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The Depositional Environment, Petrography, and Tectonic Implications of Informally Named Middle to Late Eocene Marine Strata, Western Olympic Peninsula, Washington

Benjamin Nickolas Adams
Western Washington University

THE DEPOSITIONAL ENVIRONMENT, PETROGRAPHY, AND TECTONIC IMPLICATIONS OF INFORMALLY NAMED MIDDLE TO LATE EOCENE MARINE STRATA, WESTERN OLYMPIC PENINSULA, WASHINGTON

A Thesis Presented to the
Faculty of Western Washington University

In Partial Fullfillment of
the Requirments for the Degree of
Master of Science

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by
Benjamin Nickolas Adams
June 1988

MASTER'S THESIS

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MASTER'S THESIS

Name: Ben Fackler-Adams (Ben Adams)

Signature: ______________________

Date: 5/12/18

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Accepted in Partial Completion

of the Requirments for the Degree

Master of Science

Graduate Dean

Committee Chair

ABSTRACT

The informally named marine strata examined in this study comprise fault bounded slivers of middle to late Eocene (Ulatizian to Narizian) siltstone, sandstone, and conglomerate exposed on the northwestern Olympic Peninsula. The strata are divided into three lithofacies: the sandstone of Bahobohosh, the siltstone of Waatch Point and the siltstone and sandstone of Bear Creek by Snavley et al.(1986). Six facies have been identified consisting of strata deposited by high- and low-density turbidites, storm waves, slumping, tidal or littoral currents, and debris flows. Relationships among the facies indicate shallow marine deposition that shoaled from below to above storm wave-base on the outer shelf.

The sandstone and conglomerate of the study unit consist mainly of predominantly angular to sub-angular, moderately to very poorly sorted lithic arenites. Quartz and plagioclase are the most common monocrystalline grains with potassium feldspar and epidote present in significant quantities. Lithic grains comprise 35% of all grains. The predominant types are polycrystalline quartz (including chert) followed by intrabasinal sedimentary clasts and basaltic volcanic lithics. A diverse source area consisting of dioritic, granodioritic, and granitic plutonic rocks or gneisses, basaltic volcanics, chert, and greenschist-grade metasedimentary and metavolcanic rocks is indicated.

The study unit most likely had a Vancouver Island source. Erosion of the Sicker, Vancouver, and Bonanza Groups and of the Island Intrusions and West Coast Complex, which together comprise Wrangellia on Vancouver Island, could generate the sediments of the study unit. The western position of the study unit argues against sources further east that would

have required large amounts of littoral transport to reach the depositional site. The probable Vancouver Island source and the shallow marine facies of the study unit imply that it formed as a sequence onlapping Vancouver Island. This probable onlap, in conjunction with the petrologic similarities between the study unit and the western portion of the coeval Aldwell Formation, that indicate a possible coextensive relationship, have implications regarding the Paleogene tectonics of the Pacific Northwest, particularly the setting of the Crescent terrane.

The Paleogene was a tectonically dynamic period in the northeast Pacific Basin. Subduction rates of the Kula and Farallon plates beneath North America were very high (> 100 km/my on the average), and major reorganizations of the Kula-Farallon ridge were taking place. The basaltic basement of the Crescent terrane, which the Aldwell Formation overlies, was generated during the early Eocene in a setting that may have been allochthonous (accreted oceanic plate or oceanic island chain) or autochthonous to North America (continental-margin-rift). If the study unit developed as a sequence onlapping Vancouver Island that was coextensive with the western portion of the Aldwell Formation, the Crescent terrane basalts must have been proximal to Vancouver Island during the middle to late Eocene. Therefore, an allochthonous origin for the Crescent terrane is unlikely.

Coeval shoaling sequences along western North America suggest eustatic control of shoaling in the study unit. However, the shoaling could have resulted from the uplift of the southern edge of Vancouver Island due to the underthrusting of the Crescent terrane or from the approach of the Kula-Farallon ridge to the Pacific Northwest during the Paleogene. Immature sediments and rapid sedimentation rates on the shelf could have resulted from either process.

ACKNOWLEDGMENTS

The love, support, and comraderie of everyone who was a part of my life during my time at Western gave me the juice to accomplish my goals and enjoy life at the same time.

My greatest love and thanks go to my parents, Richard and Phyllis. Their encouragement, and confidence in all of my endeavours have taught me that life's only limitations are self-imposed. The emotional, spiritual, and financial support I received from them have been invaluable. I love you both very much.

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My second family also deserves mention. From the moment I arrived at Western (to Patty's welcome), I felt the tight-knit warmth of the geo-community. I feel lucky (and somewhat amazed) to know all the wonderful people who have been my friends at Western; what a crew. I have especially fond memories of: participants in the Anomalies gigs, the 1985 and 1986 AGU trips, my roomates at Frog Hollow during my time as an autochthonous refugee, my ski-mates, and my housemates at Casa de Franklin (Malleta and Anna-Maria). I feel that these folks (you know who you are) are my life-long friends and I hope that we can stay in touch (at least off and on).

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With out the help of Bill Wilson and Clint Burgess in the instrument center at Western Washington University the geochemical portionn of this study would not have been completed.

I thank the Makah Tribal Council for thier cooperation and for acccess to tribally owned lands.

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INTRODUCTION

The purpose of this thesis is twofold. First, it is an investigation and analysis of the petrology, stratigraphy, and depositional environment of Eocene marine sedimentary strata on the Olympic Peninsula, Washington. The study unit is a fault-bounded block located between the Crescent thrust fault and the Calahwah left-lateral fault in the northwest corner of the Olympic Peninsula (Figures 1,2). Prior to this study, these strata have been mentioned only in passing or dealt with briefly. Therefore, one aim of this study is to provide a comprehensive and up-to-date petrologic and sedimentologic treatment of these marine strata. The petrology of the study unit was examined through both thin-section analysis of sandstones and field examination of conglomerates. Stratigraphic and facies relationships were determined through field observation and the measurement and analysis of six stratigraphic sections (Appendix 1). Second, the results of these petrologic and sedimentologic investigations are used to discuss the tectonic and paleogeographic implications raised by the geology of the study unit.

The discussion of these tectonic and paleogeographic implications within the context of existing plate-tectonic reconstructions is the second objective of this study. Addressing these implications is necessary due to the uncertainty and confusion about the origin of the Paleogene rocks comprising the Olympic Peninsula, and at a larger scale the origin of the Paleogene basement of the Washington-Oregon Coast Range. The study unit has been assigned a stratigraphic position directly overlying these basalts, which are designated the Crescent Formation which form the basement of the Coast Range on the Olympic Peninsula. It is this

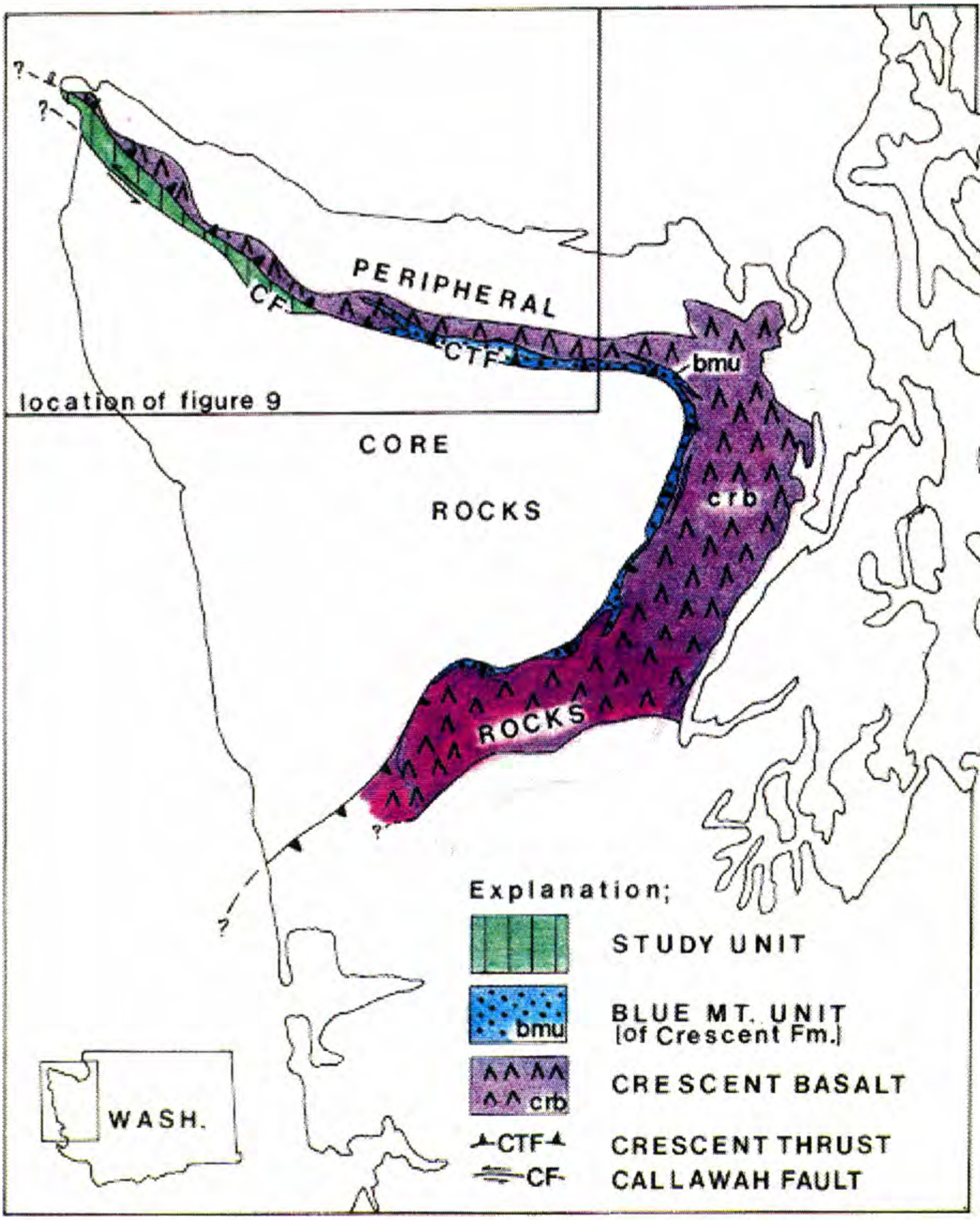


Figure 1; Generalized geologic map of the Olympic Peninsula showing the core and peripheral rocks, the study unit, and the two members of the Crescent Formation, the Blue Mountain unit and the Crescent basalt. The Crescent thrust fault, which separates the core and peripheral rocks, also bounds the study unit to the north. The Callawah fault bounds the study unit to the south.

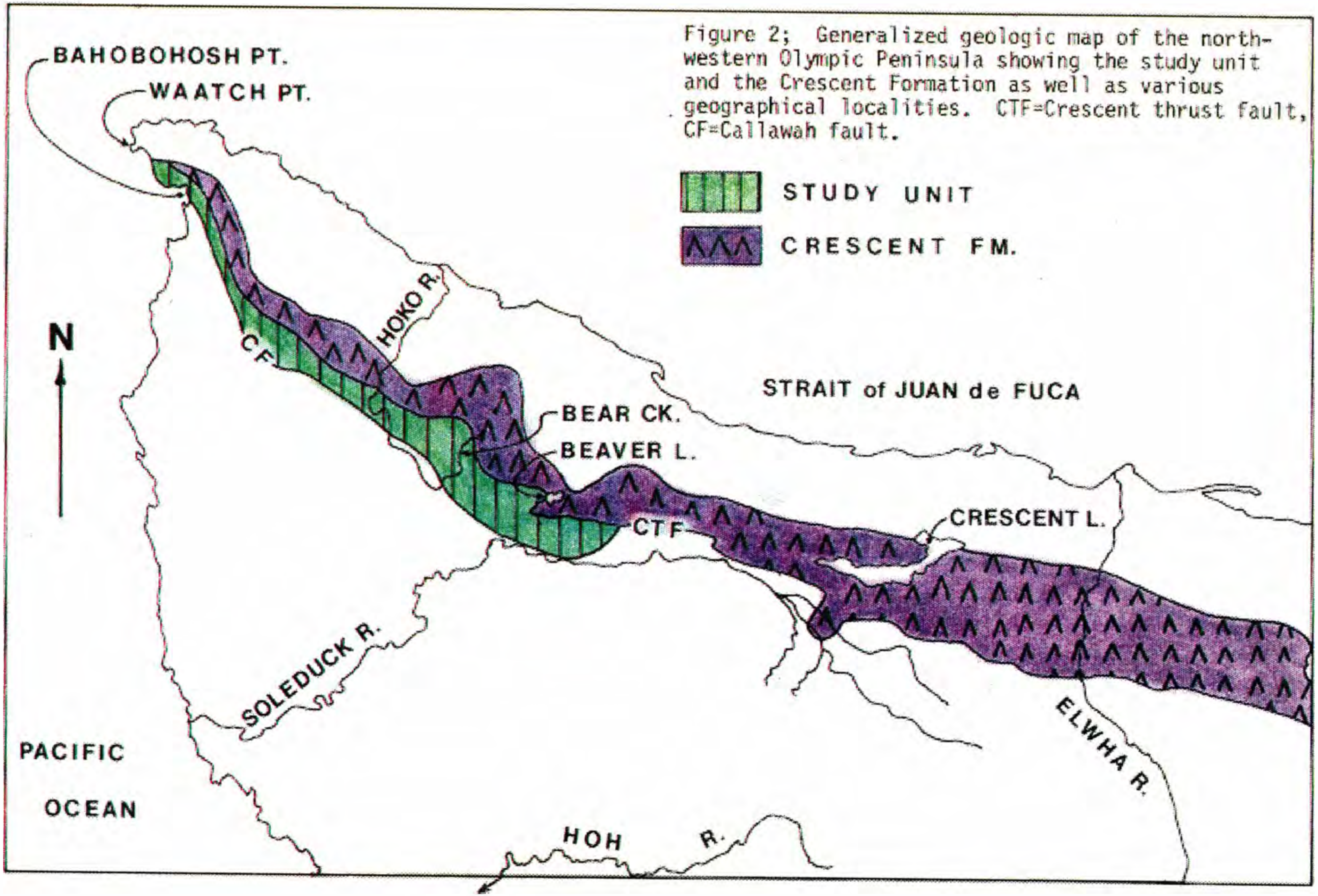


Figure 2; Generalized geologic map of the northwestern Olympic Peninsula showing the study unit and the Crescent Formation as well as various geographical localities. CTF=Crescent thrust fault, CF=Callawah fault.

position that makes the geology of the study unit relevant to the geologic history of the Washington-Oregon Coast Range. On yet a larger scale there is also considerable uncertainty in the Paleogene arrangement of the Kula-Farallon ridge and the location of the Kula-Farallon-North America triple junction (Figure 3). The Paleogene locations of these major tectonic boundaries are of great importance in determining the geologic history of the Coast Range basement. Analysis of the implications generated by this geologic study could provide some insight in attempting to answer some questions concerning Pacific Northwest geology.

Foremost among questions regarding the Coast Range is: what plate tectonic environment produced its basaltic basement and associated sediment? Models involving accretion of oceanic island chains or oceanic crust imply allochthonous formation of the Coast Range basalt and of coextensive to immediately overlying sediments. Conversely, generation of the basalt in a continental-margin rift environment implies autochthonous generation of the basalt and a continental source for coextensive and overlying sediments. The Geologic Setting section presents a detailed discussion of the various models for the formation of the Coast Range. Another important question about the Coast Range is: what sort of translation and dispersal history has the Coast Range had? By determining the provenance of the study unit, some constraints can be placed on the tectonic history and the paleogeography of the Pacific Northwest.

By attempting to delineate specific source areas petrographically and by using the stratigraphic analysis of the study unit to determine the nature of the sedimentary basin, this study tries to clarify the plate tectonic framework and paleogeography of the Pacific Northwest during the Paleogene.

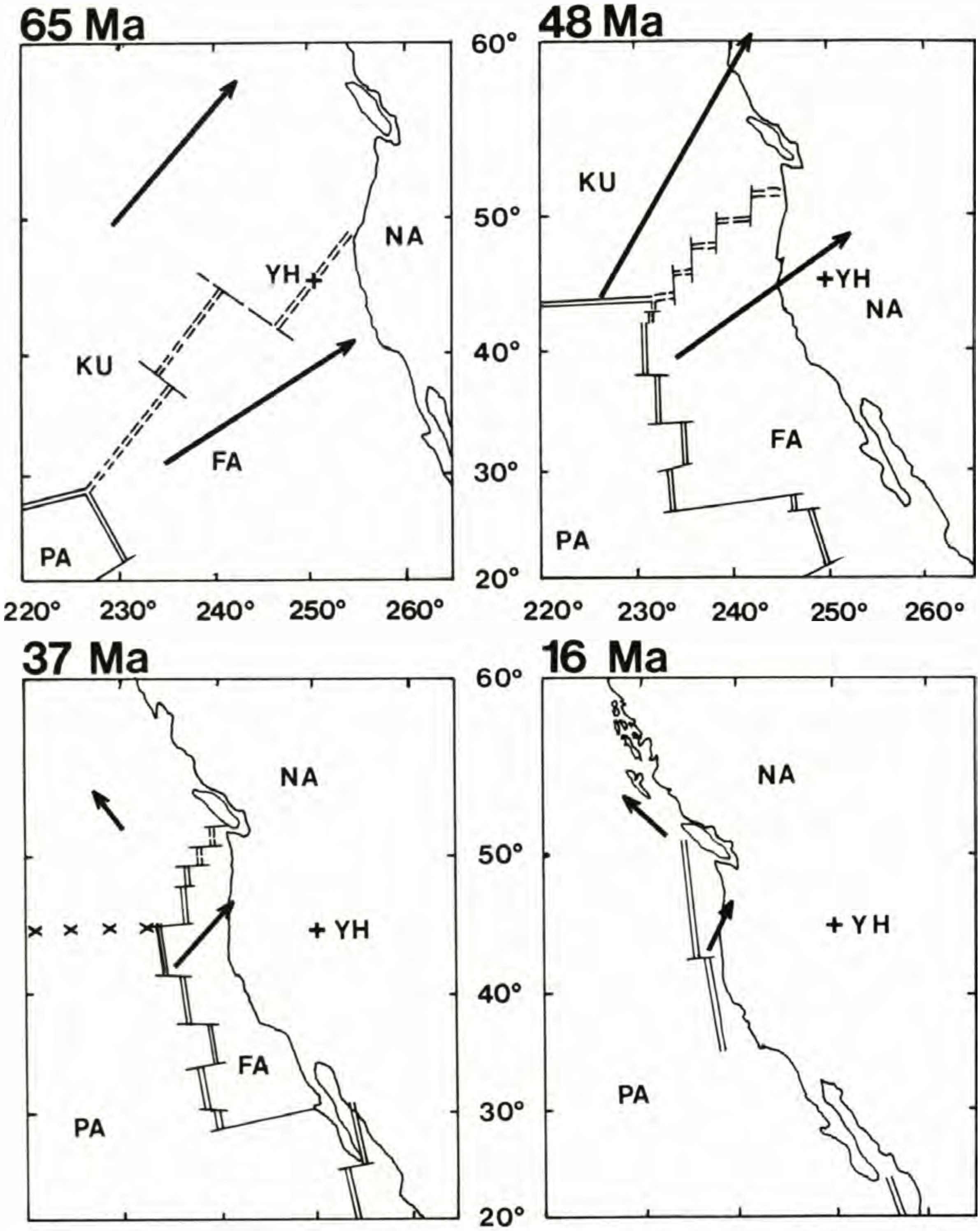


Figure 3; Plate tectonic reconstructions for 65, 48, 37, and 16 Ma showing the Kula (KU), Farallon (FA), Pacific (PA), and North American (NA) plates. The cross shows the probable location of the Yellowstone hotspot over time (YH). The arrows indicate the motion of the oceanic plates relative to North America. Note the dramaitc rearrangment of the Kula-Farallon boundery over time. Modifided from Wells et al., 1984.

TECTONIC AND GEOLOGIC SETTING

The Paleocene was a time of both tectonic and climatic change, on a global scale as well as in the northeastern Pacific basin. Worldwide, a general cooling trend occurred, beginning in the middle Eocene and reaching full intensity toward the late Oligocene (Shackelton and Kennett, 1975; Oberhansli and Hsu, 1986). At least two factors caused this gradual cooling. First, plate-tectonic displacements resulted in changes in oceanic circulation. The gradual deepening of oceanic basins between Greenland and Scandinavia and between Australia and Antarctica, as they rifted apart, allowed cold bottom waters formed at high latitudes to reach and circulate into the major ocean basins (Oberhansli and Hsu, 1986). Second, the encroachment of the African plate restricted equatorial currents flowing through the western Tethys Sea. This tectonic alteration of oceanic circulation patterns brought an end to the production of very warm surface waters through unrestricted circum-equatorial circulation with little or no input of cold bottom waters from the polar regions (Oberhansli and Hsu, 1986). These warm equatorial surface waters had warmed the oceans to high latitudes through advection by Gulf Stream-style currents. In conjunction with these plate tectonic/oceanographic effects, a general cooling trend linked to a 30 million-year-period climatic cycle aided in the gradual cooling of the globe through the middle to late Eocene and early Oligocene (Fischer, 1982).

Thus unrestricted equatorial circulation with little influx of cold Arctic bottom waters to the ocean basins had produced tropical and subtropical conditions extending into mid-latitudes during the early Eocene (Frakes, 1986). While stable isotope, foraminiferal, and floral data record a tectonically-induced global cooling during the middle and late Eocene (Oberhansli and Hsu, 1986), resulting in the onset of polar glaciation, cooling did not lead to an increase in the latitudinal temperature gradient from low to middle latitudes. This shifting of the temperate climatic belt into higher latitudes than are observed today is possibly the result of sluggishness in the rearrangement of oceanic circulation patterns (Oberhansli and Hsu, 1986). Temperature gradients at high latitudes steeper than those observed today allowed glaciation to begin while maintaining subtropical conditions into mid-latitudes (Frakes, 1986).

The occurrence of tropical and sub-tropical conditions at middle latitudes in conjunction with active plate movements in the northeastern Pacific basin during the Paleogene (Wells et al., 1984; Engebretson et al., 1985) provided weathering and sediment transport conditions that were favorable to rapid sedimentation rates in tectonically active basins. The Paleogene sedimentary rocks of the Olympic Peninsula are an example of strata deposited under these conditions.

The paleogeography of the Pacific Northwest is currently a subject of various interpretations and models (Simpson and Cox, 1977; Magill et al., 1981, Wells et al., 1984, among others). However, the majority of models and interpretations are constrained by paleomagnetic and plate tectonic interpretations and limited knowledge of plate boundary locations.

Plate tectonic reconstructions for the northeastern Pacific and relative plate motion geometries developed by Engebretson (1982) and Engebretson et al. (1985) are a re-evaluation of considerable work by many researchers (Atwater, 1970; Atwater and Molnar, 1973; Coney, 1972, 1978; Byrne, 1979, among others). These reconstructions (Figure 3) provide a framework in which to consider the Tertiary paleogeography of the Pacific

Northwest and the origins of the Washington-Oregon Coast Range, which comprises the basement of the study unit.

Four important characteristics of Pacific Northwest plate tectonics are shown by the reconstructions (Wells et al., 1984):

1. The Kula and Farallon plates moved northeast relative to North America and the hot spots throughout the Paleogene (Figure 3).

2. Previously high Farallon-North America and Kula-Farallon convergence rates fell rapidly between 43 and 28 Ma, with the major decrease at 43 Ma probably related to the death of the Kula-Farallon spreading ridge (Engebretson et al., 1985).

3. The Kula-Farallon ridge underwent at least three major reorganizations between 61 and 43 Ma (Figure 3)(Wells et al.,1984). These changes were coincident with changes in plate motions (rates and directions) along the Kula-Pacific, Farallon-Pacific, and Farallon-North America plate boundaries.

4. The Yellowstone hot spot, if it existed, was situated just off shore of Oregon during the Paleocene and early Eocene (Figure 3).

In addition, the plate tectonic reconstructions place the Kula-Farallon-North America triple junction at approximately the latitude of the Pacific Northwest during the Paleogene (Wells et al., 1984; Engebretson et al., 1985). However, the locations of Yellowstone hot spot and the Kula-Farallon-North America triple junction are very poorly constrained and, due this uncertainty interpretations based on their location are highly speculative.

Various models exist for the formation of the Coast Range. Accreted oceanic plate (Glassley, 1974), accreted oceanic island chain (Glassley, 1974; Cady, 1975; Magill et al., 1981; Duncan, 1982, Armentrout, in press)

(Figure 4a), accreted leaky transform volcanics (Wells et al., 1984) (Figure 4b), and accreted oceanic island arc (Lyttle and Clark, 1975) are all models that have been proposed.

The more or less in situ generation of the Coast Range basaltic basement through tectonic dismemberment of the continental margin by oblique convergence has been proposed by some workers (Wells et al.,1984) and implied by others (Moore et al., 1983; Plumley et al., 1983). This model calls for a geometry similar to that of the present-day Gulf of California or the Andaman Sea (Curray et al., 1979), where highly oblique convergence transports a volcanic/sedimentary terrane northward (Figure 5). Large rift basins floored by volcanic and hypabyssal basaltic rocks are left in the wake of these rifted terranes (Wells et al., 1984; Clowes et al., 1987). Of all the models, the rift-continental-margin model as delineated by Wells et al. (1984) (Figure 6) is favored here, because it accommodates the greatest number of geological constraints. Nevertheless, large uncertainties are inherent in any model generated from Paleogene plate tectonic reconstructions of western North America due the poorly constrained locations of the plate boundaries. The formation of the Coast Range basalt near the continental margin accounts for the presence of interbedded continentally-derived sediments within the basalts (Cady, 1975; Einarsen, 1987). In addition, the oblique-convergence model accommodates the preferred area of formation for the Chugach and Prince William terranes as proposed by Moore et al. (1983) and Plumley et al. (1983) (Figure 6). These two terranes are interpreted to have formed as subduction complexes at approximately $40^{\circ} \pm 6^{\circ}$ north latitude (Plumley et al., 1983).

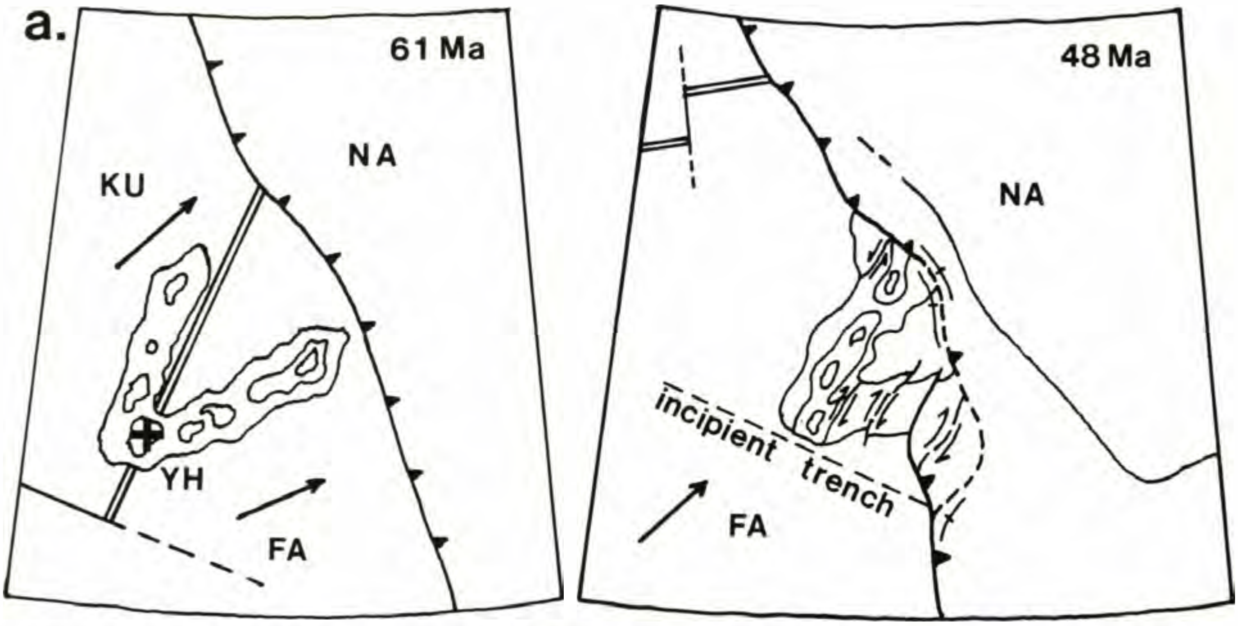


Figure 4A; Accreted oceanic island chain model of Coast range basalt formation. Arrows indicate the motion of the Kula plate (KU) and the Farallon plate (FA) relaive to North America (NA). Note the younging towards the center pattern implied by this model and the complex accretionary history of the terrane. Modified from Wells et al., 1984.

