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The Sedimentary Petrography, Depositional Environment and Tectonic Setting of the Aldwell Formation, Northern Olympic Peninsula, Washington

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THE SEDIMENTARY PETROGRAPHY, DEPOSITIONAL ENVIRONMENT AND TECTONIC SETTING OF THE ALDWELL FORMATION, NORTHERN OLYMPIC PENINSULA, WASHINGTON

by

Keith Marcott

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

Dean of Graduate School

Chairman

MASTER'S THESIS

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THE SEDIMENTARY PETROGRAPHY, DEPOSITIONAL ENVIRONMENT AND TECTONIC SETTING OF THE ALDWELL FORMATION, NORTHERN 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
Keith Marcott
June, 1984

ABSTRACT

The upper Eocene Aldwell Formation crops out in an east-west trending band across the northern Olympic Peninsula, Washington. Petrographic analyses indicate that the Aldwell Formation has lithologically distinctive eastern and western portions. The rocks of the eastern Aldwell are basalt-rich lithic greywackes; their mean compositions are Qm-F-Lt: 5-22-73 and polycrystalline quartz-volcanic rock fragments-total sedimentary rock fragments: 1-78-21. The rocks of the western Aldwell are chert-rich lithic arenites; their mean compositions are Qm-F-Lt: 27-19-54 and polycrystalline quartz-volcanic rock fragments-total sedimentary rock fragments: 66-11-23.

Similarities in texture, composition, and alteration products suggest that the basalts of the Crescent seamount province as the likely source for the sediments of the eastern rocks. Since the basalts of the Crescent seamount province crop out both to the north (Metchosin Volcanics) and south (Crescent Formation) of the Aldwell Formation, no definite conclusions can be drawn regarding the provenance of the eastern Aldwell sediments. However, a northern source is inferred based on the restriction of abundant basaltic detritus to the eastern rocks and a southward transport direction for the olistostromal blocks in a conglomerate unit near Lake Aldwell.

The provenance of the sediments in the western portion of the Aldwell Formation is speculative. A terrane located to the southwest of Vancouver Island during the late Eocene is proposed as the source of these sediments.

The rocks in the eastern portion of the Aldwell Formation are predominantly thin-bedded, laminated siltstones with interbedded fine

sands. The rocks in the western portion of the Aldwell Formation are thin-bedded siltstones with interbedded fine sands, commonly in thin lenses; coarse sandstone and conglomerate are also present. The eastern rocks are interpreted as having been deposited in an outer fan environment and the western rocks were deposited in a mid-fan environment, but the different lithologies indicate that deposition took place on two separate fans within the Juan de Fuca basin rather than in two areas of the same fan.

A model for the tectonic setting of the Juan de Fuca basin and surrounding area during the deposition of the Aldwell Formation is proposed in which the Crescent seamount province, moving northeast on either the Kula or Farallon plate, converged against an allochthonous terrane then located near Vancouver Island, resulting in uplift and southerly transport of Aldwell sediments.

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Several people deserve special thanks for their part in helping me complete this project. Kurt Anderson deserves thanks for endless hours of discussion concerning the Olympic Peninsula, and for helping me both in maintaining my sanity during the wettest field season I hope to ever experience as well as enjoying the Olympic Peninsula at its best. Dave Engebretson's knowledge, patience, support, and friendship greatly enhanced the quality of this thesis and certainly made it more enjoyable to work on. I'd like to thank my parents, Rene and Rita Marcott, for teaching me early to ask a lot of questions, and more importantly, to look for answers. Most of all, I thank my wife Ann, who supported me in all ways possible, and who understood that both work and play were essential to the completion of this project.

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INTRODUCTION

The Aldwell Formation is the oldest in a sequence of Tertiary sedimentary rock units that forms an east-west trending band across the northern Olympic Peninsula, Washington. These sedimentary rock units, together with the underlying Crescent Formation, comprise the peripheral rocks of the Olympic Peninsula (Fig. 1).

The Cenozoic history of the Olympic Peninsula is poorly understood. It is generally accepted that the Olympic Peninsula is comprised of one or more tectonostratigraphic terranes that originated some place other than their present location and that were subsequently accreted to the west coast of North America. Where these terranes originated and how they got to their present positions are questions that have yet to be answered satisfactorily.

The basalts of the Crescent Formation are thought to have originated as seamounts (Tabor and Cady, 1978b). The timing of the accretion of these seamounts is uncertain, but it probably took place during the late Eocene (Armentrout, 1984; Duncan, 1982). If this were true, then the deposition of the Aldwell Formation would have taken place just prior to and possibly during the accretion of the seamounts. No detailed study of the sedimentology of the Aldwell Formation has been conducted to date. The results of this study of the depositional style and composition of the sediments of the Aldwell Formation increase our understanding of the Cenozoic tectonic history of the Olympic Peninsula.

GEOLOGIC SETTING

The Olympic Peninsula is comprised of two major geologic domains: the

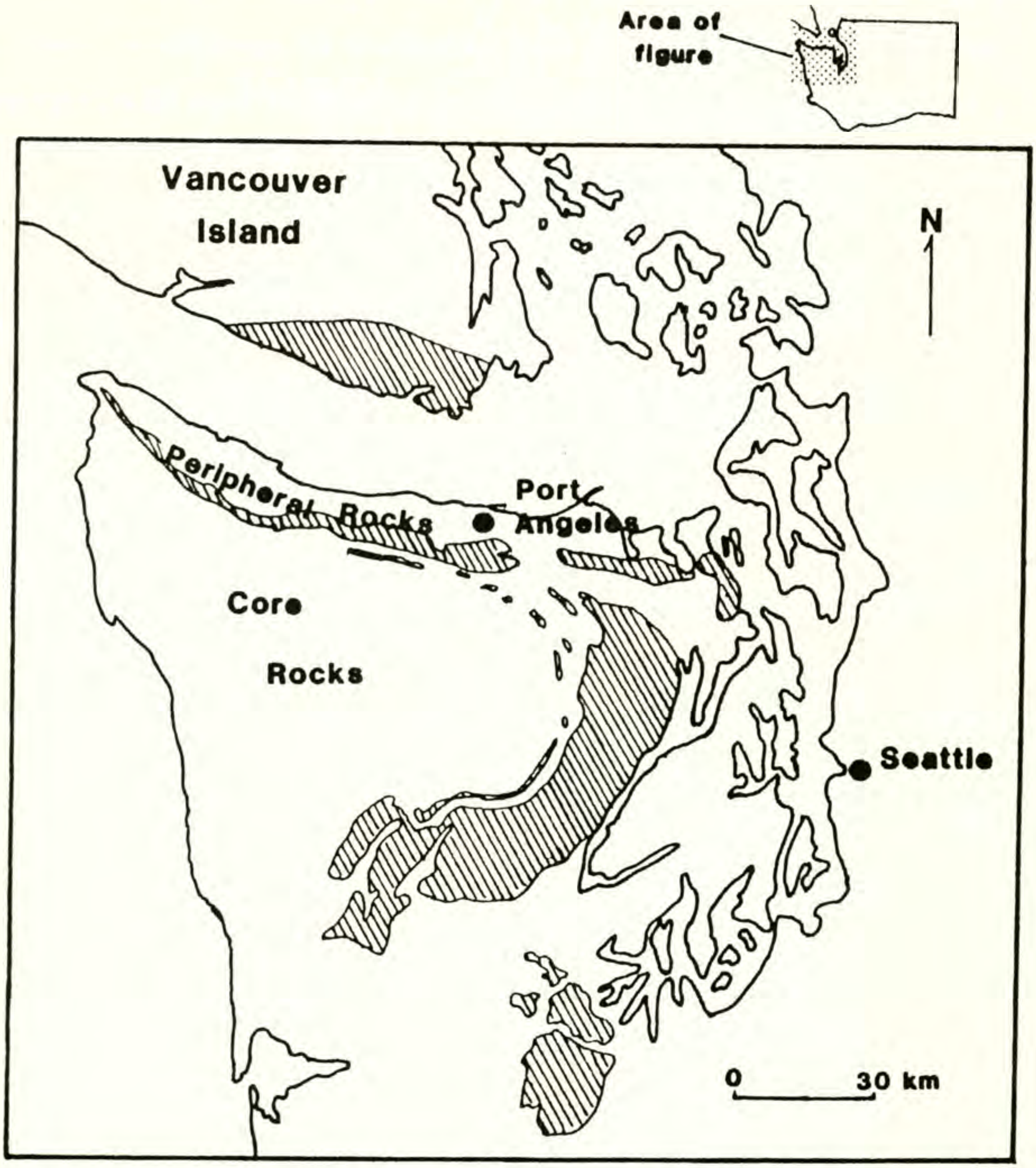


FIGURE 1. Map of the Olympic Peninsula, Washington, and surrounding area showing the location of the core rocks and the peripheral rocks. Ruled pattern indicates Tertiary basaltic rocks of oceanic origin (from Snavely, 1983).

core rocks and the peripheral rocks (Tabor and Cady, 1978a and b; Figure 1). The core rocks consist predominantly of metamorphosed marine sedimentary rocks with some interbedded volcanics. Although the core rocks as a whole young to the west, beds are often vertical or overturned with tops facing east. The age relationships of the core rocks have been explained in terms of an accretionary prism model whereby marine sedimentary rocks were thrust beneath the basalts of the Crescent Formation (Tabor and Cady, 1978b; Figure 2). The core rocks exhibit varying amounts of metamorphism ranging from zeolite facies to lowest greenschist facies.

The peripheral rocks of the Olympic Peninsula consist of the Crescent Formation and overlying marine sedimentary units. These rocks are exposed in the south limb of the northwest-trending Clallam syncline (Fig. 3). The Crescent Formation is early to middle Eocene in age (Snavely, 1983). It consists of a horseshoe-shaped belt of oceanic tholeiitic basalts underlain by marine sedimentary rocks (Tabor and Cady, 1978b). Various sedimentary units, including basaltic conglomerates and massive dark grey siltstones that overlie and in places interfinger with the basalts of the Crescent Formation, are included in the Crescent Formation based on fossil evidence (W.W. Rau, oral comm., 1984).

Overlying the Crescent Formation to the north, east, and south is a sequence of upper Eocene to upper Miocene and minor Pliocene marine sedimentary units. These units are generally stratigraphically continuous and dip away from the core (Tabor and Cady, 1978b). The oldest of these units is the Aldwell Formation.

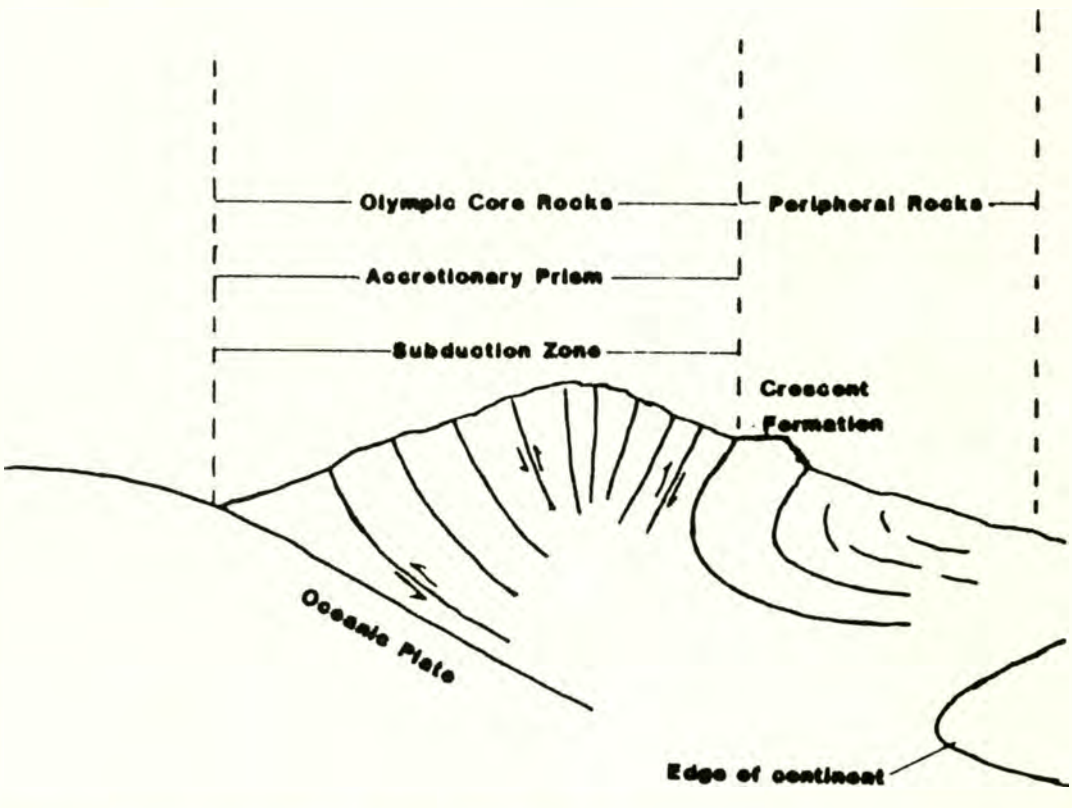


FIGURE 2. Generalized cross section east-west through the Olympic Mountains (from Tabor and Cady, 1978b).

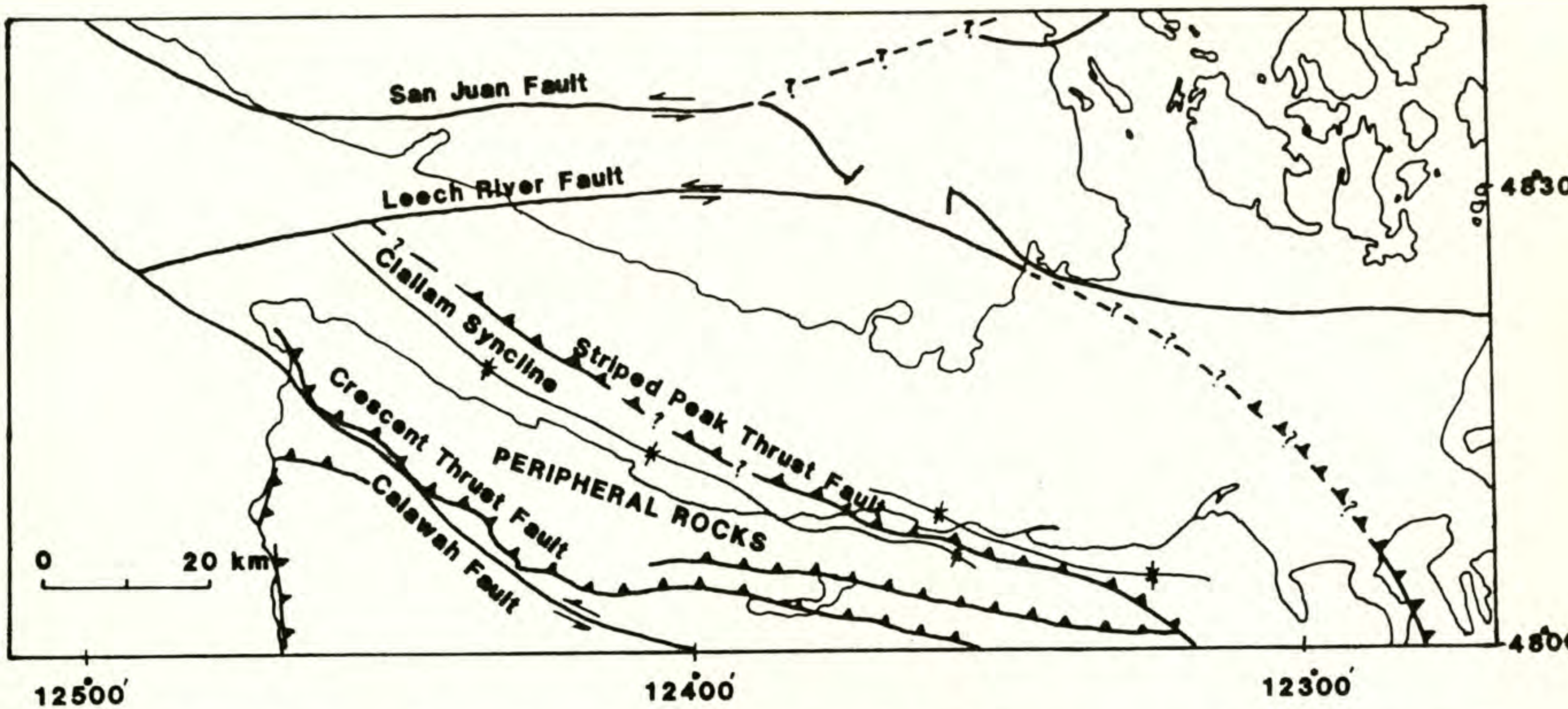


FIGURE 3. Generalized map of structures in the area adjacent to the Strait of Juan de Fuca (from Snavely, 1983).

