDY GRAVELS, GRAVELLY MUDS &amp; PEBBLY SANDS</td>
<td>A1 DISORGANIZED</td>
</tr>
<tr>
<td></td>
<td>A2 ORGANIZED</td>
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<tr>
<td>B SANDS</td>
<td>B1 DISORGANIZED</td>
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<tr>
<td>C SAND-MUD COUPLETS &amp; MUDDY SANDS</td>
<td>C1 DISORGANIZED</td>
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<tr>
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<td>G1 BILOGNIC OOZES &amp; ARLS</td>
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<td></td>
<td>G2 HEMIPELAGITES</td>
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<td></td>
<td>G3 CHEMOCLOGIC DEPOSITS</td>
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</tbody>
</table>

Figure 7. Classification scheme for deep water sediments (from Pickering and others, 1986).
Flattery quarry (CFQ), which is located at the bottom of the Flattery breccia body; Tatoosh Island, which is located near the top of the breccia body; and a summary of the eastern outcrops from the western Lyre Formation.

Facies descriptions and interpretations

Cape Flattery Quarry

Facies sequence description

Figure 8 represents the measured section exposed at the Cape Flattery quarry (see Figure 1). The measured section is located on the upper level of the quarry, with the bedding attitude of N75E, 25 degrees NW.

The most typical facies sequence, which probably represents a single depositional event, consists of an unstratified, inversely graded pebble to cobble conglomerate that abruptly passes up into an unstratified, normally graded pebbly to coarse sandstone (Facies A2.2 overlain by A2.7). The bed boundaries shown on Figure 8 do not necessarily reflect single depositional events, since bedding contacts were often hard to discern due to probable amalgamation and the lateral variability of the deposits. Most sequences are about 0.5 meter thick, with Facies A2.2 comprising the lower two-thirds of the sequence, and Facies A2.7 the upper third. Distribution grading is the norm, in which the coarse, sandy matrix as well as the clasts show vertical transitions. Beds 2, 5, 6, and 7 are comprised of crosscutting asymmetrical conglomerate lenses with broadly concave-up bases, approximately .5 meter deep and 3 meters wide, also consisting of Facies A2.2 overlain by A2.7 (Figure 9). Beds 1, 3, and 4 are distinct in their paucity
Figure 8. Measured stratigraphic section at Cape Flattery quarry (right hand margin of column represents maximum particle size within facies sequence).
Figure 9. Bed 2 at Cape Flattery quarry: showing 4 broadly concave-up lenses of Facies A2.7/A2.2 within pebbly sands.
of lenses; instead of lenses, these consist of stacks of flat-bottomed sheet flows (Figure 10). In both types of geometries, Facies A2.2 layers are clast-supported and polymodal, comprised of minor boulders, medium cobbles, pebbles, and coarse sand fractions using the grain size scale of Folk (1974). The shape of the boulders and cobbles depends on their composition: there are large angular blocks of green metaquartz diorites and meta-volcanics; the remaining lithologies are sub-rounded to rounded and range in sphericity from equant to rod-shaped (Figure 11). The pebbles are mostly well-rounded and rod-shaped; the coarse sand fraction is angular to subangular and poorly sorted. The upper portion of a sequence, Facies A2.7, is comprised of normally graded pebbly to coarse sand, identical to the sandy "matrix" of the underlying conglomeratic layer. In some instances, the sandstone lacks grading and appears to be massive, resembling Facies B1.1 instead; these two facies appear to be laterally transitional. This sand portion is often cut by discontinuous, subhorizontal to gently-dipping pebble stringers, small pebble "pods", and floating outsized clasts (Figure 11).

**Facies sequence interpretation**

Beds 2, 5, 6, & 7 at Cape Flattery quarry (Figure 8) are crosscutting lenticular deposits that closely resemble sequences in the composite conglomerate facies model of Surlyk (1984) and the R-S sequences of Massari (1984). Massari (1984) described compound sequences of amalgamated bundles of pebble-cobble conglomerate lenses interbedded with lenses or discontinuous layers of sandstone.
Figure 10. Bed 3 at Cape Flattery quarry: showing 6 amalgamated flat-bottomed sheet flows of Facies A2.7/A2.2.
Figure 11. A portion of Bed 1 at Cape Flattery quarry: showing an A2.7/A2.2 sequence of the lower inversely graded pebble to cobble conglomerate (A2.2) abruptly passing up into an unstratified, normally graded pebbly to coarse sandstone (A2.7); note the angular, green meta-volcanic clast and better rounding of the other lithologies; also note the two floating outsized cobbles at the top of the A2.7 facies.
Surlyk (1984) recorded a similar complex facies and interpreted the rocks to be products of surging coarse-grained sediment gravity flows. The successive pulses of sediment were caused by progressive headward failure on a slope, releasing material composed of a wide spectrum of grain sizes (Surlyk, 1984). Each of these flows, closely related in time and space, were characterized by an abrupt velocity increase followed by a gradual decrease, resulting in the deposition of discrete gravel and sand layers in a complex vertical and lateral pattern (Surlyk, 1984).

Beds 1, 3, & 4 at Cape Flattery quarry (Figure 8) are very similar to the inverse to normally graded conglomerate in models by Walker (1975a,b; 1977, 1978; Figure 5). He proposed that these deposits originate from a highly concentrated turbidity current, in which the large clasts were supported in the lower part of the current by dispersive pressure resulting from clast-clast interactions. Within this dispersion, the clasts were free to move with respect to one another, which permitted the eventual inverse grading, long axes of clasts oriented parallel to flow, and up-current imbrication of long axes (Walker, 1975a,b; 1977, 1978). As the flow velocity dropped below the critical level required to maintain dispersive pressure (usually caused by a decrease in slope), instantaneous deposition occurred by frictional freezing of the gravel-fluid mixture (Lowe, 1982). With this decrease in clast concentration and flow velocity, further deposition by rapid suspension-sedimentation resulted in a normally graded sequence of pebble conglomerate and pebbly sandstone (Lowe, 1982). The remaining finer sediment in the turbidity current was carried to other depositional sites further into the basin (Walker, 1975).
Tatoosh Island

Facies sequence description

Figure 12 represents the measured section on Tatoosh Island (Figure 1). The measured cliff-face, trending N80W, is located on the SE side of the island with the bedding attitude of N10E, 10 degrees SE.

This section is composed of a wide variety of facies, representing several grain sizes and grading and stratification types. Any of the following factors may account for the variety: a wide range of grain sizes present in each sediment gravity flow; the occurrence of several different types of sediment gravity flows (i.e. debris flows, density-modified turbidity currents, surging flows, etc.); sediment gravity flows originating at varying distances up slope; or, better preservation potential at this setting than at the Cape Flattery quarry setting. All would result in the wide spectrum of deposits. In any case, the facies sequences at Tatoosh reflect varying degrees of complete deposits of sandy debris flows, high and low density turbidity currents, and probable reworking of the deposits by bottom currents.

In general, most facies sequences range in thickness from 1 to 2 meters; bedding contacts, however, were difficult to identify due to probable amalgamation. Therefore, the bed boundaries shown on Figure 12 do not always represent single depositional events. The sequences are laterally persistent, with flat to locally scoured bases (Figure 13). Occasional channels possess nearly symmetrical outlines and are oriented north/south with imbrication of long axes of gravel dipping to the north. The channels range in size from 0.5 meter wide and 0.25 meter thick to 6 to 7 meters wide and 1 to
Figure 12. Measure stratigraphic section on Tatoosh Island (right hand margin of column represents maximum particle size within facies sequence).
Figure 13. Beds 1 - 4 on Tatoosh Island: showing the local scour of Bed 1, the hematite-cemented top of Bed 2, and the flat-lying, laterally persistent Bed 4 at the top of the photo.
1.5 meters thick. Their lateral position was perhaps controlled by paleo-highs, because these channels are essentially stacked vertically through the section. The coarse portion of most sequences is polymodal, consisting of minor boulders, medium to small cobbles, pebbles, and coarse sand. Bed 12 is distinct in that it consists predominantly of medium-sized boulders (MPS=42 cm). The shape of the clasts varies with size: the cobble fraction is angular to subangular and equant (Figure 14); the pebble fraction is subangular to rounded with variable sphericity. The boulder fraction reflects the same relationship as at Cape Flattery quarry: green meta-quartz diorites and meta-volcanics are blocky and angular; other lithologies are subangular to rounded. The sandstone in all the sequences is coarse to medium-grained, poorly sorted, and identical to the sandy matrix of the gravelly layers. As in the Cape Flattery quarry deposits, fossils are rare. A block of teredo-bored wood was identified on the west end of the island; rare coaly stringers were observed in bed 8 (Figure 15). A few pebble-filled tubes at the top of bed 6 are interpreted to have been burrows (Figure 16). Cementation is quite common in the lower portion of the section: the top of bed 2 consists of a rusty-orange (hematite) cemented sandstone; tabular and spherical calcite concretions were observed in the upper portion of bed 3; bed 4 is a massive, laterally persistent bench of coarse cobble conglomerate cemented by sparry calcite cement (Figure 13).
Figure 14. A portion of Facies A1.1 in lower portion of Bed 7 on Tatoosh Island: showing angular to subangular cobble-size clasts.
Figure 15. Bed 8 on Tatoosh Island: showing coaly stringers in organic-rich mudstone, Facies D2.3, overlain by Bed 9.
Figure 16. Top of Bed 6, lower portion of Bed 7, Tatoosh Island: showing top portion of Bed 6, here Facies B2.1 (parallel-stratified graded sand), with overlying Bed 7, Facies A1.1; note pebble-filled vertical tubes, approximately 5 cm long, at top of Bed 6 (one lies immediately below lens cap, below whitish clast).
Facies sequence interpretation

A typical sequence at Tatoosh, representing a single depositional event, is characterized by a normally-graded, horizontally-stratified cobble conglomerate that gradually grades upwards into a stratified, normally-graded pebbly sand, represented by Facies A2.4 overlain by A2.8 (see beds 3, 9, 13, & 14; also Figures 12 & 13). This sequence is very similar to those in the graded-stratified model of Walker (1975a,b; 1977, 1978; Figure 4). These deposits reflect gravel and sand deposition via suspension sedimentation within a decelerating high-density turbidity current; the stratified portions reflect traction mechanisms operating in response to the overlying turbidity current or subsequent reworking by bottom currents (Lowe, 1982). Curved, low-angle pebble stringers observed in Facies A2.8 (bed 9) may reflect lateral accretion onto irregular surfaces or bedforms (Surlyk, 1984). In some instances, Facies A2.8 is overlain by a thin layer of silt and mudstone, Facies D2.3 (see beds 8 and 10; also Figure 15). These gray to brown, organic-rich layers of wavy-bedded silt and mud may represent the fine sediment fraction deposited by the tail end of the passing turbidity current (Pickering and others, 1986) or perhaps deposition by a subsequent low-density turbidity current (Surlyk, 1984). Another common facies is Facies A1.1, a massive, clast-supported, unstratified, ungraded, poorly-sorted conglomerate (beds 2, 4, 12, lower portion of 7, and channel in bed 3). These deposits represent frictional freezing at the base of either a coarse-grained noncohesive sandy debris flow (Surlyk, 1984), or a high-density turbidity current (Pickering and
others, 1986). The former is suggested by large clasts protruding up through the top of the deposit, indicative of debris flows (Walker, 1978; Figure 17).

Beds 7-8, and Beds 11-13 are occurrences of the above-mentioned facies stacked in a vertical sequence, which appears quite similar to Massari’s (1984) model of a complete deposit of an evolving sediment gravity flow (Figure 6). As the grain-size populations and grain concentrations change via deposition within an evolving flow, the grain-support mechanisms change as well (Lowe, 1982; Massari, 1984). Thus, for example, a debris flow could turn into a turbulent dispersion, then to a high density turbidity current, and then into a low density turbidity current as the flow continues downslope (Lowe, 1982; Massari, 1984). The deposits in beds 7-8 and 11-13 reflect the characteristic features of this flow evolution. In most cases, these sequences aren’t deposited together, as the finer portions are deposited further downslope. The presence of these "complete" sequences may indicate the presence of surging sediment flows: abrupt velocity changes may be required for the vertical stacking of these varied grain sizes during one depositional event.

**Eastern outcrop summary**

**Facies sequence description**

With the emphasis of the study focusing on the sedimentation characteristics of breccias and conglomerates, the eastern outcrops within the Lyre Formation yielded less data due to the larger percentage of sandstone. Instead of great thicknesses predominantly of conglomerate with minor associated pebbly sandstone,
Figure 17. Beds 4 - 7 on Tatoosh Island: showing backpack and Jacob staff resting on the top of Bed 4; boulders to the left of the base of the Jacob staff are protruding up through the top of underlying, laterally persistent Bed 4. Also note scoured base of Bed 7.
the eastern outcrops contain restricted conglomerate layers confined within thick-bedded, coarse-grained sandstone or thin-bedded fine-grained sandstone and siltstone. In any case, the sedimentation features in Table 1 were recorded at each outcrop with respect to the conglomerate layers; the adjacent sandstone layers were only briefly described.

Of the outcrops examined within the western Lyre Formation, the three easternmost sites (Waatch Peak, Cheeka, and Tank outcrops; Figure 1), appeared different than the others. The conglomerate layers, ranging from two to approximately eight meters in thickness, have sharp, flat lower contacts where visible. No rip-up clasts from the underlying sediments were observed. The layers are clast supported and generally bimodal, although there is a wide range in grain sizes between the outcrops. Distinctive to these three easternmost sites, however, is the high degree of clast rounding and polished surface texture within each size mode; angular clasts were rarely observed (Figure 18). The sphericity changes with clast size; boulders are rod to equant in shape; cobbles appear disc-shaped, pebbles are mostly equant. The medium to fine sand matrix is subangular, poorly sorted, contains minor amounts of clay and organic debris, and appears identical to the adjacent sandstone layers. Stratification was not observed within the conglomerate layers; grading may be inverse to normal, ungraded, or normal. No fossils, trace or otherwise, were observed.

Further west along strike, the nature of the conglomeratic units change (see Waatch quarry and Sec. 16 sites; Figure 1). The basal contacts are incised and beds contain large rip-ups from the underlying sand layers. Instead of a simple
Figure 18: Outcrop at Tank quarry. Eastern outcrops: showing rounded and polished boulder and cobble clasts (compare angularity to Figure 14).
conglomerate layer within thick beds of sandstone, these outcrops exhibit more complex depositional patterns including crosscutting lenses and incomplete, alternating layers of conglomerate and sandstone. The units are unstratified and either nongraded or inversely graded; in all cases, bedding contacts were difficult to discern. Both sites are composed of clast-supported, polymodal conglomerate layers. Notably, the rounding and sphericity of boulders and cobbles here also is controlled by composition. As at the Cape Flattery quarry, the green meta-quartz diorite and meta-volcanic clasts are present and are angular and blocky; the remaining lithologies are subrounded to rounded with high sphericity. The coarse-grained sand matrix is poorly-sorted, angular, and identical to the interbedded sandstone layers.

**Facies sequence interpretation**

The conglomeratic layers in the three easternmost sites (Waatch Peak, Cheeka, and Tank outcrops) generally resemble sequences composed of Facies A2.2 overlain by A2.7, an inversely graded conglomerate grading up into a normally graded pebbly sand. These are deposits of high-density turbidity currents (Pickering and others, 1986). These high-density turbidity currents were probably uncommon events in a setting dominated by mostly low density turbidity currents, hence the predominance of thick-bedded sandstone and interbedded sandstone and siltstone.