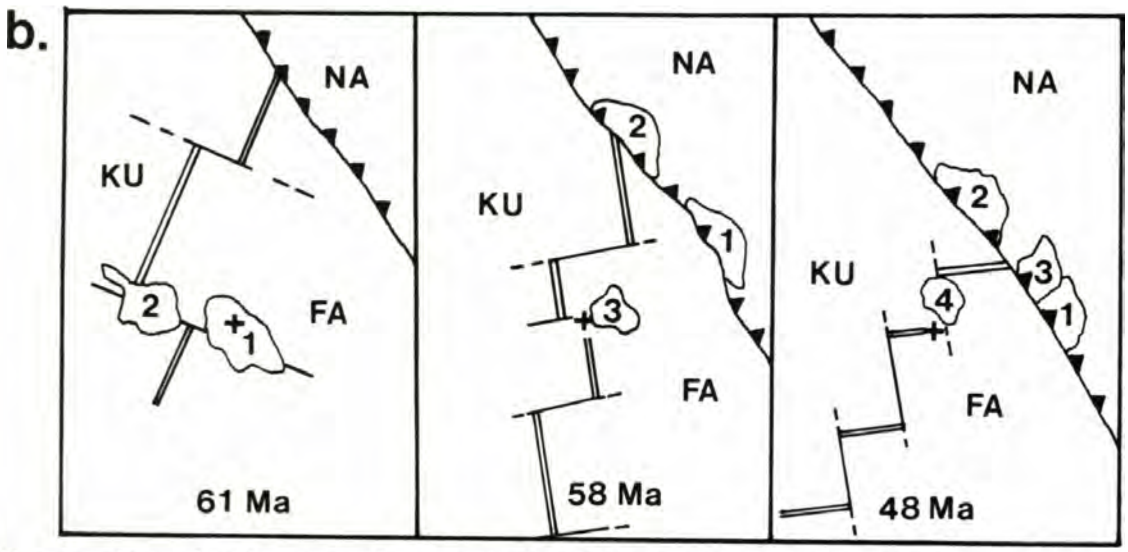


Figure 4B; Leaky trnsform model of Coast Range basalt formation. Kula (KU) and Farallon (FA) plate reconstructions at 61, 58, and 48 Ma. Note again the dramatic rearrangment of the kula-Farallon boundary and the complex accretionary history required by this model. Modified from Wells et al., 1984.

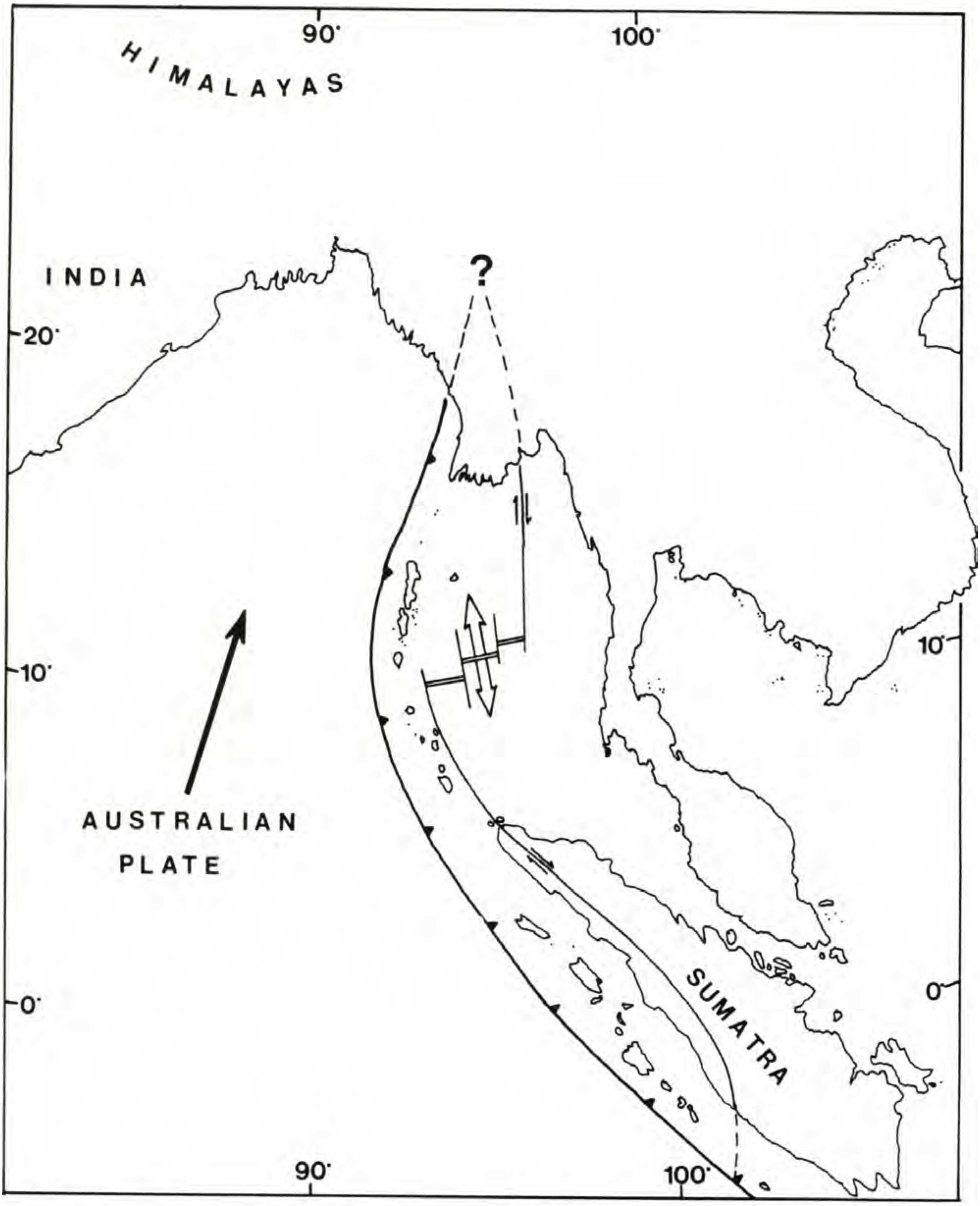


Figure 5, Modern tectonic arrangement of the eastern Indian Ocean. Highly oblique convergence of the Australian Plate has caused tectonic dismemberment and poleward translation of portions of the Sumatra arc and forearc. As a result spreading ridges have developed in the Andaman Sea. Modified from Curray et al., 1979.

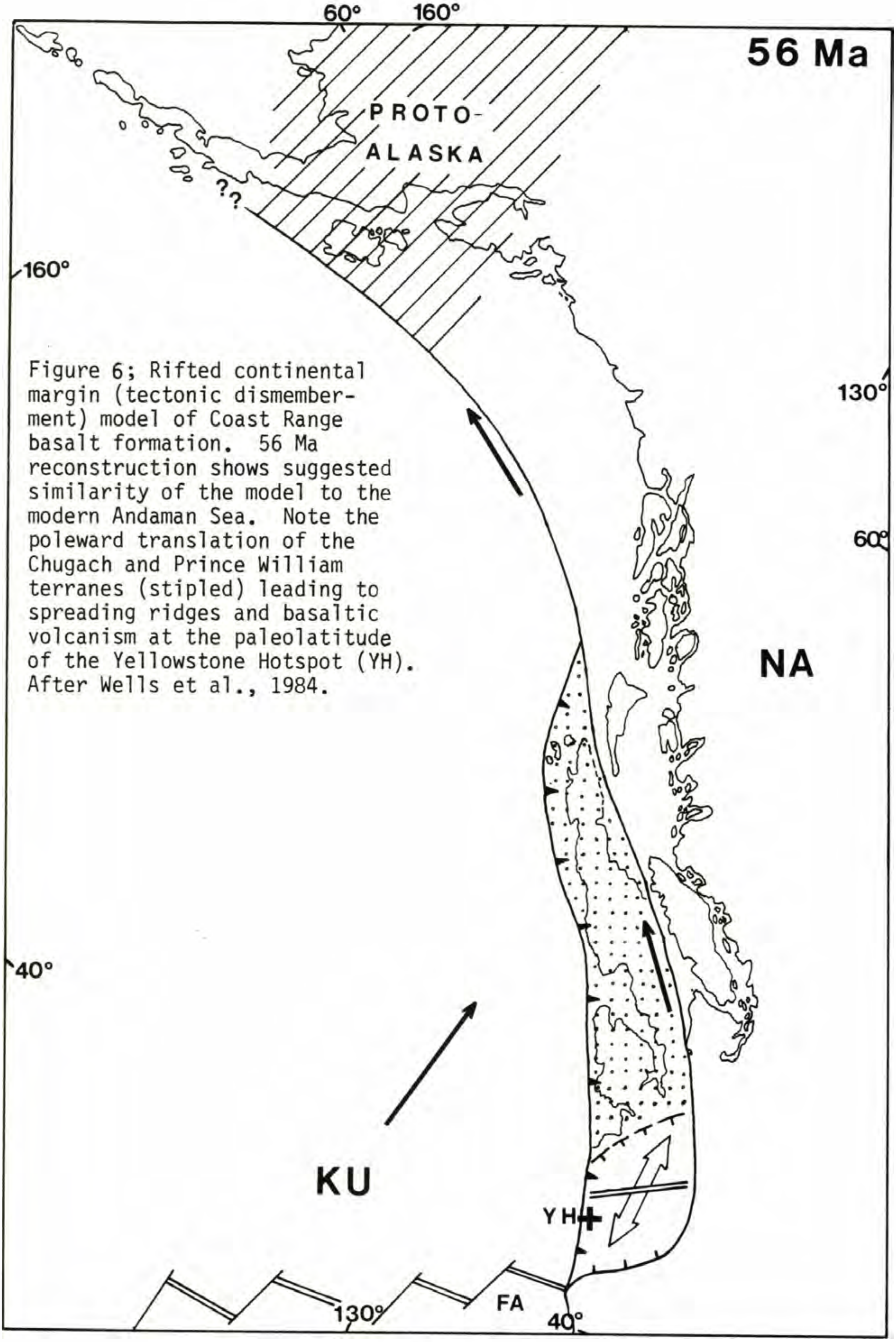


Figure 6; Rifted continental margin (tectonic dismemberment) model of Coast Range basalt formation. 56 Ma reconstruction shows suggested similarity of the model to the modern Andaman Sea. Note the poleward translation of the Chugach and Prince William terranes (stipled) leading to spreading ridges and basaltic volcanism at the paleolatitude of the Yellowstone Hotspot (YH). After Wells et al., 1984.

Regardless of which model is assumed, the basic paleogeography at about 48 Ma is the same (Dickinson, 1979; Hammond, 1979; Nilsen and McKee, 1979; Wells et al., 1984; Armentrout, in press). The basaltic basement of the Coast Range was part of the North American plate. A series of elongate blocks of this basaltic crustal material as well as the Klamath Mountains probably formed the northern and eastern margins of the Columbia embayment (Figure 7). Northeastward-directed subduction of the Kula and Farallon plates prior to 48 Ma had probably resulted in arc magmatism in the Challis/Absaroka arc (Snyder et al., 1976). Between 48 and 43 Ma an approximately 5 to 20^{o} northward shift in subduction direction occurred along the North American margin (Wells et al., 1984; Engebretson et al., 1985). This shift in plate motion could have initiated the clockwise rotation of the Coast Range and Klamath blocks away from the Challis/Absaroka arc and toward its present position (Hammond, 1979; Wells et al., 1984). In this scenario, rotation of the Coast Range blocks occurred differentially (Wells and Coe, 1979; Beck and Plumley, 1980) with minimal rotation of the northernmost block until the latest Paleogene and early Neogene (Moyer, 1985). Initial rotation of the Coast Range and Klamath blocks away from the Challis/Absaroka arc may have occurred along the Olympic-Wallowa lineament (OWL) according to Hammond (1979)(Figure 7).

During this probable rotation of the Coast Range and Klamath blocks a major change was taking place in Pacific Northwest geology. The locus of arc magmatism was shifting from the Challis/Absaroka arc to the ancestral Cascade arc. Magmatism in the Challis/Absaroka arc ceased at 41 Ma in northestern Washington (Pearson and Obradovich, 1977) and at 38 Ma in Idaho (Armstrong, 1975). Cascade arc magamatism initiated at approximately 37 Ma (Vance, 1982).

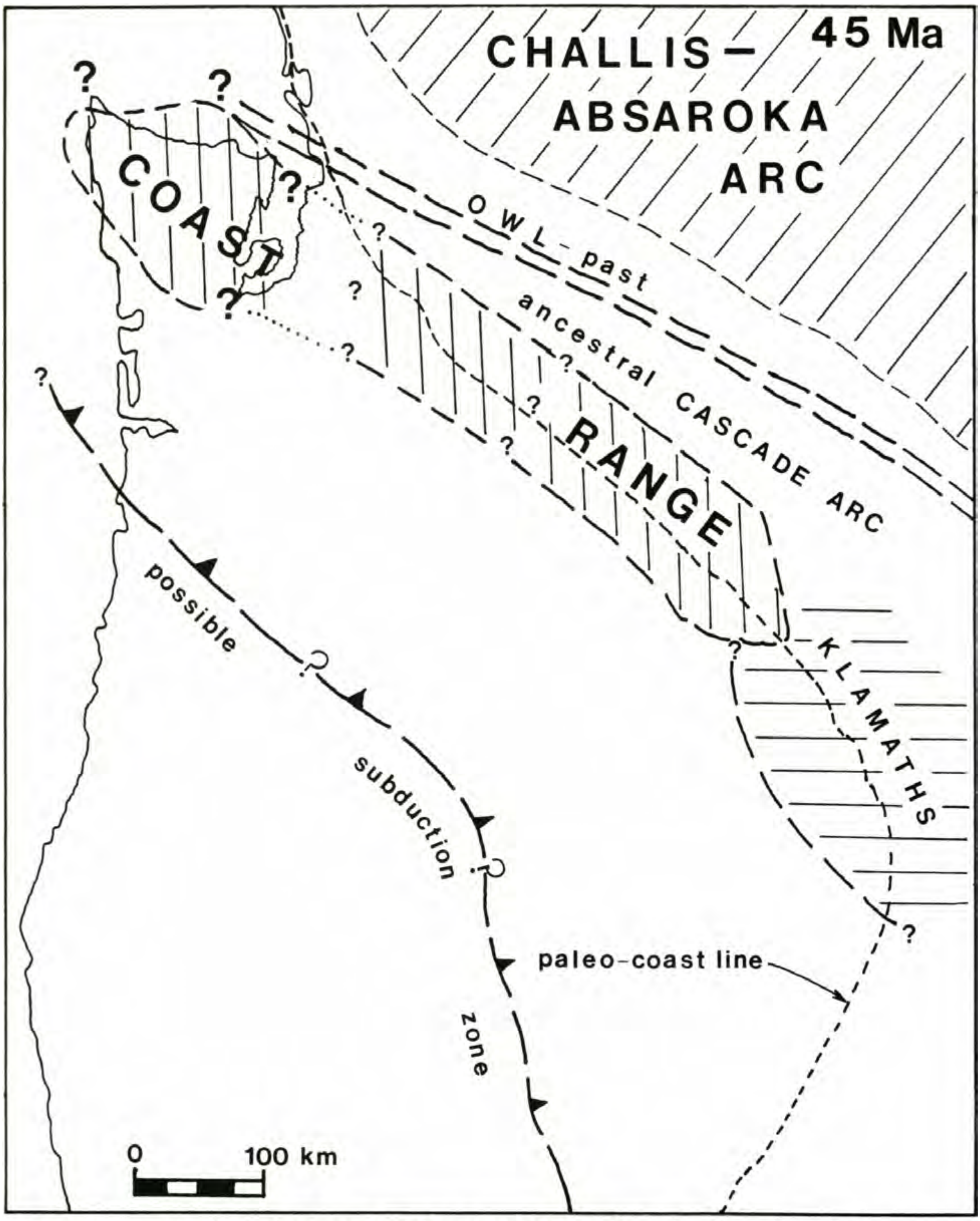


Figure 7; 45 Ma paleogeographic reconstruction showing the post-accretionary location of the Coast Range/Klamath block, Challis-Absaroka arc magmatism, and the proto- Cascade arc. Rotation of the Coast Range/Klamath block is believed to have initiated along the Olympic-Wallowa lineament (OWL). After Hammond, 1979.

The minimal rotation of the northern Coast Range relative to other Coast Range blocks probably resulted from buttressing of this northern block against the thick pre-Tertiary crust Vancouver Island and the Northwest Cascades that flanked the northern and northeastern edges of the Coast Range (Beck and Engebretson, 1982). High rates of northeast-directed Kula and/or Farallon plate subduction (~10 cm/yr) beneath North America from early Eocene through Miocene time could have caused oroclinal bending of the northern Coast Range block and thrust it under the Tertiary margin of North America (Beck and Engebretson, 1982). Thrusting of the recently formed, and probably buoyant, basaltic rock of this northern block under Vancouver Island and the North Cascades could have produced uplift of this overriding plate (Figure 8). This uplift would result in rapid erosion of the uplifted areas and provide large quantities of sediment to the ancestral Cascade forearc. These sediments are represented by the Paleogene sedimentary rocks of the Olypmic Peninsula, Vancouver Island, and western Washington.

Cenozoic rocks of the Olympic Peninsula have been divided into two main provinces, the core rocks and the peripheral rocks (Tabor and Cady, 1978) (Figure 1). These provinces were subsequently redefined as the Olympic Core terrane and the Crescent terrane by Silberling and Jones (1984) as their geologic and tectonic histories became better understood. Most recently, Snavely et al. (1986) have defined a number of "subterranes" within these main provinces (see Previous Work section).

The Olympic Core terrane consists of highly deformed, penetratively sheared, Eocene to Miocene sediments and interbedded volcanics that have been metamorphosed from zeolite through lower greenschist facies (Tabor and Cady, 1978). Fault-bounded structural packages, produced by imbricate

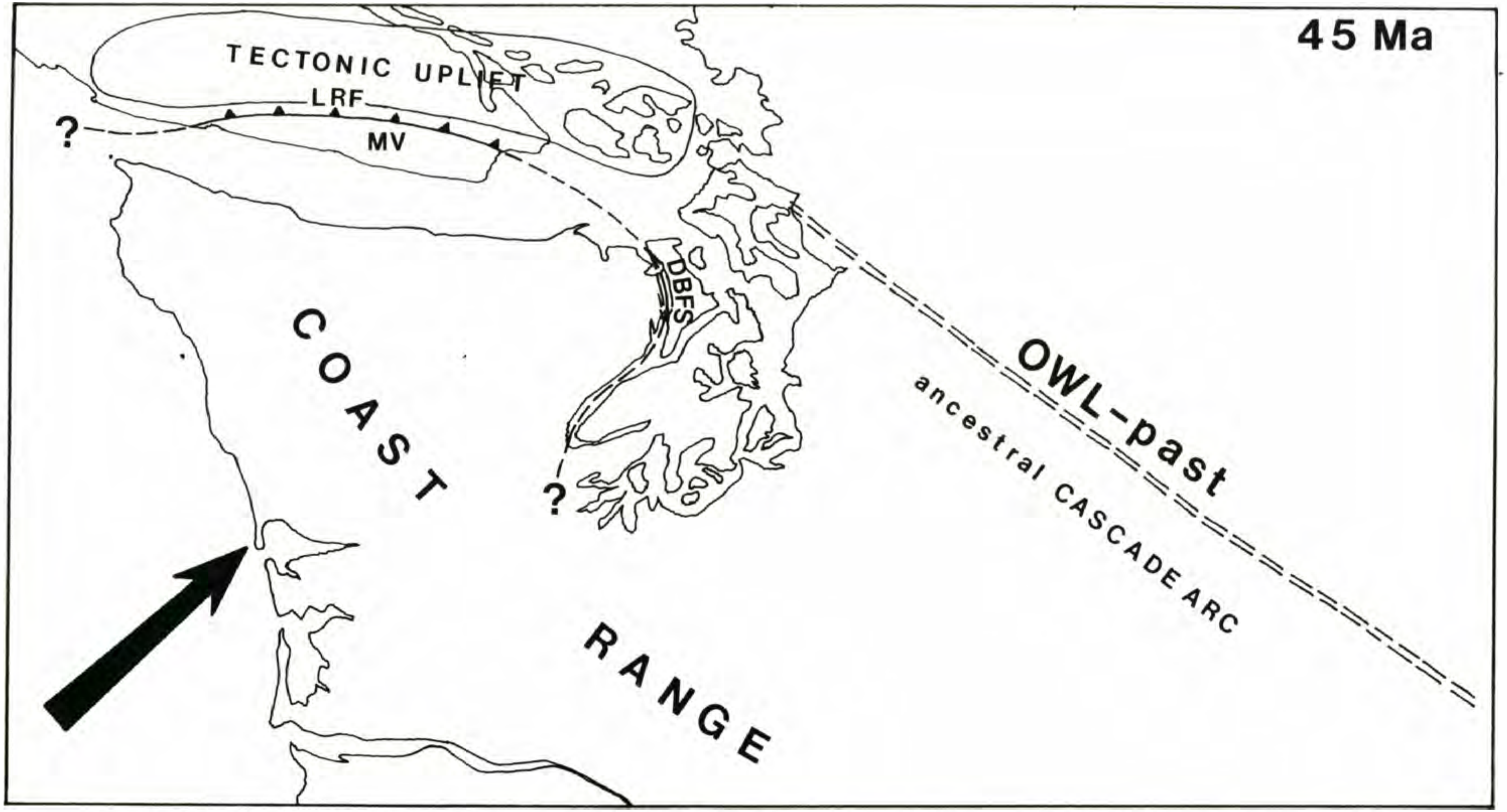


Figure 8; 45 Ma reconstruction showing the direction of Farallon plate subduction, the possible tectonic boundary between the Coast Range and North America along the Leech River (LRF) and Discovery Bay (DBFS) faults, and the locations of the ancestral Cascade arc and the Olympic Wallowa lineament. Note the area of possible tectonic uplift resulting from underthrusting of the Crescent terrane. After Hammond, 1979.

thrusting and underplating of marine sediments in a subduction complex, young westward while dipping, and becoming more recrystallized and sheared eastward. These packages have been thrust under the Crescent terrane along the Crescent and associated thrust faults (Tabor and Cady, 1978) (Figures 1,9).

The Crescent terrane is comprised of the Crescent Formation and overlying marine sedimentary units. The Crescent Formation consists of an arcuate belt of early to middle Eocene tholeiitic basaltic rocks and interbedded marine sediments (Figure 1).

Strata overlying the Crescent Formation are middle Eocene to Miocene marine sediments with minor volcanics (Armentrout, in press; Snavely et al., 1986). Underplating and imbricate thrusting of the core rocks have tilted and exposed the full sequence of peripheral rocks (Figure 9). Consequently, the peripheral rocks are mildly folded (overturned in places), faulted and generally dip away from the core.

The study unit consists of strata assigned to the Crescent terrane (see Previous Work section) that have been tectonically emplaced between the Olympic Core Terrane and the base of the Crescent Terrane (Figures 1, 2). These strata form a thin sliver of rocks that crops out between Cape Flattery and Beaver Lake. This sliver is bounded on the north by the western extension of the Crescent thrust fault and on the south by the Calahwah strike-slip fault (Figures 1,2).

The Metchosin Volcanics on southern Vancouver Island are correlative to the Crescent Formation (Cady, 1975; Armentrout et al., 1983, Armentrout and Suek, 1985; Massey, 1986). The shallowly northwest-dipping Leech River fault (Clowes et al., 1987) separates this northernmost portion of the Crescent terrane from the rest of Vancouver Island (Figure 8). The

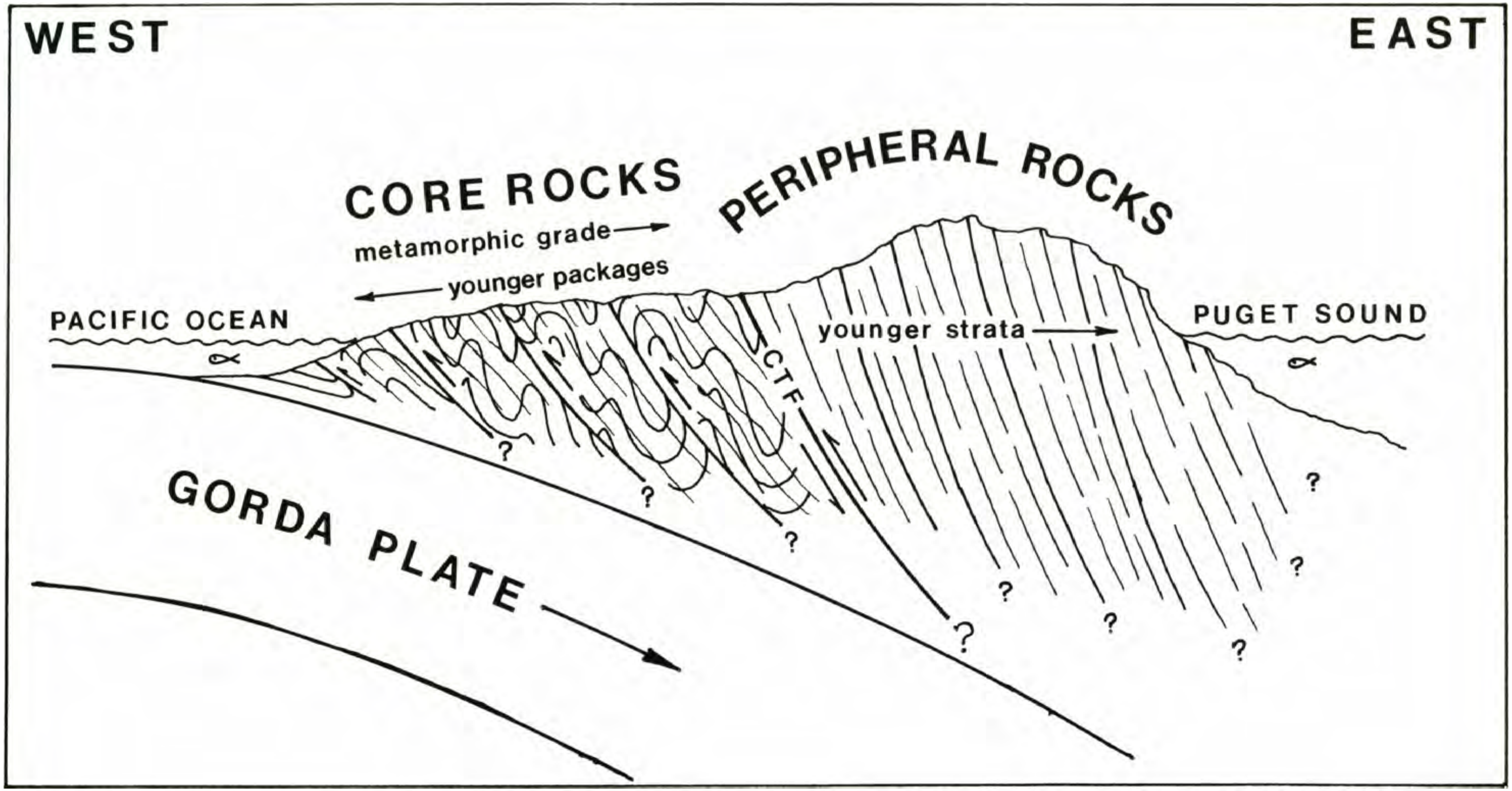


Figure 9; Cartoon cross-section of the Olympic Peninsula (West to East) showing the subducting Gorda plate (Farallon remnant) and the core and peripheral rocks. CTF=Crescent thrust fault. See text.

east-dipping Discovery Bay fault system (Figure 8) is believed by some to be the southern extension of the Leech River fault (MacLeod et al., 1977; Fairchild, 1979; Fairchild and Cowan, 1982). As such, these two faults could form a major tectonic boundary between the accreted Crescent terrane (Coast Range) and North America (Fairchild and Armentrout, 1984). However, after examination of new gravity and magnetic data, Roberts and Engebretson (1987) have proposed that the boundary lies further east where an extreme gravity low is present.

In summary, the sediments of the study unit were deposited during the middle to late Eocene in a tectonically active basin that was probably the result of tectonic dismemberment of the continental margin. The active tectonics of the basin and the relative proximity of the source areas resulted in the delivery of texturally immature sediment to the basin as well as producing high sedimentation rates. The tropical to subtropical paleoclimate of the region contributed to deep weathering of the source areas and aided in the rapid transport of the sediment to its depocenter.

PREVIOUS WORK

Until recently, the treatment of the sedimentary unit analysed here has been inconsistent in the literature with regard to both the formation names applied to it and its stratigraphic position within the peripheral rocks.

The Solduc Formation was originally used by Reagan (1909) in describing exposures of Eocene marine sedimentary rocks south of the Crescent Formation between the Elwah River and Beaver Lake (Figure 9). Weaver (1937) used the name Solduc Formation in reference to these Eocene marine sedimentary rocks and called rocks of the study unit exposed along the northwestern edge of Cape Flattery the Hoh Formation. However, in a subsequent publication, Weaver et al.(1944) named the rocks exposed between the Solduc River and Crescent Lake as the type locality of the Hoh Formation (Figure 9). In the same publication, Weaver inconsistently states that only the rocks exposed in the vicinity of the mouth of the Hoh River should be termed the Hoh Formation.

Drugg (1958) returned to the use of Solduc Formation in referring to rocks exposed south of the Crescent Formation in the Hoh River area and to those exposed along the Solduc River to the west. He placed them stratigraphically below the Crescent Formation on the basis of their position adjacent to its base and apparent lack of faulting.

Due to this confusion, subsequent authors have dropped these names altogether. Gower (1960) assigns these now informally-named rocks to a position stratigraphically below the Crescent Formation on the basis of reported microfossil occurrences from rocks exposed in the southern portion of the Olympic Peninsula, near Humptulips, that are tentatively correlated with this northern sedimentary unit. Gower described these rocks as argillites and "greywackes", lumping together two units subsequently differentiated into the early to middle Eocene Blue Mountain unit (Figure 7) and unnamed middle to late Eocene marine sedimentary rocks by Tabor and Cady (1978).