PREVIOUS WORK

The Aldwell Formation was named and described by Brown and others (1960). In earlier work on the Tertiary stratigraphy of western Washington, Weaver (1937) referred to these same rocks as the Boundary Shale and included them as the upper member of the middle Eocene Crescent Formation. Drugg (1958), in describing the biostratigraphy of the Hoko River area, also used the name Boundary Shale for these rocks, but proposed that the unit be included in the overlying Lyre Formation. Subsequent unpublished Master of Science theses concerning the biostatigraphy of areas on the northern Olympic Peninsula by Bagley (1959), Carroll (1959), Strain (1964), and McWilliams (1965) retain the name Boundary Shale to refer to these rocks. Tabor and Cady (1978a) pointed out that the Aldwell Formation, as defined by Brown and others (1960), includes part, if not all, of the rocks referred to as the Boundary Shale by earlier workers. In this study, I will follow the usage of Brown and others (1960).

Additional studies involving the Aldwell Formation have been concerned primarily with mapping. Portions of the Aldwell have been mapped at a scale of 1:62,500 in the Port Angeles-Lake Crescent area by Brown and others (1960) and in the Pysht quadrangle by Gower (1960). The Aldwell Formation has been mapped in its entirety at a scale of 1:125,000 as part of the geologic map of the Olympic Peninsula (Tabor and Cady, 1978a).

Little work has been done on the Aldwell Formation with respect to assessing depositional environment and sedimentary provenance. Rau (1964) stated that the Aldwell probably represents a deep marine deposit based on the foraminiferal assemblage, the almost total absence of megafossils, and the fine-grained nature of the sediments. Snavely (1983) reported that a large conglomerate unit within the Aldwell Formation near Lake Aldwell was derived from Striped Peak to the north (Fig. 4), based on the composition of the clasts in the conglomerate. Pearl (1977) conducted a semi-quantitative petrographic study on all of the Tertiary sedimentary rocks of the northwestern Olympic Peninsula. With respect to the Aldwell Formation, he stated that some of its sandstones contain basalt fragments, which may have been derived from the Crescent Formation.

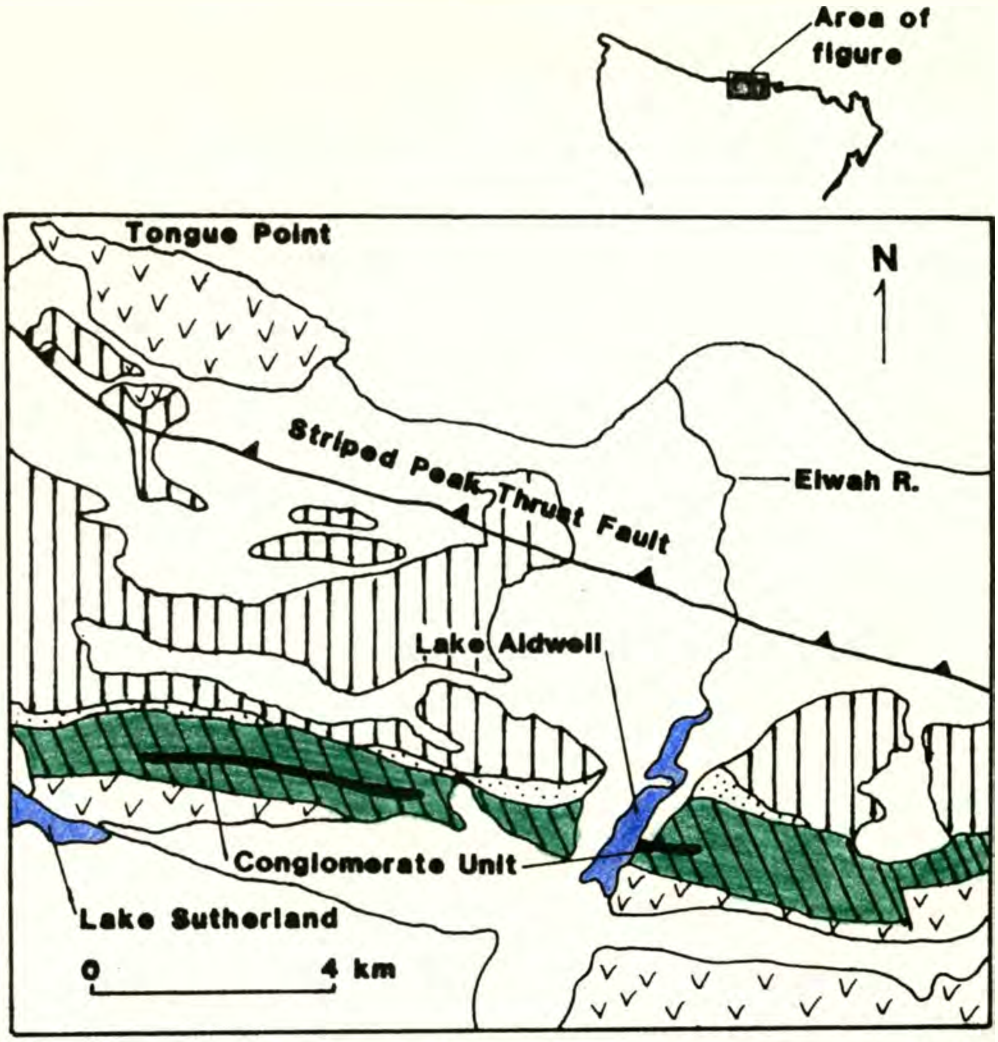
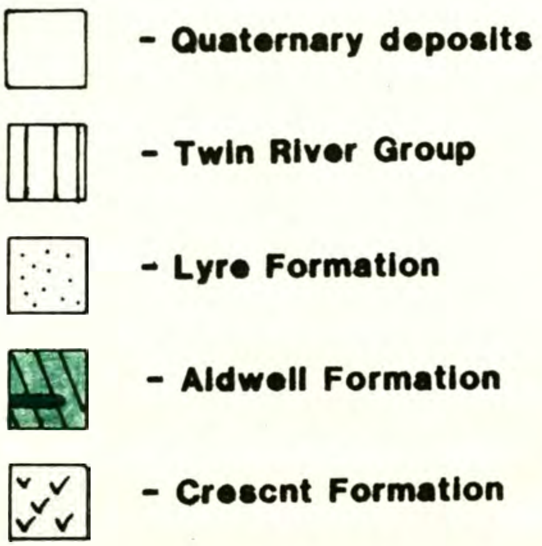


FIGURE 4. Geologic map of the area surrounding Lake Aldwell, Olympic Peninsula, Washington (from Tabor and Cady, 1978a).



DESCRIPTION OF THE ALDWELL FORMATION

The Aldwell Formation consists primarily of dark grey, poorly indurated, thin bedded siltstone with interbedded fine sands. Thicker beds of coarse sandstone and small pebble conglomerate are also present but much less common. A mappable, lens-shaped body of boulder conglomerate composed predominantly of volcanic clasts occurs in the lower portion of the Formation near Lake Aldwell (Fig. 4). The Aldwell Formation is 900 meters thick along Lake Aldwell; but its thickness varies greatly along strike, and it is totally absent in places (Fig. 5).

Exposures of the Aldwell Formation are generally poor, with most outcrops restricted to actively eroding portions of stream channels. In outcrop, the siltstones often weather spheroidally (Fig. 6). The coarser beds are generally more resistant and are easily distinguished in the field. Calcite-cemented concretions occur throughout the Aldwell Formation, most commonly in the finer sediments. The concretions are elongate parallel to bedding and weather to a lighter color than the surrounding rock (Fig. 7).

The Aldwell Formation is early to late Narizian (48-41 Ma; Snavely and Landu, 1983) based on foraminiferal assemblages (Snavely, 1983). Sediments of the Aldwell were deposited at bathyal depths (approximately 1500 m) and rest unconformably on Ulatisian sediments of the underlying Crescent Formation. Fossil evidence indicates that at least some of the Ulatisian sediments were deposited in shallow water. The unconformity is correlated with a similar unconformity that separates rocks of the Narizian McIntosh Formation of southwest Washington from underlying sediments (W.W. Rau, oral comm., 1984).

At the top of the Formation, the Aldwell in some places is in contact with sediments of the upper Eocene Lyre Formation and in other places in contact with the upper Eocene Hoko River Formation (Fig. 5).

The contact between the Aldwell and Hoko River Formations is not exposed in any of the transects completed in this study. However, Gower (1960) reported that the Aldwell Formation grades into the overlying sediments of the Hoko River Formation (then known as the Lower Member of the Twin River Formation) in the area of the Pysht quadrangle. Tabor and Cady (1978a) mapped the contact between the Hoko River Formation and the Aldwell Formation as mostly conformable. Along the Sekiu River in the western portion of the study area, a wedge of Hoko River Formation is in fault contact with the Aldwell Formation (Figure 21, Appendix 1).

Ansfield (1972) interpreted the contact between the Aldwell and lower member of the Lyre Formation as conformable and probably gradational in most places. Along the Hoko River, however, the lower, fine-grained member of the Lyre Formation is absent; and siltstones and sandstones of the Aldwell Formation are directly overlain by conglomerates of the upper member of the Lyre Formation. Included within the conglomerate are large blocks of contorted concretionary siltstone, which appear to be semi-indurated Aldwell sediments carried downslope in a debris flow. It therefore seems likely that, along the Hoko River, the contact between the Aldwell and Lyre Formations is conformable but not gradational. Further west, in the Sekiu River area, fine-grained sediments of the Aldwell grade upward into pebbly siltstone of the Lyre Formation. The contact between the Aldwell and Lyre Formations was not observed elsewhere.

FIGURE 5. Geologic map of the northern Olympic Peninsula, Washington, showing the distribution of the Aldwell and adjacent formations. The symbols used are the same as those in Figure 4 (from Tabor and Cady, 1978a).

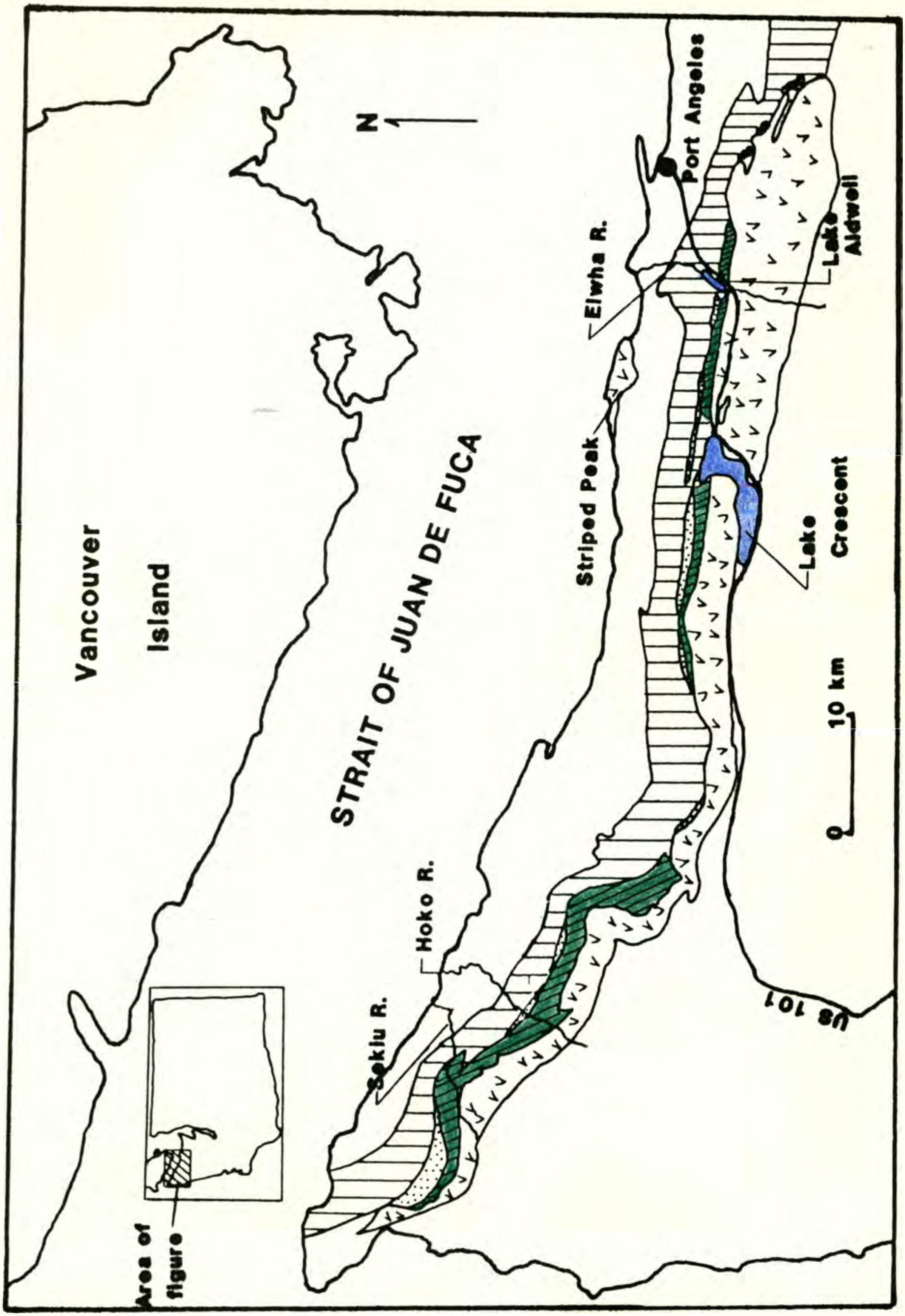

Vancouver
Island
STRAIT OF JUAN DE FUCA
N
Port Angeles
Elwha R.
Lake
Aldwell
Striped Peak
Lake
Crescent
0
10 km
Hoko R.
Sekiu R.
US 101
Area of
figure

FIGURE 6. Spheroidal weathering in siltstone near Lake Aldwell. Card in photograph is 8 cm long.

FIGURE 7. Light colored concretions (arrows) elongate parallel to bedding. Note hammer in center of photograph for scale.

DEPOSITIONAL ENVIRONMENT

The lack of good exposures makes the study of depositional features of the Aldwell Formation difficult. Outcrops are not extensive, being continuous for no more than 10 to 20 m laterally; and the long covered intervals between outcrops make measuring section impractical. As a result, sand/shale ratios and cyclic variations could not be meaningfully assessed.

GENERAL CHARACTERISTICS

In general, the rocks of the Aldwell Formation occur as thin-bedded, poorly indurated siltstones with interbedded fine sands and hemipelagic muds. Thicker, more firmly indurated coarse sandstone and conglomerate beds are present but much less common. The style of deposition varies somewhat from the eastern portion to the western portion of the formation. This, along with a distinct difference in lithologies, has led me to consider the two areas of the Aldwell Formation separately. Between the eastern and western portions the Aldwell Formation pinches out, and rocks of the Twin River Group directly overlie the Crescent Formation (Fig. 5).

DEPOSITIONAL FEATURES OF THE EASTERN PORTION OF THE ALDWELL FORMATION

The rocks in the eastern portion of the Aldwell Formation are typically thin bedded siltstones with interbedded fine sands (0.13 to 0.17 mm) and hemipelagic muds. As far as can be determined, these beds are laterally continuous and are often uninterrupted for hundreds of meters of stratigraphic section. The siltstone beds have a mean thickness of 4 cm, and the interbedded fine sandstones have a mean thickness of 3 cm. The hemipelagic muds commonly occur in very thin beds no more than three centimeters thick. Both the siltstones and fine sandstones are commonly laminated (Fig. 8), and the fine sandstones are occasionally graded. Bouma sequences are very difficult to distinguish because of the lack of fresh outcrop and the fine-grained nature of the sediments; but d,e sequences are the most common with a,d,e and c,d,e sequences occurring less frequently.

As mentioned earlier, coarse sandstones and conglomerates are present in the eastern Aldwell Formation, but they are much less common than the fine-grained sediments, occurring only sporadically throughout the section. These coarse-grained units generally exist as 10 to 20 cm thick beds, although some beds up to 50 cm thick were observed. The bottom contacts are quite sharp, indicating scouring of the underlying sediments. Graded beds are present in some cases (Fig. 9), and poorly developed laminations were observed in rare instances. In general, Bouma sequences do not describe these sediments; although some a,e sequences are present. In the few instances where the outcrop is large enough to examine the extent of beds, these units appear fairly continuous.