The outcrops of the middle sections (Waatch quarry and Sec. 16) consist of a wider array of facies, representing both A and B facies groups of Pickering and others (1986; Figure 7). These deposits, in part resembling the complex gravel and sand
units of Massari (1984), were probably deposited by surging, very turbulent high-density turbidity currents, producing the rip-ups, complex bedding patterns, and the wide range of grain sizes within single depositional events.

Discussion

Table 3 summarizes the sedimentation characteristics observed at the representative outcrops of the Flattery breccia and western Lyre Formation. The majority of the facies sequences were deposited by sediment gravity flows, such as high-density turbidity currents, surging high-density turbidity currents, or sandy debris flows. The deposits of single events (i.e. A2.7/A2.2) are either in the form of flat-bottomed sheet flows or have a cross-cutting channelled or lenticular relationship. In places the contacts are erosional; in others, specifically some broad, concave-up isolated conglomerate lenses, the contacts appear to represent infills of slides or slumps. Texturally, the coarse gravel facies are polymodal, and the sand facies are poorly sorted as well. The clast shape varies along strike. In the west, angular clasts of green meta-quartz diorites and meta-volcanics are mixed with clasts of a wide range of lithologies that range in shape from subangular to rounded. The three easternmost outcrops lack angular clasts of any composition, consisting instead of clasts of a wide range of lithologies that are rounded and almost polished; the sand matrix is also fine to medium in texture (in contrast to coarse in the west) and is poorly sorted and subangular. These data suggest the presence of two different sources of detritus to the
<table>
<thead>
<tr>
<th>Outcrop</th>
<th>Facies Sequence(s) Observed</th>
<th>Comparable Facies Model</th>
<th>Probable Flow Mechanism</th>
<th>Clast Shape</th>
<th>Misc.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tatoosh Island</td>
<td>A2.8/A2.4</td>
<td>graded stratified model of Walker, 1975a,b</td>
<td>high density turbidity current</td>
<td>angular and subangular to subrounded</td>
<td></td>
</tr>
<tr>
<td></td>
<td>A1.1</td>
<td>Ra unit (Massari, 1984)</td>
<td>&quot;highly concentrated flow moving as a rigid plug&quot;</td>
<td>sandy debris flow</td>
<td></td>
</tr>
<tr>
<td></td>
<td>D2.3/A2.8/A2.3/A1.1 &amp; A2.8/A2.4/A1.1/A2.2</td>
<td>Model #3 (Surlyk, 1984)</td>
<td>surging gravelly to sandy high density turbidity current</td>
<td>subrounded</td>
<td></td>
</tr>
<tr>
<td>Cape Flattery quarry</td>
<td>A2.7/A2.2</td>
<td>flat-bottomed sheet flows</td>
<td>high density turbidity current</td>
<td>angular and subangular to subrounded</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>x-cutting channels</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>central outcrops (See 16, Waatch quarry)</td>
<td>A2.7/A2.2</td>
<td>inverse to normal model (Walker, 1975a,b)</td>
<td>high density turbidity current</td>
<td>angular and subangular to subrounded</td>
<td>more massive to thick-bedded sandstones</td>
</tr>
<tr>
<td></td>
<td></td>
<td>R-S sequence (Massari, 1984)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Composite conglomerate model #13 (Surlyk, 1984)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>eastern outcrops (Waatch Peak, Cheeka Peak, Tank quarry)</td>
<td>A2.7/A2.2</td>
<td>x-cutting channels</td>
<td>surging high density turbidity current</td>
<td>angular and subangular to subrounded</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>inverse to normal (Walker, 1975a,b)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>flat-bottomed sheet flows</td>
<td>high density turbidity current</td>
<td>rounded to subrounded (almost polished)</td>
<td>interbedded cong. layers w/ mostly thin-bedded ss &amp; slst</td>
</tr>
<tr>
<td></td>
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</table>
Flattery breccia and western Lyre Formation based on the textural and compositional differences.

As mentioned in the beginning of this chapter, the reason for investigating the sedimentology of the Flattery breccia was to determine if it represented a proximal (shallow?) coarse clastic wedge adjacent to a landmass now faulted away. A subaerial setting such as an alluvial fan was ruled out due the presence of marine foraminifera, the lack of paleosols, and the failure of common proximal-distal relationships associated with alluvial fans. These relationships, such as a decrease in mean pebble size (MPS, mean of ten largest clasts) and angularity of clasts down fan, as well as a decreasing ratio of MPS to bed thickness (MPS:BTh) down fan, were measured going west to east along strike. A shallow, nearshore setting such as the shallow subaqueous portion of an alluvial-fan delta was also rejected due to the lack of typical nearshore features such as wavy or hummocky cross strata, swash laminae, foreset/topset bedding, spits and bars, and discoid beach gravels, and to the lack of shelf fauna.

At this point, one problem at hand is determining what type of "deeper"-water setting would best represent the Flattery breccia: for example, submarine fan channels, deeper slopes of steep-faced, coarse-grained alluvial-fan deltas, or wedges of coarse detritus resedimented into deeper environments. A second problem is attempting to find and use acceptable terms and definitions with regard to identifying these settings. Nemec (1990) reports that, in recent years, much research has been done on fan deltas and submarine fans, corresponding with a muddle of changing classification systems and terms. Regardless of classification, however, these deeper-water settings are
generally dominated by sediment gravity flows, hence similar deposits (Wescott and Ethridge, 1980). Therefore, determinations of depositional setting are best made knowing the facies relationships in the direction of the feeder system of these fans or deposits. Unfortunately, the Flattery breccia and western Lyre Formation, as well as the other formations rimming the northern Peninsula, represent just a slice of the entire system. With respect to the Flattery breccia, an appropriate comparison cannot be made with the Carmanah Group on Vancouver Island, as the oldest rocks are slightly younger than the Flattery breccia and are exposed in a narrow strip along the central portion of the western Vancouver Island coast; therefore they may not have been in the same depositional basin. Therefore, without any known proximal-distal relationships, only inferences can be made with respect to the depositional setting based on the sedimentological features observed in this study and the stratigraphic and lithologic relationships of the Flattery breccia and adjacent strata.

As mentioned above, the textural and compositional changes observed along strike from west to east suggest two separate sources of detritus being supplied to the Flattery breccia and western Lyre Formation. Surlyk (1984) described the Wollaston Forland Group as deposits of an apron of coalescing fans, with detritus being emitted all along the associated fault scarp and from all parts of the fan(s). That process of fan deposition could result in localized differences in composition and texture of the detritus, perhaps related to the nearshore depositional settings and residence time of the detritus along the shoreline. For example, a rocky shore setting would produce more angular detritus than a beach setting, which is a relationship suggested in the
field area along strike from west to east, respectively. Perhaps that type of setting, in which there were adjacent fans along the coastline, would explain the difference in clast shape and lithology that is observed along strike from the Flattery breccia east into the Lyre Formation. The sediment supply associated with fan aprons is distinct from the classical submarine fan model of a single point source at the fan’s apex. However, as sediment supply changed at the apex, so could the distributory channels switch further down-fan, resulting in an interfingering relationship between detritus types.

A different approach could follow Massari and Colella (1988), who reported that coarse-grained deep-marine sequences often represent cannibalized or eroded alluvial-fan delta or nearshore material, most likely resulting from rapid periodic lowering of sea level (or uplift) due to tectonic movements. Such sequences show an onlapping relationship with the underlying slope or basin-fill deposits and their boundaries may be regarded as minor unconformities (Massari and Colella, 1988). The outcrop pattern of the Flattery breccia and western Lyre Formation, as mapped by Snavely and others (1986b), reveals an onlapping against the underlying Aldwell Formation, and an unconformity with the Crescent Formation and rocks of the terrane south of the Crescent fault and north of the Calawah fault (Figure 1). Massari and Colella (1988) also report that resedimented material often accumulates locally, due to an irregular submarine topography (caused by rising anticlines, thrust blocks, etc.) that would dam and divert the material. The typical irregular submarine topography
associated with the Crescent basalts may explain the locally increased thickness of the Flattery breccia and conglomerates seen in the western portion of the field area.

Finally, analysis of foraminifera within the Lyre Formation and limited data within the Flattery breccia generally indicate outer neritic to upper bathyal environments (50 - 150 meters; Rau, 1964; Snavely and others, 1986a). These data, however, should serve as guidelines only, since shallow forms may be redeposited in deeper-water environments. To summarize, then, the Flattery breccia and western Lyre Formation may represent either deeper-than-wave-base portions of interfingering alluvial fan-deltas, resedimented wedges of coarse-grained detritus deposited in slope or base of slope depths, or interfingering lobes of coarse detritus on a submarine fan.
CHAPTER 3: PETROLOGY

Methods

The outcrop extent of the Flattery breccia limited sampling to available logging-road exposures and quarries. Sampling was carried out vertically through the section and laterally from Tatoosh Island eastward into the western Lyre Formation (Figure 1). Samples were also taken at Portage Head and Point of the Arches, areas which were previously mapped as the Flattery breccia by Tabor and Cady (1978a; see Chapter 1, previous work section, for a description of previous mapping in the field area).

At the majority of the sites, three grain-size fractions were sampled: 1) coarse sand, 2) pebbles, and 3) cobbles and boulders. The sand fraction represented either the coarse-grained sandy matrix associated with conglomerate beds or the thick-bedded coarse-grained sandstone beds. The pebble fraction was sampled by collecting a large block of pebbly conglomerate or by extracting a large number (approximately fifty) of pebbles present in a randomly designated area of a conglomerate bed. The cobble/boulder fraction was sampled by breaking off approximately ten to fifteen clasts within that size fraction within a designated area of a conglomerate bed. However, the limited sampling of the pebble and cobble/boulder fraction failed to document any consistent trends; therefore, the petrologic analysis was mainly based on the sandstone fraction.

Fifty thin sections were prepared from the sandstone samples, half-stained for identification of potassium feldspar and plagioclase, and used to study lithology, texture, and diagenetic changes. Two separate point counts were performed on
eighteen of these thin sections, using a point count spacing of 1 X 2 mm. A 300-point whole-rock count was performed to obtain an overall composition of the rock. These whole-rock counts employed the Gazzi-Dickinson method of point counting, in which mineral grains 1/16mm or larger within a lithic grain are counted as monominerals (Ingersoll and others, 1984). A 200-point rock-fragment count was performed separately to better identify source-rock types. A rock fragment is defined as a grain consisting of two or more mineral grains of any size; e.g., fine- and coarse-grained rock fragments. For example, when landing on a sand-sized mineral within a rock fragment, it was identified as that rock fragment type. The only grains tabulated as minerals were those occurring as discrete, individual grains; and they were counted in the "other" category. Therefore, this point count did not follow the Gazzi-Dickinson method (Ingersoll and others, 1984). Table 4 lists the grain categories used in the point counts, and their definitions are listed in Appendix 1.

The sandstones are classified as lithic arenites and lithic wackes, following the scheme of Dott (1964). The grain size varies from 1/8 mm to 7 mm, with an average of 1 mm, placing them in the category of coarse to very coarse sandstones, following the grain size scale of Folk (1974). The sandstones are poorly sorted, with individual grains predominantly subangular in shape. The grain contacts are consistently long to concavo-convex, with the exception of floating contacts in one calcite-cemented sample. Point counts performed on the sandstones revealed an average composition of 93% rock-fragment grains, which, combined with the coarse grain size, poor sorting, high angularity, and long to concavo-convex grain contacts, is characteristic of
# TABLE 4
Grain categories used in point counts

## Whole Rock Point Count

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qpc</td>
<td>monocrystalline quartz</td>
</tr>
<tr>
<td>K</td>
<td>potassium feldspar</td>
</tr>
<tr>
<td>P</td>
<td>plagioclase</td>
</tr>
<tr>
<td>Op</td>
<td>polycrystalline quartz (chert)</td>
</tr>
<tr>
<td>Lsm</td>
<td>sedimentary and metasedimentary lithics</td>
</tr>
<tr>
<td>Lvm</td>
<td>volcanic and metavolcanic lithics</td>
</tr>
<tr>
<td>Am</td>
<td>amphiboles</td>
</tr>
<tr>
<td>Pyx</td>
<td>pyroxenes</td>
</tr>
<tr>
<td>Mi</td>
<td>micas</td>
</tr>
<tr>
<td>Op</td>
<td>opaques</td>
</tr>
<tr>
<td>Acc</td>
<td>accessory minerals</td>
</tr>
<tr>
<td>Cmt</td>
<td>cement</td>
</tr>
<tr>
<td>Mtx</td>
<td>matrix</td>
</tr>
<tr>
<td>Misc</td>
<td>miscellaneous</td>
</tr>
</tbody>
</table>

## Rock Fragment Point Count

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qpc</td>
<td>chert</td>
</tr>
<tr>
<td>Sh</td>
<td>shale</td>
</tr>
<tr>
<td>Arg</td>
<td>argillite</td>
</tr>
<tr>
<td>Ss</td>
<td>sandstone</td>
</tr>
<tr>
<td>Sm</td>
<td>misc. sedimentary</td>
</tr>
<tr>
<td>Vf</td>
<td>felsic volcanics</td>
</tr>
<tr>
<td>Vi-m</td>
<td>intermediate to mafic volcanics</td>
</tr>
<tr>
<td>Pf</td>
<td>felsic plutonics</td>
</tr>
<tr>
<td>Pi-m</td>
<td>intermediate to mafic plutonics</td>
</tr>
<tr>
<td>VPm</td>
<td>misc. volcanics and plutonics</td>
</tr>
<tr>
<td>Qpf</td>
<td>foliated polycrystalline quartz</td>
</tr>
<tr>
<td>Tec</td>
<td>tectonite</td>
</tr>
<tr>
<td>Ma</td>
<td>metamorphic assemblages</td>
</tr>
<tr>
<td>Mm</td>
<td>misc. metamorphic</td>
</tr>
<tr>
<td>Op</td>
<td>undifferentiated polycrystalline quartz</td>
</tr>
<tr>
<td>Ot</td>
<td>other</td>
</tr>
</tbody>
</table>
immature sandstones.

**Descriptive petrography**

The following petrographic description of Flattery breccia sands will follow the categories of the rock-fragment point counts. As mentioned previously, the average sandstone was composed of 93% rock fragments, most of which are coarse-grained, e.g., having individual mineral grains larger than 1/16 mm within a rock fragment larger. For a clearer picture of the sources of the sandstones, it was necessary that a point count include various coarse-grained, as well as fine-grained, rock-fragment categories. Percentages of monominerallic grains and fine-grained lithic grains, which were tabulated in the whole-rock point count, are not as useful as indicators of source rock types.

Specific monominerallic grain categories, as well as cement, matrix, and other miscellaneous items, will be described in the Other (Ot) category. Unless otherwise mentioned, the individual rock-fragments vary in size from 1/8 to 7 mm, with an average size of 1 mm. The average shape of the grains is subangular, unless otherwise noted.

Please refer to Appendix 2 for the raw data and percentages of both the whole-rock and rock-fragment point counts.
**Sedimentary rock fragments**

**Qpc: chert.** Chert was a very common constituent in the samples. There appeared to be several varieties: clean, clear (in plane light) grains; light brown, light green, and pale red (in plane light) grains with impurities, such as clays, opaques, or hematite staining; grains with radiolarian tests or ghosts; recrystallized and deformed grains with veins and styolites; and any combination of the above characteristics. Therefore, the wide variety of chert types may indicate more than one source terrane of chert. Due to their composition, chert fragments were rarely deformed by adjacent grains, nor were they altered or replaced.