A 1972 Ph.D. thesis by V.J. Ansfield dealing with the Lyre Formation (Figure 10) incorrectly treated the study unit as the lower member of the Lyre Formation. Stratigraphic and paleocurrent data from the study unit was collected and analysed. While Ansfield's (1972) stratigraphic treatment was incomplete and oversimplified, the petrologic and paleocurrent data are relatively complete and largely in good agreement with this study.

Tabor and Cady (1978) placed the study unit in thrust contact with the base of the Crescent Formation but stratigraphically younger than it (middle to late Eocene) (Figure 10) on the basis of microfossil occurrences. They provide a brief lithologic description of the unnamed unit and compare it to the lower member of the Twin River Foramtion and the Lyre Formation of the peripheral rocks. Tabor and Cady reference written communication with P. D. Snavely, Jr., N. S. MacLeod, and J. E. Pearl in 1974 as their source for the microfossil date assigned to the sedimentary unit.

Muller et al. (1983) reported a structural relationship of this unit to the Crescent Formation similar to that reported by Tabor and Cady (1978) but correlated it stratigraphically witn the upper Eocene Aldwell Formation. More recently this unnamed Eocene rock unit was examined by Snavely et al. (1986) in their U.S.G.S. Open-File Report 86-344B which consists primarily of a detailed map. Here the rocks, described as the newly delineated terrane south of the Crescent thrust fault and north of the Calawah fault, are broken into four lithofacies of two distinct ages

(Figure 10). The sandstone of Bahobohosh and the siltstone and sandstone of Waatch Point are differentiated on the basis of lithology and assigned to the Narizian Stage. The assignment of these units to the Narizian Stage makes them coeval with the Aldwell Formation to which they have been compared (Figure 10). The third unit, the siltstone and sandstone of Bear Creek, is assigned to the early Narizian to late Ulatisian Stages and consists of lithologies very similar to those of the younger units.

The fourth unit assigned to their terrane by Snavely et al. (1986) consists of the Ulatisian sedimentary and basaltic strata of Hobuck Lake (Figure 10), which were previously assigned to the Crescent Formation (Penutian and Ulatisian Stages) by Tabor and Cady (1978). This switch in affinity is justified on the basis of occurrences of upper Ulatisian Stage foraminifera in this unit as well as depositional relationships with the Crescent Formation. The Hobuck Lake unit will not be considered in this study.

Armentrout (in press) delineates a series of five unconformity-bounded sequences which encompass Crescent terrane stratigraphy (Figure 11). The first two sequences are pertinent to this study. Sequence I consists of the Crescent Formation and associated marine sedimentary rocks in addition to the correlative Metchosin Volcanics (Cady, 1975; Armentrout, 1983, Armentrout and Suek, 1985), Siletz River Volcanics (Snavely et al., 1968), and Roseburg Formation (Baldwin, 1964). The sequence grades from late Paleocene marine basalts to late middle Eocene shallow marine and locally subaerial volcanic rocks (Cady, 1975; Armentrout, in press). This pattern is interpreted to represent localized building of eruptive centers (Snavely et al., 1968; Cady, 1975). According to Armentrout (in press) the base of Sequence I is not exposed

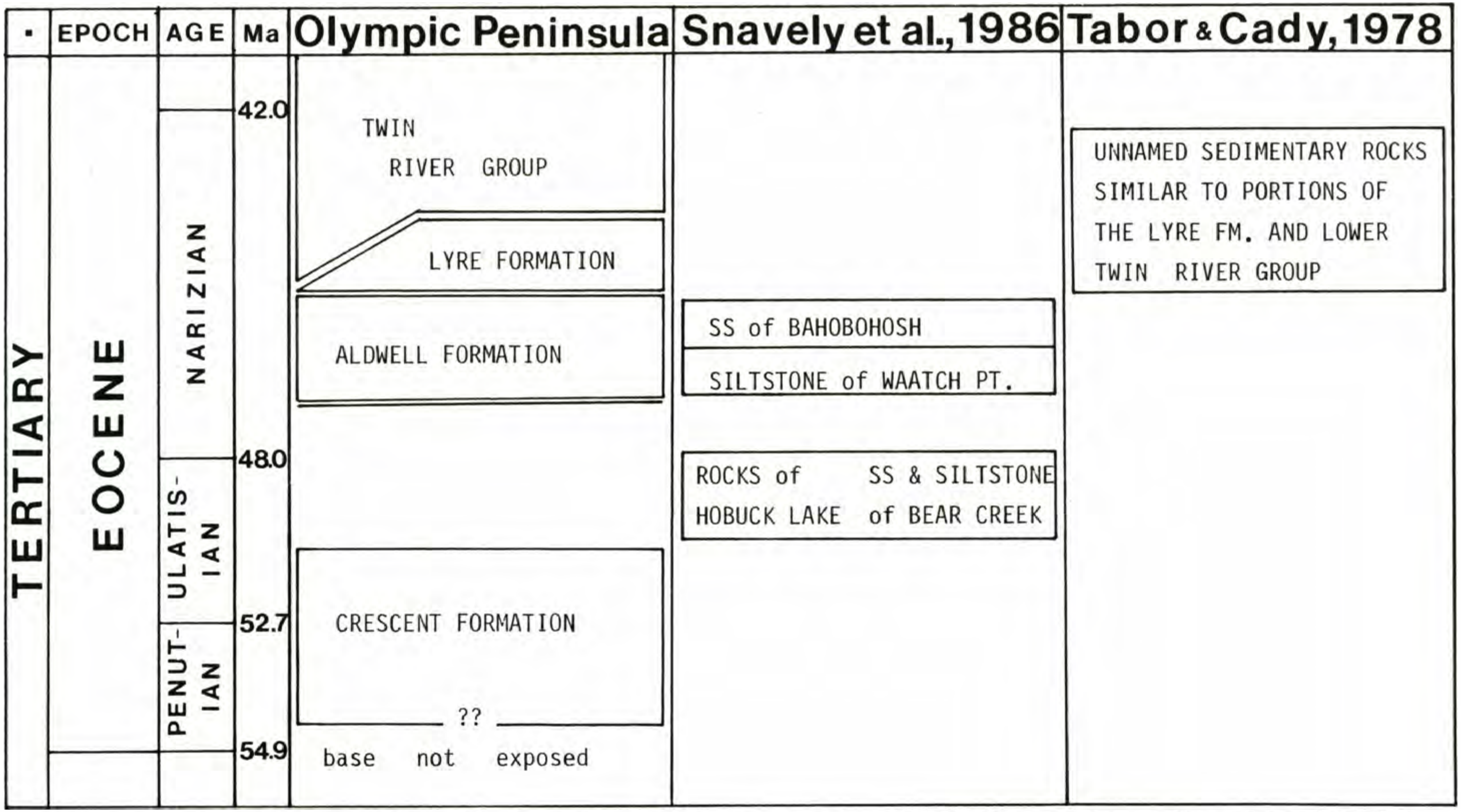


Figure 10; Composite stratigraphic comparison chart for the northwest Olympic Peninsula. Stratigraphy of the Olympic Peninsula After Tabor and Cady, 1978. Also shown are the stratigraphic assignments of the study unit by Snavely et al., 1986 and by Tabor and Cady, 1978.

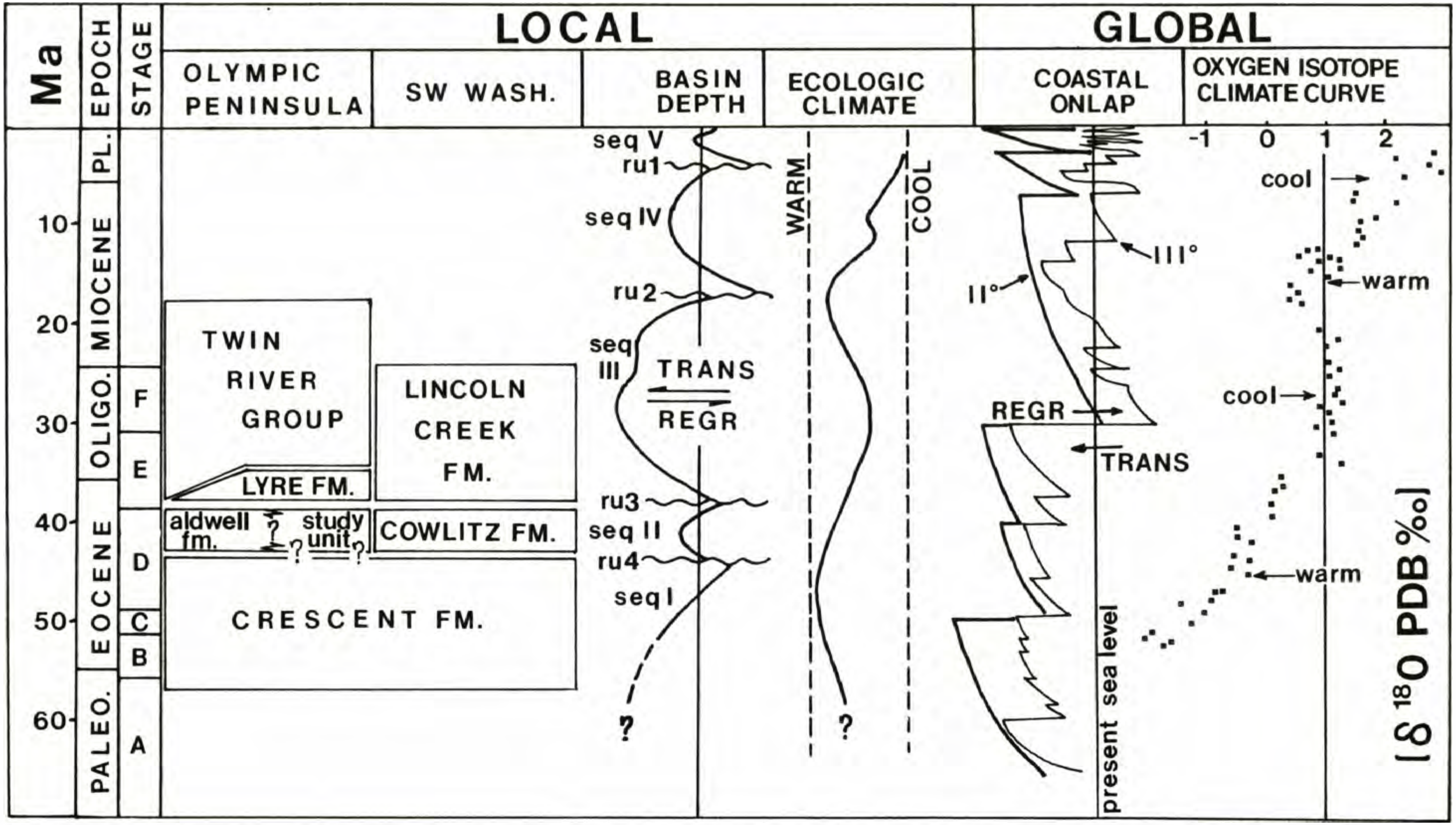


Figure 11; Cenozoic patterns of bathymetry and climate on the Olympic Peninsula compared with global coastal onlap and oxygen-isotope derived climatic curves. Note the relatively good fit between global and Olympic Peninsula bathymetric and climatic fluctuations. From Armentrout, in press.

but is presumably unconformably overlying earliest Paleocene deep marine sedimentary rocks.

Sequence II consists of middle to late Eocene shallow marine and in some cases deltaic sedimentary rocks represented by the Cowlitz Formation and the correlative Aldwell, Lyre, and Coaledo Formations (Armentrout et al., 1983; Snavely et al., 1977). Sequence II is separated from Sequence I by a regional unconformity, designated RU_4 by Armentrout, believed to have resulted from uplift in the forearc region caused by northeast-directed subduction (Wells et al., 1984). Sequence II is separated from Sequence III by another regional unconformity, RU_3, that is interpreted to result from thermal uplift associated with the onset of ancestral Cascade arc magmatism (Armentrout, 1973; Wells et al., 1984).

Strata comprising Sequence II record a deepening and then shallowing of relative sea level within the local basins that Armentrout (in press) interprets as possibly resulting from local tectonic events. However, examination of the literature covering units of similar age (Cowlitz Formation, Snavely et al., 1951; Coaledo Formation, Chan and Dott, 1986; Poway Group, Kennedy, 1975) reveals a similar trend for all of western North America during the middle to late Eocene. This similarity suggests eustatic control of water depth in Sequence II.

Thus Sequence II encompasses middle to late Eocene sediments and volcanics deposited during the transgressive-regressive cycle of relative sea level change. That at least some of the transgressive-regressive cycle could be due to eustatic effects is suggested by the occurrence of similar sea level fluctuations recorded in middle to late Eocene strata the length of western North America.

DEPOSITIONAL ENVIRONMENT

INTRODUCTION

The lithofacies described by Snavely et al. (1986) and discussed in the previous section are separated geographically (Figures 10, 12). Exposure of the Bahobohosh and Waatch Point lithofacies occurs primarily along the cliffs and wave-cut benches on the western coast of Cape Flattery (Figure 12). Inland, the Bear Creek Lithofacies is exposed along the more limited logging road cuts and associated quarries. As a result more is known about the stratigraphy and sedimentology of the coastally exposed lithofacies.

The strata of the unit as a whole are disrupted and truncated by many mapped (Snavely et al., 1986) and unmapped faults and are folded in places. Consequently, correlation of measured sections (Appendix 1) and recognition of repeated sequences is difficult. Despite this problem, approximately 550 meters of section were measured and described in detail (see Appendix 1). On the basis of these observations, five facies, some of which are subdivided into subfacies, have been delineated (Table 1).

Facies A consists of thinly interbedded sandstone and shaley siltstone. Facies B contains interbedded shaley siltstone and varying proportions of coarser, thicker sandstone. Facies C consists of hummocky cross-stratified (HCS) beds. Lenticular, high-angle cross-stratified pebbly sandstone to granule conglomerate beds comprise facies D. Disorganized to normally graded conglomerate beds of three distinct types comprise facies E. Facies F consists of convoluted or olistrostromal intervals originally resembling facies, A, B, and possibly C.

The interbedded sandstone and siltstone of facies A occur as a "stratigraphic matrix" or background sedimentary deposit that the other

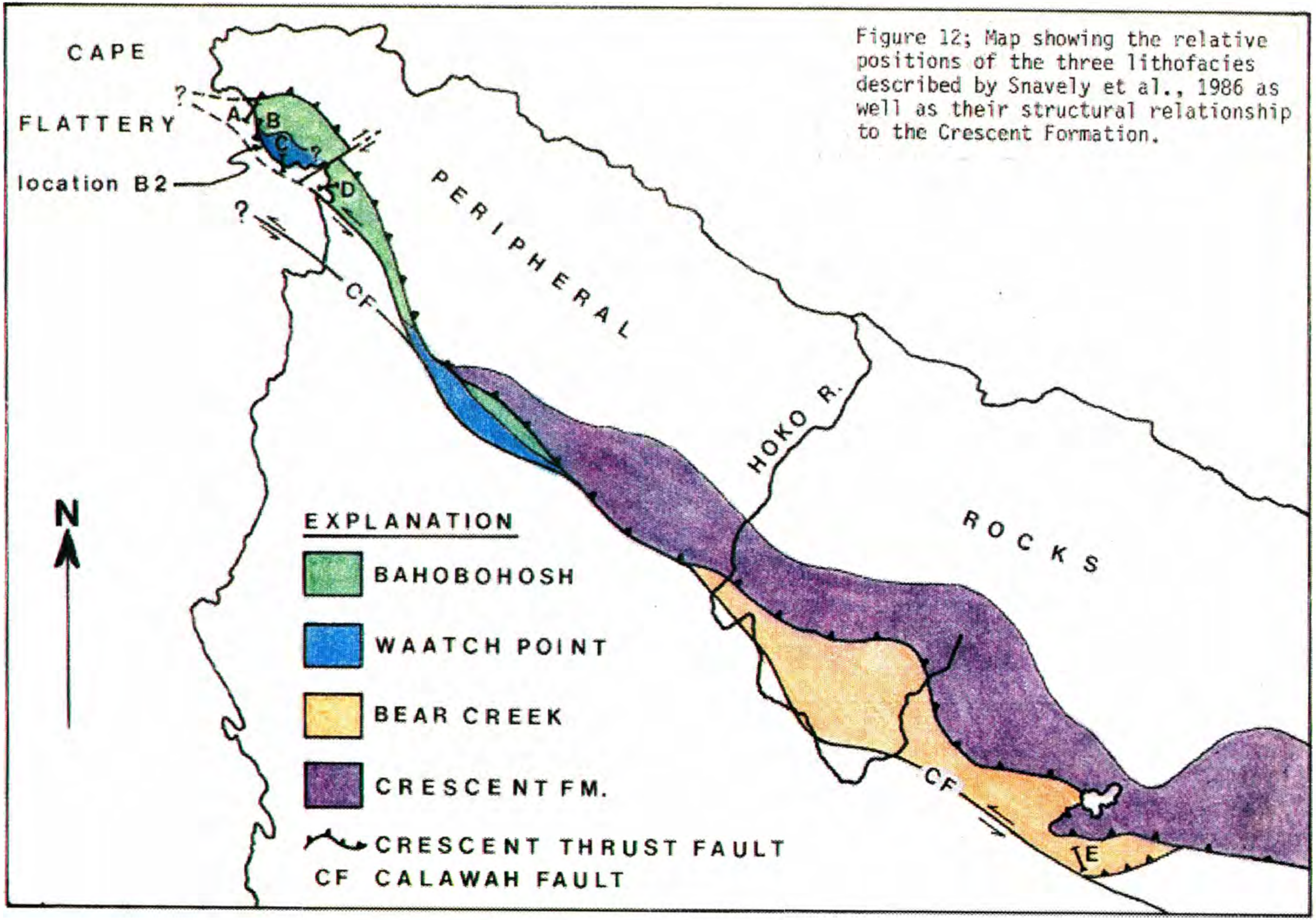


Figure 12; Map showing the relative positions of the three lithofacies described by Snavely et al., 1986 as well as their structural relationship to the Crescent Formation.

Table 1; Table compiling the sedimentary characteristics and ichnology of the facies and their interrelationship and environmental interpretation.

FACIES		DOMINANT CHARACTERISTICS	BED THICKNESS	BEDFORM	RELATIONSHIP TO OTHER FACIES	ICHNOFOSSILS PRESENT	ENVIRONMENTAL INTERPRETATION
A		BOUMA Tb-e,Tc-e,Tde THIN, FINE SANDSTONE TO SILTSTONE TURBIDITES	1-4 cm (1.5 ave)	TABULAR TO WAVY W/SHARP TO SCOURED BASES	VERTICALLY GRADATIONAL W/FACIES B1. ASSOC. W/ALL OTHER FACIES.	Chondrites, Planolites, Paleophycus Rhizocorallium	INTERCHANNEL SHELF AND UPPER SLOPE DEPOSITS BELOW STORM WAVE BASE.
B	1	BOUMA Ta-d,Tb-e,Tc-e COARSE SANDSTONE TO SILTSTONE TURBIDITES	3-30 cm (10 ave)	TABULAR WITH SHARP TO SCOURED BASE	VERTICALLY GRADATIONAL W/ FACIES A. ASSOC. W/ ALL OTHER FACIES.	Thalassinoides, Planolites, Paleophycus, Chondrites Rhizocorallium	INTERCHANNEL SHELF AND UPPER SLOPE DEPOSITS BELOW STORM WAVE BASE.
	2	BOUMA Tab,Ta-c MEDIUM SANDSTONE TO GRANULE CONGLOMERATE TURBIDITES	5-150 cm (35 ave)	TABULAR TO LENTICULAR W/SHARP TO SCOURED BASE	FACIES B2 BEDS OFTEN PINCHOUT AGAINST FACIES A & B1 BEDS.	Thalassinoides, rare Planolites	SHELF CHANNEL-FILLING TURBIDITES
C	1	HUMMOCKY CROSS-STRATIFIED FINE TO COARSE SANDSTONE.	10-100 cm (35 ave)	TABULAR W/ SHARP TO SCOURED BASE	FACIES C1 OCCURS DOMINANTLY AS INDIVIDUAL BEDS ASSOC. W/FACIES B1	rare Thalassinoides	INTERCHANNEL STORM DEPOSITS ABOVE STORM WAVE BASE
	2	MICRO-HUMMOCKY CROSS-STRATIFIED FINE TO MEDIUM SANDSTONE	3-10 cm (5 ave.)	DISCRETE HUMMOCKS W/ SHARP BASES	DISCRETE HUMMOCKS PASS LATERALLY INTO FACIES A, B1.	Planolites, Paleophycus, Rhizocorallium, Thalassinoides	DEEPER AND/OR MORE DISTAL STORM DEPOSITS ABOVE STORM WAVE BASE
	3	HUMMOCKY CROSS-STRATIFIED INTERVALS @ TOPS OF CONGLOMERATES.	5-40 cm (15 ave)	TABULAR WITH DIFUSE BASES	GRADE DOWNWARD INTO FACIES E1	none	STORM-WAVE REWORKED TOPS OF DEBRIS FLOW DEPOSITS.

TABLE 1; continued

FACIES		DOMINANT CHARACTERISTICS	BED THICKNESS	BEDFORM	RELATIONSHIP TO OTHER FACIES	ICHNOFOSSILS PRESENT	ENVIRONMENTAL INTERPRETATION
D		HIGH-ANGLE CROSS-BEDDED MEDIUM SAND-STONE TO GRANULE CONGLOMERATE	5-50 cm (15 ave)	LENTICULAR W/ SCOURED BASE	COMMONLY INTER-BEDDED W/ STRATA OF FACIES B1,C, E1, and E3.	rare <u>Thalassinoides</u>	CHANNELIZED TIDAL OR SHELF CURRENT DEPOSIT
E	1	MATRIX-SUPPORTED DISORGANIZED CONGLOMERATE	50 cm to 12 m	TABULAR W/ SCOURED AND LOAD CAST BASES	COMMONLY INTER-BEDDED W/ FACIES B AND C BEDS.	NONE	SUBMARINE DEBRIS-FLOW DEPOSITS
	2	CHANNELIZED MATRIX-SUPPORTED NORMALLY GRADED TO DISORGAN-IZED CONGLOMERATE	10-150cm (70 ave)	LENTICULAR W/ DEEPLY SCOURED BASES	COMMONLY SCOURED INTO FACIES B1. OFTEN GRADES UP-WARDS TO FACIES E1	NONE	CHANNEL FILLING DEBRIS FLOW TO HIGH-DENSITY TURBIDITE DEPOSITS
	3	MATRIX-SUPPORTED DISORGANIZED TO NORMALLY GRADED INTRACLAST CONGLOM.	10-70 cm (30 ave)	TABULAR TO LENTICULAR W/ SHARP BASES	COMMONLY ASSOC. W/ FACIES A,B,C, & D	NONE	INTRABASINALLY DERIVED GRAVITY-FLOW DEPOSITS
F	1	CONVOLUTED FACIES A, B, AND C STRATA	5-70 cm (25 ave)	TABULAR TO LENTICULAR W/ SHARP BASES & DIFUSE TOPS	COMMONLY INTER-BEDDED W/ FACIES A,B, & C STRATA	rare <u>Thalassinoides</u>	SLUMPED FACIES A AND B1 STRATA
	2	THICK INTERVALS OF LARGE CONVOLUTED BLOCKS	5-15 m	TABULAR (?) W/SHARP BASES MAY GRADE TO FACIES E1.	COMMONLY ASSOC. W/ FACIES A,B,C, AND E 1 STRATA.	NONE	OLISTOSTROMES

facies were deposited on or derived from. This "stratigraphic matrix" suggests that facies B, C, D, E, and F represent deviations from some background sedimentation condition represented by facies A. Sedimentation rates were probably high to very high throughout the deposition of the study unit. High sedimentation rates in the study unit are indicated by the abundance of soft-sediment deformation and scour, and the scarcity of bioturbated horizons (see Paleoecology section).

FACIES DESCRIPTIONS AND INTERPRETATIONS

Facies A

Description--This facies consists of interbeded thin, fine-grained sandstone (beds 1-5 cm thick, averaging 2 cm) and shaley siltstone (beds 1-4 cm thick, averaging 1.5 cm). The sandstone/siltstone ratio averages about 3:2.

The sandstone beds commonly have sharp bases and show frequent scour and less frequent loading into underlying beds (Figure 13). The tops of the sandstone beds are generally sharp and, less frequently, gradational into overlying siltstone beds. The beds are laterally extensive to discontinuous and commonly pinch and swell along strike. Where scoured bases are common, sandstone beds are less laterally continuous. Internally the sandstone beds are parallel-laminated or graded with frequently associated ripple cross-lamination.

The shaley siltstones are dark, laminated or structureless, and more laterally continuous than the sandstone beds (Figure 13). Ripple cross-laminations are common in siltstone beds where the lower contact is gradational with the underlying sandstones.

Figure 13; FAcies A strata exhibiting scour and load casts of sandstone beds into silt-stone beds. Note the wavy appearance of the strata.

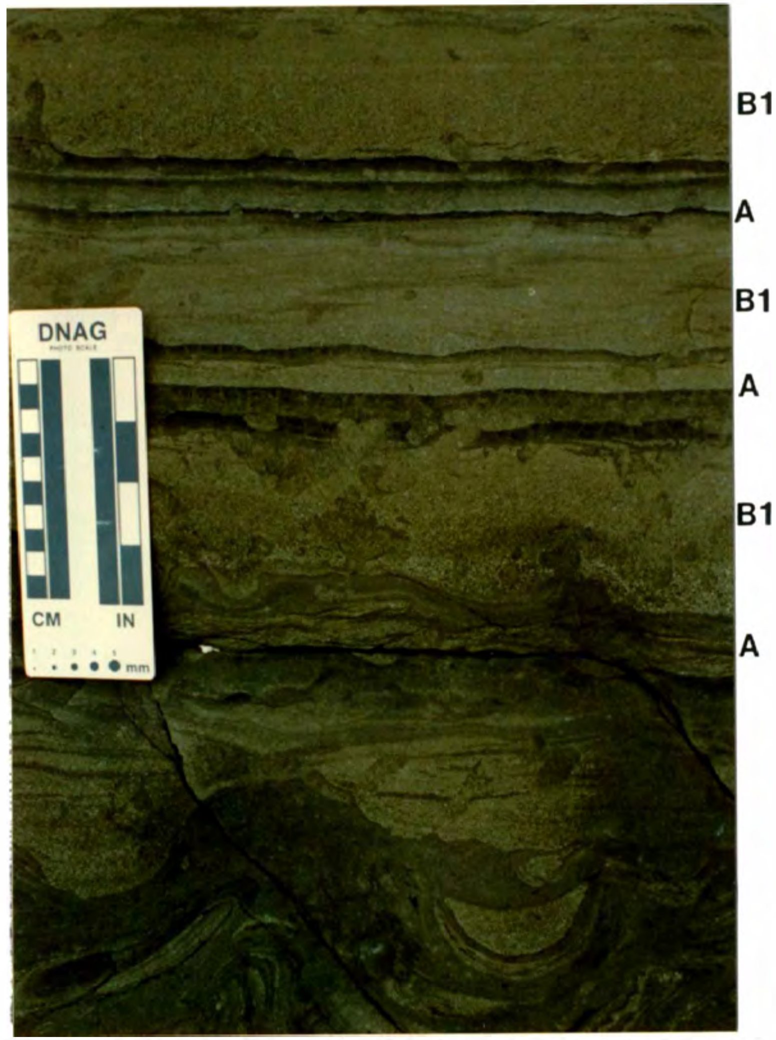


Figure 14; Faices A strata in this interval are mildly bioturbated. Note load casts and soft-sediment deformation. Facies A strata are interbedded with Facies B1 strata.

Facies A strata are frequently mildly bioturbated (Figure 14), generally exhibiting a greater degree of bioturbation than the other facies. The paleoecology of the study unit is discussed more fully below.

Discrete convoluted horizons resulting from post-depositional slumping of facies A strata are common and comprise subfacies F1 (discussed below). Fairly regularly-spaced calcareous concretionary horizons developed after compaction are another common feature of facies A strata.

Interpretation--The beds of this facies are interpreted to represent primarily turbidity current and hemipelagic deposition. The sharp, scoured, and loaded bases of the sandstone beds in conjunction with their parallel-laminated, ripple cross-laminated, and graded internal structures and the associated shaley silt deposits are indicative of Bourma Tb-e, Tc-e, Td-e, and less commonly Ta-e sequences. The laminated character of some of the shaley siltstone beds suggests that hemipelagic sedimentation was significant between turbidity current deposition. General preservation of the siltstone beds suggests that the responsible turbidity currents were low density. Low density of the turbidity currents would explain the lateral continuity of the siltstone beds and the lack of deep channeling.

There is the possibility that some of the cross-laminated sandstone beds in facies A are the result of post-depositional reworking by unidirectional shelf-parallel currents. Some cross-laminated intervals are better sorted and have sharper tops than the majority of facies A, both of whicn features are characteristic of contourites (Middleton and Hamilton, 1976).

Thus, while low-density turbidity currents and hemipelagic conditions dominated the deposition of facies A strata, current reworking of some sediment may have been periodically important.

Facies B

Description--Relatively thick, medium- to coarse-grained sandstone beds typify facies B. Facies B has two subfacies.

Subfacies B1--Subfacies B1 strata record higher energy conditions than those represented in facies A. Here the sandstone beds become coarser and thicker than in facies A (Figure 15). Bed thicknesses range from 3 to 30 cm and average about 10 cm. Bed forms are dominantly tabular, although lenticular beds with beds scoured into underlying strata are common. Internally the sandstone beds are structureless, graded, parallel-laminated, or ripple cross-laminated comprising Bouma Ta-d, Tb-e, Tc-e, and rarely Td-e sequences. Trace fossils, while present, are less common than in facies A. Convoluted and calcareous concretionary horizons are common.