DEPOSITIONAL FEATURES OF THE WESTERN PORTION OF THE ALDWELL FORMATION

The most common rock type in the western portion of the Aldwell Formation is, as in the eastern portion, thin bedded siltstone with interbedded fine sand. However, the sandstones here occur most commonly as lenses or stringers usually 1 to 2 cm thick at their thickest points. These lenses are often contorted, indicating soft sediment deformation, but they exhibit sharp upper and lower contacts with the siltstones (Fig. 10). In some instances the sandstones are somewhat more regularly bedded, and for short stratigraphic distances there is more sand than silt (Fig.

FIGURE 8. Laminated siltstones in eastern portion of the Aldwell Formation near Lake Crescent. Card in photograph is 8 cm long.

FIGURE 9. Graded bed in coarse sandstone topped by vague laminations (Bouma a,b); near Lake Crescent.

FIGURE 10. Contorted lens of fine sand within siltstone in the western portion of the Aldwell along the South Fork Sekiu River.

FIGURE 11. Sandstone with interbedded siltstone in the western portion of the Aldwell along the South Fork Sekiu River.

11). The sands are sometimes graded, exhibiting a range from medium to fine sand; and in rare cases the bottoms of beds show sole marks.

Coarse to pebbly sandstone beds occur throughout the western portion of the formation but they appear to be most common in the middle of any section. The beds have a mean thickness of 20 cm but may be up to 75 cm thick. Where outcrop permits, examination of the continuity of these beds indicates that they are generally lenticular. The beds have sharp basal contacts and often contain siltstone rip-ups, both of which indicate scouring of the underlying fine grained sediments. In most cases, the sandstones are internally structureless.

Present in the middle portion of the section is a poorly sorted, structureless conglomerate lens 150 cm thick (Fig. 12). This conglomerate lens, like the sandstones above, has a scoured base.

TURBIDITE FACIES AND FACIES ASSOCIATIONS

The regularity of bedding, grading, and partial Bouma sequences suggest that the majority of the sediments of the Aldwell Formation are turbidites. Their characteristics and depositional features are examined below in light of a submarine fan model.

Walker and Mutti (1973) described seven distinct facies that can result from deposition on a submarine fan. Their descriptions of facies A-G are summarized in Table 1. They recognized that facies associations and other characteristics can be used to determine where on a submarine fan a sequence of sediments was deposited. Table 2 is a summary of the facies associations and other criteria outlined by Walker and Mutti.

Walker and Mutti (1973) pointed out that it is extremely difficult to distinguish between outer fan and basin plain deposits in the geologic record, although the two are readily distinguishable on the basis of

FIGURE 12a. Channel fill conglomerate lens deposited directly on siltstone, South Fork Sekiu River.

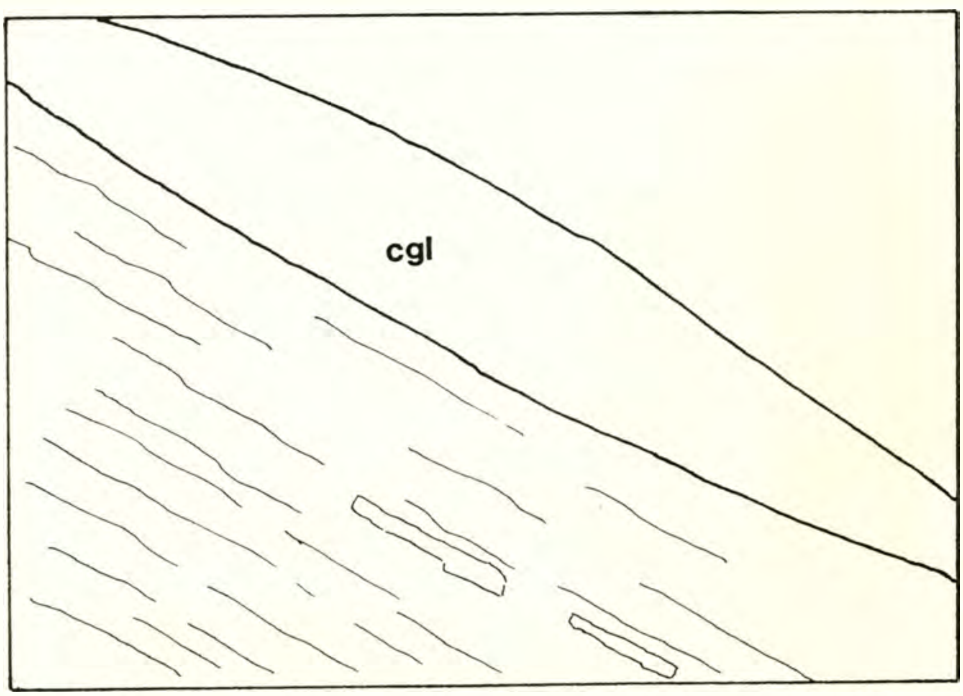


FIGURE 12b. Sketch of above, with conglomerate lens (cgl) outined.

TABLE 1. Submarine fan facies and their characteristics (from Suczek, 1977).

FACIES	DESCRIPTION	SAND/SHALE	SEDIMENT TYPES	BED THICKNESS	BED SHAPE	STRUCTURES
A1	disorganized conglomerate		clast-supported pebbles, cobbles, boulders in sand matrix	1 to several meters	very irregular	none
A2	organized conglomerate		as above	10 cm to several meters		normal and reversed grading imbrication crude stratigraphy
A3	disorganized pebbly mudstone	10:1 or more	coarse sand with pebbles	50 cm to 10 m	irregular	rare
A4	organized pebbly mudstone	10:1 or more	coarse sand with pebbles	20 cm to 2 m		normally graded beds imbrication scours, flute casts
B1	massive sandstone with dish structure		medium fine to coarse sand	50 cm to 2 m		dish structure scours
B2	massive sandstone without dish structure	10:1 or more	as above	20 cm to 2 m	lenticular	amalgymation, scours crude parallel stratification
C	classic proximal turbidites	5:1	medium to fine sand, silt, mud	10 cm to 1 m	flat bases, continuity good	Bouma sequence AE sole marks amalgymation rare
D	distal turbidites	1:1 or less	fine to very fine sand, silt, mud	1 to 10 cm	as above	Bouma sequence begins with B or C trace fossils, grading sole marks on sandstone
E	overbank deposits	1:1 or more	sand, silt, mud	less than 10 cm	wavy, sharp surfaces	climbing ripples
F	olistostromes		matrix supported conglomerate		channels, lenses	chaotic, no true bedding
G	hemipelagic sediments	low	mud, marl, occas. silt or sand	very thin	continuous	trace fossils, lamination

TABLE 2. Depositional Environments of a Submarine Fan
(modified from Walker and Mutti, 1973)

PORTION OF FAN	FACIES PRESENT	OTHER CHARACTERISTICS
SLOPE - CHANNEL	upper portion: G lower portion: A F also common	Often in stratigraphic position between turbidites and shallow marine deposits Sand bodies generally elongate
INNER FAN	A, B_2, and E most common G also present	Characterized by a single channel Sand bodies usually wider than those in slope-channel area
CHANNELED MIDDLE FAN	within channel: A, B, and C interchannel areas: D and E	Individual sand bodies discontinuous Thinning and fining upward sequences may be present
MID-FAN DEPOSITIONAL LOBE	D and C most common B_2 and A_4 may be present	Beds fairly continuous laterally Channeling insignificant Thickening and coarsening upward sequences may be present
OUTER FAN	D is dominant G may be important	Beds thin but laterally persistent
BASIN PLAIN	D and G are dominant	Beds thin but laterally persistent

morphology in modern fans. Figure 13 illustrates the relationships among the various depositional environments of an idealized submarine fan.

INTERPRETATIONS

Eastern portion of the Aldwell Formation:

The vast majority of the sediments display the fine grain size; thin, laterally continuous beds; and base-cut-out Bouma sequences that are characteristic of facies D. The coarser sandstones and conglomerates are interpreted as facies B_2 based on the thickness of beds, grain size, and the general lack of sedimentary structures.

The dominance of facies D turbidites, the regularity of bedding, and uniformity over a large stratigraphic thickness indicate that the rocks in the eastern portion of the Aldwell Formation probably were deposited in the outer fan or basin plain portion of a submarine fan (Fig. 13).

The deposition of coarse sandstone and conglomerate within the eastern Aldwell was probably controlled by tectonics. This interpretation is strongly suggested by the boulder conglomerate unit mapped by Brown and others (1960) within the lower portion of the Aldwell Formation near Lake Aldwell (Fig. 4). This unit has been inferred by Snavely (1983) to be the result of uplift along the Striped Peak Thrust Fault to the north (Fig. 4). According to Snavely, this uplift resulted in large blocks being shed southward into the basin and deposited as a conglomerate unit within the Aldwell. Although the massive conglomerate unit does not extend as far west as Lake Crescent, where most of the coarse units were observed in this study, it seems likely that the deposition of these coarse-grained units in such a distal portion of the submarine fan was the result of tectonic control.

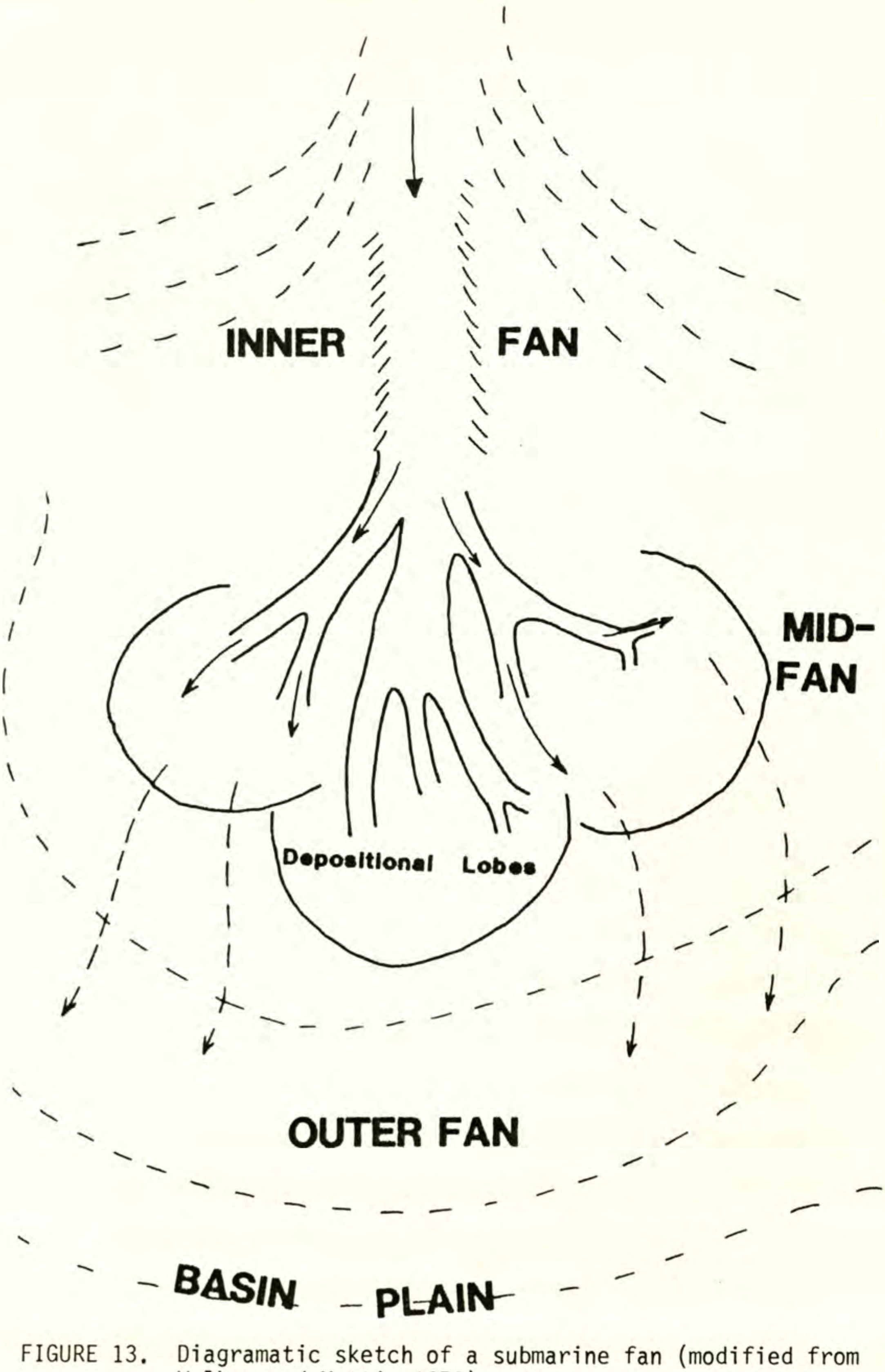


FIGURE 13. Diagramatic sketch of a submarine fan (modified from Walker and Mutti, 1973).

Western portion of the Aldwell Formation:

Interbedded siltsones and fine sandstones are the major rocks in the western portion. However, graded sandstones and medium sands are more common than in the eastern portion of the Aldwell. Most of these sediments are interpreted as belonging to facies C of Walker and Mutti (1973). A gradation between facies C and D also seems to be present. Walker and Mutti (1973) pointed out that such gradations are common in sediments deposited in submarine fans.

Numerous discontinuous stringers of sandstone seen in the western Aldwell best fit facies E. Mutti described a sequence of thin-bedded turbidites from the Hecho Group in Spain as being characterized by sandstones that exhibited "common lensing and wedging over short distances" (Mutti, 1977, p. 116). He interpreted these sediments to be overbank deposits associated with the interchannel area of the channeled middle fan. It appears likely that the sandstone lenses in the western portion of the Aldwell Formation are of similar origin.

The coarse to pebbly sandstones most common to the middle of the stratigraphic section are interpreted as facies B_2 based on grain size, bed thickness, scouring, and lack of internal structure. In his description of the Hecho Group sediments, Mutti (1977) also pointed out that lenses of sandstone with scoured basal contacts are often associated with the deposits he described. He interpreted these as partially confined, more coarse-grained, overbank deposits analogous to crevasse-splays. Facies B_2 sandstones in the western portion of the Aldwell Formation are interpreted to be of similar origin.

The thick, poorly sorted, lens-shaped conglomerate probably represents a channel fill deposit and best fits facies A_3.

The predominance of facies C,D, and E, the discontinuity of most sandstone beds, and the presence in lesser amounts of facies B_2 and A_3 indicate that these sediments were deposited primarily in the channeled middle-fan area of a submarine fan. The general lack of coarse units in the lower portion of the section perhaps indicates that the sediments of the lower portion were deposited in a middle fan depositional lobe (Fig. 13).

As the sediments in the western portion of the Aldwell Formation appear to have been deposited in a mid-fan environment and those in the east appear to have been deposited in an outer fan or basin plain environment, it might be argued that these two facies represent deposition in two areas of a single fan. However, the distinctive compositions of these two portions of the Aldwell demonstrate that the sediments were derived from separate sources. Thus, it is likely that the eastern and western portions of the Aldwell Formation are part of two separate submarine fans. This interpretation gains some support from the map pattern of the Aldwell. The Aldwell pinches out along strike between the eastern and western portions (Fig. 5). The observed map pattern and presence of two fans may have resulted from a topographic high in the depositional basin of the Aldwell Formation.

PETROGRAPHIC PROCEDURES

Samples were collected along four transects, two in the eastern portion and two in the western portion. Two of the transects are shown in detail in Figures 20 and 21 (Appendix 1). The other two transects were conducted along Lake Aldwell in the east (Fig. 4) and the Hoko River in the west (Fig. 5). In all, approximately 100 thin sections (perpendicular to bedding where possible) were examined. The thin sections were either half stained for plagioclase and orthoclase feldspars or two thin sections were made for a single sample, one stained and one unstained.

To determine modal composition, point counts of 20 slides were made. The slides were chosen based on the following criteria:

1) grain size should be as close to medium sand as possible.

2) there should be as little matrix as possible.

3) there should be as little alteration of framework grains as possible.

These criteria were adhered to only roughly, because many of the rocks are greywackes (over 15% matrix) with extensive alteration and replacement of framework grains. Furthermore, the majority of the rocks of the Aldwell Formation are poorly indurated siltstones that present problems in obtaining samples and making thin sections. Therefore, I was forced to make thin sections of the coarser-grained rocks, because these rocks are more firmly indurated and less weathered. In an effort to minimize the effect of this bias on my determination of composition, point counts were also made on several samples in the fine sand range.