**Sh: shale.** The shale rock fragments range from clay-size to silt-size (siltstone) shales. Quartz-rich shale fragments are clear to light brown in plane light, while the clay-rich and carbonaceous shale fragments are dark brown, occasionally red, to nearly opaque in plane light. Some clay-rich shales contain radiolarian ghosts. Shale fragments that were squashed, deformed, and confined to void spaces may have actually been matrix. This misinterpretation is suggested by comparing the percentages of shale rock fragments between a sample with identified matrix and one that has cement; the percentage of shale fragments drops significantly in the cemented sample, suggesting that a sandstone free of matrix may represent the actual composition more accurately without this possible misidentification. Another explanation for the reduction in shale rock fragments in cemented samples is preferential replacement of shale fragments by cement. Regardless, intrabasinal sediments may be one of the sources of shale fragments.
Arg: argillite. As defined in Appendix 1, argillite fragments are distinguished from shale fragments by the presence of deformation characteristics, such as veining and styolites. These characteristics theoretically exclude those grains representing intrabasinal sediments. Argillite fragments range from clay-size to silt-size and are most often brown to dark brown, but occasionally red, in plane light. They contain clays, opaques, and carbonaceous material. The red grains often contain ghosts of radiolarians. Complex veining, styolites, and laminae are common, but a distinct foliation, such as that in tectonite rock fragments (see below), was absent.

SS: sandstone. Volcanic lithic wackes, some of them murky, are the most common sandstone type, followed by quartz wackes and feldspathic wackes.

Sm: miscellaneous sedimentary fragments. As defined in Appendix 1, any sedimentary grain not fitting into the above categories has been assigned to this category. No carbonate rock fragments were observed. The grains in this category were badly altered and unidentifiable, but had some sedimentary characteristics.

Igneous rock fragments

Vf: felsic volcanics. One third to one half of the felsic volcanic fragments are altered felsic tuffs, with other compositions including dacites, quartz latites, quartz andesites, and rhyolites. The altered felsic tuffs are dusty to pale green in plane light, and look very similar to chert in cross polars due to the devitrification of the glassy groundmass. In most cases, however, the grain retained light pink plagioclase stain, the internal grain sizes are a bit larger than in chert, there are often isolated crystal
outlines, and, unlike chert, the tuff grains are often squashed and deformed against more competent sand grains. The other felsic volcanic fragments contain quartz phenocrysts in a microgranular groundmass consisting of quartz and plagioclase intergrowths.

**Vi-m: intermediate to mafic volcanics.** The population of Vi-m grains is composed of one quarter to one half altered mafic tuffs, with the remainder of the compositions consisting of andesites and basalts. The altered mafic tuffs have very low relief, are light green in plane light, retain a pink plagioclase stain, and often contain altered plagioclase laths, oxidized opaques, chlorite, zeolites (often laumontite, which stains red), calcite, and/or sausserite, along with the characteristic vitric textures of tuffs. There are occasional small brown spheres within the pale green groundmass of an altered tuff fragment (vacuoles?). In addition, the glassy groundmass often is altered to palagonite, which gives the tuff fragment an orange color in plane light. There are only a few occurrences of dusty-brown, mafic, glassy grains that are isotropic in cross polars. The compositions of the flow rocks were determined by plagioclase composition using the A-normal method, in combination with the existing volcanic texture. Volcanic textures noted include microlitic (trachytic and hyalopilitic) and lathwork (subophitic and intersertal). Pyroxene and calcium-rich plagioclase crystals are often altered to calcite and/or sausserite. While the basalt and andesite fragments are angular to subrounded and competent, the altered tuffs are usually squashed and deformed against other grains.
**Pf: felsic plutonics.** Felsic plutonics are predominantly tonalite fragments, with subordinate granodiorite and granite. Potassium feldspar, identified by sodium cobaltinitrate stain and Carlsbad and cross-hatch twinning, is very uncommon. The felsic plutonic fragments are typically large (2 mm) and subangular to subrounded in shape.

**Pi-m: intermediate to mafic plutonics.** There were few intermediate to mafic plutonics observed in the point counts. Diorite, quartz diorite, and gabbro were the compositions noted, with abundant diorite, consisting of altered twinned plagioclase, a trace to no quartz, chlorite, and uralitized hornblende.

**VPm: miscellaneous volcanics and plutonics.** Unfortunately, clasts in this category are fairly common. As defined, those igneous rock fragments not fitting into the above categories would be assigned to this category. In most of the grains, a vague igneous texture was recognizable, but the mineral assemblage was so altered by calcite, sausserite, and/or clay minerals that the composition, felsic or intermediate to mafic, was impossible to discern. Perhaps the source of these rock fragments was hydrothermally altered.

**Metamorphic rock fragments**

**Qpf: foliated polycrystalline quartz.** This category, as defined in Table A.1 in Appendix 1, consists of polycrystalline quartz, with less than 15% impurities, that exhibits a foliation or a lineation, such as stretching and flattening of the individual quartz grains. The foliation is often defined by impurities such as muscovite, sericite,
or chlorite. Rock types in this category include quartz-mica schists and gneisses. These rock fragments are generally elongate, ranging in length from 3/4 to 1 1/4 mm. **Tec: tectonite.** Tectonite rock fragments are associated in occurrence with rock fragments of the preceding foliated polycrystalline quartz (Qpf) category. Rock types in this category include graphitic phyllites, slates, and graphite-schists. Phyllite fragments contain fine-grained foliated polycrystalline quartz, graphite, clay minerals (alteration?), and sericite, and often exhibit folded compositional layering parallel or subparallel to the foliation. Schist and gneiss fragments generally consist of coarse-grained foliated quartz crystals with muscovite, sericite, graphite, biotite, or chlorite defining the foliation, along with with some scattered opaques (magnetite). A garnet-bearing quartz-mica schist also was observed. Tectonite rock fragments are elongate, subrounded, range from 1/2 to 4 mm in length, and are sometimes deformed against other, more competent, sand grains. These rock fragments were derived from a metamorphic source, with perhaps a pelitic protolith. **Ma: metamorphic assemblages.** These rock fragments consist of unfoliated, or seemingly unfoliated at the coarse sand size, metamorphic mineral assemblages, predominantly characteristic of the greenschist and prehnite/pumpellyite facies of metamorphism. This category includes rock fragments comprising two or more mineral grains or crystals (e.g.; a polycrystalline epidote fragment). Discrete individual grains, primary metamorphic minerals or otherwise, were assigned to the Other (Ot) category. As defined in Appendix 1, metamorphosed mafic volcanics (e.g.; meta-basalts, spilites) were noted by their easily recognized lathwork volcanic texture.
Metamorphosed mafic volcanics make up approximately 30% of the total metamorphic assemblage category. The mafic meta-volcanics exhibit intersertal, subophitic, and ophitic textures. The composition of the plagioclase laths consistently falls in the albite to oligoclase range (An 0 - An 30). The pyroxenes are commonly altered to chlorite, calcite and/or sausserite, or occasionally actinolite. The groundmass usually consists of epidote, chlorite, occasionally prehnite or pumpellyite, with minor altered opaques. The other rock fragments in this category consist of several combinations of the typical mineral assemblages of the prehnite/pumpellyite, greenschist, and lower amphibolite facies of metamorphism. For example, the most common rock fragments are assemblages of quartz + epidote; quartz + epidote + Na plagioclase + chlorite; quartz + epidote + Na plagioclase; and epidote + Na plagioclase, respectively, with the Na plagioclase consisting of mostly albite. These mineral assemblages are most characteristic of mafic volcanic rocks metamorphosed in the prehnite/pumpellyite, greenschist, and lower amphibolite facies of metamorphism (pgs. 564-591, Hyndman, 1985). In addition, there are rock fragments consisting of various combinations of the following minerals, listed in rough order of decreasing amounts: epidote, quartz, Na plagioclase, chlorite, clinozoisite, zoisite, pumpellyite, prehnite, actinolite, muscovite, laumontite, opaques, and calcite and/or sausserite. Some of these assemblages may represent protoliths other than mafic volcanics. These rock fragments are typically angular and are generally 1/2/to 3/4 mm in size.
Mm: miscellaneous metamorphics. The rock fragments in this category predominantly consist of altered volcaniclastic sandstones with mylonitic or porphyroclastic textures.

Other grain types

Qp: undifferentiated polycrystalline quartz. Grains in this category are fairly common, because the sandstones contain a large percentage of quartz-rich (> 85% quartz) rock fragments. Those that are not chert fragments (Qpc) or foliated polycrystalline quartz fragments (Qpf) were tabulated here. As defined in Appendix 1, a tally was recorded with each Qp grain as to its probable source: Qpm (metamorphic), reQpc (recrystallized chert), and Qph (hydrothermal). Every category is fairly common and varies in abundance with respect to the other types. Qpm was characterized by fairly coarse polycrystalline quartz (generally 3-6 quartz crystals per rock fragment) that exhibits strongly sutured grain boundaries but without any elongation of the quartz crystals. This strongly sutured pattern is typical of quartzites, for example. A reQpc rock fragment, as defined in Appendix 1, consists of polycrystalline quartz with individual grains less than 31 microns (1/32mm) in size, but more than half of the rock fragment consisting of coarser-grained polycrystalline quartz. These recrystallized chert fragments are often veined and speckled with opaques. Qph rock fragments are coarsely polycrystalline, and display inclusions or vacuoles within the individual quartz crystals, making the grain somewhat milky in
plane light. They sometimes exhibit an aggrading grain size, as would occur in vein or fracture filling.

**Ot:** other. As mentioned previously, the rock-fragment point counts revealed the sandstones to be composed of, on the average, 93% rock fragment grains. The following is a brief description of the other constituents, mainly monomineralic grains, cement, and matrix.

Discrete grains of Qm (monocrystalline quartz) typically have undulose extinction and are angular. A few clear, vacuole-free crystals with sharp crystal outlines and straight extinction were observed, suggesting a volcanic source. There are also several occurrences in samples from the eastern portion of the field area of discrete monocrystalline quartz grains that contain inclusions of vermicular chlorite, which is indicative of a hydrothermal source (Blatt and others, 1980). Most of the quartz grains were probably derived from a plutonic or metamorphic source. The sandstones were nearly devoid of K (potassium feldspar), but when present it was adequately stained yellow with sodium cobaltinitrite. The composition observed was untwinned orthoclase. The compositions of P (plagioclase feldspar) were determined using the A-normal method, with compositions consistently falling between An - 0 to An - 30 (albite and oligoclase). The albitic compositions were very faintly stained with amaranth, while the more calcic compositions were a distinct pink. The plagioclase grains are generally untwinned and partially altered, often to sausserite, while the only fresh plagioclase grains observed are preserved in a calcite-cemented sample. The plagioclase was derived mostly from a plutonic or metamorphic source.
Discrete mafic minerals such as Am (amphibole) and Pyx (pyroxene) are very rare, but include actinolite, anthopolite, hornblende, clinopyroxene (augite) and orthopyroxene. Mi (mica) consists mostly of white mica, muscovite and sericite, with minor occurrences of biotite. Op (opques) grains were observed within rock fragments and also as discrete grains of magnetite, graphite, pyrite, and leucoxene. Other monominerallics occurring as discrete grains consist predominantly of greenschist and prehnite/pumpellyite facies minerals, including epidote, chlorite, laumontite, zoisite, pumpellyite, prehnite, clinozoisite, calcite and/or sausserite, garnet, serpentine, sphene, and talc. Cmt (cement) consists of calcite, hematite, zeolite (laumontite), and phyllosilicate compositions, with more than one type occurring in a sample, although most samples are only partially cemented (averaging 5.6% of sample in whole-rock counts). Tatoosh Island samples contain, on the average, 28% calcite cement, which is a murky, granular, sparry calcite cement with scattered pyrite cubes. The calite cement often cannibalized grain boundaries, with only minor occurrences of total replacement of individual grains. The laumontite cement picked up the pink amaranth stain, and the hematite cement is orange in plane light, opaque in cross polars. There was little Mtx (matrix) observed in the samples, but due to the compacted textural nature of the sand (e.g.; long and concavo-convex grain contacts), original matrix may have been misidentified as shale rock fragments. As compaction took place, the original matrix may have been confined to the void spaces between more competent sand grains, eventually resembling crushed shale fragments. The only fossils observed were radiolarian tests in chert fragments and an isolated foraminifera; the minor
Petrologic trends

The purpose of the rock-fragment point-counts was to more clearly characterize the sources of the Flattery breccia sands. The point-count data revealed varying percentages in the different rock-fragment categories when viewed along strike from west to east, but little variation going up section (see Appendix 2). To facilitate the visualization of these petrologic trends, the 16 rock-fragment categories were partially recombined into 10 groups. These groups were based on 1) rock-fragment categories that reflected a trend on their own, e.g., chert fragments drop off to the east along strike; 2) two rock-fragment categories that represent rock types frequently found together, probably indicating association at the source, e.g., shale and sandstone; and 3) rock-fragment categories with few occurrences added to another category, e.g., argillite and miscellaneous sedimentary rock fragments. Table 5 lists the rock-fragment point-count categories with the new groups used in graphing the petrologic trends. The original rock-fragment point-count data were recombined for these new groups, and the totals are presented in percentage form in Appendix 3.

The compositional differences between the sandstones, and the resulting petrologic trends, may be the result of a variety of factors, such as the effects on composition of different grain sizes amongst the samples, different depositional mechanisms, and post-depositional diagenetic changes. An attempt was made to
<table>
<thead>
<tr>
<th>Rock-fragment point-count categories recombin...</th>
<th><strong>Recombined groups for petrologic trends</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Qpc: chert</td>
<td>Pt + VPm: total plutonics and misc. volcanics and plutonics</td>
</tr>
<tr>
<td>Sh: shale</td>
<td>Ma + Mm: metamorphic assemblages and misc. metamorphics</td>
</tr>
<tr>
<td>Arg: argillite</td>
<td>Vi-m: intermediate to mafic volcanics</td>
</tr>
<tr>
<td>Ss: sandstone</td>
<td>Qpc: chert</td>
</tr>
<tr>
<td>Sm: misc. sedimentary</td>
<td>Vf: felsic volcanics</td>
</tr>
<tr>
<td>Vf: felsic volcanics</td>
<td>Ot: other</td>
</tr>
<tr>
<td>Vi-m: intermediate to mafic volcanics</td>
<td></td>
</tr>
<tr>
<td>Pf: felsic plutonics</td>
<td></td>
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<tr>
<td>Qp: undifferentiated polycrystalline quartz</td>
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<tr>
<td>Qpf + Tec: foliated polycrystalline quartz and tectonites</td>
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</tr>
<tr>
<td>Arg + Sm: argillite and misc. sedimentary fragments</td>
<td></td>
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<tr>
<td>Sh + SS: shale and sandstone</td>
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</tbody>
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TABLE 5

Rock-fragment point-count categories recombin... to show petrologic trends

**Rock-fragment point-count categories**

Qpc: chert
Sh: shale
Arg: argillite
Ss: sandstone
Sm: misc. sedimentary
Vf: felsic volcanics
Vi-m: intermediate to mafic volcanics
Pf: felsic plutonics

**Recombined groups for petrologic trends**

Pt + VPm: total plutonics and misc. volcanics and plutonics
Ma + Mm: metamorphic assemblages and misc. metamorphics
Vi-m: intermediate to mafic volcanics
Qpc: chert
study sandstone samples of the same grain size (coarse sand with an average size of 1 mm) in order to remove any grain-size-dependent compositional bias. As previously discussed in Chapter 2, the Flattery breccia and western Lyre Formation sands and gravels were predominantly deposited by high-density turbidity currents in slope and base of slope environments and were probably buried rapidly by subsequent deposits, as suggested by the highly compacted texture. This burial would have eliminated the possibility of subsequent breakdown and winnowing-out of less competent lithologies; consequently, the sandstone samples should have compositions close to the original sand-size detritus. There were minor occurrences of cement cannibalizing grain boundaries. However, only rarely was a grain completely replaced by the cement, or by any other secondary mineral, so there is no possibility of compositional bias due to diagenesis. Therefore, the petrologic trends in the field area may be explained as reflecting a difference in source along strike.