Sandstone beds of facies B1 occur predominantly as isolated beds interbedded with facies A (Figure 15) and facies C strata. Amalgamated sets of two or three facies B1 beds occur occasionally. Gradual to relatively abrupt coarsening/thickening and thinning/fining sequences are present in which facies A strata grade into or from facies B1 strata.

Subfacies B2--Strata of this subfacies are characterized by thick (5-150 cm thick, about 40 cm average) medium-grained to pebbly sandstone beds. The beds are tabular to lenticular and display amalgamation (Figure 16), massive bedding, graded bedding, Bouma Ta-b sequences, abundant rip-up clasts, pebbly channel-lag deposits, pebble stringers, and scoured bases. Fine-grained sandstone and shaley siltstone interbeds 1-4 cm thick

Figure 15; Siltstone interbedded with thick bedded, coarse grained sandstone together comprising Facies B1. Note also the interbedded conglomerate beds of Facies E1.

Figure 16; Amalgamated turbidites of Facies B2.

exhibiting parallel and ripple cross-lamination are occasionally present. Tabular to lenticular beds of conglomerate containing shaley siltstone rip-up clasts (facies E3) are commonly intercalated with facies B2 strata.

Bioturbation of facies B2 is restricted to oblique and horizontal occurrences of Thalassinoides. Traces are found at the tops and bases of beds, especially where fine-grained interbeds are present. Plant debris in the form of carbonaceous stringers and carbonized plan fragments is fairly common at the bases or tops of facies B2 strata.

As stated above, facies B2 sandstone beds commonly occur as amalgamated sets. Lateral tracing of facies B2 strata shows them to pinch out against the thinly bedded stata of facies A and B1. The bases of facies B2 sequences are uniformly sharp. Upsection, facies B2 strata grade gradually to abruptly into strata of facies A or B1 (Figure 17).

Interpretation

Subfacies B1--The sandstone beds of subfacies B1 are interpreted to represent the deposits of low-density turbidity current on the basis of the Bouma sequences that they contain. The coarser and thicker nature of beds in subfacies B1 relative to facies A indicates that higher energy conditions and possibly greater sediment supply prevailed during facies B1 deposition. This inference is supported by the shift from finer, lower energy Bouma sequences in facies A to coarser, slightly higher energy Bouma sequences in subfacies B1. The presence of lenticular beds in subfacies B1 that are relatively deeply scoured into underlying strata also indicates higher energy conditions.

Subfacies B2--The sandstone beds of subfacies B2 also represent turbidity-current deposits. The amalgamation, Bouma Ta-b sequences, massive beds, abundant rip-up clasts, and scoured bases present

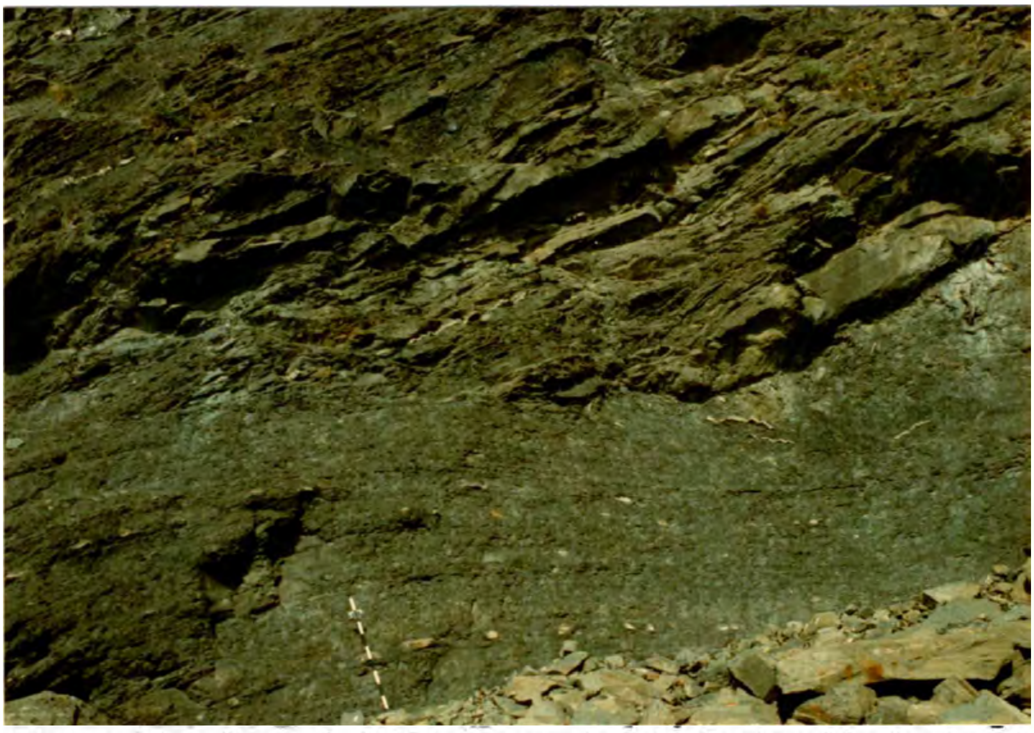


Figure 17; Channel filling geometry in Facies B2 strata at location B2 (see Figure 12). Channel filling strata grade upward into Facies B1 and then Facies A strata. Strata comprising the channel walls and floor are Facies A.

Figure 18; An isolated hummocky cross stratified horizon exhibiting the H, X, and M zones (see Figure 19) in the Bahobohosh lithofacies. Knife for scale.
This facies C1 horizon is interbedded with Facies A and B1 strata.

in the subfacies B2 sandstones indicate deposition under higher energy and possibly higher density conditions than were prevailing during facies A and B1 deposition. Pinchout of these sandstones against facies A and B1 strata indicates incised channel relationships. The higher-energy conditions recorded by the facies B2 beds could have resulted from the confining of the turbidites by the channel walls. Channel-filling relationships are well exposed at locality B2 (Figures 12, 17).

Facies C

Description--The occurrence of hummocky cross-stratification (HCS) (Harms et al., 1975; Dott and Bourgeois, 1982) typifies facies C. Variability in the character and bedding associations of HCS beds allows subdivision of facies C into three subfacies.

Subfacies C1--Of the three subfacies delineated here, subfacies C1 contains the most classical HCS beds (Figure 18). While complete HFXM and HFXMb hummocky units are present, the HFX, HFM, FXM, and HM variations of this sequence are more common (Dott and Bourgeois, 1982) (see Figures 19, 20 for explanation). Hummocky beds range in thickness from 10 to 100 cm and average about 35 cm. The bases of subfacies C1 beds are uniformly sharp. Scour into underlying strata is very common (Figure 21). Scours are often filled with rip-up clasts or pebble lags. The tops of individual beds or amalgamated sets are sharp or gradational into facies A or B1 strata. Where HCS beds are especially thick (>30 cm), the bottom portion of the bed may be structureless. In many cases the tops of HCS beds have been truncated. Where hummocks are preserved, they are of minimal relief (3-5 cm) and are spaced from 1 to 2 meters apart (Figure 18).

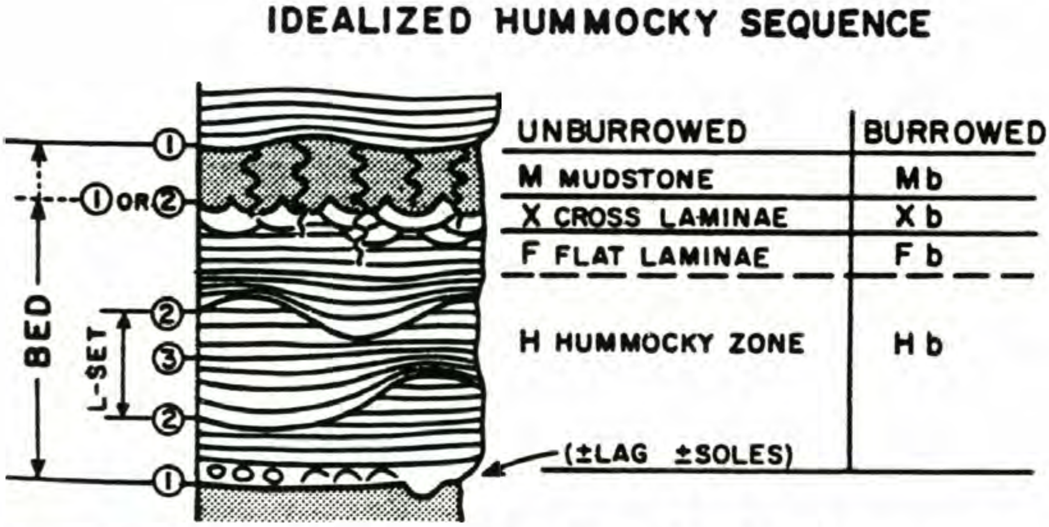


Figure 19; The idealized hummocky cross stratified sequence comprised of the various component zones. From Dott and Bourgeois, 1982.

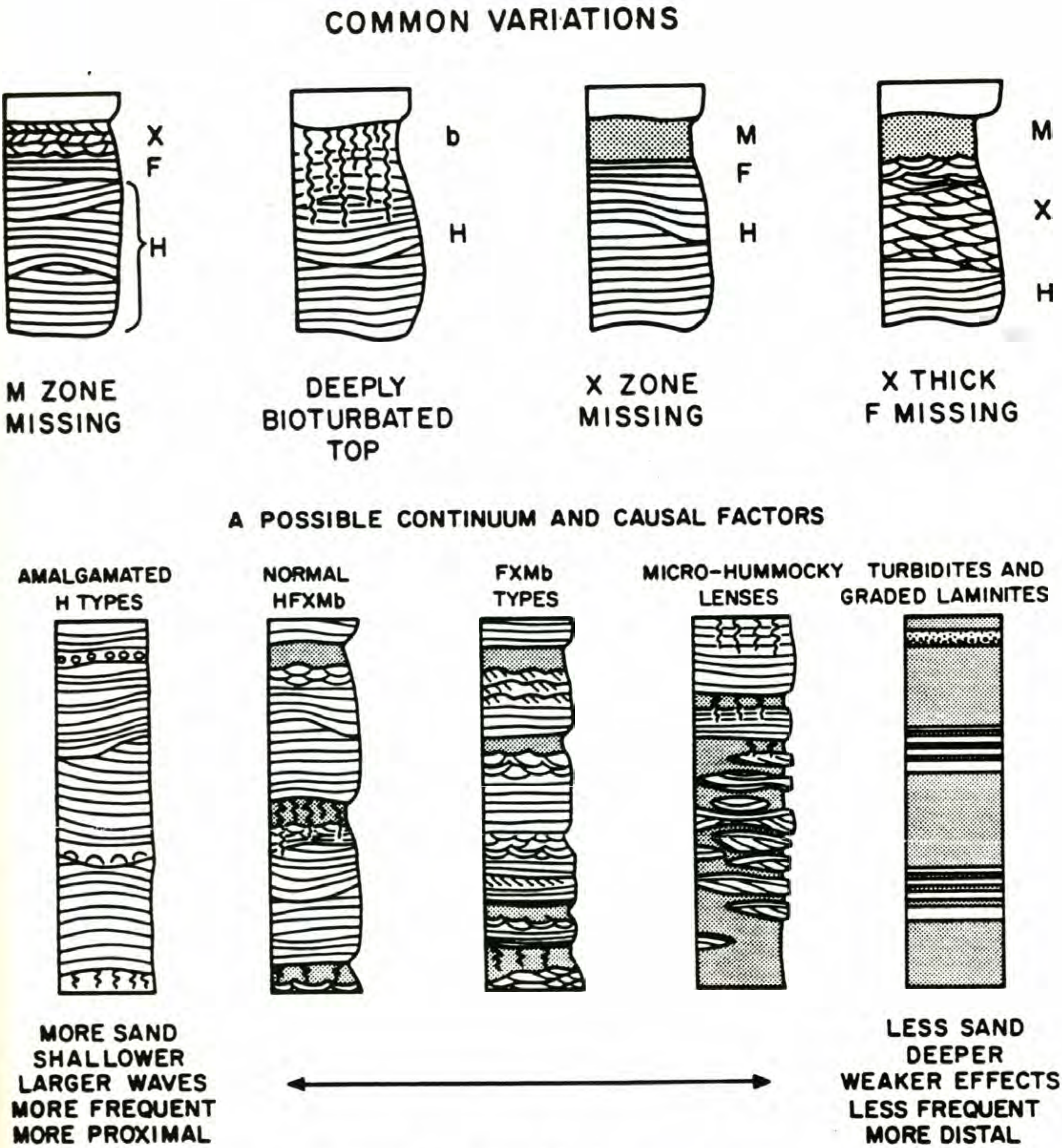


Figure 20; Common variations from the ideal hummocky unit. The two left examples are the most common variations (TOP). The bottom figure shows the variations and possible environmental factors effecting HCS. From Dott and Bourgeois, 1982.

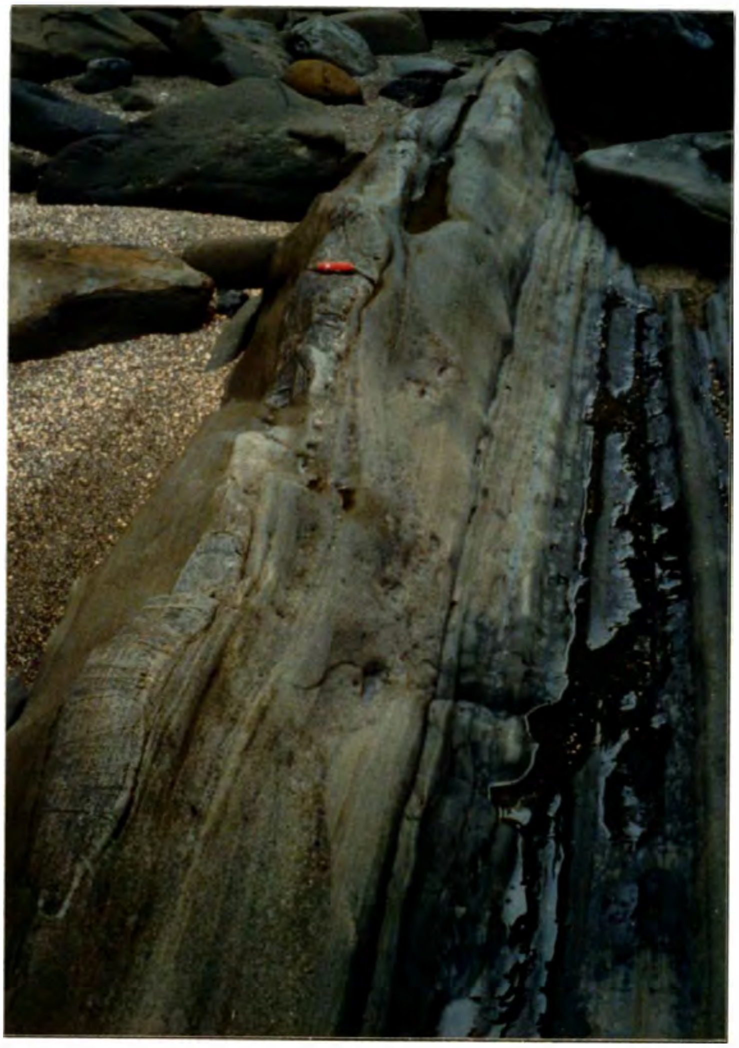


Figure 21; Facies C1 strata. Two HCS beds at the center of the photo are amalgamated along a surface showing deep scour. Knife for scale.

HCS occurs predominantly as individual beds, although occasional amalgamation of HCS beds is observed. In such cases the overlying HCS beds are often deeply scoured into the underlying ones (Figure 21). HCS beds of subfacies C1 are ubiquitously interbedded with subfacies B1 strata (Figure 18). Spacing between HCS beds is fairly regular throughout most of the measured sections (Appendix 1). However, HCS beds are occasionally more closely vertically spaced, especially where amalgamation occurs.

Subfacies C2--Subfacies C2 strata differ from facies B1 strata only by the addition of curving internal laminations and low-angle truncations to the thicker portions of sandstone beds. Such beds are laterally discontinuous (approximately 1 meter maximum) or taper to thin parallel-laminated tabular-bedded sandstone.

Subfacies C3--Subfacies C3 is defined as HCS that has developed at the top of thick conglomerate beds. The HCS intervals here are more coarse grained than subfacies C1 or C2. Hummock morphology is generally well preserved with hummocks occurring every 1 to 2 meters and having 3-10 cm of relief (see Appendix 1, Archawat Ck. North section, meter 129). The curving internal laminations of the hummocks grade downward 20-40 cm into the underlying conglomerate.

Interpretation

HCS has been shown by various workers to indicate wave-modified sediment-gravity flow deposits followed by suspended-load sediments as storm-wave energy wanes (Harms et al., 1975; Walker, 1975; Bourgeois, 1980; Dott and Bourgeois, 1982). Fairweather sedimentation and bioturbation complete the depositional sequence. HCS beds are deposited between fairweather and storm wave-base (Figure 22). Variations in the idealized sequence (Figure 20) are the common, if not dominant, mode of

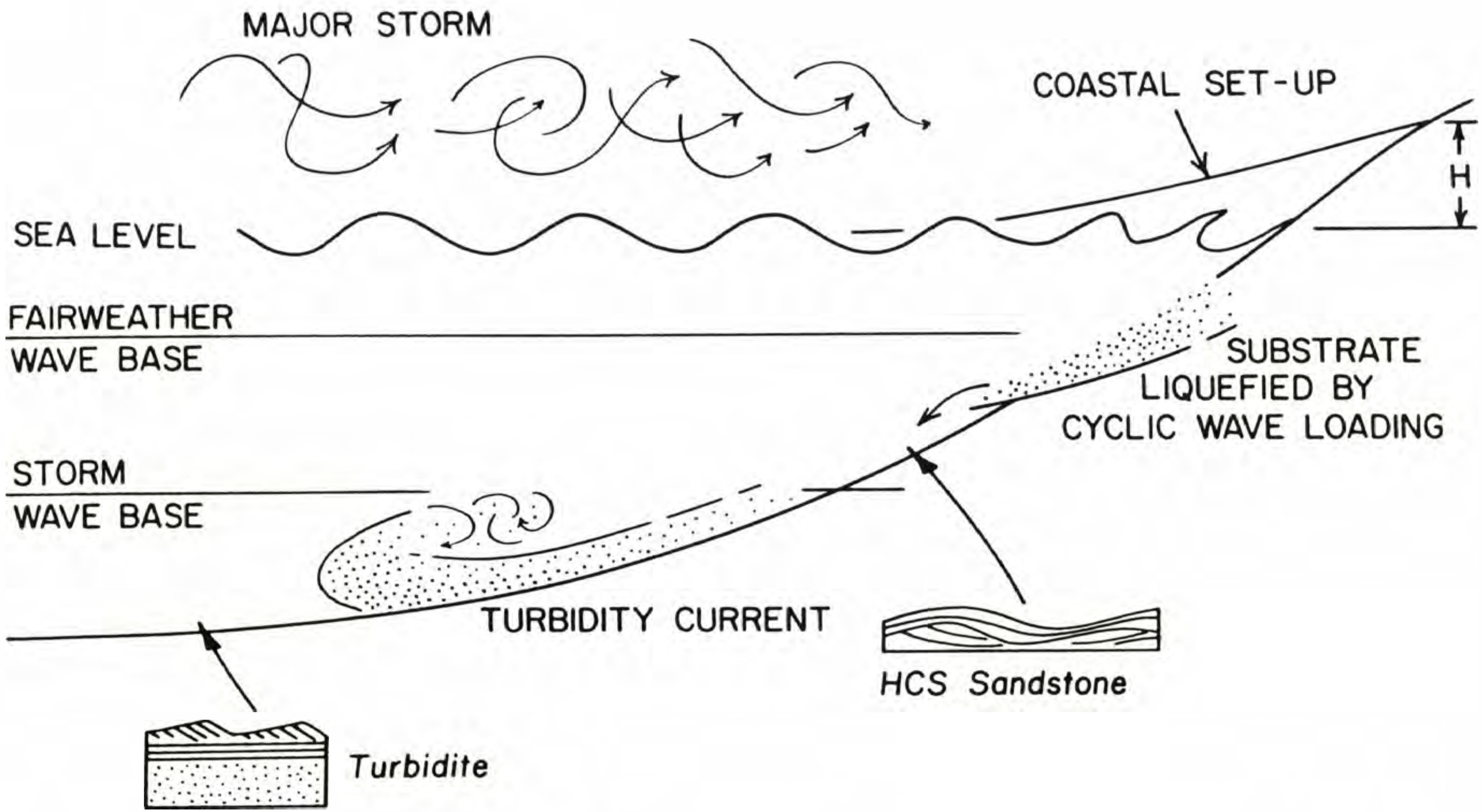


Figure 22; Storm-generation model for the formation of hummocky cross-stratification. Storm waves mobilize sediment above fairweather wave base that moves off-shore as a turbidity current. Sediment deposited by these turbidity currents above storm-wave base is reworked into hummocky cross-stratified intervals. From Walker, 1985.

occurrence as with the Bouma model for turbidites. Factors controlling these variations include sediment supply; bathymetry; tidal range; frequency, duration, proximity, and magnitude of storms; and degree of bioturbation (Dott and Bourgeois, 1982) (Figure 20).

Subfacies C1--The presence of complete idealized HCS sequences, as well as numerous variations (HFX, HFM, FXM, and HM types) in subfacies C1 strata record a wide range of storm-wave-dominated depositional conditions. Therefore, I conclude that deposition of subfacies C1 strata occurred in a hydraulically dynamic paleoenvironment between fairweather and storm wave-base. The depth of storm-wave base has been estimated at 30 meters by Harms et al. (1975) and at 80 meters by Dott and Bourgeois (1982). Storm-generated oscillation and bottom currents, tidal currents, unidirectional currents, and flood-generated bottom currents could all combine to deposit and modify sediments above such depths. The deletion or expansion of one or more of the idealized sequence intervals would result from changes in the magnitude and duration of tractive current flow-regimes responsible for the various intervals. Thus, the spectrum of HCS variations present in subfacies C1 represents deposition of HCS beds under conditions that oscillated from being higher intensity to being lower intensity than those that would produce an idealized HCS sequence. In addition to the variation of depositional conditions, the presence of amalgamated, normal, and FXM sequences indicates that environmental conditions such as sediment supply, bathymetry, and storm conditions were variable during deposition of subfacies C1 strata.

Subfacies C2--Interbedded sandstone and siltstone similar to subfacies B1 in which locally thickened beds display curving internal laminations and low-angle truncations, defined here as subfacies C2, have been described by Dott and Bourgeois (1982). Such strata, termed micro-HCS,are interpreted to result from storm-wave-dominated deposition in which sediment supply or storm influence are less than those required for formation of classical HCS (Figure 18, 19, 20, 22).

Subfacies C3--Subfacies C3 strata are interpreted to represent conditions opposite of those producing subfacies C2. Rather than lacking sediment during deposition, subfacies C3 strata were sediment-swamped. Storm waves were able to modify only the upper portion of the conglomerates. Whether the conglomerates are the result of resedimentation by storm processes or were deposited prior to the storm responsible for the HCS interval is unclear.

Facies D

Description--Facies D strata consist of lenticular beds of high-angle, cross-stratified coarse-grained sandstone to medium pebble conglomerate (Figure 23). Bed thicknesses range from 5 to 50 cm and average about 15 cm. Facies D beds are scoured into underlying strata. Occurrences of facies D beds are rare, isolated, and always associated with facies B1 or C1 stata (Figure 23).

Interpretation--The coarseness, high-angle cross-stratification, and incised nature of facies D beds indicate that they are deposited by relatively high-velocity unidirectional flow. Their association with facies C1 strata constrains their formation to relatively shallow water above storm wave base. These considerations suggest tidal currents or sublittoral (shelf) currents as possible mechanisms for their deposition.

Facies E

Description--Facies E consists of conglomeratic strata with three

Figure 23; High-angle cross stratified conglomerate of Facies D interbedded with the sandstone and siltstone of Facies B1.

distinct types of bedding characteristics that are subdivided into three subfacies.

Subfacies E1--Conglomerates of this facies consist of pebble- to boulder-sized clasts that are predominantly disorganized and matrix-supported (Walker, 1975) (Figure 24). Indistinct normal grading is occasionally observed. The matrix is silt to medium sand. The coarse-grained clasts are angular to well rounded (Figure 24) and compositionally immature (see the Petrology section). Beds range in thickness from 50 cm up to 12 meters. The bases of subfacies E1 beds are sharp and very commonly scoured or load cast (Figure 25). Convoluted bedding is commonly observed below subfacies E1 strata. At Bahobohosh Point (Figure 12), subfacies E1 conglomerates grade downward into olistostromal deposits (subfacies F2).

Subfacies E2--Conglomerates of subfacies E2 are markedly channelized. The channels are amalgamated and contain channel-lag deposits. Clasts range from pebble to cobble size, are sub-rounded to well rounded, and compositionally immature. The channel deposts are matrix-supported and range from disorganized to normally graded (see Appendix 1, Archawat Ck. South section, meters 7-17). Graded channel deposits often fine upward into pebbly sandstone. The lower contacts of subfacies E2 intervals are sharp and often scoured into underlying strata. Subfacies E2 often grades upward into subfacies E1.

Subfacies E3--Subfacies E3 consists of tabular to lenticular, disorganized to normally graded matrix-supported conglomerate beds 10 to 70 cm thick. The beds average about 30 cm thickness. The coarse-grained portion of subfacies E3 consists predominantly of deformed to undeformed shaley siltstone rip-up clasts. The supporting matrix is siltstone to

Figure 24; Facies E1 conglomerate that is disorganized and matrix supported. Note the scoured basal contact of the conglomerate with the underlying Facies B1 strata (Archawat Ck. North section, see Appendix 1).

Figure 25; Facies E1 conglomerate exhibiting load cast and injected basal contact with underlying Facies B1 and A strata (Archawat Ck. North section).

fine-grained sandstone. Basal contacts of subfacies E3 beds are sharp and very commonly deeply scoured.

Interpretation

Subfacies E1--The disorganized, poorly sorted, matrix-supported character of facies E1 conglomerates is indicative of debris-flow deposits (Walker, 1975). The scour and load casts at the bases of these conglomerates indicate rapid high-energy deposition. The roundness of the clasts suggests that they were resedimented from previously existing conglomeratic strata shoreward of the depositional site.

Subfacies E2--Subfacies E2 conglomerates are interpreted as debris flow and high-density turbidity current deposits. Both processes could produce amalgamation of channels. Debris flows produced the matrix-supported, disorganized conglomerate beds. High-density turbidity currents produced the matrix-supported normally graded beds. Their channelized shapes suggest that they may represent early stages of resedimentation, an interpretation supported by the frequent grading of subfacies E2 beds into subfacies E1 intervals (see Appendix 1, Archawat Ck. South section, m 7-17).

Subfacies E3--Subfacies E3 is interpreted to result from high-density turbidity currents on the basis of the abundance of deeply scoured basal contacts and convoluted rip-up clasts in the strata. The presence of deformed rip-up clasts as the only framework component of these strata suggests that they might have originated as slump material. This conclusion is supported by the presence of abundant convoluted intervals in the study unit.

Facies F

Description--Facies F strata are comprised of slump-produced intervals of two distinct types.

Subfacies F1--Subfacies F1 consists of extensively soft sediment deformed and convoluted intervals 5 to 100 cm thick (Figure 26). Convoluted strata originally resembled facies A and B1. The degree of disruption varies from deformed but continuous strata to completely disrupted intervals in which original bedding features are destroyed. The basal contacts of subfacies F1 strata vary from being sharp in deformed intervals to being scoured where disruption is most complete.

Subfacies F2--Subfacies F2 consists of thick disorganized conglomerate beds that contain deformed intrabasinal blocks in a matrix of compositionally immature fine-grained sandstone to cobble conglomerate (Figure 27). Subfacies F2 intervals are from 10 to 50 meters thick. The intrabasinal blocks are from 10 cm to 10 meters long and consist of facies A, B1, and C1 materal. The bases of subfacies F2 intervals are deeply scoured. Toward their tops, they commonly grade into facies E1 strata. The proportion of large intrabasinal blocks varies laterally and from outcrop to outcrop.

Interpretation

Subfacies F1--Subfacies F1 strata are interpreted to represent slumped facies A and B1 strata. In some cases dewatering structures indicate that the deformation was clearly intrastratal. In others the overlying bed has scoured into the convoluted horizon. Therefore, both bedding-plane shearing and slumping at the sediment-water interface were processes that produced subfacies F1 strata.

Figure 26; Facies F1 horizon of highly convoluted and disrupted strata that originally resembled Facies A. Note the undisturbed interbeds.

Figure 27; Facies F2 horizon consisting of a thick interval of broken formation containing convoluted coherent blocks of stratified sediment in a disrupted matrix. Convoluted blocks resemble Facies A nad B1 strata.

Subfacies F2--Subfacies F2 intervals are interpreted to be olistostromal deposits on the basis of the large proportion of deformed intrabasinal blocks they contain and their relationship to other facies. The mechanism of generation for these large-scale olistostromal movements is unclear. Seismic events and tsunamis as well as local oversteepening of sedimentary slopes are possible causes for the initiation of downslope movement. The presence of coarse conglomeratic facies E1 intervals above some subfacies F2 intervals suggests that the olistostromes may have been produced by loading and tractive flow caused by the emplacement of debris flows.