Two separate point counts were made of each thin section: a 300-point count of all the major constituents of the rock, and a 200-point count of only rock fragments. The 300-point counts were conducted to determine the overall composition of the rocks. The following categories were counted for each sample: monocrystalline quartz, potassium feldspar, plagioclase felspar, matrix, cement, lithic grains, pumpellyite, heavy minerals, and miscellaneous. In these counts, all grains of fine sand size or larger are counted in the category in which they fall regardless of whether or not they are subgrains of a larger rock fragment. This method was used in an attempt to eliminate the bias that grain size may exert on the overall composition of the rock.

The 200-point rock fragment counts were conducted in order to more accurately determine the types and quantities of rock fragments present. The following categories were counted for each sample: polycrystalline quartz plus chert, altered vitric volcanic rock fragments, lathwork volcanic rock fragments, felsic volcanic rock fragments, sedimentary rock fragments, metasedimentary rock fragments, and miscellaneous rock fragments. Complete descriptions of each category are in Appendix 2.

DESCRIPTIVE PETROGRAPHY

Point count data for all of the samples counted are presented in Appendix 3. These data were recalculated to produce the grain parameters given in Table 3. A brief examination of these data, presented in different form in Figures 14 and 15, indicates that the lithologies of the eastern and western portions of the Aldwell Formation are markedly different. The following descriptions are based on thin section analyses. Classification is based on Dott (1964). The matrix classification is after Dickinson (1970).

TABLE 3. Grain Parameters

$Q = Qm + Qp$	where	Q = total quartzose grains
		Qm = monocrystalline quartz grains
		Qp = polycrystalline aphanitic quartz grains
$F = P + K$	where	F = total feldspar grains
		P = plagioclase feldspar grains
		K = orthoclase feldspar grains
$Lt = L + Qp$	where	Lt = total aphanitic lithic grains
		L = unstable lithic grains
$Rv = Rvl + Rvv + Rvo$	where	Rv = total volcanic rock fragments
		Rvl = lathwork volcanic rock fragments
		Rvv = vitric volcanic rock fragments
		Rvo = other volcanic rock fragments
$Rst = Rs + Rms$	where	Rst = total sedimentary rock fragments
		Rs = sedimentary rock fragments
		Rms = metasedimentary rock fragments

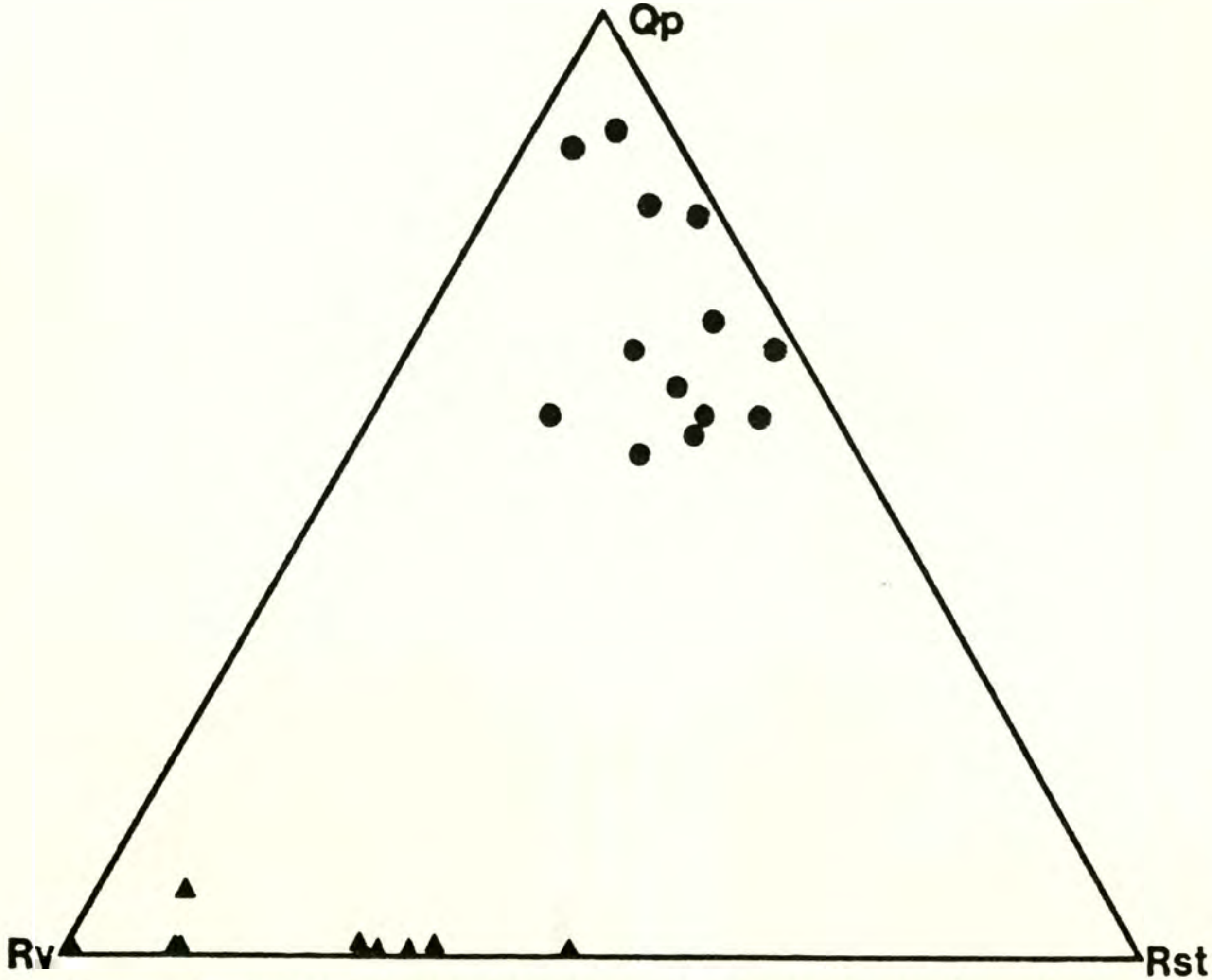
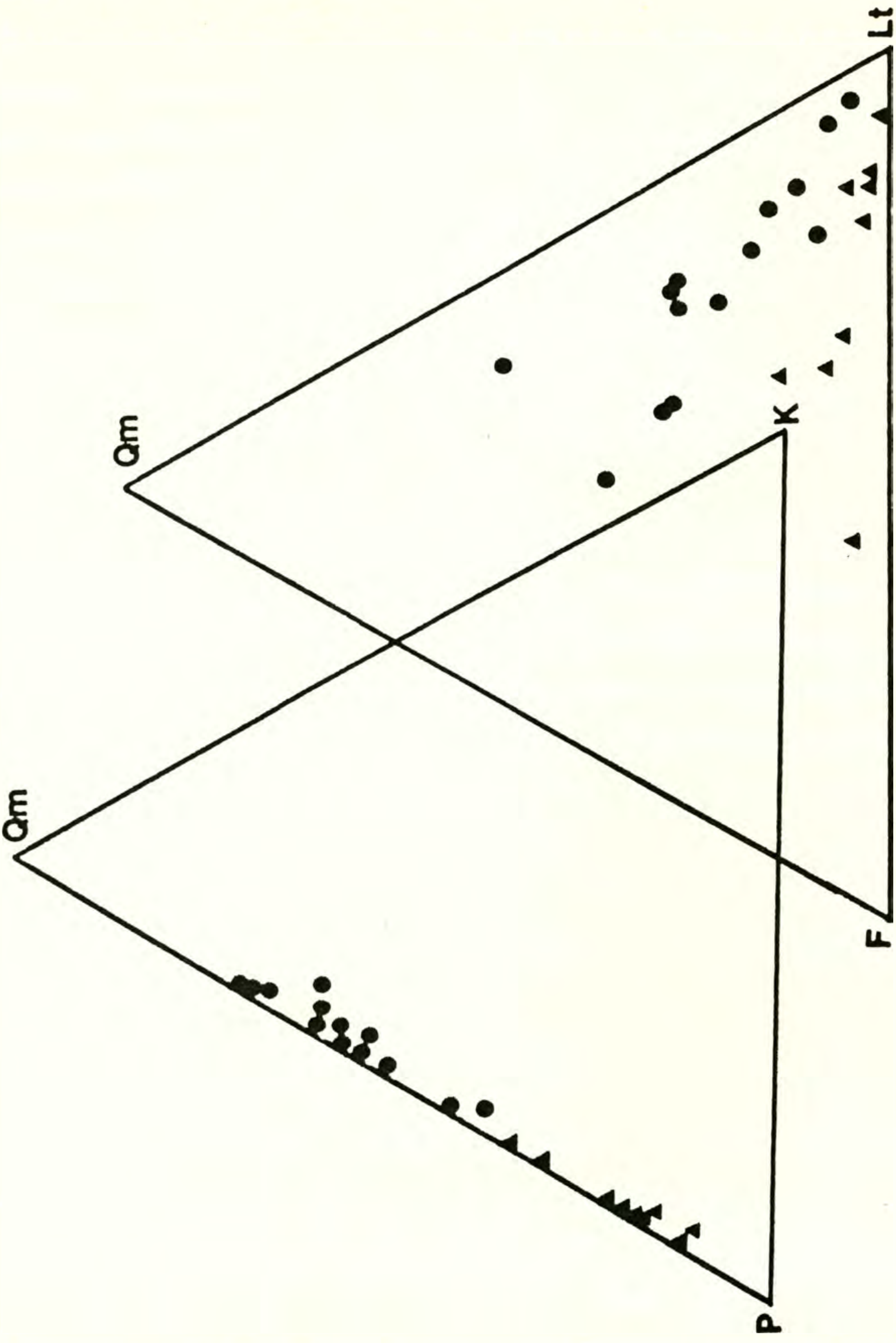


FIGURE 14. Comparison of rock fragment types of the two portions of the Aldwell Formation. Circles indicate western Aldwell, triangles indicate eastern Aldwell. Calculations of grain parameters given in Table 3.

FIGURE 15. Triangular diagrams indicating modal compositions of the eastern and western portions of the Aldwell Formation. Calculations of grain parameters given in Table 3. Symbols used are the same as those in Figure 14.


Qm
P
K
Qm
F
Lt

Eastern Portion of the Aldwell Formation:

The rocks of the eastern portion of the Aldwell Formation are lithic greywackes. The amount of matrix in the samples analysed ranges from 0 to 31% with a mean of 18%. Two of the three samples that contained less than 15% matrix were from concretions.

Lithic grains average 44% of the total rock, and a plot of Qp-Rv-Rst (Fig. 14) indicates that a strong majority of the rock fragments (78%) are of volcanic origin. The volcanic fragments are basaltic, with felsic volcanics occurring in trace amounts (<1%). However, some felsic clasts may have been counted as chert (see Appendix 2 for explanation). Intermediate volcanic fragments are absent.

The basaltic nature of the rock fragments is reflected in the feldspar content of the rock. The Qm-P-K diagram in Figure 15 indicates that plagioclase dominates both monocrystalline quartz and orthoclase. The mean P/F ratio is < 0.99. The average quartz content of these rocks is 5%; most of the quartz is monocrystalline and relatively clear. Monocrystalline quartz occasionally occurs as euhedral crystals. Other constituents include heavy minerals (usually epidote, pyroxene, magnetite, and pyrite), pumpellyite, celadonite (rare), and cement. The cement is almost always carbonate; trace amounts of laumontite and silica cements were found in three samples.

Mean grain size for samples for which point counts were made ranges from fine to very coarse sand (0.25 to 1.5 mm). Most samples are in the medium sand range. Coarser-grained samples seem to contain a larger percentage of sedimentary rock fragments. The samples exhibit poor to moderate sorting. Grains are generally subangular to subrounded, although examples of both angular (most often Rvv) and well rounded (most often Rs) grains were observed. On the whole, the rocks are texturally immature.

Western Portion of the Aldwell Formation:

The rocks of the western portion of the Aldwell Formation are predominantly lithic arenites. The amount of matrix ranges from 0 to 21% with a mean of 7%. Only two samples contain enough matrix to be classified as greywackes; both are fine grained, with most of the matrix consisting of broken-down framework grains (i.e., pseudomatrix).

Lithic grains average 51% of the total rock. A plot of Qp-Rv-Rst (Fig. 14) indicates that 66% of the total rock fragments are polycrystalline quartz. Most of the polycrystalline quartz is in the form of chert. The chert is often somewhat murky and in some cases contains ghosts of radiolarians. Metasedimentary and sedimentary rock fragments account for the next largest portion (as much as 36%) of the rock fragments. Low grade metamorphic rocks, most of which are probably argillite, are the most common constituents in this group.

Total quartz (including quartz in lithic grains) accounts for an average of 50% of the rock. Most of this is in chert grains. The Qm-P-K diagram in Figure 15 indicates that these rocks have more monocrystalline quartz than the rocks in the eastern portion of the Aldwell. The mean P/F ratio is 0.97. Epidote is the most common heavy mineral. Pyroxene, pyrite, and magnetite also are present. Other constituents include pumpellyite, cement, chlorite, and celadonite (rare). These rocks generally contain very little cement. Carbonate is the most common cement, but laumontite is the predominant cement in some samples. Silica cement is present in trace amounts.

Mean grain size of samples on which point counts were made ranges from fine to coarse sand (0.2 to 1.8 mm). Most are in the medium sand range. The samples are generally moderately well sorted. Some are well sorted. Most grains are subangular to subrounded. Chert and metasedimentary grains exhibit the highest degree of rounding. Rocks in the western portion of the Aldwell Formation are predominantly submature, although several samples are mature.

POST-DEPOSITIONAL CHANGES

Post-depositional changes that affected the sediments of the Aldwell Formation were precipitation of cement; alteration of detrital framework grains to calcite, pumpellyite, and chlorite; and the recrystallization of protomatrix to form orthomatrix and the breakdown of weak framework grains to form pseudomatrix.

Cement occurs as calcite, laumontite, and silica. Calcite is by far the most common. Calcite is much more common in the eastern portion of the Aldwell Formation than in the western portion. It is often seen replacing framework grains, especially plagioclase and basaltic rock fragments. In some cases entire grains have been replaced, and it is impossible to determine the protoliths.

The greater abundance of calcite in the eastern rocks is assumed to be at least in part related to the greater abundance of calcium-rich basaltic rock fragments. However, Pettijohn and others (1972) pointed out that Cenozoic greywackes often contain large amounts of carbonate cement, which is probably related to the abundant pelagic foraminifera originally contained in the sediments. A combination of both of the above factors probably explains the disparity in cementation between the eastern and western rocks.

The concretions present throughout the Aldwell Formation are calcite-cemented. Samples from concretions contain framework grains floating in calcite. Laminations in surrounding beds continue through concretions undisturbed, indicating that cementation took place following consolidation of the sediments (Weeks, 1957).

Laumontite cement was recognized in more than trace amounts only in the western portion of the Aldwell Formation. Samples containing laumontite have little or no calcite cement. Blatt and others (1980) reported that, in carbonate-rich sediments, the partial pressure of CO_2 is too high for laumontite to form, and calcite will precipitate as the stable, calcium-rich authigenic mineral. Laumontite also is a common alteration product of calcic plagioclase during deep burial diagenesis (Blatt and others, 1980).

Silica cement occurs as fine-grained polycrystalline quartz only in trace amounts. It is possible that, in some cases, this material is not cement, but actually crushed chert grains.

Pumpellyite occurs both detritally and as an alteration product of framework grains and matrix. Basaltic rock fragments are the most common framework grains affected. Pumpellyite is also present interstitially and can be seen crossing grain boundaries. It is therefore inferred to have formed _in situ_.

The matrix in these rocks formed after deposition. Whatever original protomatrix was present has been recrystallized to form orthomatrix or replaced, commonly by very murky, fine grained calcite. Many sedimentary and some metasedimentary grains have been crushed and squeezed between more resistant framework grains to form psuedomatrix. No precipitated phyllosilcates (epimatrix) seem to be present, although epimatrix and crushed metasedimentary grains would be difficult to distinguish.

The occurrence of pumpellyite and laumontite in the rocks of the Aldwell Formation indicates that these sediments have been subjected to pressure-temperature conditions very close to or within the field of metamorphism. The cut-off between deep burial diagenisis and metamorphism is ill-defined. Since rocks of the Aldwell Formation do not exhibit any preferred grain orientation or any other textures normally associated with metamorphism, and since vitric fragments often exhibit their original shapes, the post-depositional changes affecting these sediments appear to be the result of deep burial diagenesis.