Figures 19 and 20 illustrate the recombined data of the new rock-fragment groups in area graphs (refer to Figure 1 for sample locations). As shown in Figure 19, the relative abundances of the rock-fragment groups do not appear to change significantly overall going up section. The two sandstones at the right in Figure 19, labelled FSB and CFT, are coarse, calcite-cemented sandstones from the Hoko River Formation, sampled and thin-sectioned by Jennifer De Chant (1989). These sandstones were point-counted in this study to note any change in composition going up section from the Flattery breccia into the channeled sandstones and breccia lenses of the Hoko River Formation. Figure 20, which presents the compositions along strike
Figure 19. Rock-fragment point-count data from Flattery breccia sandstones; refer to Figure 1 for sample locations. As mentioned in text, note relative abundancies of rock fragment groups do not change significantly going up section.
Figure 20. Rock-fragment point-count data from Flattery breccia sandstones; refer to Figure 1 for sample locations. As mentioned in text, note decrease in chert and argillite rock fragments to the east and decrease in foliated polycrystalline quartz (meta-qtz) and tectonites to the west.
from west to east, does show some distinct petrologic trends. Chert and argillite (Qpc and Arg + Sm), common in the western portion of the field area, drop off substantially in the three easternmost sample sites, Waatch Peak, Cheeka Peak, and Tank quarry. Conversely, foliated polycrystalline quartz and tectonites (Qpf + Tec), which represent quartz-mica schists and graphitic phyllites, are scarce in the western portion of the field area, but increase dramatically in the three easternmost sample sites.

Additionally, the informal tally of undifferentiated polycrystalline quartz grains (Qp; see explanation in descriptive petrography section) reveals that metamorphic, polycrystalline quartz (Qpm) dominated the Qp category in the three easternmost sample sites, following the increase of quartz-mica schist fragments. Other than that, the felsic volcanics, intermediate to mafic volcanics, metamorphosed mafic volcanics (metamorphic mineral assemblages, Ma), and plutonics do not seem to follow any particular trend but instead are included in the detritus equally up section (Figure 19) and along strike (Figure 20).

Another relationship that shows up on both graphs involves the relative amounts of the shale and sandstone (Sh + SS) category and the Other (Ot) category, which consists predominantly of cement and discrete monominerallic grains. Referring to Figure 19, the stratigraphically highest three samples labelled Tatoosh (ave.), FSB, and CFT, all calcite-cemented samples, show that the percentages of shale and sandstone rock fragments drop off substantially as the Other category (cement) increases; or as matrix is replaced by cement, the number of shale and sandstone (Sh + SS) grains decreases. I had suspected that matrix may have been misidentified as
shale rock fragments due to the highly compacted texture of the sandstone; this suspicion may be confirmed by these graphs. Figure 20 illustrates this same pattern, since the three easternmost samples, Waatch Peak, Cheeka Peak, and Tank quarry, are also cemented. On the other hand, there may actually be more intrabasinal rock fragments in the western portion of the field area (Figure 20) and low in the section (Figure 19).

Discussion

The focus of the petrographic portion of this study was to characterize the composition of the sands and gravels of the Flattery breccia and western Lyre Formation and then delineate the type of source rocks required for the compositions observed. To summarize the petrologic trends: the sands in the western portion of the field area predominantly consist of a chert and argillite source, while the sands of the eastern portion contain a graphitic phyllite and quartz-mica schist source. Both portions, however, received detritus from felsic volcanics, intermediate to mafic volcanics, metamorphosed mafic volcanics (metamorphic mineral assemblages, Ma), clastics, and plutonics.

Pebble counts of the coarse clast (pebble to boulder size) population were not performed due to the difficulty in differentiating in the field among common, quartz-rich, fine-grained clasts such as chert, quartzites, and metamorphosed aphyric felsic volcanics and tuffs. The limited sampling of the coarse clast population failed to document any petrologic trends along strike or up section. Ansfield (1972), Pearl
(1977), Snavely (1983), and Snavely and others (1986b) report a wide range of clast lithologies along strike (amphibolite, andesite, argillite, arkosic-lithic sandstone, basalt, dacite, diorite, felsic volcanic, gabbro, gneiss, granite, granodiorite, limestone, metabasalt, meta-quartz diorite, meta-tuff, phyllite, quartzite, tuff, wacke). However, their data appear to confirm this study's observations (reported in Chapter 2) that green angular blocks of meta-quartz diorite and meta-volcanics occur predominantly in the western portion of the field area. However, Ansfield (1972), Pearl (1977), Snavely (1983), and Snavely and others (1986b) also report the occurrences of phyllitic clasts, as well as chert and argillite clasts, all along strike throughout the Flattery breccia and western Lyre Formation. These rock types are nearly mutually exclusive as rock fragments in the sandstones along strike. This discrepancy between sand and gravel compositional trends may suggest a complex pattern of detritus availability with respect to grain size and source rock type. As mentioned in the Chapter 2, a possible depositional setting for the Flattery breccia and western Lyre Formation sands and gravels is as coarse-grained, submarine wedges of detritus deposited on the slope or base of slope, adjacent to a narrow shelf along a tectonically active coastline. Surlyk (1984) suggested that such settings often have detritus being emitted all along a faulted basin margin, instead of from a point source, which would provide the potential for varying compositions and textures in the resulting apron of resedimented deep-water deposits. Such a setting could easily explain the compositional and textural differences observed along strike, from the Flattery breccia east into the western Lyre Formation.
CHAPTER 4: PROVENANCE

Provenance of the Flattery breccia and western Lyre Formation is interpreted here primarily by petrographic means, with some additional data from a limited paleocurrent analysis of conglomerate fabric. Results from whole-rock point-counts and rock-fragment point-counts on sandstone samples, as well as a brief study of the pebble/cobble/boulder fraction of the breccia and conglomerate, are used to determine possible source areas for the Flattery breccia. The detritus in the Flattery breccia and western Lyre Formation contains a wide variety of rock types with petrologic trends observed along strike from west to east (see Chapter 3, Figures 19 and 20).

Source areas for the Flattery breccia

The present-day geographic positions of various tectonic assemblages in the Pacific Northwest are shown in Figure 2, some of which may have contributed detritus to the Flattery breccia during the middle Eocene. However, the relative positions of some of these assemblages may have been different at the time of Flattery breccia deposition (44 to 42 Ma). Pacht (1984) suggested that the Upper Cretaceous Nanaimo Group, located on the southeastern flank of Vancouver Island, requires nearby positions of Vancouver Island (Wrangellia portion), the Coast Plutonic Complex, the San Juan Islands, and the North Cascades (San Juan/Cascade Nappes of Brandon and others, 1988), as the Nanaimo Group is comprised of detritus from all four sources. The Nanaimo Group does not contain detritus from the Pacific Rim terrane, specifically the Leech River Complex, indicating that this terrane may not have been
emergent and/or in its present position by the Upper Cretaceous. In fact, Brandon (1985; and others, 1988) and Johnson (1984) have suggested that the Pacific Rim terrane was displaced northwestward from a western continuation of Wrangellia and the San Juan-Cascade Nappes by a major transform fault in the earliest Tertiary. Subsequently, the early Eocene basalts (Crescent terrane) were available as a source although not necessarily accreted to the continent by mid-Eocene. This uncertainty in outcrop configuration also applies to the rocks of the Olympic Core terrane and Ozette terrane.

The Flattery breccia overall is a very coarse unit, with angular to subrounded boulders and gravels and texturally and compositionally immature sands, which suggest the detritus had a relatively short transport distance with little reworking. Therefore, I have restricted the possibilities to nearby source areas such as the present day San Juan Islands, portions of the Olympic Peninsula, and Vancouver Island. These source areas are discussed below in order of increasing likelihood of an important contribution to the Flattery breccia.

San Juan Islands

The San Juan Islands consist of a complex arrangement of a Late Cretaceous thrust system with surrounding external units (Brandon and others, 1988). The Paleozoic and Mesozoic units found within the San Juan thrust system have undergone low temperature-high pressure metamorphism associated with the Late Cretaceous thrusting, resulting in a lawsonite-prehnite-aragonite metamorphic assemblage. The
upper Mesozoic external units were never subjected to the high-pressure metamorphic conditions and are therefore devoid of this metamorphic assemblage.

Briefly, the San Juan thrust system consists of stacked thrust sheets that have been divided into lower and upper halves (Brandon and others, 1988). The older, lower half consists of: (1) the Turtleback terrane, a Paleozoic arc sequence of volcanic and plutonic rocks; (2) the Deadman Bay terrane, upper Paleozoic and lower Mesozoic pillow basalt, chert and limestone; and (3) the Garrison terrane, Permo-Triassic high pressure metamorphic rocks (Brandon and others, 1988). The younger, upper half is composed of: (1) the Constitution Formation, an upper Mesozoic clastic overlap sequence; (2) the Lopez Structural Complex, an imbricated assemblage of native and exotic units; and (3) the Decatur terrane, a Jurassic ophiolite complex with an overlying Jura-Cretaceous clastic sequence (Brandon and others, 1988). The external units consist of: (1) the Upper Cretaceous Nanaimo Group, marine and non-marine sandstone, conglomerate, and shale; and (2) the Haro terrane, which includes the Haro Formation and the Spieden Group, an upper Triassic arc-volcanic sequence of andesitic sandstone and conglomerate.

Together, the various terranes of the San Juan Islands contain rock types similar to most of those found in the Flattery breccia. Considering the diverse lithologies found both in the rocks of the San Juans Islands and in the Flattery breccia sands, it would be very difficult to prove that the San Juans were not a source. However, quartz-mica schists and graphitic phyllite (Qpf and Tec), common in the eastern Lyre Formation outcrops, are notably absent from the San Juan Islands.
Another consideration is the apparent lack of any lawsonite in the Flattery breccia sands; lawsonite is a pervasive metamorphic mineral that is found in nearly all rock types involved in the Late Cretaceous thrust system. In addition, limestone rock fragments were not observed in the Flattery breccia sands; limestone occurs in the Eastsound Group of the Turtleback Terrane, as well as in the Deadman Bay Volcanics. It also appears that all of the chert in the San Juan Islands is radiolarian-bearing chert; the chert (Qpc) observed in the Flattery breccia contains a variety of chert types, including radiolarian-bearing, but the majority of the chert fragments are brown, dirty, recrystallized, and veined, but radiolarian-free. So, while the San Juan Islands may have contributed detritus to the Flattery breccia deposits, it appears that another source terrane is also required to supply specific compositions not found in the present-day San Juan Islands.

**Olympic Peninsula**

Silbering and Jones (1984) divided the Olympic Peninsula into lithotectonic terranes, three of those being the Crescent, the Olympic Core, and the Ozette terranes (Figure 2; see Chapter 1 for more descriptions of these terranes). Since a majority of the rocks in these terranes are the same age or younger than the Flattery breccia, much of the Olympic Peninsula is ruled out as a major source. There is, however, the possibility that a few units on the Peninsula contributed to the Flattery breccia, and they will be discussed below, with emphasis on the Ozette terrane rocks.
**Olympic Core terrane**

The Olympic Core terrane represents an Eocene through Miocene subduction complex consisting of metamorphosed and unmetamorphosed basalts and marine sediments (Tabor and Cady, 1978a). As mentioned in Chapter 1, these rocks include slates, phyllites, and semischists of the prehnite-pumpellyite to greenschist facies, as well as unmetamorphosed marine sediments. In addition, recent work by Brandon and Calderwood (1990) revealed a high-pressure assemblage of lawsonite + quartz + calcite in sandstones from the central part of the Olympic Core.

With respect to whether the Olympic Core rocks contributed detritus to the Flattery breccia, the late Miocene Montesano Formation, located in the southern portion of the Olympic Peninsula, records the unroofing of the Olympic Mountains, or the uplift of the Olympic Core terrane (Bigelow, 1987). In addition, apatite fission-track dates indicate cooling of the core rocks at about 7 to 12 Ma (Brandon and Vance, in press). Therefore, the Olympic Core terrane is ruled out as a source to the Flattery breccia.

**Ozette terrane: a comprehensive discussion**

As defined by Silberling and Jones (1984), the Olympic Peninsula portion of the Ozette terrane is bounded on the north by the Calawah fault, on the south by the Ozette fault, and on the east at the convergence of the two faults (Figure 2). The Ozette terrane roughly corresponds to the Sooes terrane of Snavely and others (1986b), and consists of several fault-bounded blocks (Figure 1). Onshore, located at
the Point of the Arches headland, the Ozette terrane includes the Jurassic massive to gneissic quartz diorite and gabbro that contains irregular bodies of hornblendeite and cataclastic plagioclase gneiss (Tabor and Cady, 1978a); the diorite is Jurassic or older based on K/Ar hornblende age of 144 +/- 2.4 m.y. (Snavely and others, 1986b). The gabbro is overlain by Cretaceous sandstone, argillite, chert, and pillow basalt, which in turn is in fault contact with a Tertiary/Cretaceous (?) melange zone of sheared siltstone with angular polished blocks of pre-Tertiary rocks including silicified sandstone, metadacite and metatuff, basalt, and phyllite (Snavely and others, 1986b). A lower Eocene (K-Ar hornblende age of 59 +/- 3 m.y.) dacite sill intrudes the Cretaceous rocks (Snavely and others, 1986b). The whole assemblage is overlain unconformably by lower Eocene pillow basalt and middle Eocene sediments that are equivalent to rocks north of the Calawah fault (Snavely and others, 1986b). To the southeast the Ozette terrane consists mostly of middle Eocene melange and broken formation overlain by less deformed Eocene and Oligocene strata (Silberling and Jones, 1984).

Notably, Tabor and Cady (1978a) mapped the overlying Eocene sediments as the Flattery breccia, describing the breccia as containing pre-Tertiary clasts similar to the rocks in the pre-Tertiary plutonic assemblage. They also mapped the Flattery breccia on the south side of Portage Head, which is just north of Point of the Arches. Snavely and others (1986b) removed the Flattery breccia designation in both headland areas and renamed the unit there the Tertiary Point of the Arches conglomerate and sandstone (Tpac), which is part of the Sooes Terrane. However, in using Tabor and Cady’s map (1978a) as a basis for this study, I studied the Point of the Arches
(POTA) and Portage Head (PORT) conglomerate outcrops with respect to sedimentology and lithology, with the intention of determining if the pre-Tertiary plutonic assemblage located at Point of the Arches sourced the Flattery breccia and Lyre Formation to the north of the Calawah Fault as well. Briefly, the POTA conglomerate outcrop is much different in sedimentology and lithology than the Flattery breccia, with the PORT outcrop almost transitional between the two. Figure 21 shows the rock-fragment point-count data from both outcrops in stacked bar diagrams (please see Appendices 3 and 4 for point-count raw data). Comparing Figure 21 with Figures 19 and 20 shows that the POTA sample looks different at a glance, with felsic volcanics (Vf) being the most significant difference, followed by the large amount of igneous rock fragments in general compared to the Flattery breccia/Lyre Formation samples. The POTA sandstone sample is composed of at least 50% igneous rock fragments, consisting mostly of felsic volcanics such as tuffs, quartz keratophyre, quartz andesites, dacites, rhyolites; several volcanic euhedral quartz grains were also observed. Intermediate to mafic volcanics consist of andesites, trachytes, latites, and basalts. The metamorphic assemblage (Ma) category is also large, consisting predominantly of quartz + epidote, and quartz + plagioclase + epidote rock fragments, in addition to chlorite, prehnite, pumpellyite, zoisite, and laumontite. Potassium feldspar, which is absent to rare in the Flattery breccia/Lyre Formation sands, was observed in the rhyolite and trachyte grains, as well as arkosic sandstone fragments. On a larger scale, the most common clasts in the POTA conglomerate are meta-basalts and meta-quartz andesites (angular, 15 to 45 cm in diameter) and meta-
Figure 21. Rock-fragment point-count data from Tpac sandstones south of the Calaway fault: refer to Figure 1 for sample locations. As mentioned in text, note difference in composition of Point of the Arches (POTA) sample and similarity of Portage Head (PORT) sample with Flattery breccia sandstones (Figures 19 or 20).
dacites and meta-tuffs (angular, 20 to 50 cm in diameter), with other compositions including diorite, gabbro, argillite, and sandstone.