PALEOECOLOGY

Introduction

Macro-scopic evidence of the Eocene paleo-community is limited to ichnofossils. Macroscopic body fossils were not observed. The strata of the study unit are about equally divided between barren and burrowed intervals. Five distinctive types of lebensspuren were observed. The presence of other unidentified types is probable. Abundances of the various traces varied considerably from facies to facies (Table 1).

Types of Ichnofossils

Thalassinoides (Figure 28)--The ichnofossil *Thalassinoides* is a dwelling/feeding structure similar to those produced in the modern environment by the decapod shrimp *Callianassa* (Hantzschel, 1975). *Thalassinoides* is found in strata deposited in nearshore to sublittoral environments. In the study unit, this ichnofossil occurs as horizontal to inclined burrows 0.5 to 1.5 cm in diameter that branch extensively,

Figure 28; Thalassinoides ichnofossil exposed on the base of a Facies B2 turbidite.

Figure 29; A bedding plane exposure of the ichnofossil Chondrites in Facies A strata.

forming two or three dimensional structures. They are found most commonly in the sandier strata and are filled with coarser sediment or reddish staining.

Chondrites (Figure 29)--Chondrites is a feeding structure ascribed to deposit-feeding worms (Hantzschel, 1975). Observed traces are 1 to 3 mm diameter burrows inclined to bedding that are concentrated in zones 5 to 10 cm thick and 10 to 20 cm wide. The burrows commonly cut across each other and are filled with sediment of the save size and color as surrounding stata. Chondrites occurrences are limited to siltstone and thin sandstone beds.

Planolites (Figure 30)--This ichnofossil is a feeding structure believed to be produced by deposit-feeding worms (Hantzschel, 1975). Occurrances in the study unit are unbranching cylindrical burrows 0.5 to 1 cm in diameter that are horizontal or more rarely inclined to bedding. Infilling sediment is generally coarser and of a different color than surrounding strata. Occurrences of Planolites are dominantly limited to the sandy strata.

Paleophycus--The origin and characteristics of Paleophycus are identical to those of Planolites except that Paleophycus is filled with sediment similar to surrounding strata (Hantzschel, 1975). This suggests tnat it results from non-feeding movement of some organism through the substrate (i.e., the sediments are not modified).

Rhizocorallium (Figure 31)--Rhizocorallium is interpreted to result from the deposit-feeding or dewelling/feeding behavior of infaunal organisms, probably worms (Hantzschel, 1975). Occurrences of Rhizocorallium in the study unit are sparse. Where it is observed, it consists of horizontal to inclined U-shaped burrows about 1 cm in diameter

Figure 30; Numerous occurrences of the ichnofossil Planolites in Facies B1 strata.

that extend 5 to 10 cm into underlying strata. Arms of the burrows are fairly parallel and connected by spreite. Rhizocorallium burrows generally penetrate sandy strata and sole out in dark siltstone.

Figure 31; Rhizocorallium ichnofossils in Facies B1 strata. Note that the traces originate from a Facies C2 interval.

Other ichnofossils that are possibly present in the study unit include Cochichnus, Cylindrichnus, Diplocraterion, Gyrochortes, and Muensteria. The general lack of bedding-plane exposures in the study unit makes identification of horizontal traces such as Cochlichnus, Gyrochortes, and Muensteria difficult. Vertical and near vertical burrows are fairly common in the study unit. Cylindrichnus could be misidentified as vertical portions of Thalassinoides burrows. The same relationship could exist between Diplocraterion and Rhizocorallium traces. Vertically oriented poritions of U-shaped tubes with spreite observed in the study unit could be Diplocraterion rather than the upper vertical portions of Rhizocorallium as I interpreted them.

Paleoenvironmental Interpretation

The fairly diverse yet rare ichnocoenosis suggests that the community was comprised of opportunist species that inhabited a stressed environment. The abundance of non-bioturbated strata indicates that sedimentation occurred too fast for bioturbation or occurred while no organisms were present. Ichnofossils tend to be concentrated in the finer-grained facies (A, B1, C2). The traces that occur in predominantly sandy strata (facies B2, C1, D) are Thalassinoides and Rhizocorallium (Figures 28,31). It is reasonable to assume that organisms producing the other traces were unable to endure the rapid to catastrophic sedimentation or storm-wave dominated conditions represented by facies other than A, B1, and C2.

Examination of the ichnocoenosis as a whole indicates that these traces comprise the Cruziana ichnofacies (Figure 32). This ichnofacies is confined to the sublittoral zone below fairweather wave base but not storm wave base where unconsolidated, poorly sorted sediments accumulate (Frey

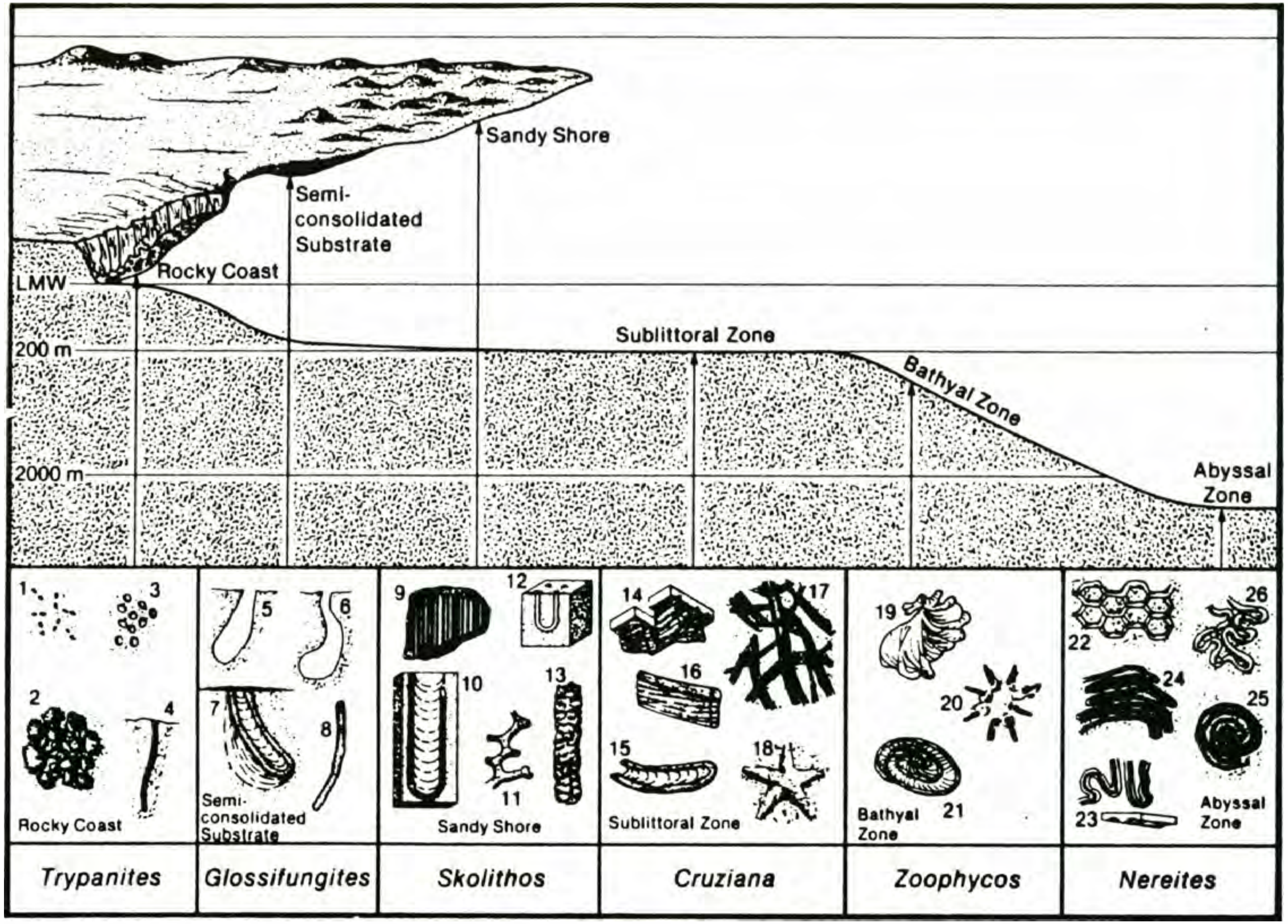


Figure 32; Recurring marine ichnofacies set in representative environments. Typical trace fossils associated with each ichnofacies are also shown. From Frey and Pemberton, 1984.

and Pemberton, 1984). The segregation of the ichnofossils into a higher energy, sandier assemblage and a lower energy, siltier assemblage suggests that during higher energy conditions a Skolithos-type assemblage (Figure 32) may have prevailed. Subsequent return to lower energy conditions would require recolonization by Cruziana-type organisms and could account for the extensive barren zones. However, it is also possible that these lower-energy assemblage traces were reworked by active shelf processes.

SYNTHESIS AND DISCUSSION

Environmental Interpretation of Facies

The hydraulic, bathymetric, stratigraphic and paleoecologic characteristics of the various facies are indicative of a variety of paleoenvironmental conditions. Interpretations and implications of salient facies are discussed below.

Facies A--The relatively rhythmic, if locally laterally discontinuous, stratigraphy of facies A represents shelf to upper slope sediments deposited below storm-wave base. The rhythmic nature of the facies could be the result of tidal cycles (Leithold and Bourgeois, 1984). Ebb-tide conditions would wash sediment from any nearby deltas and the nearshore into the pro-delta generating low-density turbidity currents. Resultant turbidites comprise the sandy portion of facies A. Settling of suspended sediments during slack tide would produce the laminated shaley siltstone beds in facies A. The abundant convoluted horizons (facies F1) in facies A strata indicate a fairly steep paleoslope. Facies A strata are found only in the Waatch Point and Bear Creek lithofacies.

Facies B1--Where sediment supply was locally higher, such as directly seaward of a delta distributary channel, turbidity currents would be coarser-grained and more voluminous while suspended load sedimentation would remain relatively constant. This sedimentary relationship would result in the thicker and coarser deposits of facies B1 strata found in all three lithofacies. Another possibility is that facies B1 strata were deposited during periods of high fluvial discharge to nearby deltas.

Facies C1 and C2--The presence of HCS beds indicates that a large portion of the study unit was deposited above storm-wave base (Harms et al., 1975; Dott and Bourgeois, 1982) (Figure 28). Occurrences of HCS are confined to the Bahobohosh lithofacies (Figure 12). The changes in sediment supply, bathymetry, storm characteristics and proximity implied by the differences between facies C1 and C2 suggest that climatic and shelf sedimentary conditions were highly variable during the middle to late Eocene.

Facies D--The presence of high-angle cross-stratified facies D beds associated with facies C1 strata indicates that tidal currents probably affected the sublittoral sedimentary environment. No other process operating below fairweather wave base could produce the high velocity unidirectional flow capable of developing high-angle cross-stratification in coarse sediment. The relative scarcity of facies D beds suggests that they may have low preservation on storm-wave dominated shelves. Facies D beds are found only in the Bahobohosh lithofacies.

Facies E1 and E2--The thickest conglomerates of facies E1 and E2 represent a marked shift in the sedimentary style of the study unit. Thinner facies E1 and E2 strata are probably high-density flow conglomeratic equivalents of the turbidites in facies B1 and B2. The thicker strata (>1m) may be the result of catastrophic events, such as earthquakes, tsunamis, or major storms, that mobilized coarse-grained material in the delta. The catastrophic nature of these deposits is indicated by their sharp upper and lower contacts, intercalation with relatively quiet water facies B1 and C1 strata, and occasional association with olistostromes (facies F2). These thick facies E1 and E2 deposits are found only in the Bahobohosh lithofacies.

Consideration of the many processes that produced this array of facies shows that, during the deposition of this middle to late Eocene unit the shallow marine environment was very dynamic.

Deposition of the Waatch Point and Bear Creek lithofacies was dominated by turbidity currents, slumping, and hemipelagic processes below storm-wave base. Strata of facies A, B, F, and to a lesser degree E3 comprise these lithofacies (Table 1).

The Bahobohosh lithofacies was deposited under higher energy conditions above storm-wave base. Turbidity currents; tidal currents; tractive, oscillating, wave-generated currents; debris flows; slumping; hemipelagic processes; and possibly unidirectional shelf-parallel currents all contributed to the formation of this lithofacies. Strata of facies B, C, D, E, and F comprise the Bahobohosh lithofacies (Table 1).

Studies of similar stratigraphic sequences from the ancient environment include Walker (1966), Carter and Lundquist (1975), Lohmar (1977), McCabe (1978), Hamblin and Walker (1979), Howell and Link (1979), Moore (1979), Bourgeois (1980), Leithold and Bourgeois (1984), Buck and Bottjer (1985), and Chan and Dott (1986). Studies of special interest here include Dott and Bird (1979), in which a sequence nearly identical to the study unit and of the same age from the Eocene of central Oregon is described, and Houbolt and Jonker (1968) whose scuba exploration of the modern delta-channel-fan system of the Rhone River and Lake Geneva revealed environmental conditions similar to those that produced facies A, B1, B2, and F1. Turbidity currents were observed sloughing off the Rhone River delta and carrying fine- to medium-grained sand basinward through small channels. The channels faded downslope, and the sediment was deposited in a series of lobes.

The relative stratigraphic positions of the three lithofacies (Figure 33) show that they record a shoaling sequence. Deeper water siltstone-rich strata of the Bear Creek lithofacies are assigned a stratigraphic position below the Waatch Point lithofacies, which grades upward into the shallower storm-wave dominated strata of the Bahobohosh lithofacies. The nature of the events responsible for this shoaling are complex. Three possible end member models exist for such a sequence.

First, there is the possibility that the strata record a eustatic sea-level regression. Most, but not all, eustatic sea-level changes are believed to result from changes in ocean basin volume driven by fluctuations in rates of spreading at mid-ocean ridges (Vail et al., 1977). If the shoaling sequence were the result of eustatic sea-level regression, sequences of similar age and stratigraphy should be found along western North America. Middle to late Eocene strata recording the same shoaling shallow marine sequence are present along the coast.

The middle Eocene Elkton Siltstone Member of the Tyee Formation located near Coos Bay, Oregon (Figure 33), consists of shoaling shelf and slope deposits. Dott and Bird (1979) describe this sequence as stratigraphically transitional between the thick-bedded sandy upper submarine ramp strata of the underlying Tyee Formation (Heller and Dickinson, 1985) and the wave dominated deltaic strata of the overlying

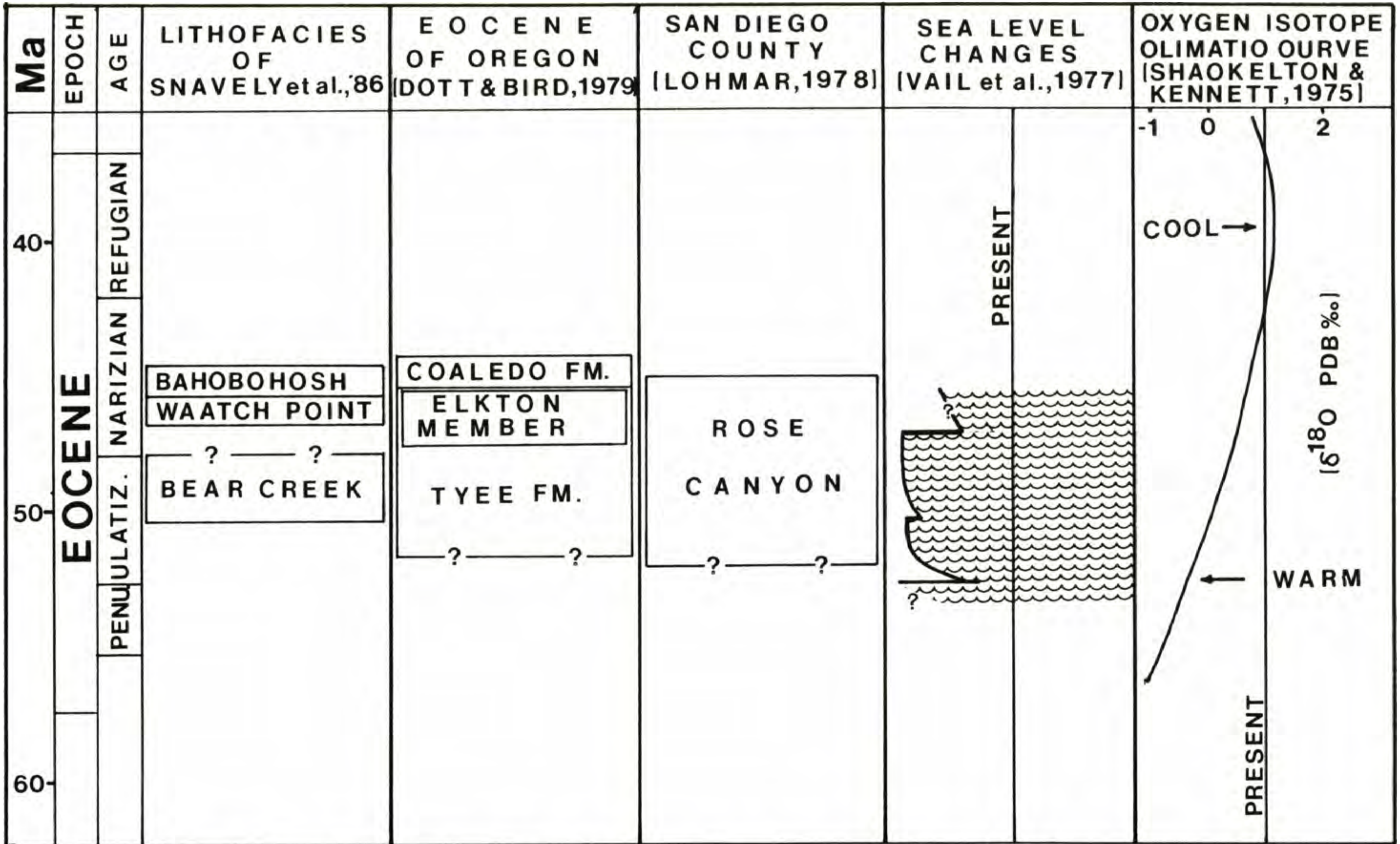


Figure 33; Stratigraphic relationships of the lithofacies comprising the study unit (Snavely et al., 1986) and a comparison with Eocene shallow marine units from Oregon and San Diego, California. The relative sealevel curve of Vail et al.(1977) and the oxygen-isotope climatic curve of Shackelton and Kennett (1975) are also shown.

Coaledo Formation. Turbidites and channel-filling strata dominate the lower portion of the sequence. Upsection, HCS begins to appear just below the base of the Coaledo Formation where the HCS model was first described in detail (Dott and Bourgeois, 1982).

Further south in San Diego County, California, upper Ulatizian and lower Narizian strata of the Rose Canyon Formation (Figure 33) record a shift from inner fan to shelf canyon sedimentation (Lohmar, 1977; Lohmar and Warme, 1979). Detailed paleo-bathymetric analysis of microfossils from the Rose Canyon Formation indicates that in southern California a high stand of sea-level occurred during the Ulatizian followed by a low stand during the Narizian. The Narizian low stand washed conglomeratic sediments from the Stadium Delta onto the shelf. This sequence of eustatic sea-level changes has fairly good fit with isotopic evidence for the initiation of glaciation at high latitudes during the middle and late Eocene (Shackelton and Kennett, 1977; Oberhansli and Hsu, 1986) (Figure 33 and Geologic Setting section).

The striking similarity and correlation among these three middle to late Eocene sequences suggest that eustatic sea-level regression could have been a dominant factor in controlling the shoaling of the study unit.

Second, tectonic uplift of the shelf would produce a similar stratigraphic signature. The tectonically active nature of the North American continent margin during the middle to late Eocene is accepted by most workers (Wells et al., 1984; Simpson and Cox, 1977; Byrne, 1979; among others). During this period the oceanic plates adjacent to North America (Kula and Farallon) were moving very rapidly (Kula-21 km/m.y., Farallon-130 km/m.y.) and experiencing rapid and abrupt changes in motion (Engebretson et al., 1986; Wells et al., 1984) (Figure 2b). In addition, the Kula-Farallon spreading ridge was close to the continental margin (Wells et al.,1984; Engebretson et al.,1985)(Figure 1). Such rapid plate movements and the proximity of the spreading ridge to the continental margin would result in a shallow angle of subduction at the North American margin and more coupling between North America and the down-going slab (DeLong et al., 1978). The probably result of such coupling would be tectonic uplift of the continental margin (DeLong et al., 1978). Frequent and intense seismic activity also results from such coupling.

In addition to the effects of plate motion, other tectonic processes during the middle to late Eocene could have produced uplift in the Pacific Northwest. During the middle to late Eocene, the Coast Range/Klamath block was undergoing clockwise rotation (Hammond, 1979). The Metchosin Volcanics (correlative with the Crescent Formation) were possibly being thrust under the southern edge of Vancouver Island (Massey, 1986; Yorath et al., 1985) as the result of compression caused by this rotation (Figure 5). This thrusting activity could have produced uplift along the southern edge of Vancouver Island (Heller et al.,1987), a probable site of deposition for the study unit. Tectonic uplift in conjunction with the tropical to subtropical climate of the middle latitudes during the middle to late Eocene (see Geologic Setting section) would combine to produce high rates of erosion supplying large quantities of sediment to nearby basins.

Third, shoaling could have resulted from sedimentation rates on the shelf being greater than the subsidence of the basin. In light of the evidence for high sedimentation rates discussed above, this model cannot be discounted.

Despite the apparent eustatic control of shoaling suggested by the correlation of sea level changes in three sedimentary sequences along the coast of western North America, eustatic effects cannot be isolated as a major control of this shoaling. It has been shown by various workers that accreted terranes experience subsidence and uplift resulting from obduction, translation, and suturing long after these processes have ceased (Emery and Aubrey, 1986; Uchupi and Aubrey, 1988, among others). The deposition of the three shoaling sequences on different accreted terranes (Coney et al., 1980) would result in differential rates of subsidence and uplift among the three sequences. Consequently, unequivocal designation of a eustatic cause of the shoaling in these three sequences is not possible. Nevertheless, the occurrence of the shoaling in the three sequences during a eustatic drop in sea level (Figure 33) is probably not fortuitous. In addition to the possible eustatic control of shoaling in the study unit tectonic effects may have also occured. Deposition of the study unit occurred during rapid northwest-directed subduction of the Kula and/or Farallon plates (Engebretson et al., 1986). In addition, the Crescent terrane was being deformed against North America (Beck and Engebretson, 1982). These two processes could have caused uplift of the basement of the study unit as it was deposited resulting in a shoaling sequence. However, it is impossible to say whether eustatic or tectonic effects were both responsible for the shoaling or whether one dominated.

SUMMARY

Evidence compiled above points to a storm-dominated pro-delta shelf to slope environment as the site of deposition for these middle to late Eocene strata (Figure 34). The source area was probably relatively mountainous with areas of high relief close to the coast (see Provenance

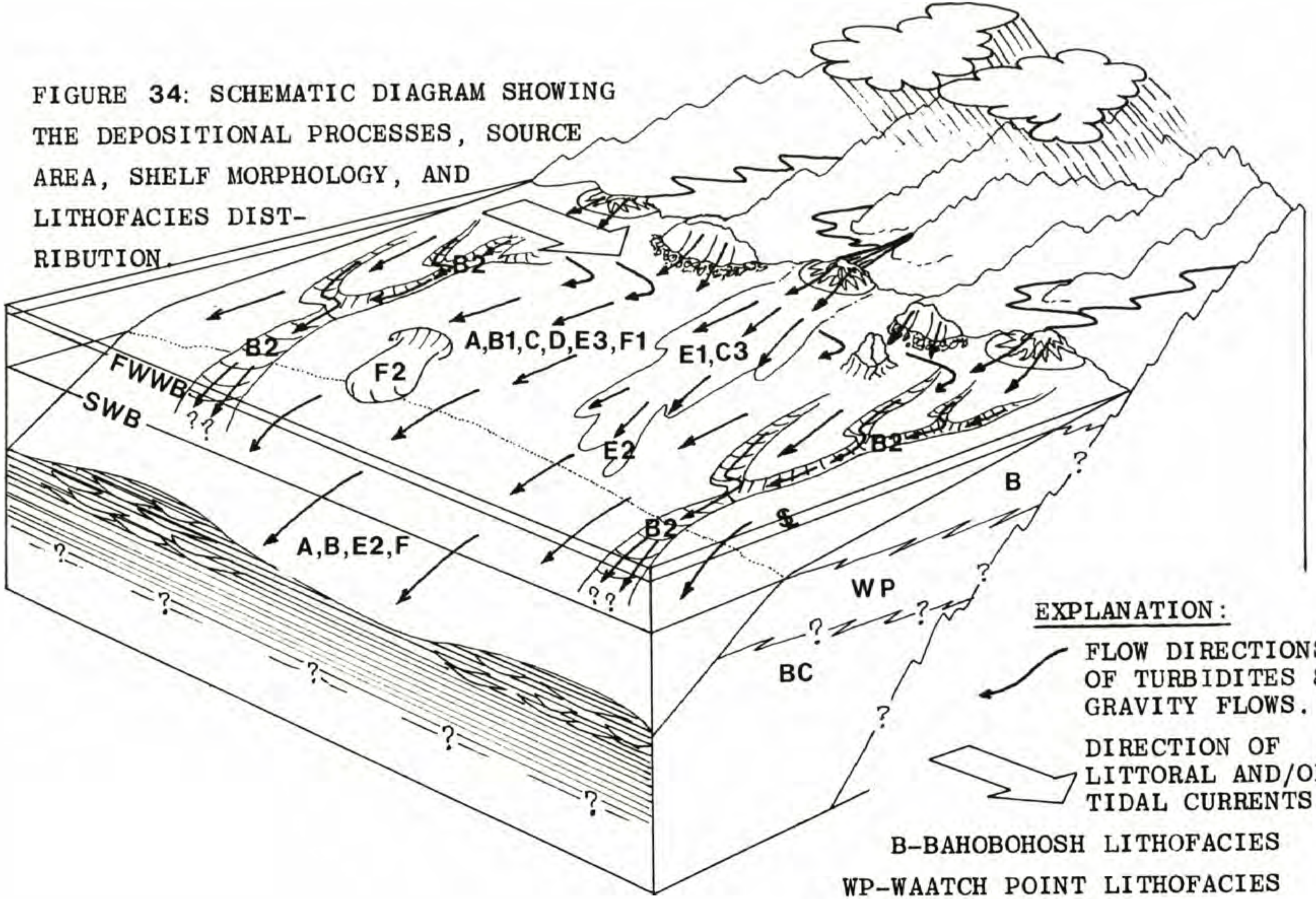


FIGURE 34: SCHEMATIC DIAGRAM SHOWING THE DEPOSITIONAL PROCESSES, SOURCE AREA, SHELF MORPHOLOGY, AND LITHOFACIES DISTRIBUTION.

section). Numerous coarse-grained deltas probably supplied sediment to the narrow shelf. Sedimentation on the shelf during the early history of the sequence was dominantly fine-grained, as most coarse sediment was transported across the shelf through small channels and gullies and probably into the upper channels of a submarine fan or submarine ramp (Heller and Dickinson, 1985). As deposition proceded, the sequence became coarser-grained, possibly as a consequence of shoaling. Deposition of debris flows and olistostromes resulting from this shoaling and perhaps occasional catastrophic events (earthquakes, tsunamis, or major storms) punctuated this coarsening trend.

GEOCHEMISTRY

INTRODUCTION

Various geochemical parameters were studied as part of the depositional environment analysis of the study unit. The intent of this geochemical investigation was to qualify the oxygenation conditions under which the study unit was deposited. One main goal of this study is to address the implications that the geology of the study unit has for the paleogeography of the Pacific Northwest. Studying the oxygenation of the study unit could place some constraints on the nature of the sedimentary basin. If the strata represent deposition under well oxygenated conditions then it is probable that the basin was well mixed with the open ocean. However, if the basin was found, through geochemical analysis, to have been anoxic or dysaerobic, then the possibility that the basin was silled would be an important paleogeographic consideration.

This geochemical investigation is modeled after a study by D.L. Gautier (1986) in which the organic carbon and sulfide mineral abundances and sulfur-isotope compositions of Cretaceous shales from the western interior seaway of North America were analysed. Gautier's samples were taken from rocks ranging in degree of bioturbation and that are thermally immature with respect to petroleum generation. Gautier's study was designed to show whether or not the sulfur-isotope compositions of marine shales are a good indicator of the oxygenation in pre-diagenetic sediments and in the overlying water column.