PROVENANCE

Provenance determination for the Aldwell Formation must be based on petrology, since no reliable paleocurrent indicators were observed. The Qm-F-Lt diagram (Figure 15) indicates that the rocks of the Aldwell Formation are strongly dominated by lithics. Separate rock fragment counts were conducted in order to more accurately determine the types and quantities of rock fragments present. This information was used to help determine the source of the Aldwell sediments.

POSSIBLE SOURCES FOR SEDIMENTS IN THE EASTERN PORTION OF THE ALDWELL FORMATION

Basaltic clasts are the dominant type of rock fragment in the eastern portion of the Aldwell Formation (Fig. 14). Sedimentary rock fragments are the next most abundant, but since these were probably derived from within the basin, they are not useful indicators of provenance. Felsic clasts are common in the conglomerate unit along Lake Aldwell. Chert is virtually absent in the eastern portion of the Aldwell.

Snavely (1983) interpreted the conglomerate unit in the lower portion of the Aldwell Formation as having been transported southward as olistrostromal debris shed from the uplifted block along the Striped Peak thrust fault to the north. His conclusion is based on the petrographic similarity between clasts in the conglomerate and the felsic volcanics at Striped Peak. Although I agree with this interpretation, the rest of the sediments in the eastern portion of the Aldwell Formation need not have been derived from a northern source.

Possible nearby sources for the basalt in the Aldwell Formation are the middle Eocene Crescent Formation and Metchosin Volcanics and the

Triassic Karmutsen Formation on Vancouver Island (Fig. 18). The Metchosin Volcanics are considered by most workers to be equivalent to the Crescent Formation (Macleod and others, 1976). I will refer to the Crescent and Metchosin basalts collectively as the Crescent seamount province.

Samples of basalt from the Crescent Formation appear fresher than the basaltic clasts in the Aldwell, but they exhibit similar textures and both are commonly altered to pumpellyite (Fig. 16a and b). The heavy minerals present in the basalts of the Crescent Formation are lacking in the lathwork basalt clasts of the Aldwell, but these minerals could have been replaced by the calcite that is very common in basalt fragments. The presence of angular fragments of altered vitric basalt in the eastern portion of the Aldwell Formation (Fig. 17) indicates that the source of the basalt originally must have been close by, or the angularity of the clasts would not have been preserved.

Although the Karmutsen basalts appear similar to the basalts of the Crescent seamount province in thin section (Pearl, 1977), the Karmutsen Formation is north of the San Juan Fault (Fig. 18) and was farther away from the probable location of Aldwell Formation deposition. Proposed left-lateral offset along the San Juan and Leech River Faults (Fairchild and Cowan, 1982) suggests that the Karmutsen Formation was even further away during Aldwell deposition than it is at present. The Crescent seamount province therefore is the more likely choice for a source of basalt. However, basalts of the Crescent seamount province crop out both to the south and north of the Aldwell Formation (Fig. 18). The question therefore remains as to whether the source of the sediments in the eastern portion of the Aldwell Formation was to the north, the south, or in both directions.

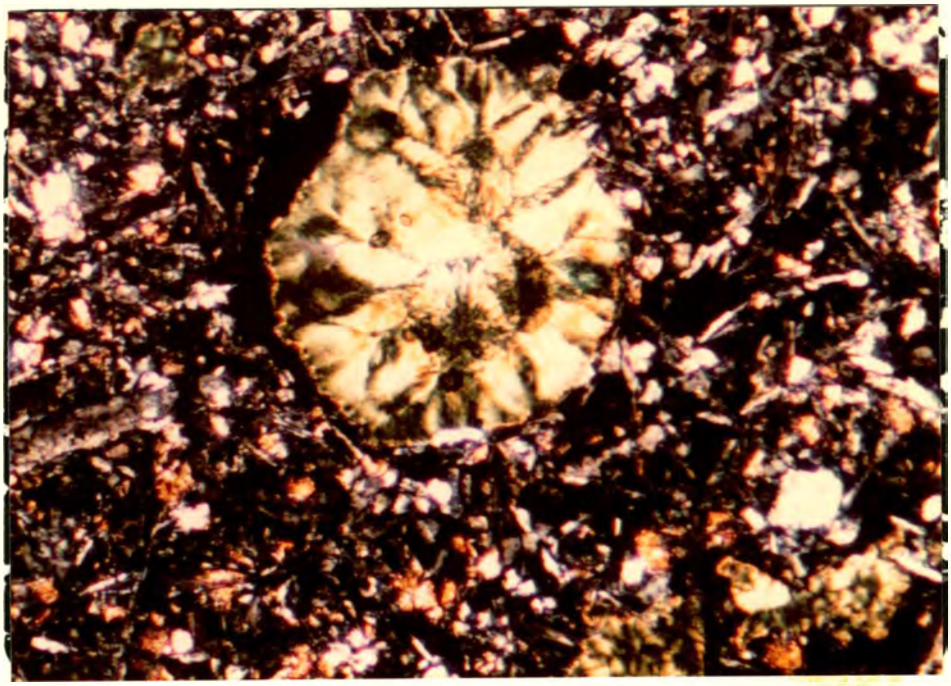


FIGURE 16a. Basalt of the Crescent Formation. Note radial pumpellyite in center of photomicrograph. Long dimension is 2.1 mm. Crossed nicols.

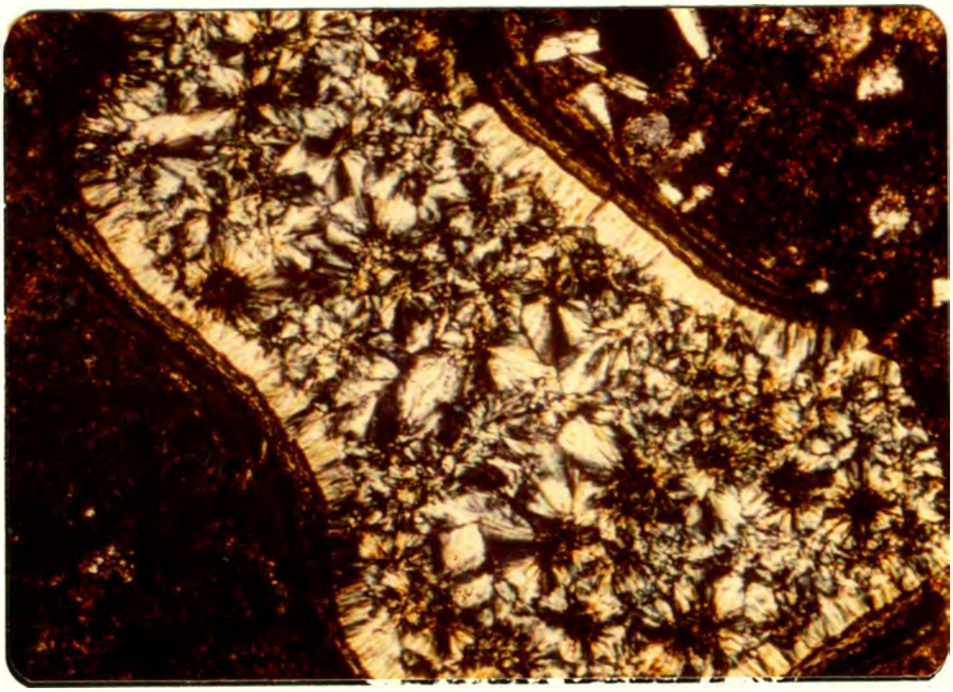


FIGURE 16b. Vitric basalt fragment altered to radial pumpellyite, eastern portion of the Aldwell. Long dimension of photomicrograph is 2.1 mm. Crossed nicols.

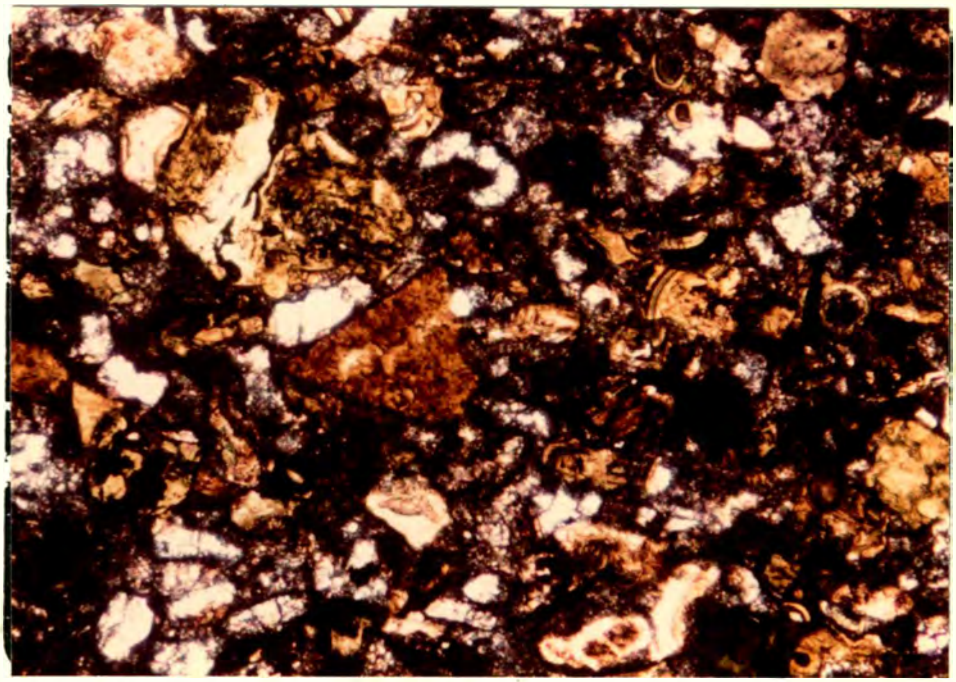
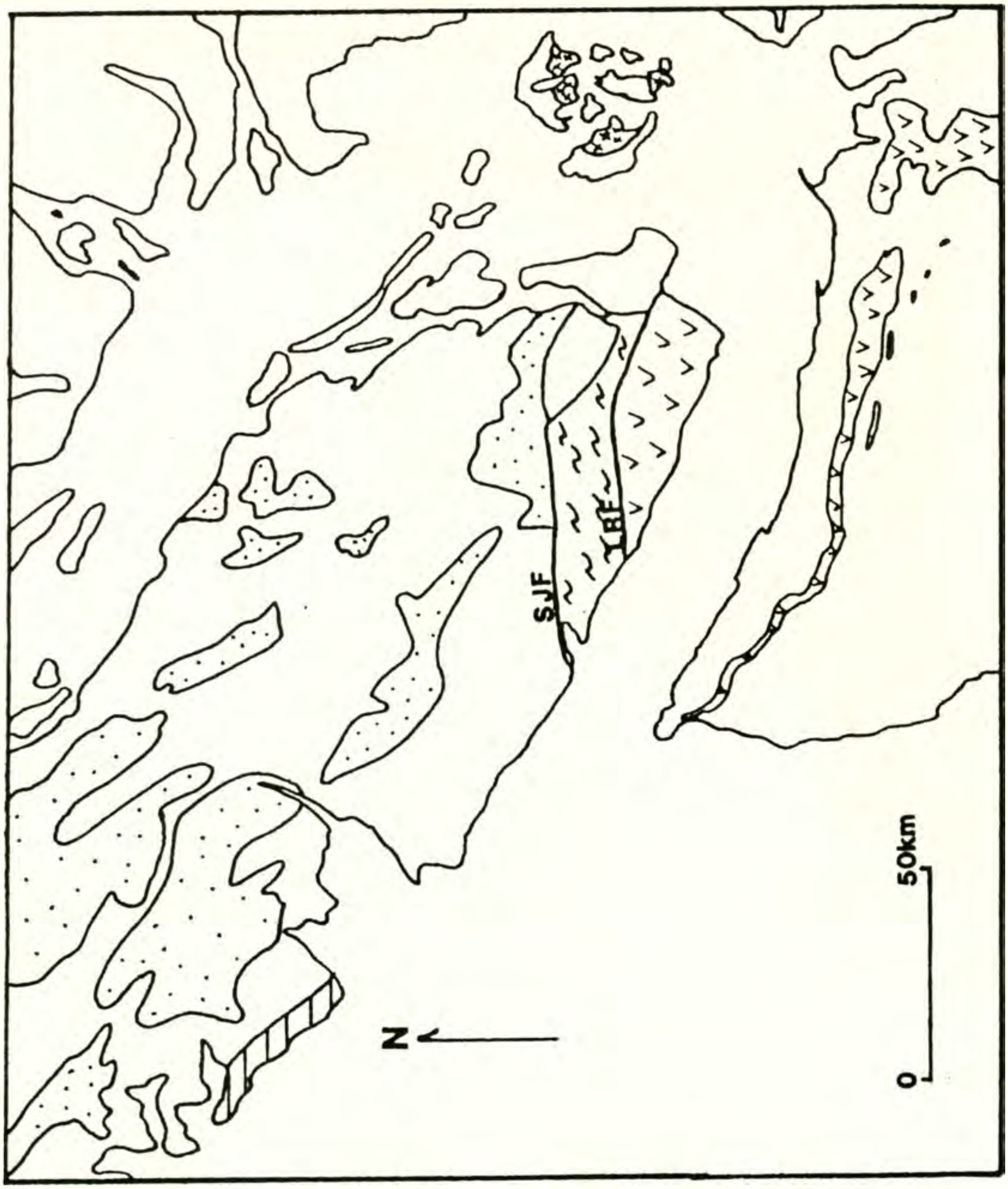


FIGURE 17. Vitric basalt fragments altered to clays, eastern portion of the Aldwell Formation. Preservation of angular shapes indicates short distance of transport. Long dimension of photomicrograph is 2.1 mm. Plane light.

FIGURE 18. Possible source rocks for the sediments of the Aldwell Formation. -basalts of the Crescent seamount province. -Karmutsen Formation, -Pacific Rim Complex, -Leech River Complex, -Orcas and Constitution Formations. SJF=San Juan Fault, LRF=Leech River Fault.


SJF
LRF
N
0
50km

The northern portion of the Crescent seamount province is adjacent only to the eastern portion of the Aldwell Formation. If the basaltic rock fragments were derived from the Crescent Formation to the south, one would expect to find abundant basalt clasts throughout the entire area of outcrop of Aldwell Formation, since the Crescent Formation is in close proximity to the Aldwell along its entire length. However, basalt clasts are only minor constituents of the western portion of the Aldwell Formation.

Although it is likely that the eastern portion of the Aldwell Formation received most of its sediments from the Crescent seamount province, no definite conclusion can be drawn as to whether the majority of the material came from the north, the south, or from both directions. However, based on the northerly source for the conglomerate unit and the restriction of abundant basaltic detritus to the eastern portion of the formation, I favor a predominantly northern source for the sediments in the eastern portion of the Aldwell Formation.

POSSIBLE SOURCES FOR THE SEDIMENTS IN WESTERN PORTION OF THE ALDWELL FORMATION

The source area for the rocks in the western portion of the Aldwell Formation is even more difficult to pin down. The Qp-Rv-Rst diagram (Figure 14) indicates that, in the western portion, chert clasts are by far the most common constituent. Low grade metamorphic rock fragments are also important, although not in all samples (Appendix 2). The most common heavy mineral is epidote. Epidote is a common alteration mineral in the rocks of southern Vancouver Island (Ansfield, 1972); and ample chert and metamorphosed sediments occur in areas near the Aldwell Formation today.

The tectonic setting of the Olympic Peninsula during the Eocene must be considered in determining which of these sources could have supplied sediments to the western portion of the basin in which the Aldwell Formation was deposited.

There is abundant chert and argillite on the San Juan Islands (Fig. 18) in the Jurassic-Cretaceous Constitution Formation and the Triassic-Jurassic Orcas Formation (Muller, 1980). Petrographic data from the Cretaceous Nanaimo Group, which crops out on eastern Vancouver Island and the San Juan Islands, indicate that Vancouver Island (north of the San Juan Fault), the northern San Juan Islands, and the North Cascades have not moved appreciably with respect to each other since the Nanaimo sediments were deposited (Pacht, in press). The eastern portion of the Aldwell Formation is essentially devoid of chert clasts. It is difficult to imagine chert clasts being transported from the San Juan Islands, east of the Olympic Peninsula, to the western portion of the Aldwell Formation while totally bypassing the eastern portion of the basin. The Orcas and Constitution Formations are therefore ruled out as probable sources of the sediments in the western portion of the Aldwell Formation.