Sedimentologically, the POTA conglomerate appears to be a debris-flow deposit. Bedding is generally very hard to identify since features such as scoured channel bottoms, grading, inbrication, and cross beds are difficult to pick out (Figure 22). The matrix consists of clay with some organic matter, with a large range in clast sizes from pebbles to boulders in excess of 80 cm in diameter; the clasts range from angular to subrounded.

With these limited data, it cannot be proven that the pre-Tertiary plutonic assemblage contributed to the Flattery breccia and Lyre Formation on the north side of the Calawah fault, but a few generalizations can be made. As described in the discussions in Chapters 2 & 3, at least two source systems provided sand-sized detritus to the Flattery breccia and Lyre Formation; the Flattery breccia system is rich in chert and argillite, but lacks any substantial graphitic phyllite and quartz-mica schist. The Lyre Formation system is rich in graphitic phyllite and quartz-mica schist, but lacks any substantial chert and argillite. The POTA sample does not fit either of these two petrologic patterns. If the Ozette terrane sourced all three conglomerates, one should expect to see more similarities in composition.

Another point about the pre-Tertiary plutonic assemblage at POTA being a source may be made with the meta-dacite clasts which are so abundant in the POTA conglomerate unit. The meta-dacite clasts are visually quite distinctive: large (20 to 50 cm in diameter), gray-green, angular, blocky rocks with white glomeroporphyritic
Figure 22: Outcrop at Point of the Arches: showing matrix-supported debris flow deposit.
plagioclase laths (0.5 to 4 mm) and large (0.5 to 12 mm), glassy quartz phenocrysts in a fine-grained groundmass. In addition, they have polished surfaces. Upon closer study, these clasts were determined to be sodic rhyodacite, void of potassium feldspar unless it was occult in the spherulitic groundmass. Radial prehnite was observed in spaces between spherulites and also altering the dusty plagioclase laths, but not affecting the euhedral quartz crystals. R. Scott Babcock (personal communication 4/26/88) suggested that this was a very fresh, young (Eocene?) flow rock. The "meta"-dacite is so abundant and distinctive as a clast on the north side of the POTA that it was therefore watched for in the Flattery breccia and Lyre Formation outcrops north of the Calawah Fault in subsequent outings. Although the Flattery breccia and Lyre Formation contain a wide array of meta-volcanic clasts, this particular rock type was not observed. Despite the crude method of study (similar-appearing clasts were returned to the lab, thin sectioned, and compared to the sodic rhyodacite), the apparent absence of clasts of this composition in the Flattery breccia and Lyre Formation suggests that what supplied detritus to the POTA conglomerate unit did not supply detritus to the rocks north of the Calawah Fault. I say "what" supplied detritus to the Pota conglomerate because I have not found any lithologic description within the pre-Tertiary plutonic assemblage and associated rocks that match the sodic rhyodacite description. As mentioned previously, the Tertiary/Cretaceous (?) melange contains polished angular blocks of pre-Tertiary rocks including meta-dacite (Snavely and others, 1986b). The lower Eocene dacite sill is described as fine-grained and
hornblende-bearing (Snively and others, 1986b); the sodic rhyodacite is not fine-grained, and does not contain any hornblende.

The Portage Head conglomerate outcrop (PORT) varies much less from the Flattery breccia/Lyre Formation than the POTA outcrop with respect to sedimentology and lithology, although differences exist. Figure 21 shows the rock-fragment data; this particular PORT sandstone sample looks quite similar to sample CFT, which is taken from the lowest channel of the overlying Hoko River Formation, sampled by DeChant (1989; see figure 19). However, the PORT sample is cemented with laumontite and contains potassium feldspar in the form of orthoclase grains and arkosic sediments. Sedimentologically, the PORT outcrop may represent a more distal position as compared to the POTA outcrop; bedding was identified by features such as grading and scoured channel bottoms, and the detritus is better sorted in that there is less clay and a smaller range in clast size. There is a combination of angular to rounded clasts as well. Whereas the POTA outcrop appears to be a proximal or slope-deposited debris flow, the PORT outcrop may represent more distal deposits of sheet flows and turbidity currents.

To summarize, the pre-Tertiary plutonic assemblage located at POTA is comprised of rock types that match in part the rock fragments found in the Flattery breccia. I have concluded that it did not play a large part in supplying detritus to the Flattery breccia/Lyre Formation for the following reasons: 1) the large difference in composition, most notably the felsic volcanics, between the Flattery breccia/Lyre Formation sands and the POTA sample at Point of the Arches; 2) the distinctive
rhyodacite component, a very abundant clast in the Point of the Arches outcrop, that was apparently absent in both the Flattery breccia and Lyre Formation outcrops; and 3) the different sedimentological characteristics of the POTA conglomerate and the Flattery breccia/Lyre Formation conglomerate require different depositional settings.

**Crescent terrane**

The Crescent Formation will be considered here as the portion of the Crescent terrane on the Olympic Peninsula that possibly contributed to the Flattery breccia detritus. In general, the Crescent Formation includes pillowed to massive submarine basalt flows, interbedded volcanic sandstone and foraminiferal limestone, and shallow water and subaerial basalt flows (Tabor and Cady, 1978a). In the Cape Flattery area, Snavely and others (1986b) also reported basaltic-breccias and -conglomerates, interbeds of red and green limey argillite, pipe-like bodies of silicified volcanic rocks, and diabase and gabbro dikes and sills.

With respect to source, the Crescent Formation contributed to the detritus of the underlying Aldwell Formation, as Snavely (1983) reported the Aldwell Formation as having a 100 m basal section of massive basaltic sandstone, basalt-pebble conglomerate, and mudflow breccia where it overlies the Crescent Formation. Just northeast of Lake Crescent, Snavely (1983) also interpreted the basaltic and felsic volcanic clasts interbedded in the lower part of the Aldwell Formation as being derived from the Crescent Formation as a result of uplift on the Striped Peak thrust fault. Therefore, the Crescent Formation may have also contributed detritus to parts of
the Flattery breccia. Snavely (1983) described the Crescent basalt in the northwest portion of the Peninsula as containing clinopyroxene and calcic plagioclase microphenocrysts in a altered chloritic groundmass of basaltic glass. However, most of the basalt grains in the Flattery breccia consist of albitized (Na-rich) plagioclase and pyroxenes many of which are altered to calcite and sausserite. Zeolite minerals, calcite, pumpellyite, and less commonly epidote occur in veins and vesicles in the Crescent basalts (Snavely, 1983); these minerals are often found in polycrystalline rock fragments of the metamorphic mineral assemblage (Ma) point-count category; epidote-quartz fragments are the most abundant. Snavely and others (1986) reported 1/4 to 2 meter-thick tuff beds in the Crescent Formation in the Cape Flattery area. In the Flattery breccia/Lyre Formation sandstones, mafic tuffs comprise almost half of the intermediate to mafic volcanic point-count category (Vi-m). Because tuff fragments wouldn’t generally survive long-distance transport, they may have been derived from the Crescent Formation. Red argillites and volcanic-lithic wackes are also common among the rock fragments observed and may have been sourced by the Crescent Formation.

**Vancouver Island**

Vancouver Island can be divided into three major tectonic units that emphasize the late Eocene tectonic framework during the onset of the present-day convergent margin (Figure 2): 1) the Wrangellia terrane, a composite of Paleozoic and Mesozoic terranes, which acted as the continental backstop during Cenozoic subduction,
including overlying Jura-Cretaceous and Tertiary clastics; 2) the Pacific Rim terrane (Silberling and Jones, 1984), including the fault-bounded blocks of the Mesozoic Leech River Complex, the Pandora Peak unit (Rusmore and Cowan, 1985), and Pacific Rim Complex, which was juxtaposed with Wrangellia in the early Tertiary; and 3) the Crescent terrane (Silberling and Jones, 1984), on Vancouver Island called the Metchosin Igneous Complex, which was thrust against the Pacific Rim terrane on Vancouver Island in mid-Eocene time (Clowes and others, 1987).

Please refer to Bream (1987; pgs 4-17) for a comprehensive review of Vancouver Island geology. For basic and detailed mapping within these terranes on Vancouver Island, refer to Brandon, 1985; Fairchild, 1979; Muller, 1975, 1980b, 1982, 1983a,b; Roddick and others, 1979; Rusmore and Cowan, 1985; and Tipper and others, 1981.

**Wrangellia terrane**

Wrangellia makes up most of Vancouver Island and is composed of the following units: the Sicker Group, a Silurian through Penn/Permian volcanic arc sequence; the Vancouver Group, a Middle to Upper Triassic sequence of ocean-floor pillowed and layered basalts, overlain by Upper Triassic carbonate and clastic sediments (the Karmutsen, Quatsino, and Parson Bay Formations, respectively); the Bonanza Group and the Island Intrusions, an Early to Middle Jurassic volcanic arc complex with related granitic plutons; the Westcoast Complex and the Wark-Colquitz Complex, metamorphic complexes of greenschist to amphibolite grade thought to be derived from the Sicker and Vancouver Groups (Muller, 1983b). Clastic units
overlying Wrangellia that are considered to be autochthonous are the Kyuquot and Queen Charlotte Groups, Late Jurassic to Early Cretaceous clastic wedges that are derived from and unconformably overlie the older volcanic arc sequences on the west side of the Island; the Nanaimo Group, an Upper Cretaceous coal-bearing sequence on the east side of the Island; and the Eocene Carmanah Group, which is unconformable on all older rocks (Muller, 1983b).

The Sicker Group, a Silurian through Permian volcanic arc sequence, can be divided into four units (Muller, 1982). The oldest part, the Nitinat Formation, is composed of metabasaltic lavas with phenocrysts of uralitized pyroxene and amygdules of quartz and dark green minerals, and is interbedded with dark colored tuff. In most places these rocks are converted to epidote-actinolite-chlorite schist (Muller, 1982). The epidote/quartz assemblage prevails over any other metamorphic assemblage in the sands of the Flattery breccia, with chlorite almost ubiquitous and actinolite common; however, most schist fragments (Qpf and Tec) in the sands of the Flattery breccia were derived from a meta-pelitic source. The overlying Myra Formation consists of light colored banded silicic tuff and breccia, interbedded with black argillite and some graywacke, with most of the rocks metamorphosed to a quartz-sericite schist (Muller, 1982). In the Flattery breccia sands, quartz-mica schist is common in the schist category (Qpf and Tec), and the argillite fragments (Arg) may have been sourced from the Myra Formation as well. In addition, banded and massive green tuff, extremely common in the clast population of the Flattery breccia (generally very well rounded), show a strong resemblance to Myra Formation rocks photographed
in Muller (1980b). Boulder counts in eight Flattery breccia outcrops revealed that nearly all meta-tuff clasts, a most common composition, contain disseminated pyrite; the Myra Formation is known for its massive sulphide deposits, related to the rhyolitic volcanics (Muller, 1982).

The upper part of the Sicker Group is mainly composed of clastic sediments including argillite, siltstone, chert, graywacke, and calcarenite (Muller, 1980b). The sediment-sill unit, transitional between the Myra and Buttle Lake formations, is comprised of thinly bedded silicified argillite and siltstone interlayered with distinctive glomeroporphyritic ("flowergabbro") diabase and gabbro (Muller, 1980b). This unit could account for the argillite (Arg) and siltstones (Sh) in the Flattery breccia, and "flowergabbro" clasts were observed in at least 3 outcrops. The Buttle Lake Formation consists of fossiliferous limestone and calcarenite, interbedded with lenticular black chert (Muller, 1982). Although carbonate grains were rarely observed in the Flattery sands, carbonate, calcarenite, and black chert clasts were observed on a clast-scale (pebble- through boulder-size). Finally, the Tyee Intrusions are quartz-augen sericite schist that intrude the Sicker Group (Muller, 1977) and are Late Silurian in age (Muller, 1982). These intrusions may be the source of some quartz-mica schist fragments (Qpf and Tec) as well as monominerallic grains of quartz (Qm).

The overlying Vancouver Group is divided into three units: the Karmutsen, Quatsino, and Parson Bay Formations (Muller and others, 1981). The Karmutsen Formation is composed of a lower unit consisting of a thick pile of pillow lavas, overlain by a thinner unit of pillow breccias and aquagene tuffs, and a thick upper part
of basaltic flows with minor sedimentary interbeds (Muller and others, 1981). The spaces between pillows are typically filled with quartz, epidote, prehnite and pumpellyite nests (Muller and others, 1981), these are common constituents of the metamorphic assemblage category (Ma) in the Flattery breccia. The pillow lavas and lava flows are similar to the meta-mafic volcanics in that the plagioclase phenocrysts are commonly albitized, and thin sections of the pillow rims, as described by Muller and others (1981), are nearly identical to the Flattery breccia mafic tuff fragments.

The Quatsino and Parson Bay Formations form a coherent package of Upper Triassic sediments including brown-gray micritic limestone overlain by dark gray calcareous siltstone (Muller and others, 1981); these compositions (mostly carbonate) were not observed in the Flattery breccia sandstones, but were seen as clasts in the outcrop, notably the micritic limestone.

Overlying the Vancouver Group is the Lower Jurassic Bonanza Group volcanic arc sequence, which is coeval with the batholithic intrusions and migmatite complexes of the Island Intrusions, West Coast Complex, and Wark-Colquitz Complex (Muller, 1983a). The Bonanza Group volcanics, mostly unfoliated, consist of massive maroon and green andesitic and dacitic tuffs and flows, commonly with feldspar and hornblende phenocrysts in a feldspathic matrix (Muller, 1975). Chemical analyses yielded a variety of compositions, with tholeitic andesite being the predominant rock type (Muller and others, 1981). This unit may have sourced some of the unmetamorphosed volcanics observed in the Flattery breccia sands, such as felsic tuffs, dacites, and intermediate andesites.
The Island Intrusions, along with the Bonanza Volcanics, crop out in northwest-trending belts on Vancouver Island (Muller and others, 1981). The compositions range from quartz diorite and tonalite to leucogranite in the central portion of the Island, while in southern Vancouver Island there is generally a lower percentage of quartz and potash feldspar (Muller and others, 1981), with rocks consisting of biotite-hornblende granodiorite, quartz monzonite, and quartz diorite (Muller, 1975). Although a few granite fragments were identified in the Flattery breccia sands, most felsic plutonic rock fragments are quartz and potassium feldspar "poor", which correlates with the near absence of potassium feldspar observed as monomineralics grains. This relationship points to an Island Intrusions source located in the southerly portions of Vancouver Island.