GEOCHEMICAL THEORY

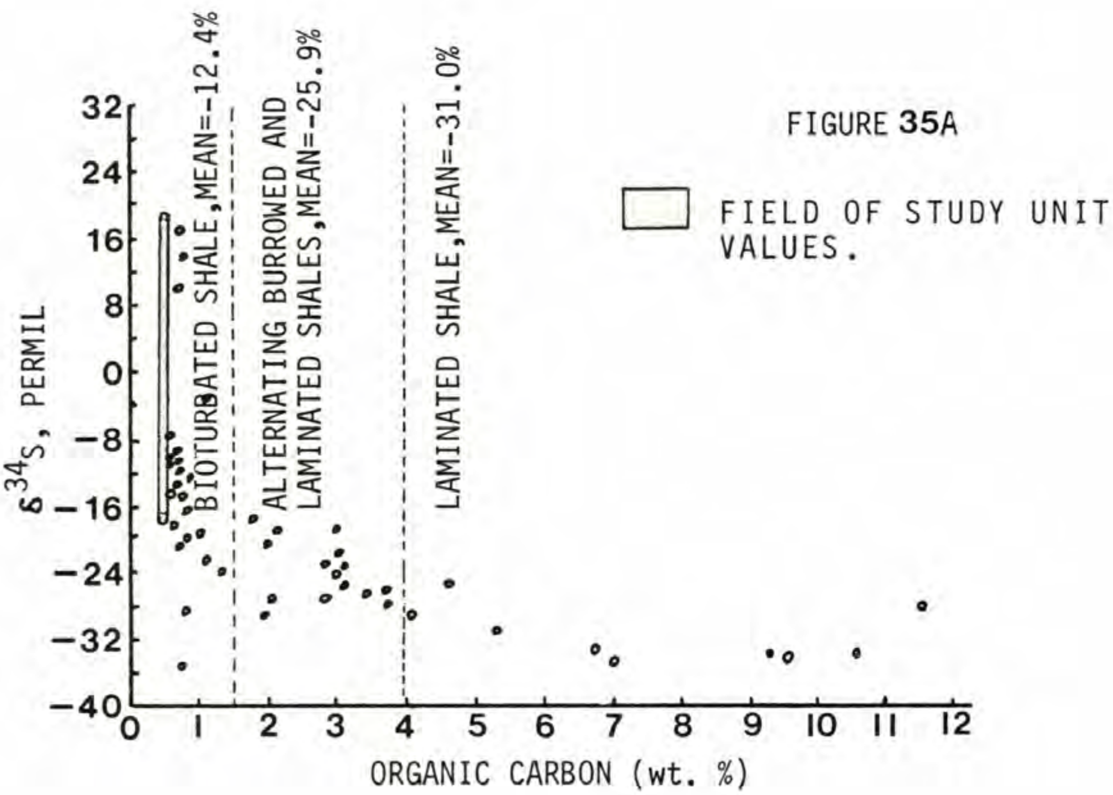
Authigenic sulfides in the marine sedimentary environment (predominantly pyrite) are generated diagenetically as a result of the reducing activity of anaerobic bacteria in the sediment. These bacteria split oxygen from sulfate ions, excreting hydrogen sulfide, in order to metabolically oxidize organic matter in the sediment. Hydrogen sulfide generated in this way is depleted in the common heavy isotope of sulfur (^{34}S) because the ^{32}S-O bonds in sulfate are more easily broken than comparable ^{34}S-O bonds (Faure, 1977). By this mechanism, ^{32}S is preferentially moved from sulfate to sulfide by anaerobic bacteria. This ^{34}S-depleted sulfide is then converted to sulfide minerals during the early stages of diagenesis (Berner and Westrich, 1985; Goldhaber, 1975). The effects of anaerobic bacteria are only significant where oxygenation levels are severely reduced and the respiring bacteria are inactive. Anaerobic bacteria consume organic matter at rates far below those of respiring bacteria due to low concentrations of sulfate in the sedimentary environment. Because oxidation rates are lowered and bioturbation does not occur, sediments deposited under anoxic conditions can be rich in organic matter relative to those deposited where oxygen levels are high. Thus, geochemical theory would predict the correlation of high percentages of organic carbon and sulfide minerals, in addition to ^{34}S-depleted sulfur-isotope signatures, in sediments deposited under anoxic conditions. Conversely, relatively oxygenated sedimentary conditions would generate low percentages of organic carbon and sulfide minerals and relatively undepleted ^{34}S values. Dysaerobic conditions would produce organic carbon, sulfide minerals, and sulfur-isotope values intermediate to these two end member conditions.

GEOCHEMICAL REALITY

Gautier (1986) found that results from his analyses of Cretaceous seaway shales matched geochemical theory fairly well. The organic carbon and sulfide mineral abundances and sulfur-isotope signatures of these shales showed good positive correlation (Figure 35). Gautier (1986) divided his samples into three categories. Shales with high percentages of organic carbon (>4%) have high percentages of sulfides and very depleted sulfur-isotope signatures ($\delta^{34}S$=-25%. to -36%.;mean $\delta^{34}S$=-31%.). These shales are all laminated. Carbon-poor samples (<1.5%) are correspondingly sulfide-poor and have less depleted but wide ranging sulfur-isotope values ($\delta^{34}S$=+16.8%. to -34.6%. ;mean $\delta^{34}S$=-12.4%.). These samples are all bioturbated. These results suggest that the activity of anaerobic bacteria and hence oxygenation conditions vary considerably, even where bioturbation is occurring. $\delta^{34}S$ values from alternating laminated and bioturbated shales have intermediate organic carbon and sulfide mineral abundances and intermediate sulfur-isotope values ($\delta^{34}S$=-16%. to -30%. ;mean $\delta^{34}S$=-25.9%.).

THIS STUDY

In comparing data from the study unit (Table 2) with that of Gautier (1986), certain problems in the interpretation of the results are found. Because the strata of the study unit vary between laminated and sparsely bioturbated, intermediate $\delta^{34}S$ values, between those of the endmember conditions of Gautier (1986) would be expected. Relatively high percentages of organic carbon and sulfide minerals would also be expected. However, the analytical results in Table 2 show that $\delta^{34}S$ values in .pa the study unit are highly variable (Figure 35A) and generally undepleted (mean $\delta^{34}S$=+1.4%.)(Table 2). In addition, the abundances of organic



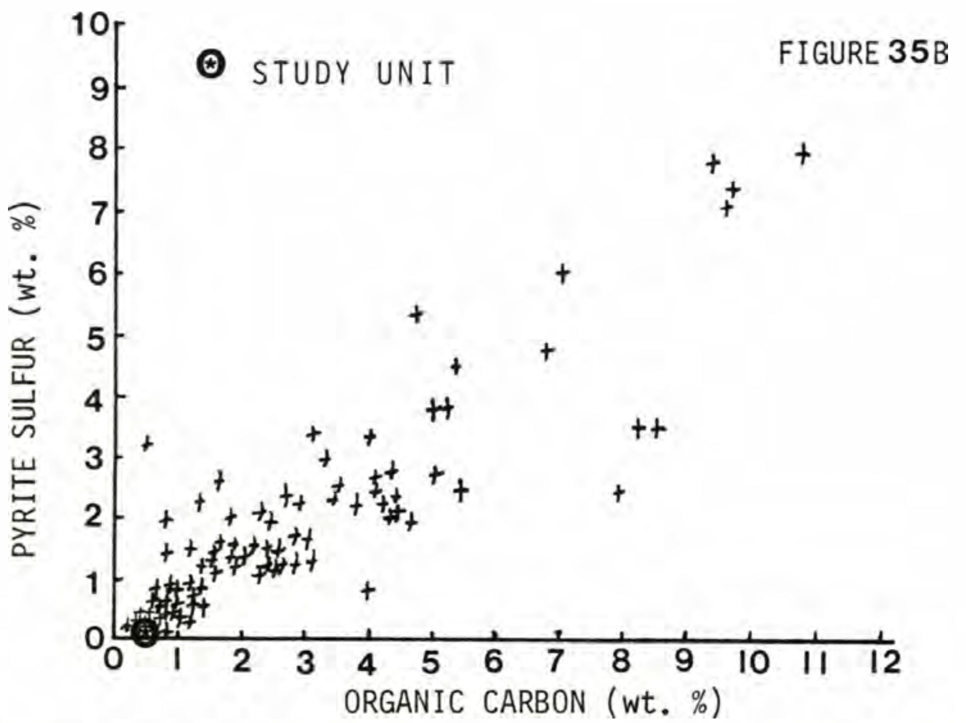


FIGURE 35; (A) PLOT-GAUTIER'S (1986) SULFUR-ISOTOPE DATA VS. WEIGHT PERCENT ORGANIC CARBON WITH FIELD OCCUPIED BY STUDY UNIT DATA. (B) PLOT-GAUTIER'S (1986) DATA; WEIGHT PERCENT ORGANIC CARBON VS. WEIGHT PERCENT SULFIDES WITH FIELD SHOWING STUDY UNIT DATA.

TABLE 2; The results of the total organic carbon, weight percent sulfide, and sulfur-isotope analyses for the study unit. Sulfur-isotope values are reported relative to troilite in the Canyon Diablo meteorite (Faure,1977).

SAMPLE #	TOTAL ORGANIC CARBON	WEIGHT PERCENT SULFIDES	delta ^{34}S
1	0.40	0.0523	-16.8
2	0.39	0.0593	-14.1
3	0.40	0.0138	+5.5
4	0.40	0.0154	NA
5	0.41	0.0284	-19.5(-18.9)*
6	0.36	0.0012	+7.5
7	0.35	0.0007	+11.6
8	0.31	0.0034	-1.9
9	0.36	0.0004	+18.1
10	0.31	0.0003	+12.7
11	0.28	0.0004	+11.1
12	0.27	0.0005	+3.6
13	0.34	0.0005	+4.7
14	0.38	0.0008	+15.3
15	0.32	0.0202	-18.4(-18.7)*
	mean=0.35	mean=0.0132	mean=+1.4

* Indicates duplicate determination

-Total organic carbon values were determined in the instrument center at Western Washington University.

- δ^{34}S and weight percent sulfide values were dtermined by the Global Geochemical Corporation, Canoga Park, CA.

carbon and sulfide minerals are extremely low (Figure 35B). The procedure used to determine the abundances of organic carbon is described in Appendix 2.

Various factors could account for this deviation from expected geochemical results. First, there is evidence that the accumulation rates of study-unit sediments were very high. Soft-sediment deformation features such as load casts, flame structures, and slump structures are very common in the study unit, indicating rapid burial of soft, recently deposited sediments. Therefore, one explanation of the geochemical results is that the sedimentary environment was well oxygenated but that the sedimentation rates were too high the allow extensive bioturbation. However, higher percentages of organic matter than are observed in the study unit would be expected under such conditions. Second, it is probable that the sediments of the study unit have been subjected to relatively high pressure and temperature after burial. Diagenetic minerals in the sandstones of the study unit, such as laumontite and other zeolites, are indicative of temperatures of $\tilde{}200^{o}$ C and pressures of less than 3kb (Winkler, 1979). Such pressure/temperature conditions have profound effects on the organic matter in the sediments. Much of the organic matter in the study unit could have been destroyed or migrated out of the the study unit. The homogeneity of the weight-percent-carbon values, which were collected from a variety of facies, supports this conclusion. Diagenetic reactions under these pressure/temperature conditions could have altered the original sulfur-isotope signature in the sulfides of the study unit. Thus, the geochemical signature in the study unit is probably not indicative of the original depositional conditions.

In conclusion, it must be conceded that the attempt to qualify the oxygenation conditions of the study unit through analysis of the relative abundances of organic carbon and sulfides and the sulfur-isotope signature in the sulfides has been unsuccessful. Although stratigraphic evidence suggests that oxygen levels in the sediments were probably high enough to support infauna, sedmentation rates were probably too high to allow the establishment of a healthy community. Applying this geochemical technique to a unit whose petrology was previously unstudied was risky. Diagenetic and very low grade metamorphic grade alteration of the study unit probably has obscured the original geochemical signature of oxygenation level. A pyrolysis/gas chromatographic analysis of the sparse organic matter in the study unit could help to clarify the thermal history of the sediments and elucidate the applicability of sulfur-isotope data to questions of depositional conditions on the shelf and to thermally mature sediments.

PETROGRAPHY

INTRODUCTION

Samples were collected in an effort to represent the wide range of grain-sizes and facies that comprise the study unit. Samples range in grain size from very fine sand to granule conglomerate. In addition, samples of the dominant clast types were collected from the coarser conglomerates. Where stratigraphy is coherent, sampling was carried out systematically to allow tracing of possible compositional changes over time and across facies boundaries. Where coarse-grained concretions occur, both the concretions and surrounding strata were sampled to provide a comparison.

Thin sections were prepared from 108 samples. Half of each thin section was stained to allow easy identification of plagioclase and potassium feldspar. Point counts of 42 of the samples were performed using the Gazzi-Dickinson method (Ingersoll et al., 1984). 400 points including monocrystalline and polycrystalline grains were counted on each thin section. Where the grains varied in composition, sub-categories were established and tallied as the point count proceeded. Categories and sub-categories (summarized in Table 3) are described in Appendix 2. Spacing of the point-count grid was selected for each thin section in order to minimize counting of grains more than once.

DESCRIPTIVE PETROGRAPHY

Relative abundances of the grain types very considerably from sample to sample (Appendix 2; Table 4). The modal composition is depicted graphically in Figure 36 . Q:F:L=48.3%:24.3%:27.4%, Qm:F:Lt = 27.6%:24.3%:47.9%. Proto-matrix and ortho-matrix (Dickinson, 1970) average 4.3% in the point-counted samples.

Table 3; Abbreviations and conventions used in reporting and discussing the point-count data. See Appendix 3 for details.

Qm: Monocrystalline quartz grains.

Chert: Microcrystalline quartz grains with less than 15% impurities.

Qp: Polycrystalline quartz grains including recrystallized chert.

P: Plagioclase feldspar grains.

K: Potassium feldspar grains.

Lss: Sedimentary lithic grains containing more than 50% silt-size sub-grains.

Lsf: Sedimentary lithic grains containing more than 50% clay-size or smaller sub-grains. Microcrystalline quartz grains with more than 15% impurities are counted here.

Lm: Metamorphic lithic grains.

Lv: Volcanic lithic grains.

Li: Intrusive lithic grains.

Misc: All grains that do not fit into other categories inclusing detrital calcite, chlorite, pumpellyite, and rare laumontite, as well as organic matter, porosity, and unidentifiable grains.

H: Accessory minerals not including opaque minerals.

O: Opaque mineral grains.

Matrix: Protomatrix and orthomatrix as defined by Dickinson (1970).

Cement: Post-depositional minerals that act as cement to the framework grains.

Table 4: Results of point counts reported as the average of all point count data and as average of data from the lithofacies divisions of Snavely et al.(1986). Ranges in point count data from all samples are also shown.

GRAIN TYPE	AVERAGE PERCENTAGE OF ALL SAMPLES	RANGE OF PERCENTAGE VALUES	GRAIN TYPE AVERAGES BY LITHOFACIES Bahobohosh	Waatch Point	Bear Creek
Qm	18.7	6.8-35.5	16.9	18.1	23.0
Chert	7.4	2.0-19.0	6.6	7.3	9.2
Qp	7.0	2.5-14.2	7.7	6.4	5.9
P	13.9	7.3-22.8	12.7	17.6	14.0
K	2.4	0-7.8	2.8	2.5	1.4
P/F ratio	(0.87)	(0-0.75)	(0.82)	(0.87)	(0.91)
Ls	13.0	1.5-25.8	16.1	10.3	7.9
Lm	2.1	0-8.5	2.0	1.7	2.5
Lv	5.2	0.8-11.8	5.8	2.7	5.7
Li*	1.2	0-2.3	1.1	0.8	1.7
L**	21.4	9.0-44.3	25.0	15.5	17.8
Lt***	35.8	12.6-53.8	39.4	29.3	32.9
Misc	2.4	0-4.7	2.0	2.0	3.5
H	3.0	0.5-6.8	3.0	3.4	2.5
O	1.5	0-8.0	0.9	2.7	1.9
Matrix	4.2	1.0-11.7	4.3	5.1	3.4
Cement	15.5	7.3-27.5	15.4	16.7	14.8
Unknown	2.9	1.9-6.4	2.6	3.2	3.1
TOTAL	100.4%	---0---	99.9%	100.5%	100.4%

* Li represents only fine grained plutonic clasts not counted as their monocrystalline components.
** L = Ls + Lm + Lv + Li
*** Lt = L + Qp + Chert

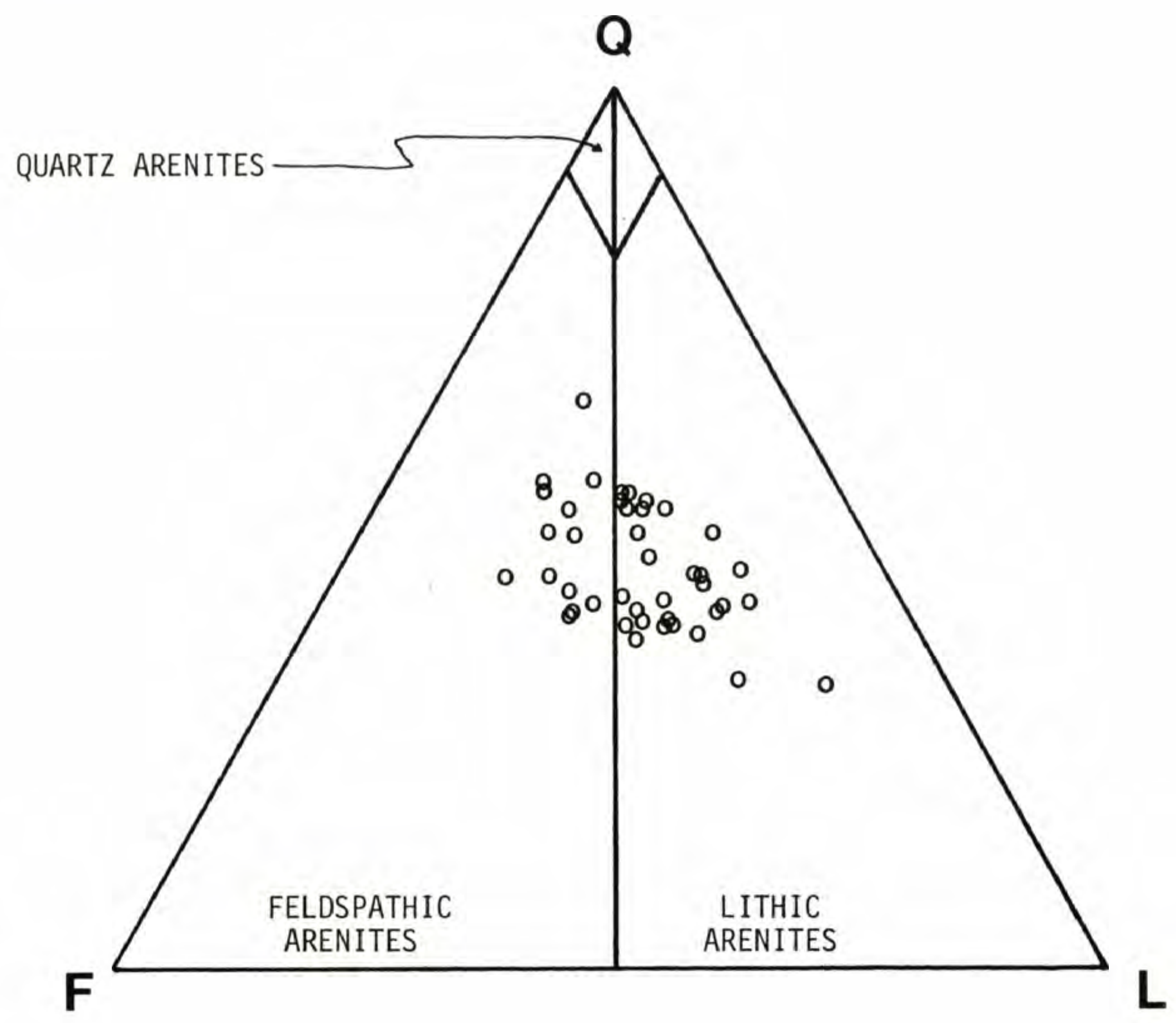


Figure 36; Modal compositions of the sandstones in the study unit (Q=monocrystalline quartz, F=total feldspar, L=all lithic grains including chert) plotted on the sandstone composition diagram of Dott, 1964.

The majority of samples fall in the lithic arenite field of Dott (1964). Arkosic and sublithic arenites are also present. There is little significant variation in composition among the map units of Snavely et al. (1986) (Table 4; Figure 36). Both concretionary and non-concretionary sandstones are well indurated, light to dark gray in fresh samples, and tan to reddish-brown where weathered.

Texturally these sandstones are very immature. Sorting is uniformly poor to very poor. Grain-sizes within samples usually vary continuously from matrix to the maximum grain-size. Individual grains range from very angular to rounded. Monocrystalline quartz, polycrystalline quartz, feldspars, plutonic lithics, and less frequently volcanic lithics are generally very angular to sub-angular. Chert, metamorphic lithics, volcanic lithics, and many accessory mineral grains are generally sub-angular. Sedimentary lithics, where not compacted, and heavy minerals were generally sub-rounded to rounded.

Compaction was a significant process in the early diagenesis of the non-concretionary sandstones. The general lack of compaction in the concretionary samples indicates that the concretions were formed prior to compaction. Sedimentary lithics are largely deformed and compressed into pseudo-matrix. More competent grains such as micaceous accessory minerals, metamorphic lithics and volcanic lithics are generally in concavo-convex or long contact with adjacent grains. The most competent grains, such as quartz, feldspar, non-micaceous heavy minerals, and plutonic lithics, although not deformed, are usually in concavo-convex or long contact with less competent surrounding grains. Grain contacts in concretionary samples are tangential with floating grains predominating. Porosity is rare or absent.

Individual grains comprising the sandstones are of great variety. Point count categories were selected to accommodate this variety (see Appendicies 3, 4).

Qm: Monocrystalline quartz grains comprise a dominant portion of the study unit (Table 4) and are generally very angular to sub-angular, although a notable number of subhedral, and less frequently euhedral, grains was observed (Figure 37). Vacuole trains and inclusions are common. However, the euhedral and subhedral grains are notably free of vacuoles and inclusions. Undulose extinction is also a common characteristic of monocrystalline quartz grains. Alteration of monocrystalline quartz grains is minimal with only rare occurrences of seritization.

Volcanic, plutonic, and metamorphic sources for the monocrystalline quartz are suggested by the presence of clear euhedral, vacuoled and inclusion-rich, and undulose quartz grains, respectively. Plutonically-derived quartz predominates.

F: Plagioclase and potassium feldspar comprise a significant portion of the study unit (Table 4). P/F ratios average 0.87 and range from 1.00 to 0.52.

Plagioclase grains are dominantly untwinned suggesting a low strain or extensively recrystallized source. A significant portion of albite- and carlsbad-twinned grains does occur. Plagioclase compositions range from albite to labradorite but are dominantly albitic. Plagioclase grains are very angular to sub-rounded and vary significantly in their degree of alteration. Samples tend to contain dominantly fresh or dominantly altered plagioclase but not a mixture. Plagioclase ranges from fresh to nearly completely replaced. Minerals replacing plagioclase (discussed

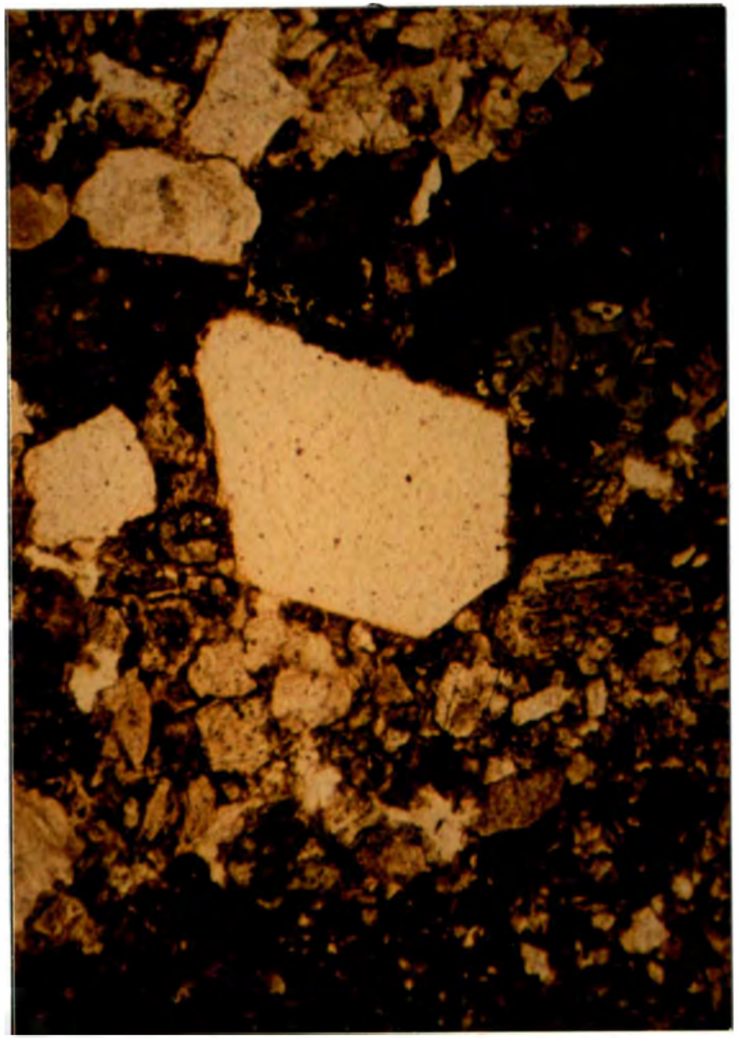


Figure 37; Euhedral quartz grain in an angular, poorly sorted sandstone. Field of view 2.7x1.8 mm. plane light.

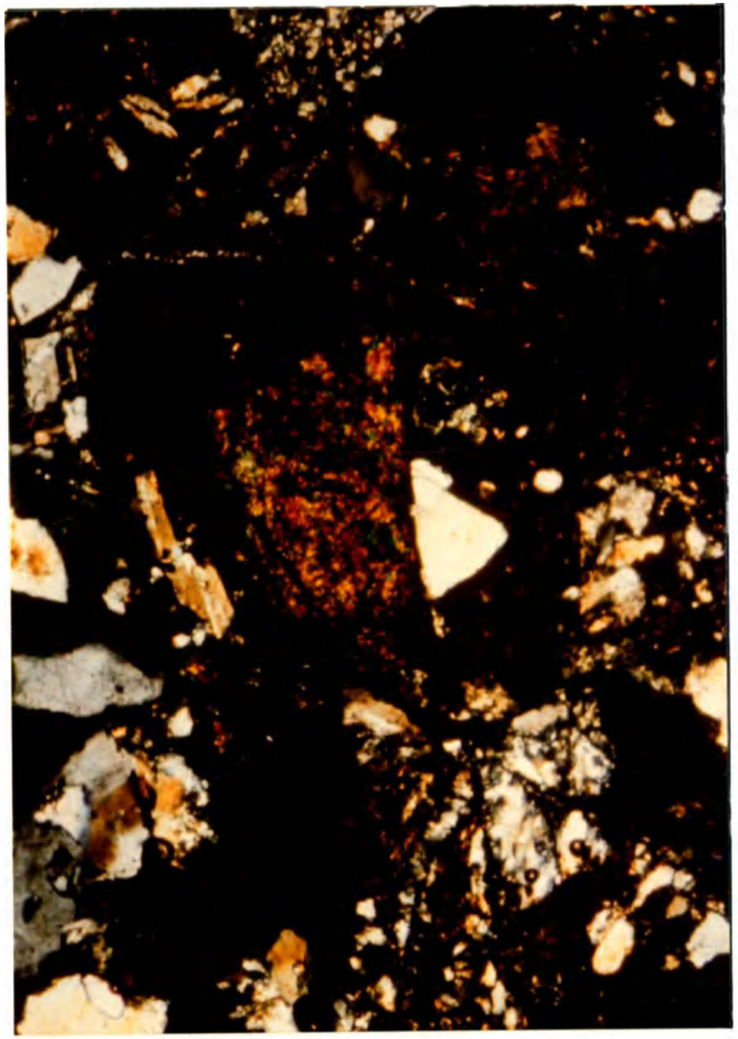


Figure 38; Psuedo-matrix surrounds an angular quartz grain and an angular epidote grain. Field of view 2.7x1.8 mm. Polarized light.

more fully below) include zeolites, sericite, calcite, chlorite, and pumpellyite. Plagioclase occurs dominantly as monocrystalline grains, although a significant portion is also present as laths in volcanic grains, in plutonic grains, and in coarse sedimentary grains.

Potassium feldspar occurs predominantly as monocrystalline orthoclase grains that are untwinned, fresh, and angular to sub-rounded. Minor quantitites are present in plutonic lithic fragments (discussed below).

The abundance of untwinned, unzoned plagioclase and significant proportion of untwinned potassium feldspar suggest a partially plutonic source for the study unit. However, high-grade regional metamorphic rocks could also provide this type of sediment.

L: Lithic grains comprise the bulk of the samples examined (Table 4).

Ls: Sedimentary lithic grains include sandstones, siltstones (LSS of Appendix 4), and shales (Lsf). Most sedimentary lithics have been compressed into pseudo-matrix (Figure 38). Where not compacted, sandstone grains are sub-rounded to rounded. The unlithified character of the sedimentary lithic grains and the abundance of rip-up clasts in the strata suggest that the majority of sedimentary lithic grains are intrabasinal in origin. However, some sandstone clasts are quartz arenites and subarkosic arenites, markedly different from the composition of the study unit suggesting extrabasinal origin.

Chert: Chert grains are sub-angular to sub-rounded. The degree of chert recrystallization varies. Some chert grains are fresh exhibiting well-preserved radiolarian tests. Others are wholly recrystallized or altered. The majority of chert grains contain very fine-grained pelitic inclusions.

Qp: Polycrystalline quartz grains other than chert exhibit segmented undulosity, deformation bands, stretched grains, and polygonized grain boundaries suggesting both metamorphic and plutonic origin. Qp grains are very angular to sub-angular. Alteration is minimal.

Lm: Metamorphic lithic grains include metasedimentary grains, metavolcanic grains, and quartz-mica tectonites (see Appendix 3 for distinctions). Metasedimentary grains predominate. Both the metasedimentary and quartz-mica tectonite grains have been largely compressed and deformed between more competent framework grains.