Other possible sources of rock fragments for the western Aldwell Formation are the Jurassic-Cretaceous chert-argillite unit within the Leech River Complex on southern Vancouver Island (Muller, 1980) and a ribbon chert unit of probable Jurassic age within the Pacific Rim Complex (Muller, 1973; Fig. 18). Both units contain abundant chert and metasedimentary rocks. According to Muller (1973), the Pacific Rim Complex was emplaced against the western edge of Vancouver Island by a combination of thrust faulting and some strike-slip motion, that probably ceased by the late Eocene. Thus, uplift in the area could have resulted in sediments being shed southward and deposited as part of the Aldwell Formation.

Although the Leech River Complex has been metamorphosed to the greenschist-amphibolite facies (Fairchild and Cowan, 1982) and exhibits a higher degree of metamorphism than the metasedimentary clasts in the Aldwell Formation, the metamorphism which affected the sediments of the Leech River Complex culminated between 38 and 41 Ma (Fairchild and Cowan, 1982). Since the sediments of the Aldwell were deposited prior to that, it is possible that the Leech River Complex was a source of the lower grade metasediments seen in the Aldwell Formation.

Snavely (oral comm., 1984) reported that a few paleocurrent indicators in the western portion of the Aldwell Formation show a southwesterly transport direction, but that no firm conclusions can be drawn from so little data. Studies of other sedimentary units in the northern Olympic Peninsula have yielded north to northwesterly sources for the upper Eocene Lyre Formation (Ansfield, 1972) and the upper Eocene to lower Oligocene Makah Formation (Snavely and others, 1980). Pearl (1977) reported that the upper Eocene Hoko River Formation also had a source area to the north. All of these studies were concerned with rocks in the western portion of the peripheral rocks.

It appears that the Leech River Complex and the Pacific Rim Complex are the two most likely sources of the chert and low-grade metasediments in western portion of the Aldwell Formation. In order to determine which of the two is the more likely source, a more detailed analysis of the possible tectonic setting during the deposition of the Aldwell is required.

DEPOSITION AND TECTONICS

In developing a model for the tectonic setting during the deposition of the sediments of the Aldwell Formation, petrographic and sedimentologic information obtained in this study was used in conjunction with an analysis of regional structures and plate interactions. The following is a summary of the evidence and assumptions that were presented earlier and that were used to develope the model:

1) An unconformity may exist between the deep water sediments of the Aldwell Formation and the underlying sediments. At least some of the underlying sediments are shallow water deposits (W.W. Rau, oral comm., 1984).

2) A period of convergence between the Crescent seamount province and Vancouver Island is documented by movement along the northwest-trending Crescent and Striped Peak thrust faults (Fig. 3) during the late Eocene. Uplift along the Striped Peak thrust fault resulted in the deposition of the conglomerate unit in the lower part of the Aldwell Formation near Lake Aldwell (Snavely, 1983).

3) The lithologies of the eastern and western portions of the Aldwell Formation reflect two different source areas. The source of the eastern portion was probably basalts of the Crescent seamount province, specifically the Metchosin Volcanics of southern Vancouver Island. The source of the western portion was probably either the Leech River Complex or the Pacific Rim Complex, both of Vancouver Island.

4) Vancouver Island (north of the San Juan Fault), the San Juan Islands, and the North Cascades were fixed with respect to one

another by the time of Nanaimo Group deposition in the late Cretaceous (Pacht, in press).

5) The Leech River Fault separates the Crescent seamount province on southern Vancouver Island from the Leech River Complex (Fig. 18) and documents probable left lateral motion between the two units. The motion is inferred to post-date the 38 to 41 Ma metamorphism that affected the Leech River Complex but not the basalts of the Crescent seamount province (Fairchild and Cowan, 1982).

6) The San Juan Fault on Vancouver Island separates the Leech River Complex from pre-Tertiary rocks to the north (Fig. 18) and probably had left lateral motion. The movement on the San Juan Fault, like that on the Leech River Fault, is inferred to have occurred after 38 to 41 Ma because rocks immediately north of the fault have not been metamorphosed (Fairchild and Cowan, 1982).

7) Although the actual origin of the basalts of the Crescent seamount province is uncertain (Wells and others, 1984; and Duncan, 1982), they are oceanic tholeiites and are generally considered to be seamounts.

8) The Crescent seamount province may have been riding on the Farallon plate or the Kula plate prior to its accretion to North America. A model for Farallon-North America and Kula-North America relative motion for the middle to late Eocene indicates that these plates were moving northeast with respect to North America (Wells and others, 1984).

DISCUSSION OF THE EVIDENCE

Based on the above, a possible model for the tectonic setting of the deposition of the Aldwell Formation has been developed. The model is a generalization of the depositional history and is intended as a first approximation, which should be of use to those who study the tectonic history of the Olympic Peninsula in the future.

A closer examination of the provenance of the western portion of the Aldwell Formation is in order in light of the structural evidence given above. The Leech River Complex is thought to have been emplaced against the southern tip of Vancouver Island by a minimum of 50 km of strike-slip motion (the amount of visible displacement) along the San Juan Fault after about 40 Ma (Cowan, 1982). Thus the Leech River Complex must have been at least 50 km west of Vancouver Island during deposition of the Aldwell Formation.

The Leech River Complex is bounded on the south by the Leech River Fault (Fig. 18), along which there was a minimum of 60 km of left lateral displacement after approximately 40 Ma (Cowan, 1982). Assuming that the basalts of the Crescent seamount province on southern Vancouver Island and the Olympic Peninsula have remained in fixed position with respect to one another through time, the displacements on the San Juan and Leech River Faults require that the seamount province was at least 110 km west of Vancouver Island during the deposition of the Aldwell Formation. Therefore, the Juan de Fuca basin, in which the sediments of the Aldwell were deposited, was far from the Pacific Rim Complex on Vancouver Island, and the "proto" Leech River terrane probably blocked sediment transport from one to the other.

Cowan (1982) has tentatively correlated the rocks of the Leech River Complex with rocks on Baranof Island in southeast Alaska. He reported that these two now separate terranes are strikingly similar in lithology and metamorphic history. If the Leech River Complex does represent a portion of a larger terrane that has since been transported northward, it is possible that such a terrane was supplying sediment to the Juan de Fuca basin during the late Eocene.

Considering the extensive paleomagnetic evidence for the long-distance transport of allochthonous terranes along the west coast of North America (Beck, 1976, 1980; Irving, 1979), it appears quite possible that the Leech River Complex was part of a larger terrane off the coast of Vancouver Island during late Eocene, as Cowan (1982) suggested. I therefore favor a "proto" Leech River terrane as the source of the chert and metasediments in the western portion of the Aldwell Formation.

MODEL

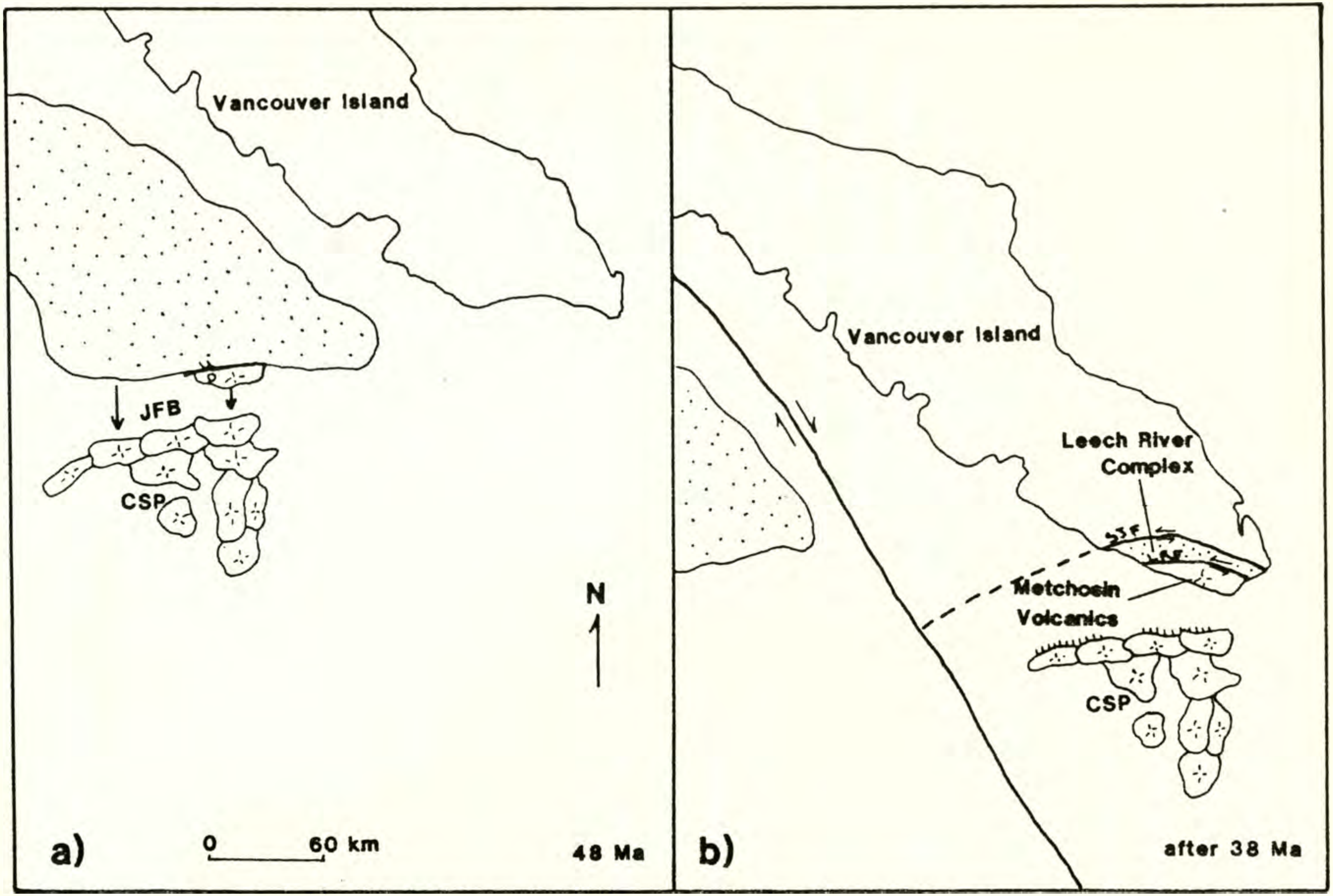
During the late Eocene, the Juan de Fuca basin was bounded on the south and northeast by the basalts of the Crescent seamount province (Fig. 19a). The Crescent seamount province may have been riding northeastward on either the Farallon or the Kula plate for part of its history (Wells and others, 1984).

Prior to Aldwell deposition, Ulatisian sediments in the upper portion of the Crescent Formation, which today crop out on the north coast of the Olympic Peninsula, were deposited on the flanks of the seamounts. The seamounts were partially above sea level and were being actively eroded. The irregular distribution of the seamount basalts would have created uneven topography with sediments being deposited at various depths; however, at least some of the sediments were deposited in shallow water. Active volcanism ceased; and the seamounts may have then experienced thermal subsidence, which lowered them below sea level and caused both erosion and deposition to be interrupted.

FIGURE 19. Diagramatic map showing possible tectonic setting (a) during and (b) after the deposition of the Aldwell Formation.

a) Positions of the "proto" Leech River terrane (stippled pattern) and the Crescent seamount province (CSP) reflect restoration of minimum proposed offset along the San Juan and Leech River Faults. The Juan de Fuca basin (JFB) was receiving sediment from two sources. (The general outline of Vancouver Island is given only as reference and is not intended to indicate the configuration of the coastline for the period of time in question.)

b) Leech River Complex and Crescent seamount province basalts of southern Vancouver Island (Metchosin Volcanics) shown in their present position. "Proto" Leech River terrane is being transported northwestward. SJF = San Juan Fault, LRF= Leech River Fault. Hachured area indicates Aldwell sediments.


Vancouver Island
JFB
CSP
N
a)
0
60 km
48 Ma
Vancouver Island
Leech River
Complex
Metchosin
Volcanics
CSP
b)
after 38 Ma

The Crescent seamount province continued to subside as it moved northeastward toward the "proto" Leech River terrane and Vancouver Island. In the Narizian (approximately 48 Ma), sediments derived from the basalts of the Crescent seamount province were transported southward into the Juan de Fuca basin; these sediments formed the Aldwell Formation. The required uplift and erosion of the northern portion of the seamount province may have been the result of the leading edge of the seamount province encountering the "proto" Leech River terrane by means of some combination of convergence and strike-slip motion. The encounter could have resulted in faulting and uplifting of the northern portion of the seamount province and the subsequent initiation of erosion and southward transport of basaltic sediments into the eastern portion of the basin. At approximately the same time, the western portion of the basin had reached a point close enough to the "proto" Leech River terrane to receive chert and low grade metasedimentary detritus from that source (Fig. 19a and Table 4).

Convergence between the Crescent seamount province and the "proto" Leech River terrane assumes that these two terranes were on different plates. It is uncertain what the nature of the boundary was between the North American and oceanic plates in this area during the Eocene, but if sediments were being shed off the "proto" Leech River terrane into the Juan de Fuca basin, there must have been no trench to trap those sediments.

As convergence continued between the seamount province and the "proto" Leech River terrane, movement was initiated along the Crescent and Striped Peak thrust faults (Fig. 3). Olistrostromal material was shed from the northern block that was rising along the Striped Peak thrust fault and deposited as a conglomerate unit in the lower portion of the

TABLE 4–Summary of Tectonic Model

EVENT	Extrusion of Crescent seamount province basalts Northeast displacement of Crescent seamount province on Farallon or Kula plate Unconformity at base of Aldwell Formation	Juxtaposition of seamount province and "proto" Leech River terrane Deposition of Aldwell Formation sediments Movement on Crescent and Striped Peak thrust faults–deposition of olistostromal unit	Culmination of Leech River Complex metamorphism Movement on San Juan and Leech River Faults–dispersion of "proto" Leech River terrane Northwestward translation of "proto" Leech River terrane
	48 Ma	41 Ma	
TIME	Before Aldwell Deposition	During Aldwell Deposition	After Aldwell Deposition

Aldwell Formation (Snavely, 1983).

The Leech River Complex was probably being metamorphosed during the time of Aldwell deposition. The basalts of the Crescent seamount province must have been far enough away so they were not effected by the metamorphism.

After Aldwell deposition, reorganization of the plate boundaries resulted in the dispersion of the "proto" Leech River terrane and the initiation of left-lateral motion along the San Juan Fault. The Leech River Complex and the Crescent seamount province moved eastward toward Vancouver Island. Major transcurrent faulting transported the "proto" Leech River terrane northwestward (Fig. 19b and Table 4). The portion of the model that concerns the dispersion of the "proto" Leech River terrane is essentially the interpretation proposed by Cowan (1982).

PROBLEMS WITH THE MODEL

This model assumes that the evidence outlined above is correct. It hinges on several key questions which at this time remain unanswered:

What is the length of time represented by the unconformity between the Aldwell Formation and the underlying sediments, and what actually transpired during that time? Thermal subsidence followed by uplift seems the simplest case.

What was the nature of the boundary between the oceanic plates and North America? The geometry of the boundary and its nature remain enigmatic. The proposed model relies on convergence between the seamount province and the "proto" Leech River terrane without true subduction. Farallon-North America and Kula-North America motion was probably highly oblique in the Eocene, and thus the boundary may have been almost completely strike-slip. The nature of the boundary would have been largely controlled by the orientation and configuration of the west coast of North America, which itself is unknown.

Perhaps most important, was there a "proto" Leech River terrane in the area during the late Eocene? Although it is very likely that allochthonous terranes existed along the west coast of North America during the Eocene, whether or not the Leech River Complex is actually a small part of a larger terrane that was in place at the right time is certainly open to debate. Perhaps the sediments of the Aldwell were derived from a source that existed near the Juan de Fuca basin during the Eocene, but that has since moved northwestward without leaving any fragments behind. Further work involving both plate motions and sedimentology should shed some light on these problems.

SUMMARY AND CONCLUSIONS

Both the sediments in the eastern portion of the Aldwell Formation and those in the western portion were deposited on submarine fans. Petrographic analyses of the Aldwell Formation indicate that the rocks in the east and west have distinctly different lithologies. The rocks of the eastern Aldwell Formation are basalt-rich lithic greywackes, while those in the western portion are chert-rich lithic arenites. Although the western rocks are interpreted as having been deposited in a mid-fan environment and the eastern rocks as having been deposited in an outer-fan environment, the different lithologies of the two portions of the formation indicate probable deposition on two separate fans rather than on two areas of a single fan.