The West Coast Complex represents the older Sicker and Vancouver Groups migmatized during Island Intrusion plutonism (Muller, 1983a), and it is divided into an amphibolite and a migmatite (Muller and others, 1981). The amphibolite unit is comprised of massive to foliated metavolcanics and metasediments: the metavolcanics (amphibolites) consist mostly of hornblende (or actinolite), patches of epidote, and altered plagioclase laths, while the metasediments consist of silicified pelitic (quartz-plagioclase schists) and minor recrystallized carbonate rocks (marble), with occurrences of fine grained quartz, calcite, grossularite, albitic plagioclase, chlorite, and veinlets of epidote-zoisite-calcite (Muller and others, 1981). This amphibolite unit also could have supplied the Flattery breccia with epidote/quartz assemblages, as well as some of the other metamorphic minerals observed such as zoisite, (clinozoisite ?),
garnet, albitic plagioclase, calcite, and chlorite. The migmatite can be divided into the leucosomes, commonly biotite-hornblende quartz diorite, tonalite, and granodiorite, and the melanosomes, consisting of diorite, gabbro, quartz diorite, and quartz gabbro (Muller and others, 1981). Low-grade metamorphism also overprinted the migmatite unit, including veins of prehnite +/- pumpellyite and hornblende and biotite replacements by actinolite, chlorite, epidote, and opaque minerals (Rusmore and Cowan, 1985). The above compositions were all observed in the clast population of the Flattery breccia, in the plutonic rock fragment categories (Pf and Pi-m), metamorphic mineral assemblages (Ma), as well as among the common alteration and metamorphic minerals (sericite, epidote, prehnite, and sphene).

Genetically equivalent to the West Coast Complex, the Wark-Colquiltz Complex (referred to as the Wark Diorite and Colquitz Gneiss in Muller, 1975) crops out near Victoria between the Leech River and San Juan Faults. The Wark Diorite consists of hornblende diorite and hornblende quartz-diorite along with agmatite (Muller, 1975). The Colquitz Gneiss is a light-colored gneissic quartz-diorite and hornblende-plagioclase-quartz-zoisite granodiorite, with minor hornblende and biotite commonly replaced by chlorite and epidote (Muller, 1975). As with the West Coast Complex, these plutonic compositions are observed in the Flattery breccia, as well as most of the metamorphic and alteration minerals.

Not part of the Wrangellia terrane but overlying it are the autochthonous Upper Jurassic to Lower Cretaceous Kyuquot and Queen Charlotte Groups clastic wedges derived from the Jurassic arc (Muller, 1977). These sediments crop out at the very
north end of Vancouver Island; therefore it appears unlikely that detritus could have reached the Flattery breccia depositional basin.

The Early Cretaceous shelf sequences mentioned above are succeeded by the coal-bearing Upper Cretaceous Nanaimo Group, which is exposed on eastern Vancouver Island and on the adjacent Gulf and San Juan Islands (Muller, 1977). Pacht (1984) reported deep-marine, marginal marine, and nonmarine facies in a rifted basin with rock types including sandstone, siltstone, shale, and conglomerate, all of varying provenance. Five sandstone petrofacies were observed: high-plagioclase arkose, chert-rich lithic arenite, dacite-rich arkose, basalt-bearing lithic arenite, and lithic arkose (Pacht, 1984). Common compositions of sand-sized clasts in the Flattery breccia sands include volcanic lithic wackes (volcaniclastics, generally mylonitized or otherwise altered), and subordinate quartz wackes and feldspathic wackes. Except for the mylonitized volcaniclastics, the quartz and feldspathic wacke fragments may have been derived from the Nanaimo Group, as well as the varying shale compositions observed. In addition, the mechanical breakdown of the Nanaimo conglomerate facies may have contributed "recycled" gravel to the Flattery breccia.

The Tertiary Carmanah Group is exposed in a narrow strip along the west and south coast of Vancouver Island. As defined by Muller and others (1981), the upper Eocene Escalante Formation is the basal member of the Carmanah Group, followed by the upper Eocene to lowest Oligocene Hesquiat Formation, and the upper Oligocene Sooke Formation. These rocks are equivalent in part to the sequence on the Olympic Peninsula, starting with the Hoko River Formation. Because the Carmanah Group
sediments are younger than the Flattery breccia, they cannot have contributed material to it.

**Pacific Rim terrane**

The Pacific Rim terrane, consisting of the fault-bounded Pacific Rim Complex, the Pandora Peak Unit, and the Leech River Complex, is composed of highly deformed assemblages of Upper Jurassic to Lower Cretaceous graywacke, pelite, chert, and metavolcanic rocks (Muller, 1983b). Brandon (1985) and Rusmore and Cowan (1985) proposed that the Pacific Rim Complex and the Pandora Peak unit are equivalent to the Constitution Formation on the San Juan Islands, which contains similar lithologies and the low temperature/high pressure lawsonite + aragonite mineral assemblage formed during the Late Cretaceous San Juan thrusting event. Whereas the Pacific Rim Complex and the Pandora Peak units also contain a low temperature/high pressure assemblage (Brandon, 1985; Rusmore and Cowan, 1985), the Leech River schist has been subjected instead to two periods of low-pressure metamorphism resulting in greenschist and amphibolite facies rocks (Fairchild and Cowan, 1982). The Leech River Complex is probably a more highly metamorphosed equivalent of the Pacific Rim Complex (Muller, 1983b) and Pandora Peak unit, and together they represent a package of Mesozoic rocks that were displaced 100-200 km northward to their present locations along a major transform fault in the earliest Tertiary (Brandon, 1985).
The Pacific Rim Complex, bounded by the West Coast and Tofino Faults, is exposed mainly in the western coastal areas of central Vancouver Island. It is comprised of a chaotic assemblage of Lower Cretaceous mudstone, sandstone, and chert (Units 1A, 1B, & 2) that overlies a lower Mesozoic calc-alkaline volcanic basement, the Ucluth Volcanics. The Ucluth Volcanics are described (Brandon, 1985) as green, aphanitic, volcanic rocks occurring as a breccia, less commonly as massive flow rocks with aquagene tuff, with irregular pods of fine-grained tuffaceous limestone, and intruded everywhere by dikes and stocks of light-colored, fine-grained diorite (Brandon, 1985). The lower unit of the overlying sedimentary rocks is composed of black mudstone melanges containing chert, sandstone, and minor tuff, conglomerate, and exotic blocks of Ucluth Volcanics and exhibiting planar fabric or highly contorted bedding (Brandon, 1985). Muller and others (1981) reported the occurrence of Buchia pacifica shells in the mudstone units. The uppermost sedimentary unit predominantly consists of contorted massive sandstone and sandy turbidites with minor interbeds of conglomerate (Brandon, 1985). Muller (1977) also reported gray and green quartzites of recrystallized chert origin and unaltered red cherts with abundant radiolarians. Most of these individual lithologies are represented in the Flattery breccia clasts and sands. Green, aphanitic meta-volcanics and meta-quartz diorites commonly occur as blocky, angular clasts in the western outcrops of the Flattery breccia, as mentioned in Chapters 1 & 2, and these may also be represented as felsic volcanic and intermediate plutonic rock fragments in the Flattery sandstones. There is an abundance of chert and argillite (mudstone?) in the Flattery
breccia sands and clasts; Ansfield (1972, pg. 123) reported individual clasts comprised of bedded chert and argillite (mudstone?). Two separate bivalve molds were also observed in black argillite clasts at the Cape Flattery quarry. A Buchia identification was tentative, however, due to poor preservation. Also, the sandstones occurring as rock fragments in the sands of the Flattery breccia consist mostly of mylonitized or altered volcaniclastics, which may have been derived from sedimentary units. However, Brandon (1985) reported that the sandstones in the melange units, and locally in the cherts, contain prehnite, lawsonite, and calcite, a low temperature/high pressure metamorphic assemblage. In the Flattery breccia sands, prehnite and calcite were frequently noted occurring as alteration products and also found in patches, veins, and voids within various lithologies. Lawsonite, however, was never observed. Therefore, albeit many similarities, the Pacific Rim Complex may not to have sourced the Flattery breccia, due to the absence of its unique, identifying signature.

The Pandora Peak Unit, previously mapped as a subunit of the Leech River Complex, is limited to three outcrops on southern Vancouver Island: Port Renfrew, Finlayson Arm, and in southeastmost Victoria (Rusmore and Cowan, 1985). The Pandora Peak unit is comprised of highly disrupted and complexly interbedded volcanic and sedimentary rocks, similar to the Pacific Rim Complex, except that the development of penetrative slaty cleavage, cataclasis, or mylonitization did not take place (albeit later faulting locally affected the rocks; Rusmore and Cowan, 1985). Black mudstone or argillite, graywacke, radiolarian chert, green tuff, and greenstone are the most common rock types; the highly altered tuff and interbedded pillows are
basaltic with relict plagioclase and clinopyroxene crystals in a groundmass of chlorite, calcite, pumpellyite, epidote, and sphene (Rusmore and Cowan, 1985). These lithologies are represented in the Flattery breccia clasts and sands (see description under Pacific Rim Complex portion). Notably, two samples from Flattery breccia boulder counts appeared identical to the green tuff/mudstone rock that was sampled during a field trip to the Victoria outcrop of the Pandora Peak. However, the graywackes and assemblages of chert, graywacke, tuff, and argillite also contain the low temperature/high pressure assemblage, with some exceptions, indicating variable metamorphic conditions within the Pandora Peak unit (Rusmore and Cowan, 1985). Lawsonite + prehnite + calcite are found in most graywacke samples in the eastern two outcrops, prehnite is absent in some samples from Finlayson Arm and Port Renfrew, and lawsonite is absent in two thirds of the Port Renfrew samples, which contain instead epidote +/- pumpellyite (Rusmore and Cowan, 1985). Brandon (1980, via Rusmore and Cowan, 1985) attributed these changes to the formation of prehnite from lawsonite. Perhaps this transition of lawsonite to prehnite, or possibly the minor amount of sandstone fragments in the Flattery breccia sands, may account for the apparent lack of lawsonite in the Flattery breccia sands.

The Leech River Complex is bounded by the Leech River, San Juan, and Survey Mountain faults. It includes, in order of abundance, metamorphosed pelitic rocks, metasandstone, and metavolcanic rocks with small amounts of conglomerate and chert, intruded syndeformationally by granitoid bodies (Fairchild, 1979). The Leech River Complex was affected by two phases of deformation, which, with corresponding
metamorphic grade, increases to the south (Rusmore and Cowan, 1985). Radiometric
dates suggest that the depositional age of the Leech River Complex is Jurassic-
Cretaceous (Fairchild, 1979), and that deformation and metamorphism culminated in
the middle Tertiary, about 42 Ma (Clowes and others, 1987).

The pelitic rocks range from graphitic quartz-sericite phyllite to staurolite-
andalusite-garnet biotite schist; and the metasandstones are consistantly quartz-
plagioclase-biotite semischist or schist, regardless of metamorphic grade (Fairchild,
1979). The metamorphic grade of the volcanic rocks ranges from greenschist to
amphibolite (Fairchild and Cowan, 1982). Greenschist-facies volcanic rocks include
light green, aphanitic flows with relict plagioclase laths, epidote (or clinozoisite),
chlorite, and actinolite, which are, in places, interbedded with phyllites and ribbon
cherts, that are recrystallized and coarse-grained (Fairchild, 1979). The amphibolite
facies metavolcanic rocks range from fine-grained magnetite-bearing chlorite-quartz-
clinozoisite-(actinolite) schist to medium- to coarse-grained hornblende schist, with
quartz, epidote, and subordinate plagioclase (Fairchild and Cowan, 1982). Interlayered
throughout the hornblende schists are epidote-quartz-rich bands (Fairchild, 1979).
The Leech River Complex was intruded by large gneissic or unfoliated trondhjemitic
composite sills that are associated with the highest grade metamorphic rocks (Fairchild
and Cowan, 1982). They consist of biotite orthogneiss, muscovite orthogneiss, and an
unfoliated biotite-hornblende trondhjemite sill (Fairchild and Cowan, 1982).

The Flattery breccia contains lithologies very similar to the above-described
rocks of the Leech River Complex. Foliated quartz and tectonite fragments (Qpf +
Tec) consist of quartz-mica schists and graphitic phyllites to garnet-bearing biotite schists. Metamorphic assemblages (Ma), albeit unfoliated at the sand-size scale, predominantly include epidote-quartz fragments, along with associations of sodium plagioclase, chlorite, sericite, muscovite, actinolite, zoisite, clinozoisite, and biotite. Reasons for removing the Leech River Complex as a source include the minor amount of hornblende (not actinolite) observed and the K-Ar biotite date, which suggests deformation and metamorphism ending around 42 Ma (Clowes and others, 1987, apparently modified from the 39 to 41 Ma date from Fairchild and Cowan, 1982). Perhaps other segments of the complex had been uplifted prior to this date and shed detritus to the Flattery breccia depositional basin between 44 to 42 Ma.

**Crescent Terrane**

On the southern tip of Vancouver Island, the Crescent terrane is represented by the Metchosin Igneous Complex (Massey, 1985), which is equivalent to the Crescent Formation on the Olympic Peninsula. Also discussed here are the Tertiary Catface Instrusions and Flores Volcanics.

Using the divisions of Muller (1977, 1982), the lower Eocene Metchosin consists of the Sooke Gabbro and the Metchosin Volcanics. The Sooke Gabbro, with dikes of leucogabbro, forms the basement to the volcanics (Muller, 1982). The Metchosin Volcanics can be subdivided into two units: the lower unit consists of pillowed and massive flows with interbedded tuff, breccia, and volcanioclastic sediments, intruded by diabase and gabbro sills and dikes (Muller, 1977); and an upper
unit composed of aquagene tuff and breccia that passes up into massive amydaloidal subaerial flows (Massey, 1985). This afore-mentioned stratigraphy represents the ophiolite sequence of the Metchosin Igneous Complex of Massey (1985). The gabbro is coarse-grained with equal parts of bytownite and diopside with minor olivine (Muller, 1982). Much of the Metchosin has been affected by low-grade to amphibolite grade metamorphism: the basalts are composed of clinopyroxene and plagioclase (partly altered to albite) phenocrysts in a dusty, chlorite-rich groundmass, with amygdules and vesicles filled with chlorite-quartz-epidote assemblages (Muller, 1982). Some of the gabbro and basalts have been deformed into amphibolites, schists, and agmatites by later faulting and intrusive activity (Muller, 1982).

The Metchosin basalts contain lithologies similar to the basaltic rock fragments (Vi-m) observed in the Flattery breccia, the meta-basalt rock fragments recorded within the metamorphic assemblage category (Ma), as well as the predominant epidote-quartz assemblages. The interbedded volcanioclastic sediments may have contributed to the volcanic-lithic wackes within the sandstone category (SS), while the Sooke gabbro and related dikes and sills may have contributed to the intermediate to mafic plutonic rock fragment category (Pi-m). The results of boulder counts not only reveal clasts of altered and metamorphosed mafic volcanics, but of metagabbros, diabases, and a mafic rock that was both fine- and coarse-grained, perhaps from a dike. These data suggest a Metchosin Igneous Complex source.

The Catface Intrusions are late Eocene to early Oligocene in age and consist of stocks of granodiorite and tonalite (Muller and others, 1981) and related sills of
feldspar porphyry (Muller, 1977). Muller and others (1981) reported that these intrude Jurassic and older rocks in many parts of Vancouver Island, and also intrude the Metchosin Volcanics. Instead, Massey (pers. comm. 3-25-88) assigned any felsic intrusions to the Metchosin as older, late stage, trondjhemitic intrusions related to the ophiolite. Massey (pers. comm. 3-25-88) went on to suggest that the Catface Intrusions are typical of forearc intrusions related to the start-up of the Cascade arc around 42 Ma. The older Paleocene Flores Volcanics, calc-alkaline dacites, are associated with the Catface Intrusions located on both sides of the West Coast fault, adjacent to the Pacific Rim Complex (Brandon, 1985). Massey (pers. comm. 3-25-88) interpreted the Flores Volcanics as similar to volcanics formed along major transform faults (West Coast fault?). With regards to a source for the Flattery breccia, the Catface Intrusions postdate its deposition, while the Flores Volcanics may have contributed to the felsic volcanics, although the present-day outcrop extent is very small.