Lv: The volcanic grains are dominantly sub-angular but range from angular to sub-rounded. Lathwork grains predominate (Figure 39) but microlithic, felsic, and vitric grains are also present. The abundance of felsic volcanics may have been underestimated due to their similarity to recrystallized and altered chert grains. As might be expected by the abundance of lathwork volcanic grains, intersertal and intergranular textures are most common. Felty, pilotaxitic, and hyalopilitic textures are also present. Vitric grains contain many microlites of plagioclase and pyroxene.

In grains containing glass, the groundmass is usually largely or wholly replaced by zeolites, chlorite, calcite, and possibly pumpellyite. In such cases, volcanic lithics were recognized on the basis of preserved textures.

The textures and mineralogy of the volcanic lithic grains suggest that predominantly mafic to intermediate volcanics were the source of the Lv grains.

Li: Intrusive lithic fragments are angular to sub-rounded. Clasts of granite, granodiorite, and quartz diorite (Figure 40) are most common,

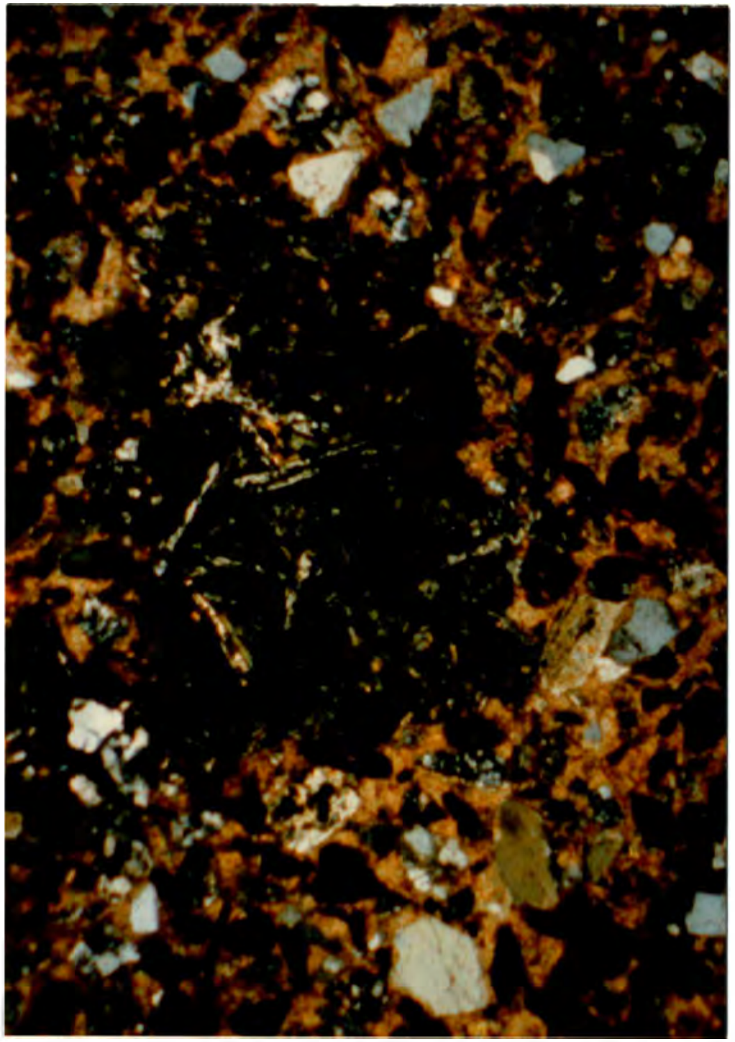


Figure 39; Altered lathwork volcanic clast surrounded by poorly sorted framework grains in a calcite cemented concretion. Field of view 3.5x2.3 mm. Polarized light.

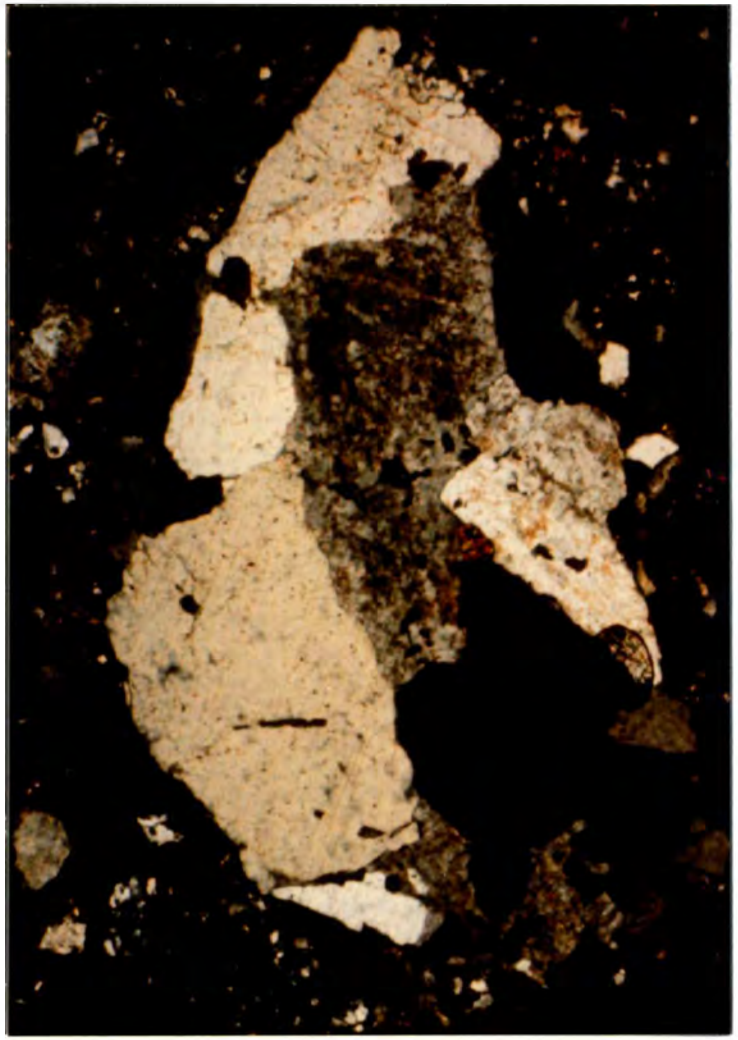


Figure 40; Probable quartz diorite clast in a poorly sorted sandstone comprised of angular clasts. Field of view 3.5x2.3 mm. Polarized light.

although gabbroic grains were also observed. In addition, some relatively fine-grained clasts consist entirely of potassium feldspar. These grains are probably the result of late-stage residual-fluid crystallization of aplites associated with pegmatites (R. S. Babcock, 1987, oral communication).

Textures of the intrusive clasts vary. The felsic grains are predominantly subhedral to anhedral epigranular. Grain boundaries are often consertal. Micrographic, granophyric, and mermikitic textures were also observed. The gabbroic grains are uniformly intergranular.

H: The heavy minerals are angular to rounded with sub-rounded grains dominating. Epidote-group minerals are the predominant grain type (Figure 38). Other minerals present are pyroxene, chlorite, pumpellyite, biotite, actinolite (Figure 41), muscovite, hornblende, zoisite, clinozoisite, zircon, tourmaline, and sphene in decreasing order of abundance. Heavy minerals commonly show considerable alteration and replacement by diagenetic minerals (see below).

The presence of epidote, actinolite, chlorite, and pumpellyite in the samples implies that very low- to low-grade metamorphic rocks were in part a source for the study unit (Winkler, 1979). A mafic protolith is a probability for this mineral assemblage (Winkler, 1979). The other common heavy minerals are largely indistinctive as to source.

In addition to the heavy-mineral grains, opaque minerals and miscellaneous mineral grains were counted. No effort was made to distinguish types of opaque minerals. Miscellaneous minerals include calcite, organic matter, zeolites, and unidentifiable grains. Only traces of each of these subcategories are present. The detrital calcite and zeolites are well rounded. Organic matter is deformed between more

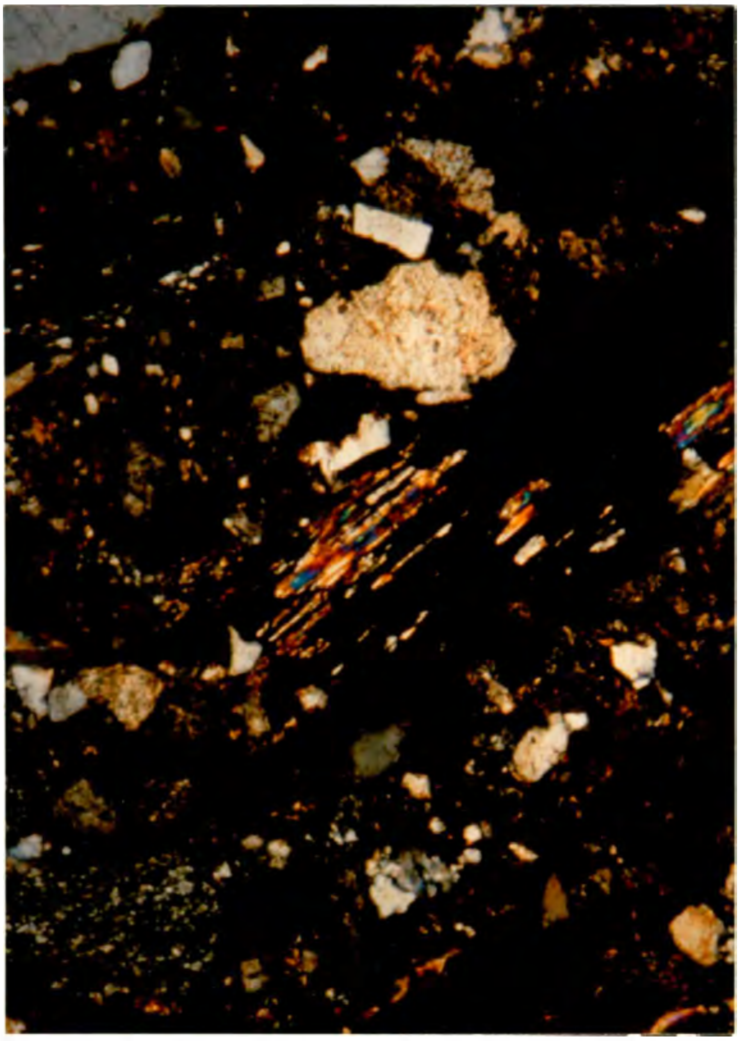


Figure 41; An actinolite grain (center of the photomicrograph) is surrounded by a variety of clast types including psuedo-matrix. Field of view 2.1x1.5 mm. Polarized light.

competent grains. Pore spaces are usually lined with diagenetic zeolites or clay minerals.

Dominant clast types from conglomeratic strata in the study unit were collected and identified under the microscope. This information shows that rip-up clasts, indurated sandstone, basalt, granitic clasts, chert, and tuffaceous limestone, in decreasing order of abundance, are the dominant clast types in the coarser portion of the conglomeratic strata. Abundances of grains in conglomerates were estimated visually. Clasts in the conglomerates reach approximately one meter in diameter. Average diameter of extrabasinal clasts is approximately five centimeters. Thus, the conglomeratic strata in the study unit have compositions similar to those of the sandstones.

POST-DEPOSITIONAL CHANGES

Post-depositional changes in the study unit involved compaction, cementation, and replacement of framework grains. Compaction occurred prior to and during cementation and grain replacement.

The result of compaction is most noticeable in the abundance of pseudo-matrix. In the non-concretionary samples, the majority of sedimentary and metasedimentary grains, together comprising approximately 13% of te study unit, have been deformed into pseudo-matrix. In addition, more rigid framework grains have been pressed into long or concavo-convex contacts. Tangential contacts are rare. Floating grains are absent. Comparison of concretionary samples with samples from surrounding strata suggests that original porosities may have been as high at 35% to 40%. Destruction of the porosity by compaction and cementation has been nearly complete.

A.

B.

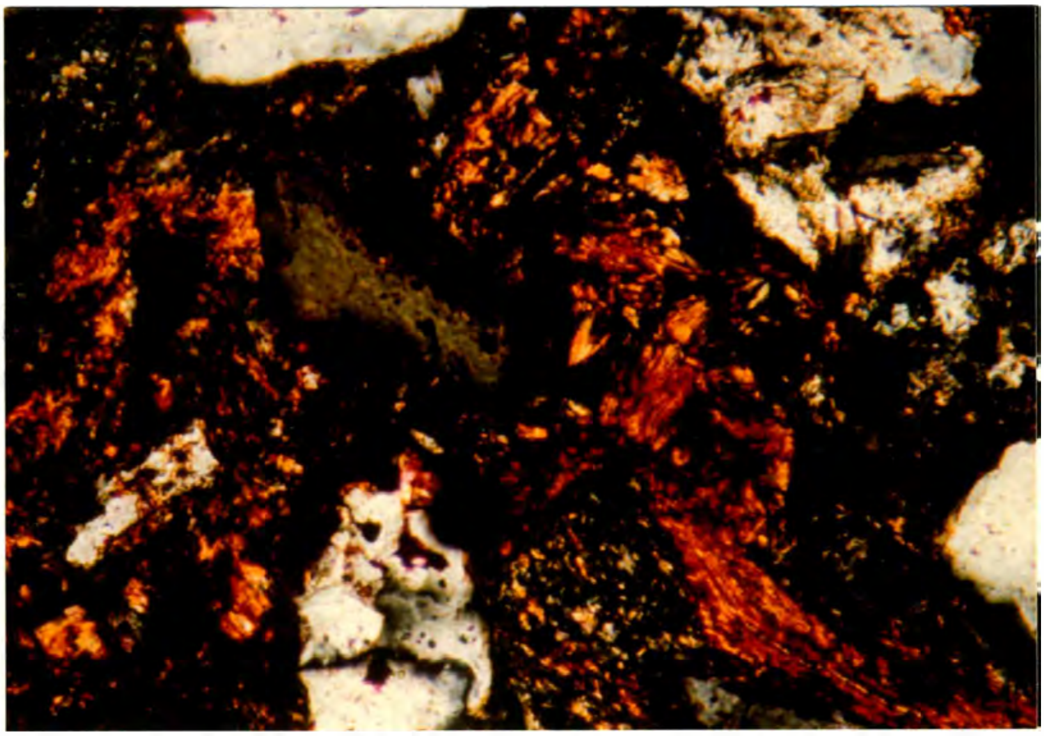


Figure 42; (A)Plane-light photomicrograph showing the common zeolite cement found in the sandstones. (B) The same view under polarized light. Field of view 0.85x0.58 mm. Note the radial structure of the zeolite in places.

Diagenetic mineralogy of the non-concretionary samples is complex. Zeolites are the most common diagenetic mineral (Figure 42) followed in abundance by clay, calcite, chlorite, and finally pyrite. Laumontite, recognized by its dark red stain, comprises up to 50% of the zeolites in eacn sample.

The textures of diagenetic minerals are various. They are divided between phyllosilicate cement, other cement, and epimatrix as defined by Dickinson (1970). Cement consists predominantly of zeolites, some of which exhibit radial growth textures. Calcite cements are sub-poikilitic and clear to murky. Pyrite cement, occurring in trace amounts, is present as blebs and aggregates of spherules. Phyllosilicate cement is homogeneous and clear. In some cases radial crystal growth and medial sutures are present. Murky, inhomogeneous, and structureless interstitial material, showing no relict clastic texture but consisting of zeolites and clay minerals falls under the classification of epimatrix (Dickinson, 1970).

The extensive occurrence of zeolites suggests that the study unit was relatively deeply buried. However, the absence of metamorphic minerals and textures indicate that maximum burial conditions did not exceed approximately 5 km depth, 200^{o}C, and 3 kb pressure (Winkler, 1979).

DISCUSSION

Concretionary vs. Non-concretionary Variations

No systematic variations between concretionary and non-concretionary samples are observed. Concretion formation appears to have occurred early in the diagenetic history of the strata. Grain contacts in concretions are few and dominantly tangential. Floating grains predominate. In addition, sedimentary lithic grains in the concretions are undeformed.

The predominance of floating grains implies that considerable replacement of framework grains has occurred. Murky and silty patches within the calcite cement of concretionary samples suggests that sedimentary lithic grains and proto-matrix were the victims of calcite replacement. Calcium-bearing heavy minerals such as epidote, augite, pumpellyite, and actinolite may also have been replaced. Some concretions show a lower proportion of heavy minerals than their non-concretionary counterparts. In addition calcite was observed replacing heavy minerals. Plagioclase grains also show considerable replacement by calcite in both concretionary and non-concretionary samples. Wholesale replacement of plagioclase may have occurred in some concretionary samples.

Variations Between Lithofacies of Snavely et al. (1986)

No marked, discernable differences exist between the Bahobohosh, Waatch Point, and Bear Creek lithofacies (Table 4; Figure 36). With three exceptions, the Bear Creek lithofacies plots more toward the Qm corner of the diagram. Samples of the Bahobohosh and Waatch lithofacies overlap considerably on the tectonic provenance plots (see Provenance section). The three anomalous samples from the Bear Creek lithofacies were collected toward the extreme eastern edge of the study unit and contain significantly more chert and lithic grains than the average for the Bear Creek lithofacies average (Table 4). This difference could be the result of a slightly different deposition regime or lateral variations in source area lithology. Nevertheless, separation of the lithofacies is not sufficient to warrant close consideration.

SUMMARY

Sandstones of the study unit are dominantly lithic arenites (Dott, 1964) with lesser amounts of arkosic and sublithic arenite. Texturally these sandstones are very immature. Sorting is poor to very poor. Grains range from rounded to very angular, although most grains are sub-angular to angular. Lithic clasts, including polycrystalline quartz and chert, are the most common grain type. Polycrystalline quartz plus chert comprise the majority of lithic grains followed closely by intrabasinal sedimentary lithics and then volcanic lithics. The volcanic lithics have dominantly lathwork textures with lesser amounts of microlitic and felsic grains. Plutonic lithic clasts are present in significant quantities. Monocrystalline grains include quartz, plagioclase, potassium feldspar, epidote, pyroxene among others.

Diagenesis of the sandstones was probably a multistage process involving calcite, clay, and zeolite cementation as well as considerable compaction.

The characteristics of the quartz and feldspar grains, the heavy mineral assemblage, and the composition of the lithic clasts all suggest that unmetamorphosed to greenschist facies basaltic volcanics, chert, and granitic to dioritic plutonic and metaplutonic rocks were the main lithologies in the source area of the study unit. The immature nature of the sediments shows that the source area was close to the site of deposition.

PROVENANCE

INTRODUCTION

The provenance of the study unit has been determined primarily from petrographic data with some help from paleocurrent indicators. Point count data and detailed petrographic observations are used to determine both the tectonic provenance and possible source areas for the study unit.

TECTONIC PROVENANCE

Modal percentages of detrital framework grains in sandstones were used by Dickinson and Suczek (1979) to delineate the gross tectonic character of sandstone source areas. Sandstones of the study unit plot in different tectonic fields on different diagrams (Figure 43,44,45,46). Switching of data points from one tectonic field to another among diagrams indicates that sediment was derived from tectonically diverse lithologic units (Suczek, 1987). The diversity of the lithic clasts in the study unit supports this conclusion. Mixing of sediment derived from tectonically diverse lithologic units is characteristic of active plate margins where many terranes have been juxtaposed (Suczek, 1987), as is certainly the case in the Pacific Northwest (Figure 47). Based on the diversity of lithic clasts in the study unit and the switching of fields among tectonic provenance plots it is probable that sediments of the study unit were derived from sources representing a variety of tectonic settings.

SOURCE AREA

Characteristics of the Source Area

Various conclusions about the conditions in the source area are possible. The angular and in some cases subhedral and euhedral nature of

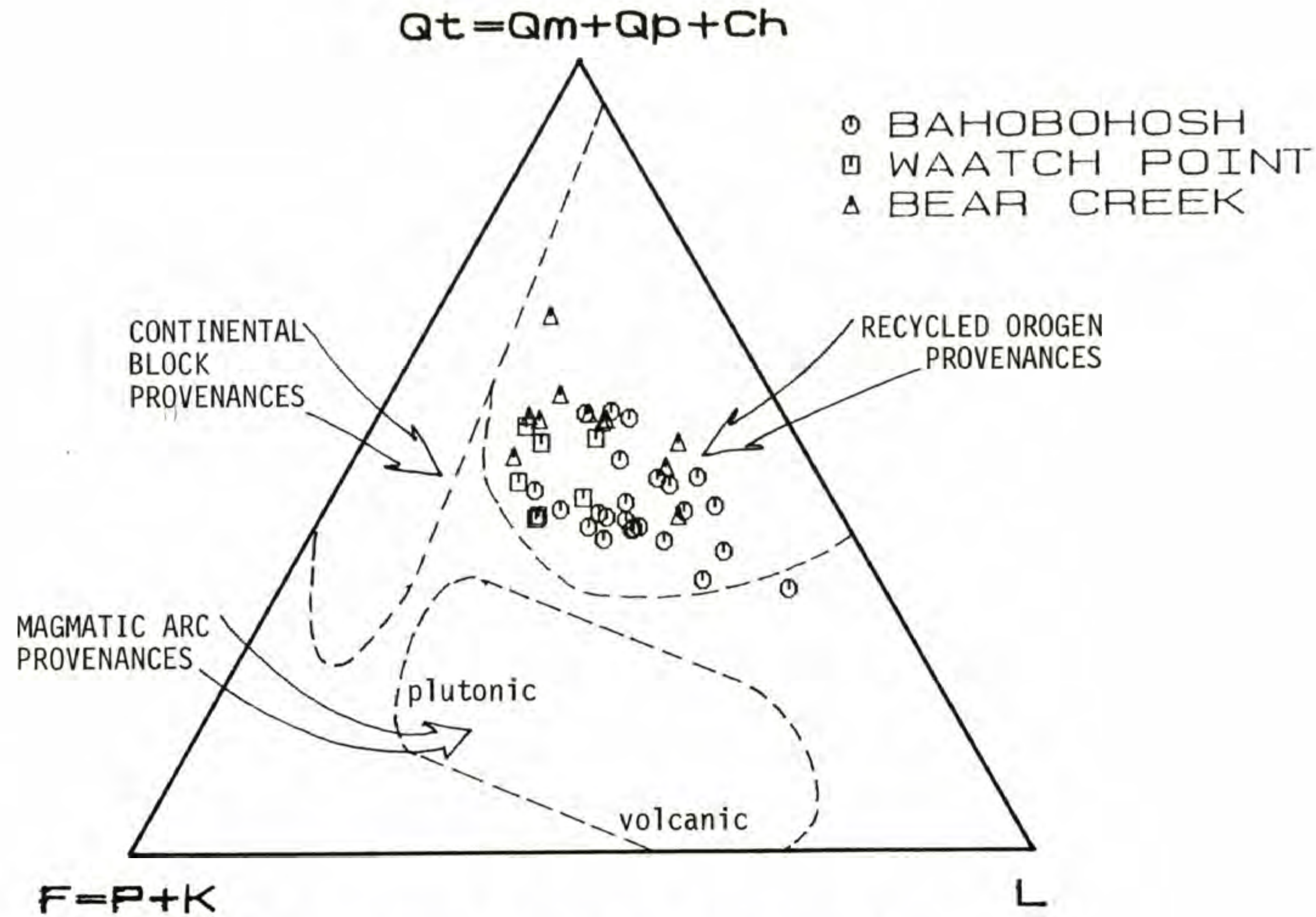


Figure **43**; Triangular QFL plor showing the various provenance types and the distribution of compositions of sandstones from the three lithofacies of Snavely et al.(1986). After Dickinson and Suczek, (1979).

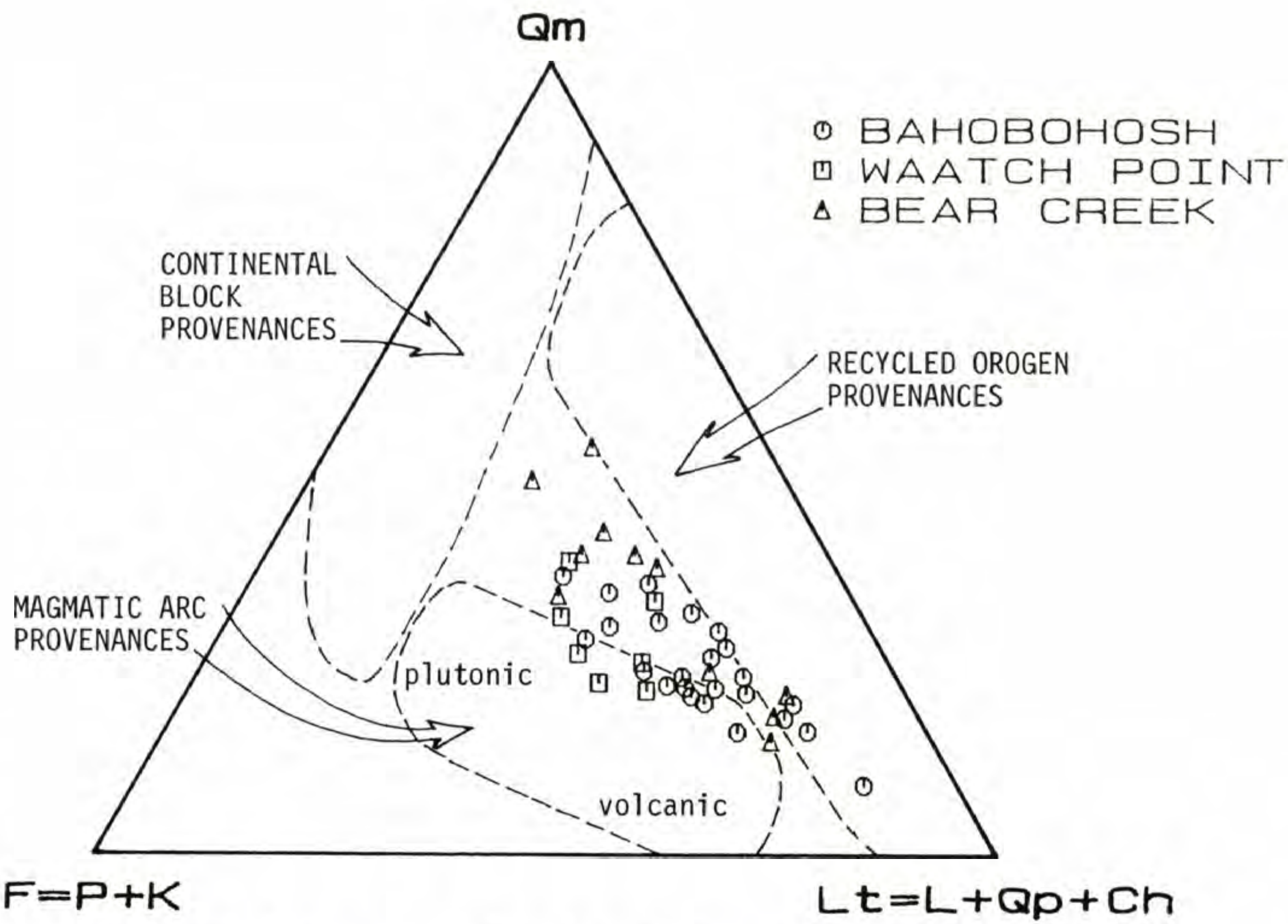


Figure **44**; Triangular QmFLt plot showing the various tectonic provenance types and the distribution of compositions of sandstones from the three lithofacies of Snavely et al.(1986). After Dickinson and Suczek,(1979).

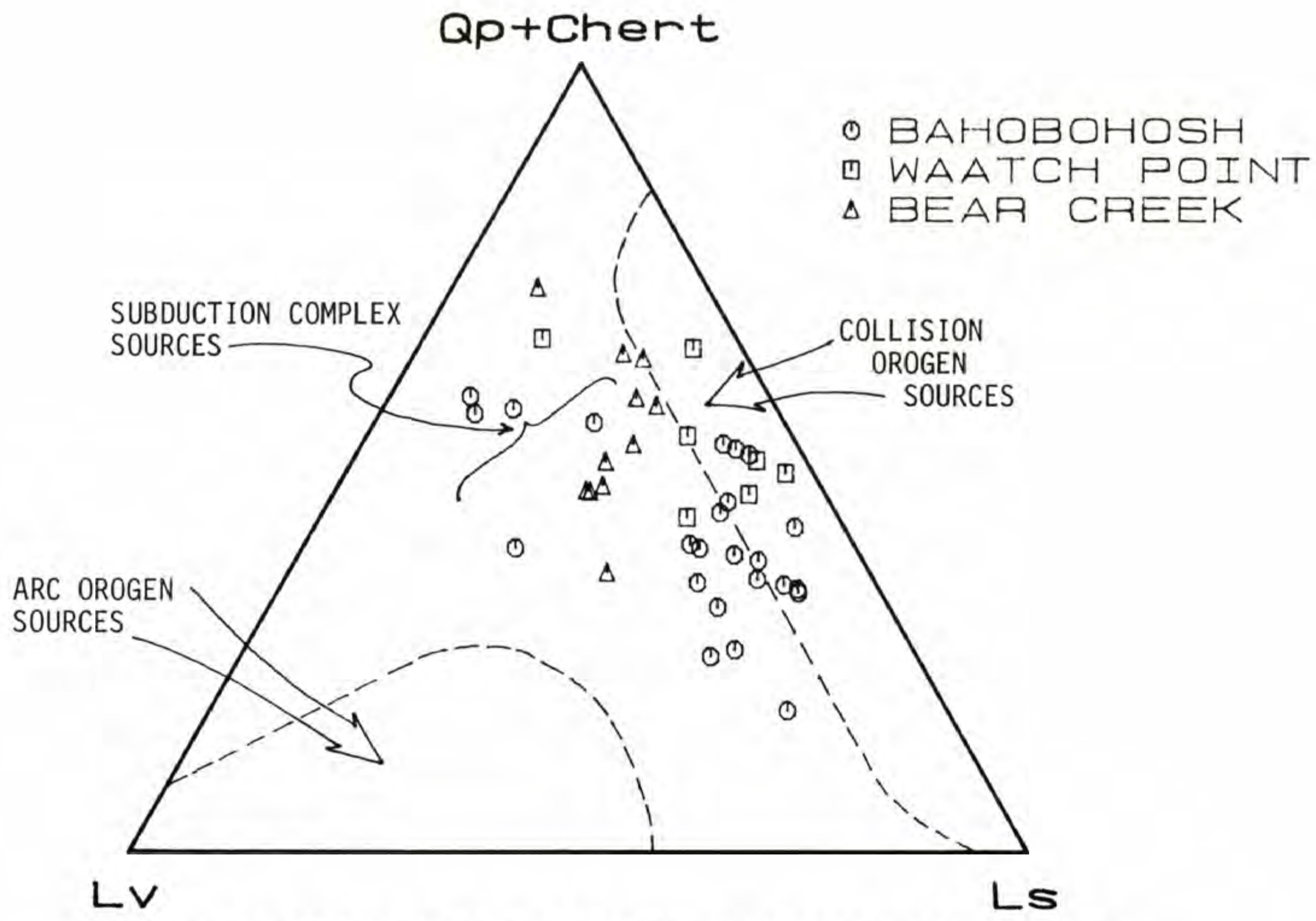


Figure **45**; Triangular QpLvLs plot showing the various tectonic provenance types and the distribution of compositions of sandstones from the three lithofacies of Snavely et al.(1986). After Dickinson and Suczek, (1979).