Based on the available data, no definite conclusions can be drawn with respect to the sources of the sediments of the Aldwell Formation. Similarities in texture, composition, and alteration products suggest that the basalts of the Crescent seamount province were the likely source of the sediments of the eastern rocks. The basalts of the Crescent seamount province crop out both to the north (Metchosin Volcanics) and south (Crescent Formation) of the Aldwell Formation, but a northern source is inferred based on the restriction of abundant basaltic detritus to the eastern rocks as well as a southward transport direction for the olistostromal blocks in the conglomerate unit near Lake Aldwell.

The source of the sediments in the western rocks is speculative. A terrane located to the southwest of Vancouver Island during the late Eocene, of which the Leech River Complex is only a small fragment (Cowan, 1982), is proposed as the source of these sediments.

A model for the tectonic setting of the the Juan de Fuca basin and surrounding area during the deposition of the Aldwell is proposed in which Aldwell sediments were deposited in a basin bounded by seamounts on the south and northeast. This seamount province moved northeast on either the Farallon or Kula plate toward Vancouver Island and the "proto" Leech River terrane. Convergence between the seamount province and the "proto" Leech River terrane resulted in uplift and southerly transport of Aldwell Formation sediments into the Juan de Fuca basin.

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APPENDIX 1

SAMPLE LOCATION MAPS

Sample location maps are given for transects along Lake Crescent in the eastern portion of the Aldwell Formation and the Sekiu River in the western portion. These maps are portions of the Lake Crescent and Clallam Bay quadrangles respectively. Sample numbers on the maps are only for those samples from which thin sections were made. Arrows in front of sample numbers indicate thin sections for which point counts were made.

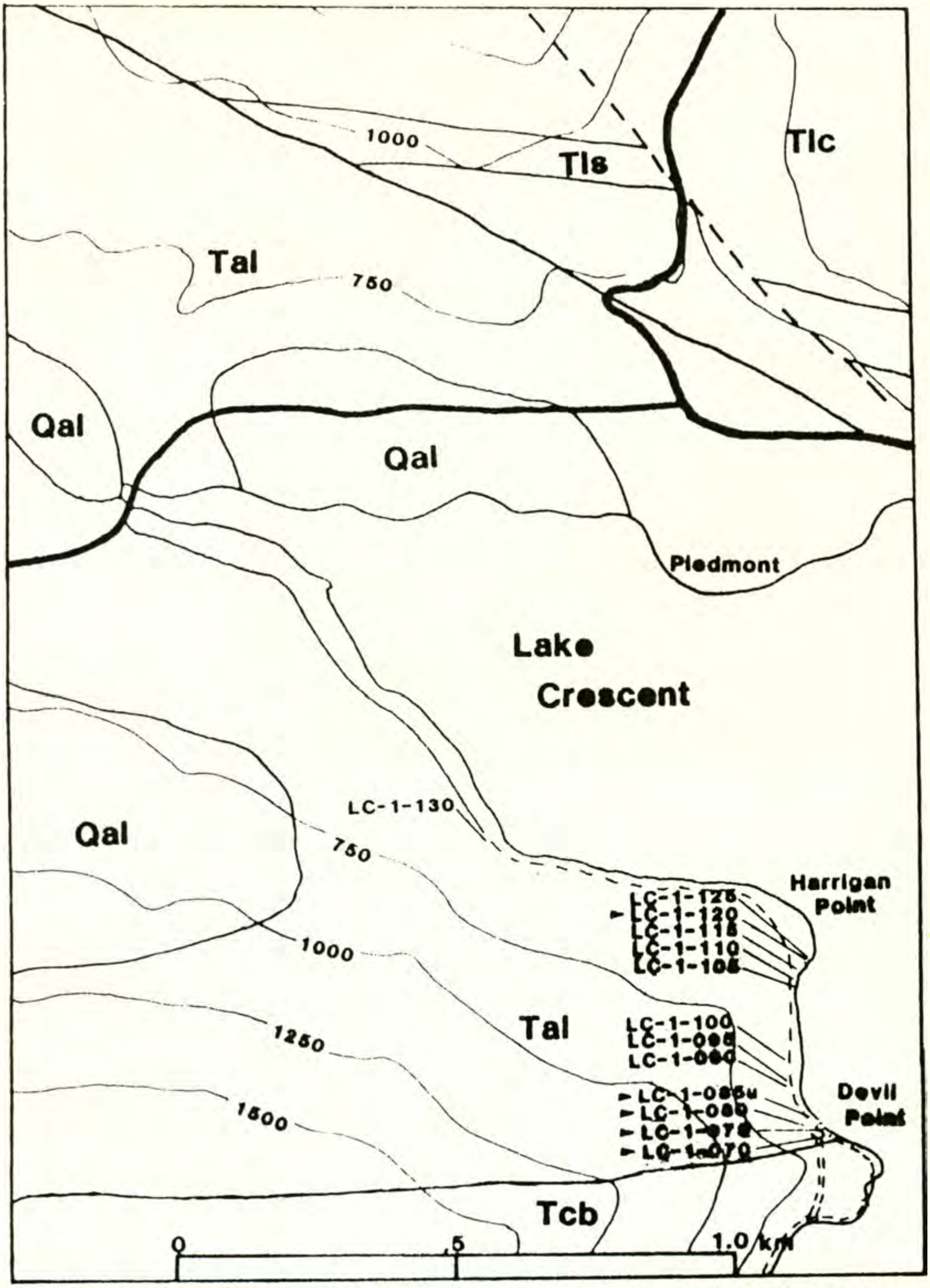

FIGURE 20. Sample location map for transect along Lake Crescent, Lake Crescent quadrangle.

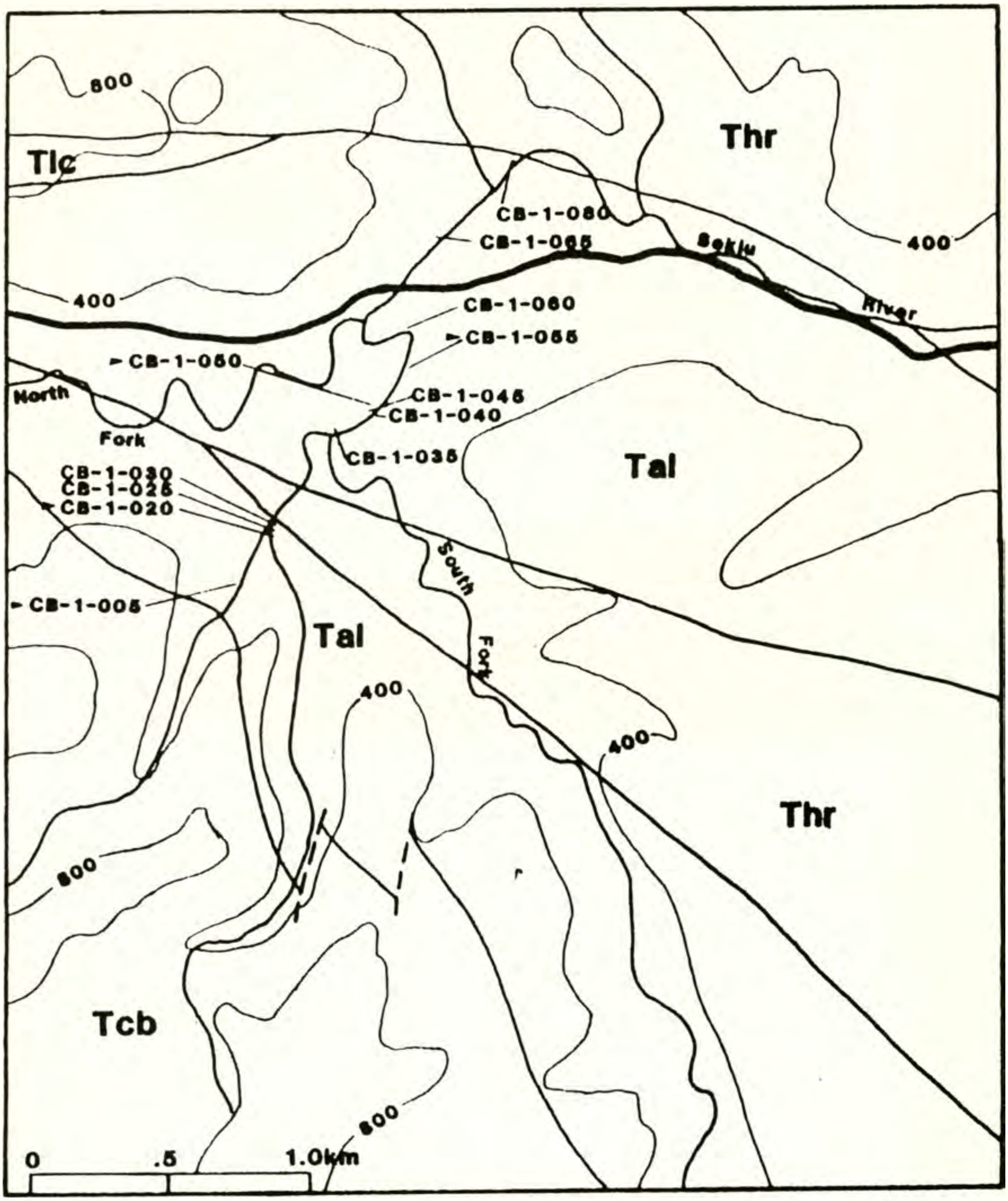

FIGURE 21. Sample location map for transect along the Sekiu River, Clallam Bay quadrangle.

APPENDIX 2

POINT COUNT CATEGORIES

Point Count Categories for 300-Point Whole Rock Counts:

Monocrystalline Quartz (Qm)- Included in this category are all quartz grains of sand size or larger including sand-size subgrains. Single monocrystalline grains are usually clear and unaltered, and euhedral crystals are occasionally observed (Fig. 22).

Plagioclase Feldspar (P)- Plagioclase was recognized with the aid of stain (pink). Included in this category are phenocrysts of sand size or larger within rock fragments (most often basaltic). Although a continuum exists between fairly fresh and highly weathered grains, most grains seem to be either one or the other. The weathered grains appear deeply etched and are commonly extensively sericitized. Plagioclase grains are commonly replaced by calcite and less often by pumpellyite. Albite twins are fairly common. Carlsbad twins also occur, but the two types of twinning rarely occur in the same grain.

Orthoclase Feldspar (K)- Orthoclase was recognized by stain (yellow). It is present in only a few samples and never in more than trace amounts.

Lithics (L)- The lithics category potentially includes all multigranular and polycrystalline clasts that contain subgrains that are silt size or smaller. However, clasts were counted in this category only if the crosshairs actually landed on a subgrain of silt size or smaller. Clasts which fall into this category are described in detail in the

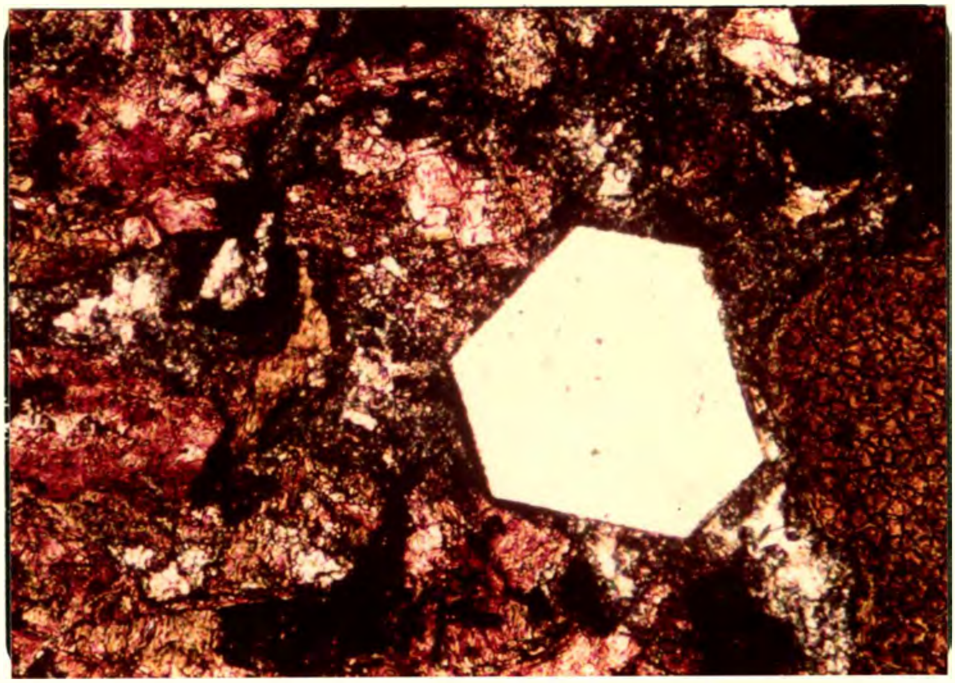

FIGURE 22. Euhedral volcanic quartz grain, eastern portion of the Aldwell. Long dimension of photomicrograph is 0.66 mm. Plane light.

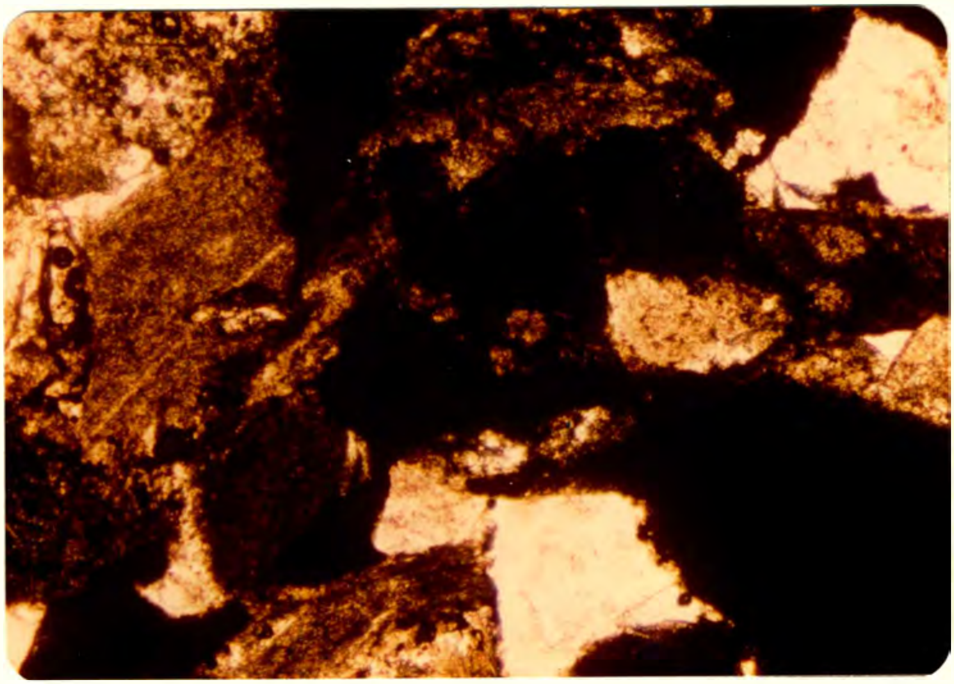

FIGURE 23. Pseudomatrix formed from crushed mudstone fragment; the mudstone has been squeezed between other more resistant framework grains. Long dimension of photomicrograph is 2.1 mm. Plane light.

section on rock fragments.

Matrix (Mat)- Matrix includes all interstitial material of clay size or smaller. Descriptive terms for matrix are after Dickinson (1970). Since these rocks have been subjected to stresses great enough to produce pumpellyite, it is doubtful that much of the original protomatrix remains. Most of the matrix appears to be orthomatrix, i.e., recrystallized protomatrix, often occurring as very murky calcite. Sedimentary and metasedimentary fragments have been crushed to form pseudomatrix (Fig. 23).

Cement (Cem)- Calcite accounts for the vast majority of the cement in these rocks. Samples from concretions exhibit framework grains floating in calcite. The calcite cement generally occurs as a granular mosaic (Fig. 24), but excellent examples of bladed and dog-tooth cement are also present. Laumontite is the second most common cement type, but it occurs only in samples with little or no calcite. Laumontite cement is recognizable as bright red patches occurring interstitially in stained sections. Silica cement was noted only in rare instances, and it is possible that what was counted as cement is actually crushed chert grains.

Pumpellyite (Pump)- Although pumpellyite was most often found as well rounded detrital grains or within volcanic rock fragments, only pumpellyite which formed in place was counted in this category. Such pumpellyite has a wavy, mat-like appearance and commonly forms at the expense of matrix. It can also be seen crossing grain boundaries.