**Paleocurrent analysis**

Reliable paleocurrent indicators common to sandstones, such as sole marks, are very rare in the Flattery breccia and western Lyre Formation due to their coarse nature. Therefore, paleocurrent analysis was limited to clast-fabric studies within the conglomeratic layers. As mentioned in Chapter 2, the long axes of clasts tend to be aligned parallel to flow at the base of a high-density dispersion due to applied shear stress at the margins of the flow (Walker, 1975a). This alignment may or may not be
accompanied by the typical imbrication of the long axes dipping up current (Massari, 1984). Regardless, when the dispersive pressure declines and traction mechanisms dominate within the flow, the long axes of clasts may then tend to roll as bed load, resulting in long axes oriented perpendicular to flow with the intermediate axes imbricated up current. Therefore, clast fabric studies may have limited application. However, in the lower portions of inverse to normal graded facies sequences (Facies A2.2 overlain by A2.7; see Chapter 2), long axes are predominantly aligned parallel to flow and also imbricated up current (Davies and Walker, 1974; Walker, 1975a, 1977; Massari, 1984). The fabric data recorded within the Flattery breccia/Lyre Formation were from these particular facies sequences.

The long-axis orientation (bearing) of nonequant pebbles and small cobbles greater than 3 cm in length were measured in suitable conglomerate strata or lenses at each of four sites. The strike and dip of the bedding was also measured, and the predominant imbrication direction of the clasts was observed. Rose diagrams were plotted by tallying the bearings in 30 degree divisions and noting the predominant imbrication direction within the conglomerate layer (Figure 23). Minimal differences in the declination (less than 4 degrees) resulted after correcting the beds to horizontal due to the low angle of dip of the beds; therefore, the data are presented without the corrections.

Plots of the limited paleocurrent data suggest that the predominant direction of current flow was from the northwest and northeast (Figure 23). The Cape Flattery quarry site and Borrow pit site suggest flow from the northwest because the long axes
Figure 23. Estimates of paleocurrent direction within the Flattery breccia. Rose diagrams showing long axis orientation data and observed imbrication directions of nonequant clasts within a conglomerate layer. Number of readings per layer in parenthesis after sample location name. No corrections made for later structural events.
are predominantly aligned and imbricated in that direction. The Mushroom Rock site also suggests flow from the northwest, as there is a predominant northwest imbrication, although the long axes are oriented perpendicular to flow. Perhaps traction forces were dominant in that particular dispersion. The Cheeka Peak site, however, suggests bifurcating flow from the northeast as both long-axis orientation and imbrication point in those directions. This difference in paleoflow direction coincides with sedimentologic and petrographic changes noted along strike from west to east (see Chapters 2 & 3). As mentioned previously, sedimentology and petrography support the existence of two separate but interfingering accumulations of detritus between the western and eastern portions of the study area. Such a setting could also account for the difference in observed paleoflow directions.

Notably, however, the west end of the Olympic Peninsula was subject to a 40 degree clockwise rotation in post-early Miocene time (Moyer, 1985; Figure 24). Therefore, back-rotating the Miocene 40 degree clockwise rotation would result in the paleocurrent indicators (long axis orientation and imbrication direction) suggesting flow from the west in the western accumulation of detritus and flow from the north in the eastern accumulation.

Discussion

Several potential source terranes have been discussed with respect to their contribution to the Flattery breccia and western Lyre Formation. In addition, the results of a limited paleocurrent study indicate flow from the west and north. Whereas
Figure 24a and b. Paleomagnetic reconstruction from Moyer (1985) depicting the 40 degrees of clockwise rotation of the western half of the northern Olympic Peninsula that occurred between 20 Ma and the present. Figure 24a represents geology in a pre-rotational setting and Figure 24b presents the geology after this rotation (from DeChant, 1989).
the immature sandstones may have been derived in part from distant source terranes, the very coarse component, such as boulders exceeding 2 meters in length (Snavely, 1983), must require a nearby source.

The San Juan Islands may have been a source, in part, of the sand fraction of the Flattery breccia/Lyre Formation. The San Juan thrust system generally contains every lithology present in the Flattery breccia/Lyre Formation, with the exception of graphitic phyllites and quartz-mica schists. Depending on the paleo-drainage system, detritus from the San Juan Islands may have crossed a low-lying southern Vancouver Island to an intermediate depositional setting(s), only to be resedimented by high-density turbidity currents traveling to the south-southeast to the Flattery breccia depositional setting.

The Olympic Core terrane has been ruled out as a source due to its late Miocene uplift age. The origin and whereabouts of the Ozette terrane are still an enigma; regardless, the Ozette terrane cannot have been a major source because of the distinct differences in sandstone compositions, clast content, and sedimentological characteristics between the Flattery breccia/Lyre Formation and the equivalent unit overlapping the pre-Tertiary assemblage, Tpac. The Crescent terrane, specifically the underlying Crescent Formation, probably supplied the Flattery breccia with basaltic detritus of all size fractions, as well as tuff fragments and greenschist-grade metamorphic mineral assemblages.

Vancouver Island is regarded as the major source of detritus to the Flattery breccia/Lyre Formation due to similar lithologies, close proximity, and agreement with
the paleocurrent directions observed. Table 6 summarizes the possible units on Vancouver Island, discussed in detail in the preceding section, which may have contributed the specific rock types to the sands and gravels. As mentioned in Chapters 2 & 3, sedimentologic and petrologic data suggest the Flattery breccia and eastern Lyre Formation represent interfingering accumulations of coarse detritus that exhibit compositional and textural trends along strike from west to east. To review the petrologic trends, the sand in the three easternmost sites is rich in phyllite and quartz-mica schist, but poor in chert and argillite. Conversely, the western field area sands are rich in chert and argillite, but poor in phyllite and quartz-mica schist. In addition, green, angular clasts (cobble-size) of meta-quartz diorite and metavolcanics appear to be associated with the chert and argillite in the sands, that is, present in the western portion of the study area, while being absent from the three easternmost sites.

Focusing on the western accumulation of detritus, I interpret these data to suggest two alternative possibilities for the source of chert and argillite sand and the angular cobbles of green meta-igneous rocks: the Pacific Rim/Pandora Peak units (combined for simplicity) were responsible for the chert and argillite sand and the angular blocks of green meta-quartz diorite and metavolcanics or the Sicker Group contributed the chert and argillite sand, and the West Coast Complex (Wark Colquitz Gneiss), the Island Intrusions, or the Bonanza Volcanics sourced the angular blocks of green meta-quartz diorite and metavolcanics (see Table 6). Certain conditions, however, seem to favor the Pacific Rim/Pandora Peak units as the predominant source of these compositions in the western accumulation. For example, the Sicker Group crops out
**TABLE 6**

POSSIBLE SOURCE ON VANCOUVER ISLAND

<table>
<thead>
<tr>
<th>Rock types observed in Flattery breccia</th>
<th>Units on Vancouver Island</th>
</tr>
</thead>
<tbody>
<tr>
<td>chert</td>
<td>Pacific Rim, Pandora Peak, Sicker (Buttle Lake Fm), Leech River Complex (minor)</td>
</tr>
<tr>
<td>shale</td>
<td>&quot;paleo&quot;-Carmanah (intrabasinal), Nanaimo, Sicker (siltstones)</td>
</tr>
<tr>
<td>argillite</td>
<td>Pacific Rim, Pandora Peak, Sicker (Myra Fm)</td>
</tr>
<tr>
<td>sandstone (volcanic-lithic)</td>
<td>Metchosin Igneous Complex, Pacific Rim, Pandora Peak, Nanaimo (minor), &quot;paleo&quot;-Carmanah (?)</td>
</tr>
<tr>
<td>felsic volcanics</td>
<td>Sicker (Myra Fm-tuffs), Bonanza Volcanics, Pacific Rim, Pandora Peak, Flores Volcanics</td>
</tr>
<tr>
<td>inter/mafic volcanics</td>
<td>Metchosin Igneous Complex, Karmutsen(?)</td>
</tr>
<tr>
<td>meta-inter/mafic volcanics (spilites)</td>
<td>Karmutsen, Metchosin Igneous Complex, Leech River Complex</td>
</tr>
<tr>
<td>felsic plutonics</td>
<td>Island Intrusions, West Coast Complex (Wark Colquitz Gneiss)</td>
</tr>
<tr>
<td>inter/mafic plutonics</td>
<td>West Coast Complex (WCG), Pacific Rim, Metchosin Igneous Complex, Sicker (minor)</td>
</tr>
<tr>
<td>quartz-mica schists</td>
<td>Leech River Complex, Tyee (minor)</td>
</tr>
<tr>
<td>graphitic phyllites, schists</td>
<td>Leech River Complex</td>
</tr>
<tr>
<td>metamorphic assemblages:</td>
<td>Sicker (Nitinat Fm), Karmutsen, West Coast Complex (WCG), Metchosin Igneous Complex</td>
</tr>
<tr>
<td>quartz epidote</td>
<td>Leech River Complex, West Coast Complex (WCG)</td>
</tr>
</tbody>
</table>
generally on the eastern side of Vancouver Island, so that chert and argillite detritus derived from this source occurring in the western portion of the Flattery breccia, but not the easternmost sites seems unlikely. In addition, both the green, meta-quartz diorite cobbles and the green metavolcanic cobbles are angular and blocky, so they were probably associated at their source and transported together into the Flattery breccia. Perhaps they were eroded from sea stacks, which would account for them being more angular than other clast types, which were presumably transported further. In the Pacific Rim/Pandora Peak units, meta-quartz diorite and green metavolcanics are more closely associated than they are in the West Coast Complex (or Wark-Colquitz Complex), the Island Intrusions, and the Bonanza Volcanics, which makes the Pacific Rim/Pandora Peak units the more likely source for those similarly-transported clasts. Finally, the absence of chert and argillite sand and angular clasts of green metaigneous clasts in the eastern accumulation of detritus may be explained by the lack of a Pacific Rim/Pandora Peak contribution to that particular depositional setting.

In summary, the Flattery breccia and western Lyre Formation represent an interfingering of two separate accumulations of coarse detritus, shown by compositional, textural, and paleocurrent changes along strike. The Pacific Rim/Pandora Peak units probably were the predominant source to the western accumulation of detritus. The Leech River Complex probably was the predominant source of sand-size detritus to the easternmost accumulation, however providing gravel-size detritus to the western accumulation, as well. Both accumulations received
relatively equal contributions from the units within Wrangellia and the Crescent terrane.
CHAPTER 5: TECTONIC SIGNIFICANCE OF THE FLATTERY BRECCIA

The deposition of the Flattery breccia from 44 to 42 Ma coincided with major tectonic events in the region including the tectonic emplacement of the Eocene basalts (Wells and others, 1984), the initiation of Cascade arc volcanism at 42 Ma (Wells and others, 1984; Babcock and others, in press, 1992a), and the metamorphism of the Leech River Complex at 42 Ma (Clowes and others, 1987). On a broader scale, these events are almost certainly related to the circum-Pacific plate reorganization at 42 Ma, which involved the demise of the Pacific-Kula ridge and a significant change in the motion of the Pacific plate over the hotspots (as seen in the bend in the Hawaiian-Emperor seamounts; Engebretson and others, 1985). This section will focus on the question "What possible effects did those plate reorganizations have on the geology of the Pacific Northwest continental margin, and does the Flattery breccia reveal any geological clues?".

Plate reorganization at 42 Ma

Figure 25 shows the general plate geometry of the Pacific Northwest during the early Eocene, prior to the deposition of the Flattery breccia. The demise of the Kula plate at 42 Ma was associated with the shut-down of the Kula/Pacific ridge system (Engebretson and others, 1985). At approximately 42 Ma, an oceanic escarpment on the Kula plate possibly encountered the Aleutian trench, resulting in the subduction of younger, possibly more buoyant lithosphere, reducing trench-pull, thereby resulting in the shut-down of Kula/Pacific spreading (Engebretson and others, 1985). The Kula
Figure 25. Early Eocene general plate geometry of the NE Pacific basin. Shaded area represents lithosphere that could be either Farallon or Kula plate. (from Babcock and others, in press, Figure 6).
plate became part of the Pacific plate; the relative motion of the Pacific plate then changed from north to northwest, with respect to the fixed hotspots, as demonstrated by the bend in the Hawaiian-Emperor seamount chain (Engebretson and others, 1985). This change in relative motion of the Pacific plate was associated with the reorientation of the Pacific/Farallon (previously the Kula/Farallon) ridge (Figure 26, Intervals 49-42 Ma & 42-36 Ma). The exact location of the Pacific (old Kula)/Farallon ridge at 42 Ma is uncertain, but reconstructions based on hotspot (Engebretson and others, 1985) and plate-circuit reconstructions (Stock and Molnar, 1989) return Chron 18, which is the Pacific (old Kula)/Farallon ridge at 42 Ma, to the vicinity of the Pacific Northwest. The proximity of the spreading ridge implies that the triple junction may have been nearby, depending on the orientation of the Pacific/Farallon ridge. Reorientation of spreading ridges can cause rapid migrations of a triple junction along a margin, hence the possibility of rapid changes of relative plate motion affecting the margin. Note the difference in convergence vectors between North America and the Kula plate in the Interval 49-42 Ma with that of the Pacific plate in the interval 42-36 Ma in Figure 26, also the difference in convergence vectors between the Pacific plate and Farallon plate in the interval 42-36. Not only would the proximity of a spreading ridge (young, buoyant crust) probably cause regional uplift along the continental margin, but rapid changes in plate motions caused by ridge reorientations or triple junction jumps would result in structural readjustments. Furthermore, the coastline in the vicinity of the Olympic Peninsula probably was associated with this style of plate interaction from at least 59 Ma (see total intervals
Figure 26. Plate motion polygons for a position near present-day Olympic Peninsula. The graphs show linear velocities relative to a fixed North America. KU=Kula plate; FA=Farallon plate; NA=North America; HS=Hotspots. To interpret the plots follow a tie line from the origin (NA), outward to the apex representing the plate of interest. The direction of the relative movement is given in degrees east of the north axis; and the velocity by the length of the tie line, with respect to the concentric circles in kilometers per million years. For example, during the interval 59-55 Ma, the Kula plate was moving almost due north with respect to North America with a relative velocity of approximately 165 km/my. The orientation of the KU-FA ridge would be perpendicular to the tie line between these plates, as shown by the heavy bars. As discussed in the text, note the reorientation of the KU-FA ridge and coinciding relative plate motions changes through time. During the interval 42-36, the PA-FA ridge represents the former KU-FA ridge (after Babcock and others, 1992, Figure 14).
63-36, Figure 26), which may explain the structural complexity of northwest Washington.

**Effects on the Flattery breccia**

Possible geological consequences of consecutive ridge reorientations and changes in relative plate motions on a continental margin are discussed in the preceding section. The plate reorganization that culminated at 42 Ma was probably associated with regional uplift along the Pacific Northwest continental margin in the vicinity of the Olympic Peninsula. How may this regional uplift be manifested in the Flattery breccia?

Most of the evidence of regional uplift shown by the Flattery breccia/Lyre Formation is petrographic. For example, clasts and rock fragments of the Leech River Complex were observed in the gravels and sands. K-Ar biotite and hornblende cooling dates of 42 Ma on Leech River schist samples (Clowes and others, 1987) imply cooling and unroofing occurred almost simultaneously with erosion and deposition in the Flattery breccia, perhaps signifying rapid uplift. The compositional change observed from west to east along strike in the Flattery breccia and western Lyre Formation, which may be explained by an interfingering of two adjacent fans, may also denote rapid dissection of southern Vancouver Island by closely-spaced rivers or feeder systems. An uplifted, dissected source terrain is often characterized by a steep, mountainous shoreline; the angular and blocky cobble and boulder clasts of
meta-igneous rocks noted to occur in the western portion of the study area were no
doubt derived from such a setting.