Heavy Minerals (Heav)- The most common heavy minerals encountered are

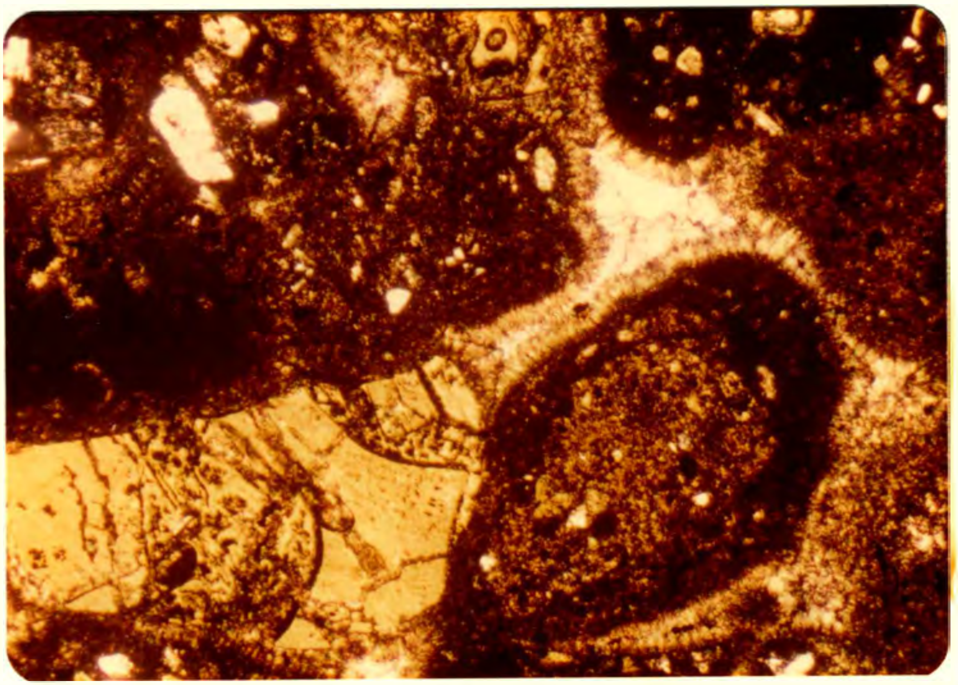

FIGURE 24. Granular mosaic and fringing calcite cements grown between siltstone fragments and altered vitric basalt grain. Long dimension of photomicrograph is 2.1 mm. Crossed nicols.

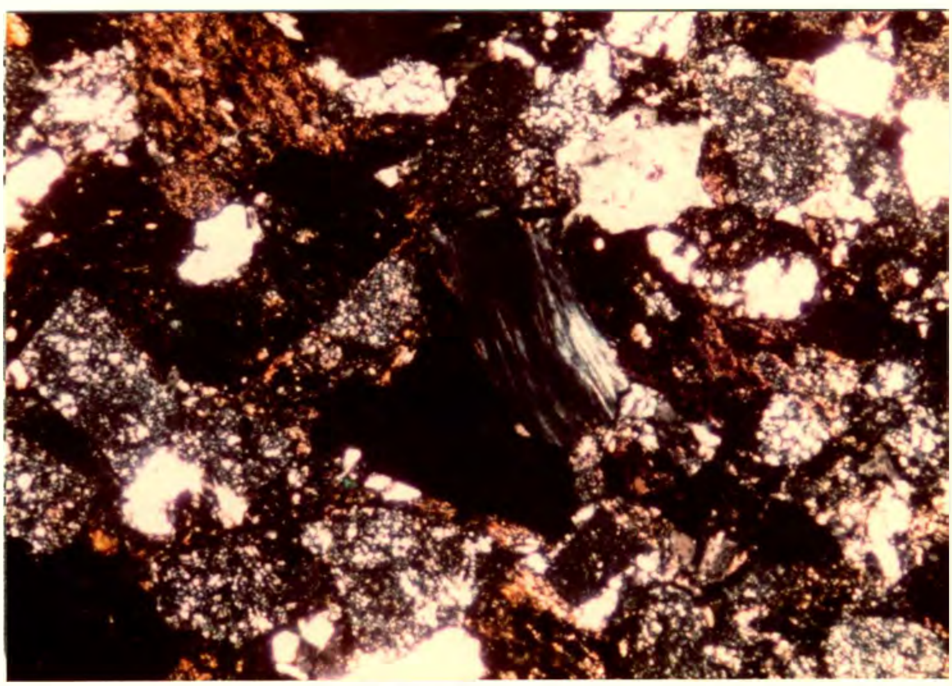

FIGURE 25. Abundant chert grains from western portion of the Aldwell. Note chlorite in center of photomicrograph. Long dimension is 2.1 mm. Crossed nicols.

epidote, pyroxene, and the opaque minerals magnetite and pyrite. Opaques were identified using reflected light.

Miscellaneous (Misc)- Both unidentifiable minerals and minerals which occur in only trace amounts were counted in this category. Of the latter, chlorite is most common (Fig. 25) but accounts for less than 1% of the rock in all but a few cases.

Point Count Categories for 200-Point Rock Fragment Count:

Polycrystalline Quartz plus Chert (Qp+Chert)- All polycrystalline quartz was counted in this category. Most grains counted were chert (Fig. 25). Chert grains are generally somewhat murky and may contain some mica. An arbitrary cut off of approximately 15% impurities was assigned to distinguish chert from sedimentary and metasedimentary fragments. Chert grains are sometimes cut by veins of coarser polycrystaline quartz. Some chert grains exhibit ghosts of radiolarians. A certain amount of error probably resulted from counting fine grained felsic volcanic fragments as chert. Most of the other polycrystalline quartz is relatively clear with sutured contacts between subgrains.

Altered Vitric Volcanics (Rvv)- These are green to brownish-green fragments which commonly retain glass shard shapes. The clasts have all been altered. Most have gone to pumpellyite, either in a very fine-grained mat, or in radial fibers or blades. In many cases, the pumpellyite itself has altered to brownish clay (Fig. 17), which x-ray diffraction indicates is layered chlorite-smectite (B. Rauch, oral comm., 1984). In some cases, small patches of silica can also be seen within these clasts.

Lathwork Volcanics (Rvl)- Lathwork volcanic fragments are generally grey-brown clasts containing abundant, randomly oriented feldspar laths (Fig. 26). The feldspars are usually quite weathered. Larger clasts may exhibit amygdules filled with radial pumpellite or a combination of pumpellyite and clays. The fragments themselves are often partially altered to pumpellyite and clays and also show various stages of calcite replacement.

Felsic Volcanics (Rvf)- Felsic volcanics occur in only trace amounts, although, as noted earlier, some felsic clasts may have been mistakenly counted as cherts. These clasts were distinguished from cherts by the occurrence of plagioclase phenocrysts.

Sedimentary Rock Fragments (Rs)- Sedimentary clasts are most commonly siltstones, although mudstone and sandstone fragments are also present. All are well rounded. In cases where grain boundaries were seen to be smeared out or wispy, or where grains were squashed between other framework grains, the "grain" was counted as matrix (Fig. 23).

Metasedimentary Rock Fragments (Rms)-Clasts that contain abundant micas with a distinct parallel orientation (Fig. 27), as well as clasts whose subgrains are elongate and/or display a distinct orientation, were counted in this category. The former appear to be phyllite, and the latter are best described as argillite.

Other- The most common clasts in this category are fossil fragments.

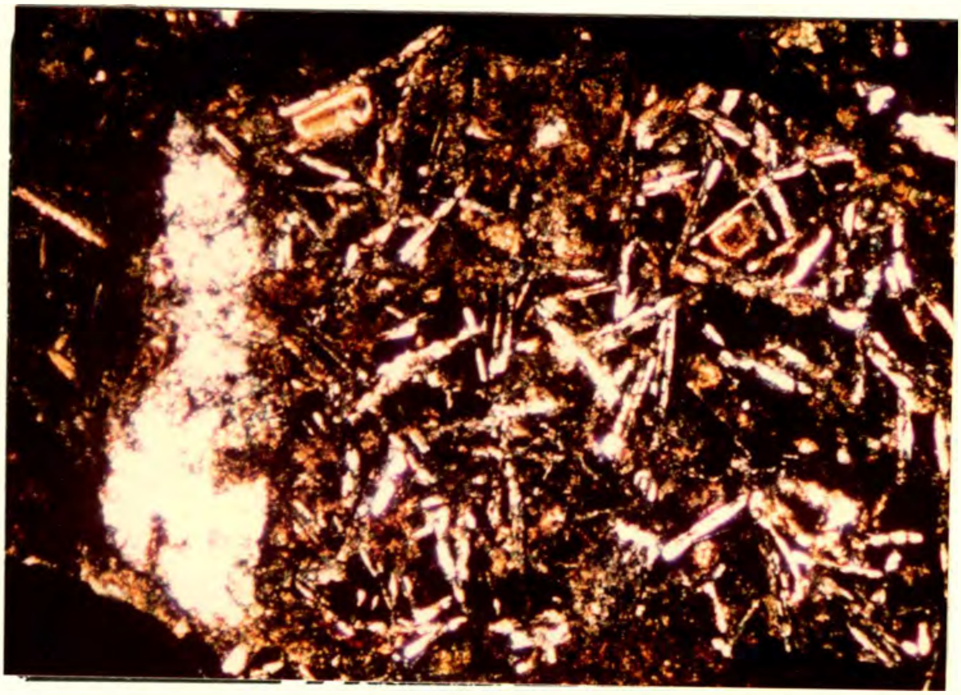

FIGURE 26. Basaltic rock fragment, eastern portion of the Aldwell. Long dimension of photomicrograph is 2.1 mm. Crossed nicols.

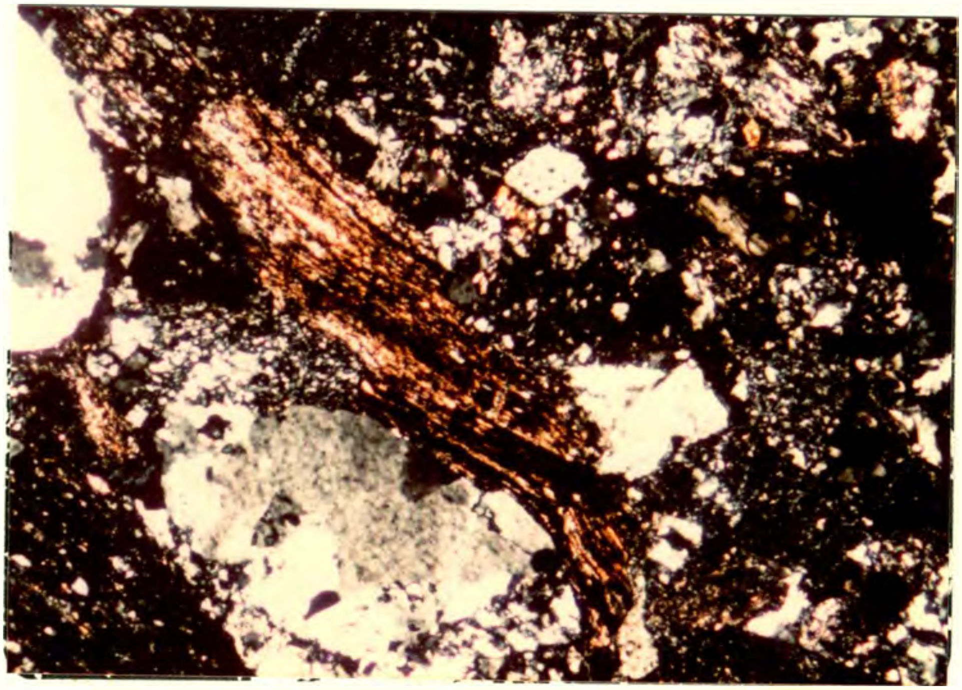

FIGURE 27. Phyllite clast showing distinct parallel alignment of micas, western portion of the Aldwell. Long dimension of photomicrograph is 2.1 mm. Crossed nicols.

Fossils observed were mainly foraminifera and rare bryozoan fragments. Plutonic clasts composed of quartz and plagioclase were also counted in this category.

Miscellaneous Rock Fragments- Unidentifiable rock fragments were counted in this category.

APPENDIX 3

POINT COUNT DATA

Point count data for the Aldwell Formation are given in table form. The data reflect the actual number of points counted in each category for a given sample. Sample numbers were assigned as follows: the first two letters are an abbreviation of the USGS topographic quadrangle from which the sample was collected, e.g., a sample beginning with the letters LP was collected from the Lake Pleasant quadrangle. The first number indicates which transect the sample was collected on. The last three numbers reflect the order in which the samples were collected on a given traverse; the numbers always begin at the lowest point in the section for any given transect. Figures 20 and 21 of Appendix 1 are sample location maps for transects made along Lake Crescent and the Sekiu River respectively.

POINT COUNT DATA FOR THE EASTERN PORTION OF THE ALDWELL FORMATION

300-point
total rock count:

Sample #	LC-1-030	LC-1-070	LC-1-075	LC-1-080	LC-1-085u
Qm	25	13	14	15	18
P	55	100	62	20	64
K	0	3	0	0	0
L	96	78	142	143	118
HEAV	20	5	4	6	1
MAT	41	68	51	77	19
CEM	48	7	14	31	71
PUMP	12	20	10	2	7
MISC	3	6	3	6	2

200-point rock
fragment count:

Qp+chert	2	2	0	1	14
Rvv	50	102	115	105	144
Rvl	69	31	19	72	17
Rvo	0	1	0	1	0
Rs	65	44	57	19	13
Rms	0	4	0	1	1
Other	12	13	9	0	7
Rmisc	2	3	0	1	4

300-point total
rock count:

Sample #	LC-1-105	LC-1-120	EL-1-050	EL-1-070
Qm	5	5	6	2
P	23	24	26	13
K	0	0	0	0
L	150	109	150	177
HEAV	2	6	0	0
MAT	0	75	93	42
CEM	111	58	23	61
PUMP	8	21	2	2
MISC	1	2	0	3

200-point rock
fragment count:

Qp+chert	*	0	0	0
Rvv	*	158	97	97
Rvl	*	17	35	9
Rvo	*	0	2	0
Rs	*	23	64	94
Rms	*	0	0	0
Other	*	0	0	0
Rmisc	*	2	2	0

Note: * indicates all lithic grains counted in the total rock count were volcanic fragments and therefore no rock fragment count was performed.

POINT COUNT DATA FOR THE WESTERN PORTION OF THE ALDWELL FORMATION

300-point
total rock count:

Sample#	LP-2-030	LP-2-035	LP-2-050	LP-3-015	LP-3-025
Qm	56	70	55	71	83
P	27	31	44	67	70
K	2	0	4	2	1
L	115	143	80	113	73
HEAV	12	6	11	1	5
MAT	64	34	0	34	53
CEM	8	8	93	3	3
PUMP	11	5	6	0	11
MISC	5	3	7	8	1

200-point rock
fragment count:

Qp+chert	159	169	107	151	126
Rvv	13	4	41	4	4
Rvl	6	6	7	0	3
Rvo	0	3	0	0	0
Rs	8	10	29	16	27
Rms	2	6	5	22	40
Other	8	0	6	6	0
Rmisc	4	2	5	1	0

300-point
total rock count:

Sample#	CB-1-005	CB-1-020	CB-1-050	CB-1-055	CB-2-063
Qm	40	33	24	66	27
P	28	23	14	30	42
K	0	2	0	0	2
L	183	206	253	141	197
HEAV	5	11	2	6	6
MAT	6	20	5	22	17
CEM	36	1	0	23	3
PUMP	1	1	1	9	0
Misc	1	7	1	3	6

300-point rock
fragment count:

Qp+chert	158	110	114	132	116
Rvv	6	5	2	1	5
Rvl	4	9	19	8	5
Rvo	3	9	5	2	2
Rs	23	15	44	25	13
Rms	6	38	16	29	39
Other	0	10	0	1	14
Rmisc	0	4	0	2	6

300-point
total rock count:

Sample#	CB-2-075	CB-2-080	CB-2-090	CF-1-015
Qm	61	49	68	100
P	46	32	29	73
K	0	1	0	4
L	158	174	148	22
HEAV	5	5	17	10
MAT	13	19	11	59
CEM	11	11	1	10
PUMP	4	4	16	12
MISC	2	5	10	10

200-point rock
fragment count:

Qp+chert	104	105	112	-
Rvv	1	6	6	-
Rvl	31	21	8	-
Rvo	11	3	0	-
Rs	48	25	24	-
Rms	4	33	45	-
Other	0	4	3	-
Rmisc	1	3	2	-

Note: - denotes that no rock fragment count was performed because of a lack of sufficient rock fragments.