On a larger scale, the coarse nature of not only the Flattery breccia, but the
entire Lyre Formation signifies a period of regional uplift in the depositional basin.
Data from this study, as well as Ansfield (1972), Pearl (1977), and Pisciotto (1972)
on the Lyre Formation, and work on the Blue Mountain unit (Einarsen, 1988), the
Aldwell Formation (Marcott, 1984), and the Hoko River Formation (DeChant, 1989),
all document compositional changes along strike, which implies multiple feeder
systems along Vancouver Island. This type of supply is consistent with deposition in
a basin associated with a tectonically active margin. Sedimentological data from this
study are inconclusive with respect to the actual type of deep-water setting the Flattery
breccia represents; however, the potential for rapid uplift in the basin supports
deposition on a steep-faced, coarse-grained fan delta or deltas, characteristic of
tectonically active basin margins.

**Further considerations**

Recent isotopic provenance studies by Heller and others (1992) have delineated
a source area, (the Omineca Crystalline Belt in southeastern British Columbia), for
several nearby Paleogene sedimentary units coeval with the Flattery breccia. These
include the autochthonous Chuckanut Formation and the Puget Group in northern
Washington, and the sandstones of the allochthonous Eastern Olympic Core, the
Western Olympic Assemblage, and the Yakutat terrane of southeastern Alaska. The
sandstones are lithic arkoses, which are distinct from the lithic wackes of the Flattery breccia/Lyre Formation compositions. Data from this study, in addition to Ansfield, 1972; Pisciotto, 1972; Pearl, 1977; Marcott, 1984, and DeChant, 1989, note that the sedimentary units on the northern Olympic Peninsula, from the Aldwell through Hoko River Formation, are nearly devoid of potassium feldspar. This difference in composition implies that the Tofino-Fuca basin, which consists of detritus from Vancouver Island, was, at least in part, isolated from the nearby depositional systems. What formed the barriers to this basin, as well as the mechanism that caused these basins to collapse upon themselves (i.e. Olympic Core sediments faulted against Tofino-Fuca basin sediments), is uncertain. However, a continental margin subjected to numerous ridge reorganizations and plate motions changes would probably be structurally complex.

Finally, one of the reasons for undertaking this study was to ascertain if an exotic terrane was once in the vicinity of the Olympic Peninsula, but had later been translated northward. The study by Heller and others (1992) on isotopic provenance certainly supports the hypothesis that at least the Yakutat terrane was nearby in the Paleogene. However, the Yakutat terrane consists mostly of Crescent-like volcanic basement, overlain by clastic sequences of Eocene through Quaternary age (Heller and others, 1992), and these rocks comprise only a small percentage of the total rock types represented in the Flattery breccia. Another possibility for a transient source would follow Cowan’s (1982) model of faulting in the Leech River Complex from the west, and translation of the remaining block up to the present-day Baranof
Island. This scenario does not necessarily solve any source problems for the Flattery breccia, because both outcrops were metamorphosed at the same time (similar K-Ar cooling dates; Cowan, 1982) thereby providing detritus at the same time. Therefore, if there were an ancient landform to the west, this study suggests that it was a western extension of Vancouver Island, including Wrangellia, and not "exotic" at all, as all the rock types observed in the Flattery breccia are available on Vancouver Island.
CHAPTER 6: CONCLUSIONS

The Flattery breccia, an informally designated unit within the middle Eocene Lyre Formation, consists of sedimentary breccia and conglomerate exposed at Cape Flattery, located at the northwestern point of the Olympic Peninsula, Washington. It is approximately 600 meters thick and interfingers to the east with the Lyre Formation proper, which consists of conglomerate and sandstone. The Flattery breccia was deposited during the late Narizian, approximately 44 to 42 Ma.

Studying sedimentation features common to conglomerates revealed the majority of the poorly sorted boulder- through sand-size detritus of the Flattery breccia and western Lyre Formation was deposited by mass sediment-gravity flows such as surging high density turbidity currents and sandy debris flows. Textural changes along strike such as the exclusive presence of angular boulders in the west, and rounded, nearly polished boulders and cobbles in the east suggest an interfingering of two separate sources of detritus. Sedimentological data obtained in this study rule out subaerial and shallow subaqueous depositional settings for the Flattery breccia and western Lyre Formation. These data, however, do not permit an exact identification of a deeper-water setting. Interfingering alluvial fan-deltas, interfingering lobes of coarse detritus on a submarine fan, or resedimented wedges of coarse-grained detritus deposited on slope or base of slope settings remain as possible depositional environments for the Flattery breccia and western Lyre Formation.

The sandstones within the Flattery breccia are classified as lithic arenites and lithic wackes, consisting on the average of 93% rock fragment grains. They are
generally coarse-grained, angular to subangular, poorly sorted, with long and concavo-convex contacts, all of which indicate rapid sedimentation and burial from a nearby source. Petrologic trends along strike support the interfingering of two sources of detritus; petrologic data remain consistent, however, going up section into the overlying Hoko River Formation.

Vancouver Island is regarded as the major source of detritus to the Flattery breccia/Lyre Formation due to matching lithologies, its close proximity, and its agreement with the paleocurrent directions observed of flow to the south and east. Wrangellia, the Crescent terrane, and the Leech River Complex appear to comprise variable parts of both sources of detritus to the Flattery breccia/Lyre Formation delineated along strike. The Pacific Rim Complex and/or the Pandora Peak unit may be exclusive to the western Flattery breccia source.

The Flattery breccia was deposited during the time of a major plate reorganization, which involved the demise of the Kula plate at 42 Ma. This plate reorganization, through numerous ridge reorientations and plate motion changes, probably caused regional uplift, perhaps rifting associated with the Eocene basalt extrusion, the initiation of Cascade arc volcanism, and metamorphism of the Leech River Complex. The Flattery breccia records evidence of regional uplift: it contains Leech River Complex detritus, which implies rapid unroofing along southern Vancouver Island, based on radiometric cooling dates; compositional changes along strike suggest a dissected source, indicative of uplifted margins; and the presence of angular and blocky cobbles and boulders indicates a rocky, steep shoreline, perhaps
with seastacks. Finally, recent work reconstructs Alaskan terranes to the vicinity of the Olympic Peninsula in the Paleogene, providing the opportunity for an "exotic" source for the Flattery breccia. Paleocurrent data do indicate transport from the west. However, an additional source terrane is not a necessity because all clasts found in the Flattery breccia can be accounted for by lithologic units exposed on Vancouver Island.
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APPENDIX 1: POINT COUNT GRAIN CATEGORY DEFINITIONS

The following grain category definitions use the grain size scale of Folk (1974)

**Whole rock point count definitions**

Monominerallic grain categories (Qm, K, P, Am, Pyx, Mi, Acc, Op) required the grain to be 1/16mm or larger, occurring as an individual grain or within a lithic grain. This procedure follows the Gazzi-Dickinson point-count method (Ingersoll and others, 1984).

**Qm**: Monocrystalline quartz, including individual grains and fine-sand sized or larger grains located within rock fragments.

**K**: Potassium feldspar, usually identified by presence of stain and/or twins.

**P**: Plagioclase feldspar, usually identified by presence of stain, twins, and characteristic lath shape.

**Qp**: Polycrystalline quartz, more specifically chert. This category required a strict definition due to a large percentage of chert-like grains within the sandstones (i.e. felsic tuffs, quartz-rich shales, metamorphic polycrystalline quartz, etc.). Chert was identified on the basis of internal grain size and percentage of impurities. The individual quartz crystals within a chert grain range between 5 and 31 microns in diameter (Carozzi, 1972); 31 microns (1/32 mm) was used as the cutoff. There were often patches and veins within chert grains that consisted of polycrystalline quartz larger than 31 microns, due to recrystallization, for example. If the grain was composed of 50% or more of crystals smaller than 31 microns, it was assigned to Qp;
if 50% of the grain consisted of crystals larger than 31 microns, it was assigned to Lsm (i.e. a quartz-rich shale), or to Qm, if the individual quartz crystal under the cross-hairs was 1/16 mm or larger.

The cutoff for impurities was 15%, which was often difficult to estimate in a clear grain with hundreds of tiny black specks. I determined this percentage by employing the following procedure: putting the grain under the 25X power objective, crossing the nichols, and inserting the condenser. With that, the percentage of impurities (clays, opaques, micas) were more easily ascertained.

Lsm: This lithic category includes shales, argillites, siltstones, and sandstones (when landing on the aphanitic portion), any Qp grain with greater than 15% impurities, and their metamorphic counterparts.

Lvm: This lithic category includes all compositions of volcanic rocks, including glassy volcanics and tuffs (fresh or devitrified), as well as altered and metamorphosed volcanics. Felsic tuffs were differentiated from chert grains by texture, internal grain sizes, and by the presence of stain.

Am: Amphiboles, including hornblende, uralitized hornblende, and calcium and sodium amphiboles.

Pyx: Clinopyroxenes and orthopyroxenes, fresh and partially altered.

Mi: Micas, including biotite, muscovite, and sericite.

Acc: Accessory minerals, including chlorite, carbonates, and all metamorphic and igneous minerals, primary and secondary.

Op: Opaques, such as pyrite, magnetite, and leucoxene.
Cmt: Cements such as calcite, hematite, phyllosilicate, zeolite, etc. Grains partially replaced by sparry calcite cement but identifiable are not counted as cement, but in the appropriate composition category.

Mtx: Proto-, ortho-, epi-, and pseudomatrix following Dickinson (1970). If the pseudomatrix could be traced to its source, it was counted as such.

Misc: Unidentifiable monominerallics or lithics, with the occurrence of organic blebs and fossils recorded.

**Rock fragment point count definitions**

A rock fragment is defined as a grain consisting of two or more mineral grains of any size; e.g., fine- and coarse-grained rock fragments. Therefore, this point count did not follow the Gazzi-Dickinson method (Ingersoll and others, 1984). For example, when landing on a sand-sized mineral within a rock fragment, it was identified as that rock-fragment type. The only grains tabulated as minerals were those occurring as discrete, individual grains; and they were counted in the "other" category (see definition below).

**Sedimentary rock fragments**

Opq (chert): This definition is identical to Qp used in the whole-rock point count (see previous definition). Refer to Table A-1 for a comparison to other quartz-rich rock fragments.
**Sh (shale):** This category includes clay- and silt-shales, ranging in composition from cherty shales to dark, carbonaceous grains. This category may include intrabasinal sediments. Refer to Table A-1 for a comparison to other quartz-rich rock fragments.

**Arg (argillite):** This category represents clay- and silt-shales that exhibit signs of deformation; e.g., complex veining and styolites, but lack a distinct foliation (see Tectonites). Compositions may range from dirty cherts to dark, carbonaceous grains. Whereas the shale category may include intrabasinal sediments, argillites are clearly extrabasinal. Refer to Table A-1 for a comparison to other quartz-rich rock fragments.

**SS (sandstone):** This category includes grains with internal grain sizes of 1/16 mm or larger. Noted compositions range among lithic, arkosic, and quartz arenite and wacke, using definitions from Pettijohn and others (1972).

**Sm (misc. sedimentary):** Any sedimentary rock fragment that doesn’t fit the above categories, including carbonate grains.

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**Igneous Rock Fragments**

The A-normal method of determining plagioclase compositions was used in the following definitions of igneous rock fragments.

**Vf (felsic volcanics):** This category includes volcanics with internal grain sizes of less than 1/4 mm that also contain crystals of either quartz or plagioclase with compositions of An < 40. It also includes altered felsic tuffs in which the original tuffaceous texture is destroyed; these rock fragments are distinguished from chert
Vi-m (intermediate to mafic volcanics): This category includes volcanics with internal grain sizes in the groundmass of less than 1/4 mm that also contain either plagioclase with compositions of An > 40, little or no quartz, or microlitic or lathwork textures. It also includes altered mafic tuffs in which the original tuffaceous texture has been devitrified and altered to palagonite or chlorite, and volcanics in which the mafic minerals and feldspars are partially altered; texture must be intact.

Pf (felsic plutonics): Includes any plutonic rock fragments with internal grain sizes of 1/4 mm and larger that contain either quartz or plagioclase with compositions of An < 40.

Pi-m (intermediate to mafic plutonics): This category includes plutonic rock fragments with internal grain sizes of 1/4 mm or larger and with either plagioclase with compositions of An > 40 or little or no quartz. Also includes grains in which the mafic minerals and feldspars are partially altered.

VPm (misc. volcanics and plutonics): Includes any igneous grains that can’t be placed into the above categories.

Metamorphic Rock Fragments

Qpf (foliated polycrystalline quartz): This category includes grains consisting of polycrystalline quartz that exhibits a foliation, defined here as a flattening or stretching of quartz grains into a parallel alignment. Impurities such as microlites or micas,
which often define the foliation, are limited to 15%. Refer to Table A-1 for a comparison to other quartz-rich rock fragments.

**Tec (tectonite):** This broad category includes grains that exhibit a foliation, defined here to include any parallel arrangement or distribution of minerals, such as slaty cleavage, schistosity, or compositional layering (Hyndman, 1985). Compositions range among quartz-, mica-, and graphite-rich meta-sediments, but foliated grains with more than 85% quartz are included in the preceding category. Refer to Table A-1 for a comparison to other quartz-rich rock fragments.

**Ma (metamorphic assemblages):** This broad category represents unfoliated (or unfoliated at the sand-size scale) metamorphic rock fragments that exhibit a distinct metamorphic mineral assemblage, most frequently being characteristic of the prehnite/pumpellyite and greenschist facies. A tally is kept on metamorphosed mafic volcanics, as their lathwork texture is readily identifiable. The presence of prehnite, pumpellyite, or epidote distinguishes a metamorphosed mafic volcanic from an altered mafic volcanic, as they both may contain chlorite. Other than mafic volcanics, protoliths are often difficult to ascertain. For a detailed list of the distinct mineral assemblages, refer to the descriptive petrology section.

**Mm (miscellaneous metamorphics):** Includes any otherwise unidentifiable metamorphic grain, with the occurrence of mylonites noted.
Other Grain Types

Qp (undifferentiated polycrystalline quartz): This category includes any polycrystalline quartz grains that don’t fall in the chert (Qpc) or foliated polycrystalline quartz (Qpf) categories. The cutoff for impurities is 15%. Refer to Table A-1 for a comparison to other quartz-rich rock fragments. An informal tally is kept with each Qp grain as to its probable source: 1) Qpm (metamorphic) grains display sutured or polygonized grain boundaries; 2) reQpc (recrystallized chert) grains have regions of the grain (but less than 50%) where the individual quartz crystals are less than 31 microns (1/32 mm) in diameter; and 3) Qph (hydrothermal) grains contain inclusions and vacuoles and often exhibit an aggrading grain size.

Ot (other): This catch-all category is used for anything other than rock fragments: individual monomineralic grains, cement, matrix, fossils, and organic blebs.
### TABLE A-2

**COMPARISON BETWEEN QUARTZ-RICH ROCK FRAGMENTS**

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<td>&lt; 31 microns (1/32 mm)</td>
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<td>&gt; 50% of grain larger than 31 u</td>
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<td>foliated, lineated, flattened texture</td>
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<tr>
<td>Qp (polyxtal. quartz)</td>
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<td>see definition for following categories: Qpm, reQpc, &amp; Qph</td>
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<td>Sh (shale)</td>
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<td>Arg (argillite)</td>
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<td>clay size to 62.5 microns (1/16 mm)</td>
<td>unfoliated, but deformed w/ complex veins, styolites, etc.</td>
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APPENDIX 2: POINT COUNT RAW DATA

Whole Rock Point Count - 300 Points

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APPENDIX 3: ROCK FRAGMENT GROUP DATA (PERCENTAGES)

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