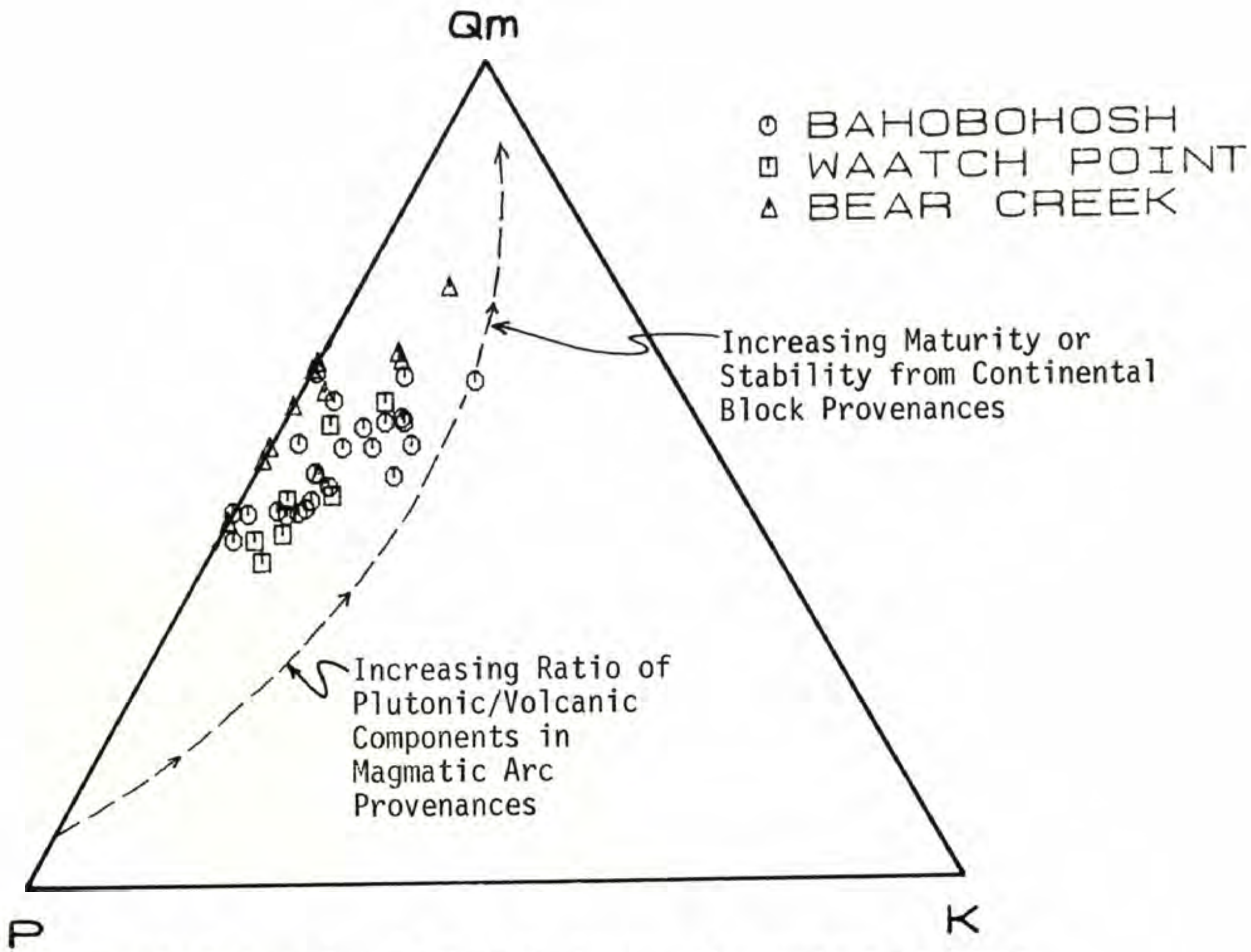


Figure **46**; Triangular QmPK plot showing the various tectonic provenance types and the distribution of compositions of sandstones from the three lithofacies of Snavely et al. (1986). After Dickinson and Suczek, (1979).

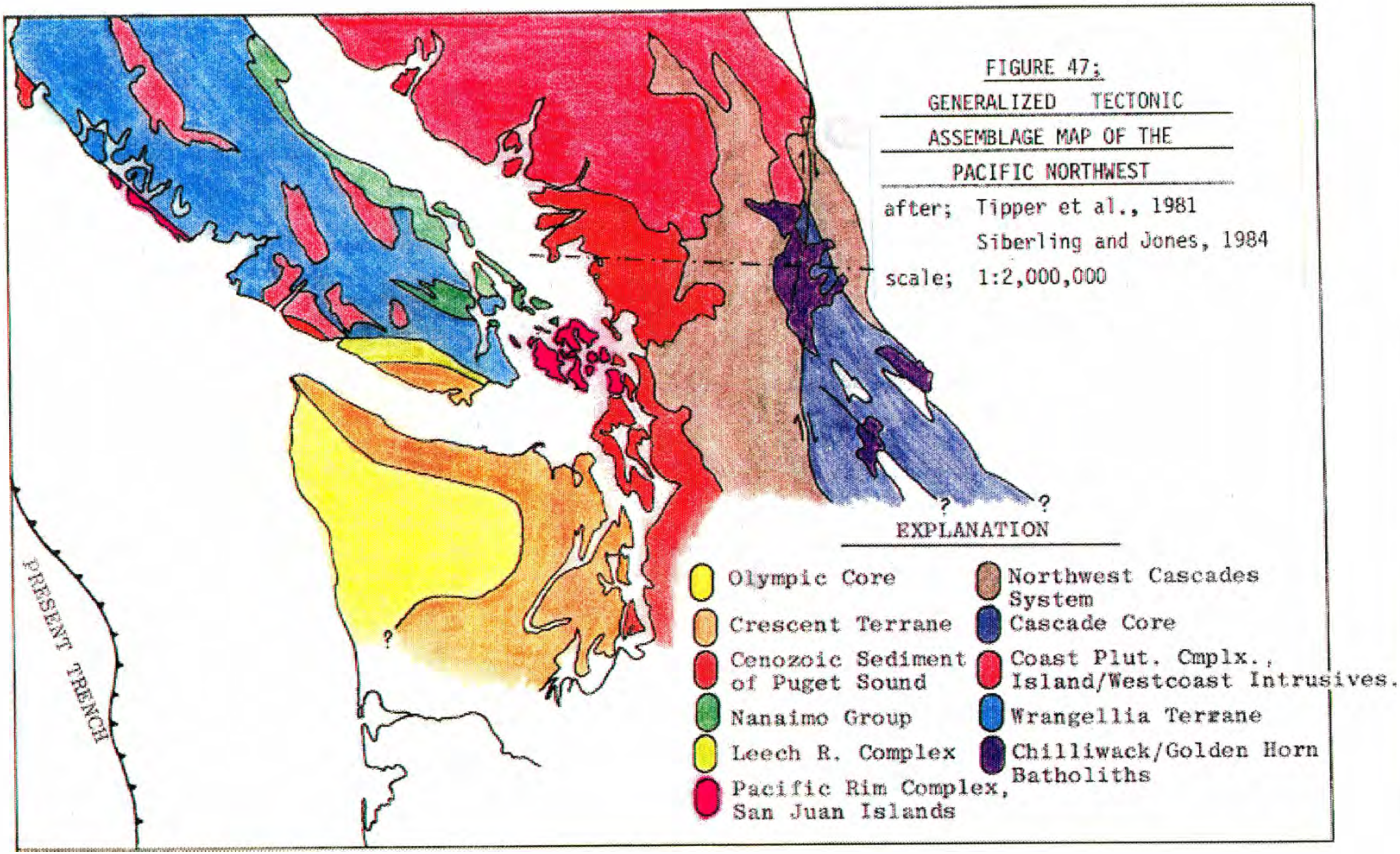


FIGURE 47;
GENERALIZED TECTONIC
ASSEMBLAGE MAP OF THE
PACIFIC NORTHWEST
after; Tipper et al., 1981
Siberling and Jones, 1984
scale; 1:2,000,000
EXPLANATION
Olympic Core
Crescent Terrane
Cenozoic Sediment of Puget Sound
Nanaimo Group
Leech R. Complex
Pacific Rim Complex, San Juan Islands
Northwest Cascades System
Cascade Core
Coast Plut. Cmplx., Island/Westcoast Intrusives.
Wrangellia Terrane
Chilliwack/Golden Horn Batholiths
PRESENT TRENCH

Table 5: Major Pre-Tertiary Lithologic Units of the Pacific Northwest.
After Pacht, 1984.

INSULAR AND PACIFIC BELTS (Muller, 1977)	NORTH CASCADES (Misch, 1966; Brown, 1987)		SAN JUAN ISLANDS (Brandon et al.,1983)	COAST PLUTONIC COMPLEX (Roddick, 1965)
	NW CASCADES SYSTEM West of Straight Creek Fault	CASCADE CORE Between Straight Creek & Ross Lake Faults		
Sicker Group (Upper Paleozoic) Intermediate to silicic volcanics. Metasediments and metavolcanics.	Chilliwack Group (Upper Paleozoic) Volcanics, volcaniclastics, chert.	Cascade River Schist Low- to Medium-grade metamorphic rocks.	Turtleback Intrusive Complex (Paleozoic) Intermediate intrusive and extrusive igneous rocks, minor limestone.	(Jurassic-Cretaceous) Largely diorite to granodiorite intrusive rocks with some intermediate metavolcanics and metasedimentary rocks.
Vancouver Group (Middle-Upper Triassic) Largely basalt with minor siltstone, limestone, & chert	Yellow Aster Complex (Devonian-Precambrian) Gabbro to trondhjemite and metamorphics	Skagit Gneiss Medium- to High-grade meta-plutonic and plutonic rocks.	Deadman Bay Volcanics (Upper Permian-Triassic) Pillow lavas, chert, and limestone.	
Bonanza Group (Middle Jurassic) Basaltic to silicic volcanics with minor clastics & limestone.	Shuksan Metamorphic Suite (Mesozoic) Graphitic to quartzose phyllite, meta-basalt, blue- & greenschist.		Orcas Chert (Triassic-Lower Jurassic) Deformed chert & basalt.	
Island Intrusions & West Coast Complex (Lower to Middle Jurassic)	Cultus Formation (Triassic-upper Jurassic) Siltstone, shale, minor sandstone, chert.		Constitution Formation (Jurassic-Lower Cretaceous) Greywacke, argillite, chert, tuff, and pillow lava.	
Wark-Colquitz Gneiss (Lower Jurassic) Diorite to Granodiorite gneiss with Paleozoic protolith (Sicker ?)	Wells Creek Volcanics (Jurassic-Cretaceous) Low grade intermediate to silicic metavolcanics.		Lopez Complex (Jurassic-Middle Cretaceous) Imbricated slices of sandstone, pebbly mudstone, pillow lava, and chert.	
Pacific Rim Complex (Mesozoic) Mafic to intermediate volcanics, metasediments, chert.	Nooksack Group (Upper Jurassic-Lower Cretaceous) Low grade volcaniclastic meta-sedimentary rocks, minor intermediate volcanics, and chert		Decatur Terrane (Upper Jurassic-Lower Cretaceous) Sandstone, mudstone, siltstone.	
Leech River Complex (Late Jurassic(?)-Cretaceous) Metasediments and chert.			Garrison Schist (Lower Triassic) mafic to intermediate metavolcanics, metasediments, and rare limestone.	
			Fidalgo Ophiolite (Middle-Upper Jurassic) Mafic to felsic plutonics and metaplutonics, ultramafic rocks, and metasediments.	

the framework grains, the dominantly fresh feldspar grains, and the high percentage of unstable grains, such as certain lithic grains and heavy minerals, show that sediment comprising the study unit was transported rapidly from areas of moderate to high relief to a nearby basin. If the basin were further from the source, unstable and angular to euhedral grains would not have survived the more prolonged transport. Varying degrees of freshness in the plagioclase grains indicate that study unit sediments may have been exposed to varying amounts of subaerial weathering. Thus, the study area may have included areas of both moderate and high relief, resulting in more subaerial residence time for some sediment and therefore more weathering of its constituents.

Analysis of fossil plants from the Eocene Chuckanut Formation (Pabst, 1968) as well as analysis of stable isotope data from DSDP cores (Shackleton and Kennett, 1975) indicate that the climate during the deposition of the study unit was tropical to subtropical (warm and humid)(see Geologic Setting section and Figure 11). The abundant rainfall and frequent storms associated with such a climate (Oberhansli and Hsu, 1986), in conjunction with the short transport distance indicated by the immaturity of the sediment and the evidence for rapid sedimentation of the study unit discussed in the Depositional Environment section, all suggest rapid erosion of the source area and a high sediment supply to the basin.

The texture and composition of Facies E1 and E2 conglomerates (see Depositional Environment section) in the study unit support these conclusions. The cobble- to boulder-sized clasts are angular to subrounded and comprised of a variety of lithologies, suggesting that the source area was nearby and of varied composition. Microscopic examination shows individual clasts from the conglomerates to range from relatively fresh to weathered, suggesting varying amounts of subaerial exposure and implying moderate to high relief of the source area. The deposition of Facies E1 and E2 as sediment gravity flows also indicates that sediment was derived from areas of moderate ot high relief and shed rapidly into the basin.

Thus, textural and compositional characteristics indicate that the sediment of the study unit was rapidly eroded from an area of moderate to high relief close to its depositional site under tropical to subtropical conditions. This combination of depositional conditions would combine to minimize the compositional modification of the sediment as it moved from its source to its site of deposition. Therefore, the composition of the study unit as determined by point counting and petrographic observation is probably representative of the composition of the source area.

Nevertheless, conclusive determination of specific source areas is problematic. The difficulty is the result of the lithologic diversity and complex juxtaposition of the tectonostratigraphic terranes that comprise the Pacific Northwest (Table 5 and Figure 47), combined with the poorly understood paleogeography and sediment dispersal patterns of the area during the early Tertiary. The complex terrane-dispersal history of the western coast of North America during the Teriary adds another factor to source area considerations (Moore et al., 1983; Wells et al.,1984). Source areas for the study unit may have been dispersed northward or destroyed by obduction.

The study unit lies between the Crescent thrust fault and the Calahwah left-lateral fault (Figure 12). This position further complicates the situation. The study unit has been correlated with middle to late Eocene strata of the Crescent terrane of the Olympic

Peninsula (see Geologic Setting section)(Snavely et al.,1986; Tabor and Cady, 1978; Armentrout, in press), but the presence of the bounding faults makes it uncertain whether these units were coextensive or their depositional basins were unrelated.

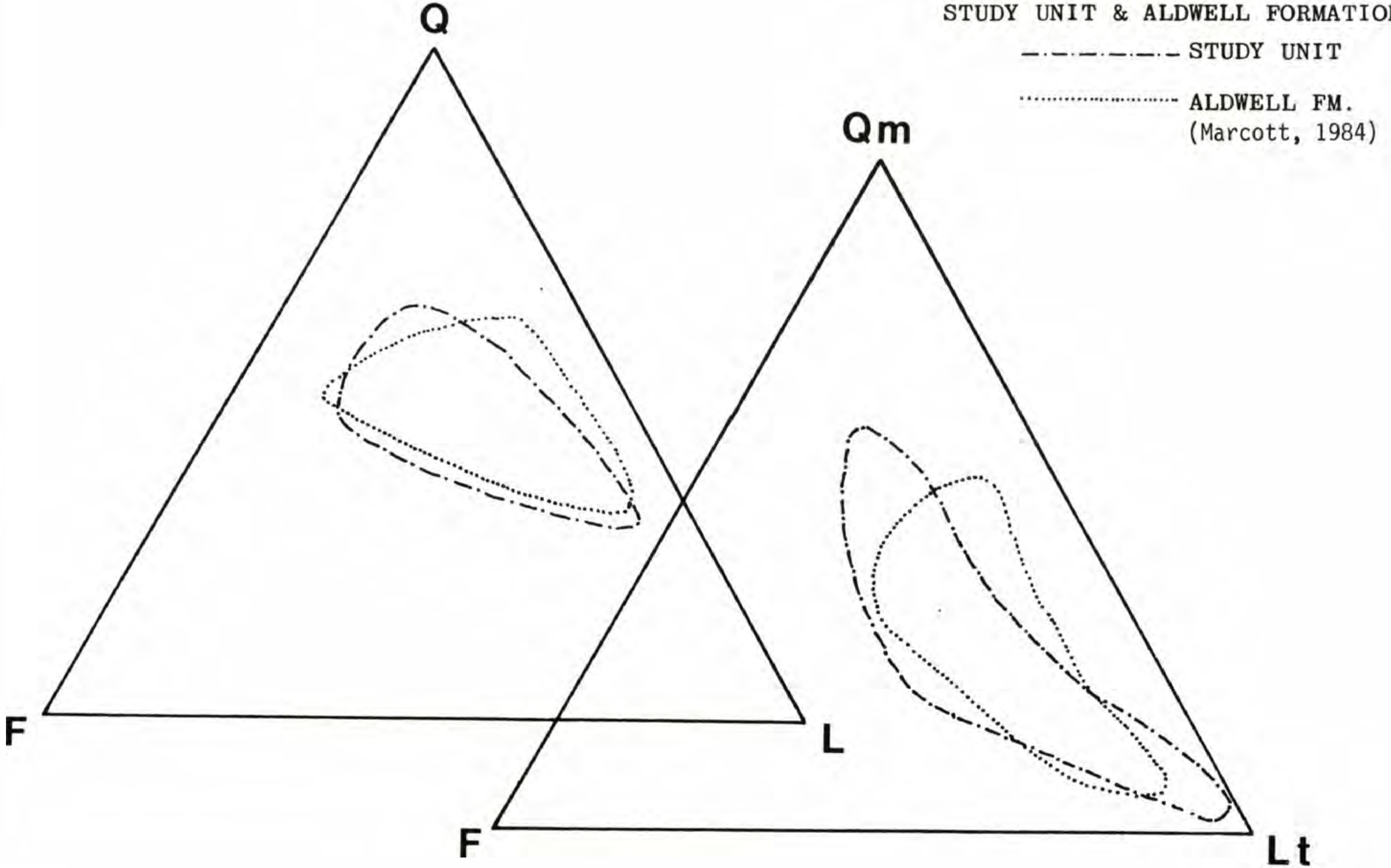
The fault-bounded position of the study unit in conjunction with uncertainty about Paleogene paleogeography and sediment dispersal patterns allows for various possibilities in developing a model for formation of the study unit. The three most likely models are: the sediment in the study unit was derived from Vancouver Island through rapid erosion and deposition; the study unit was formed to the east or southeast, received sediment from the Northwest Cascades System (Misch, 1966), the Cascade Core, and the Coast Plutonic Complex, and has been dispersed westward through oblique subduction; and sediments of the study unit were derived from some terrane to the west that has since been translated northward.

Analysis of the Provenance Models

Two of the provenance models presented above are sufficiently unlikely that, after brief discussion, they can be dismissed. Derivation of the study unit from the Northwest Cascades System (Misch, 1966), Cascade Core, and Coast Plutonic Complex requires the passage of its sediment through some portion of the extensive Paleogene fluvial system of western Washington. However, none of the sandstones deposited by that system have compositions that match those of the study unit. These fluvial sandstones are predominantly feldspathic to litho-feldspathic sub-quartz arenites (Frizzell, 1979). Derivation of the study unit from some terrane to the west requires the presence of a terrane of appropriate lithology to be outboard of the Crescent Terrane during the middle to late Eocene. Subsequently the terrane would have to have been dispersed northward by oblique subduction or strike-slip motion. Constriants on the accretionary history in Alaska (Moore et al., 1983) allow only the Prince Williams and Chugach Terranes to be far enough south during the Eocene to have provided sediment to the study unit. The Prince Williams and Chugach Terranes consit predominantly of accretionary prism to fore-arc basin sediments that have been intruded by MORB and oceanic island volcanic to plutonic rocks (Moore et al., 1983). The lithologic variety of these terranes is sufficient to have generated the mixed compostion of the study unit. However, many of the volcanic and plutonic rocks are too young (Moore et al., 1983) to have provided sediment to the study unit. In addition, there are no significant sources of chert in the two terranes, and sandstone compositions of sedimentary portions of the Prince Williams and Chugach Terranes do not match those in the study unit (Moore et al., 1983). These factors indicate that the Prince Williams and Chugach Terranes are improbable sources for the study unit.

Dismissal of these two provenance models leaves Vancouver Island is the most probable source for the study unit. Petrologic and stratigraphic evidence discussed below support a Vancouver Island source. Petrologic data from the middle to late Eocene submarine fan strata of the Aldwell Formation (Marcott, 1984) suggest that the western portion of the Aldwell Formation and the study unit were derived from the same source. Both the Aldwell Formation and the Bahobohosh and Waatch Point lithofacies have been assigned to the Narizian Age (Snavely et al., 1986). No equivalent to the Ulatisian Bear Creek lithofacies is found in the Aldwell Formation. Point-count data from the western portion of the Aldwell Formation (Marcott, 1984) overlap significantly with point count data from the study unit on triangular plots (Figures 48,49).

FIGURE 47; COMPARISON OF THE TECTONIC PROVENANCE PLOTS OF THE STUDY UNIT & ALDWELL FORMATION.



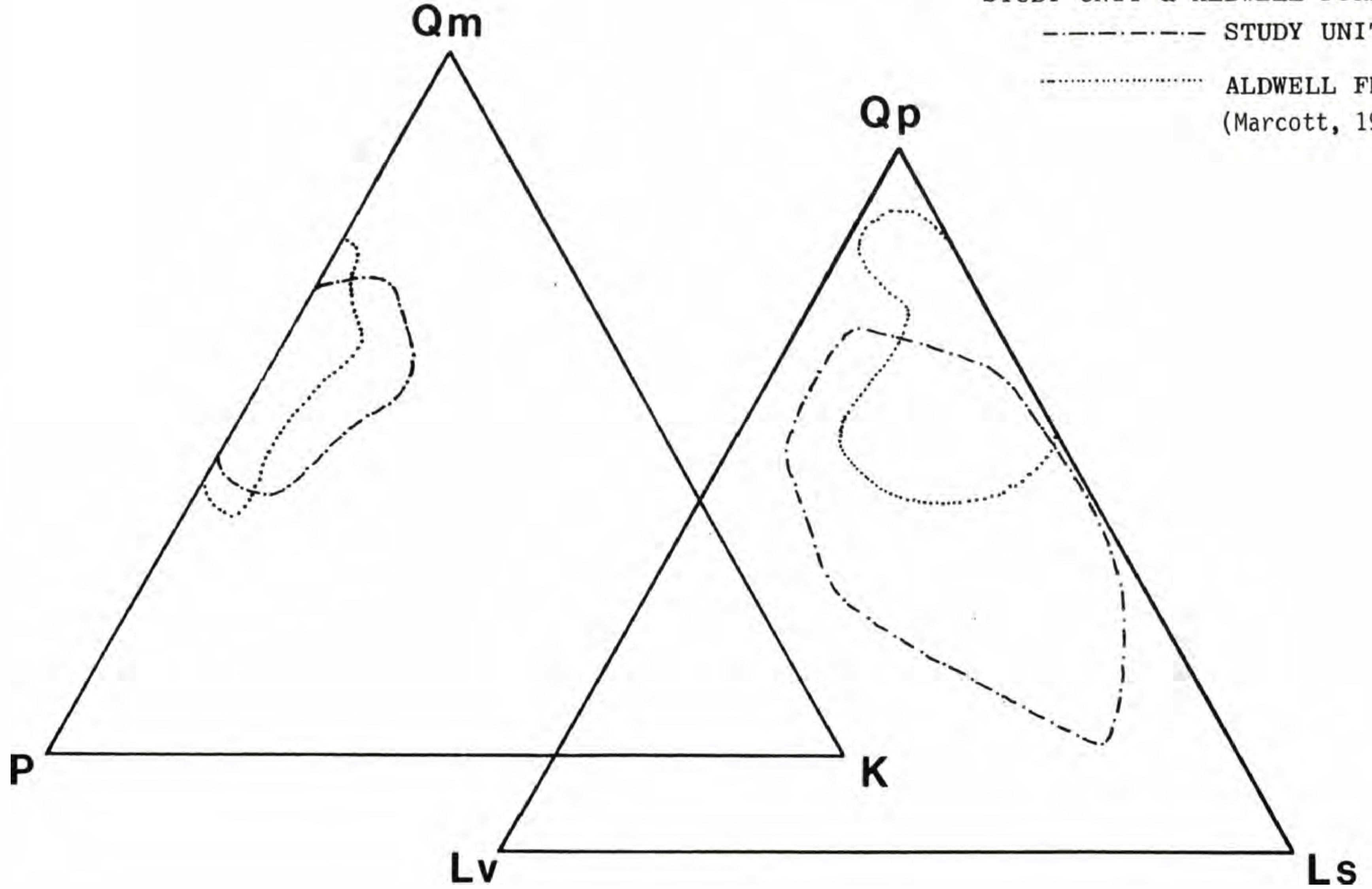


FIGURE 48; COMPARISON OF THE TECTONIC PROVENANCE PLOTS OF THE STUDY UNIT & ALDWELL FORMATION.

—·—·—·—·— STUDY UNIT

·············· ALDWELL FM. (Marcott, 1984)

Table 6: Comparison of the average detrital mode values for the study unit and the western portion of the Aldwell Formation (Marcott, 1984).

GRAIN TYPE	STUDY UNIT	ALDWELL FORMATION
Qm	19.3	19.1
P	14.8	13.2
K	2.2	<1
Qp	7.4	19.9#
Chert	7.5	
Ls	11.4	5.3
Lm	2.1	4.9
Lv	5.0	4.5
Li + misc. lithics	1.3	1.4
L*	19.8	16.1
Lt**	34.7	36.0
Heavies&	5.9	4.3
Matrix	4.3	8.5
Cement	16.9	13.8
Misc.	1.2	1.6
TOTAL	99.5%	96.4%

* L = Ls + Lm + Lv + Li

**Lt = L + Qp + Chert

Marcott (1984) reports Qp and Chert toghether.

& Heavies = H + O of this study.

Other petrologic similarities also exist (Table 6). Sandstones of the western Aldwell Formation are lithic arenites and lithic wackes (Dott, 1966) derived from Vancouver Island (Marcott, 1984). The lithic arenites contain an average of 8% matrix, and lithic grains comprise the majority of the rock. Lithic grains in the Aldwell Formation are dominantly polycrystalline quartz (including chert) followed in abundance by intrabasinal sedimentary lithics and then volcanic lithics (Table 6). Lathwork volcanic grains of predominantly basaltic and meta-basaltic composition are the most common type of volcanic grain in both units. Significant amounts of plutonic clasts are also present in both units. The mean P/F ratios of the western Aldwell Formation and the study unit are comparable. Epidote is the most common heavy mineral, and pyroxene, pumpellyite, chlorite, biotite, and muscovite are the other significant heavy minerals in both units. Although there are some discrepancies (discussed below), petrologic evidence that the western portion of the Aldwell Formation and the study unit were derived from the same source is compelling.

Differences between the two units are present but reconcilable. The major petrologic difference is in the abundance of lithic grains. The western Aldwell Formation contains significantly more polycrystalline quartz, while the study unit contains markedly higher percentages of sedimentary lithic grains (Table 6). This petrologic difference could be the result of slight areal variation in the composition of the source area. Another possibility is that differences between the hydraulic regimes present in the mid-submarine-fan environment and the shelf environment of the study unit resulted in different sediment sorting characteristics. Stratigraphic problems in correlation posed by the absence of a Bear Creek lithofacies equivalent in the Aldwell Formation could be explained by areal variation in sediment acculmulation and depositional environment. Ulatizian sedimentary and volcanic units assigned to the Crescent terrane by Snavely et al. (1986) underlie the Aldwell Formation and could be equivalent to the Bear Creek equivalent strata.

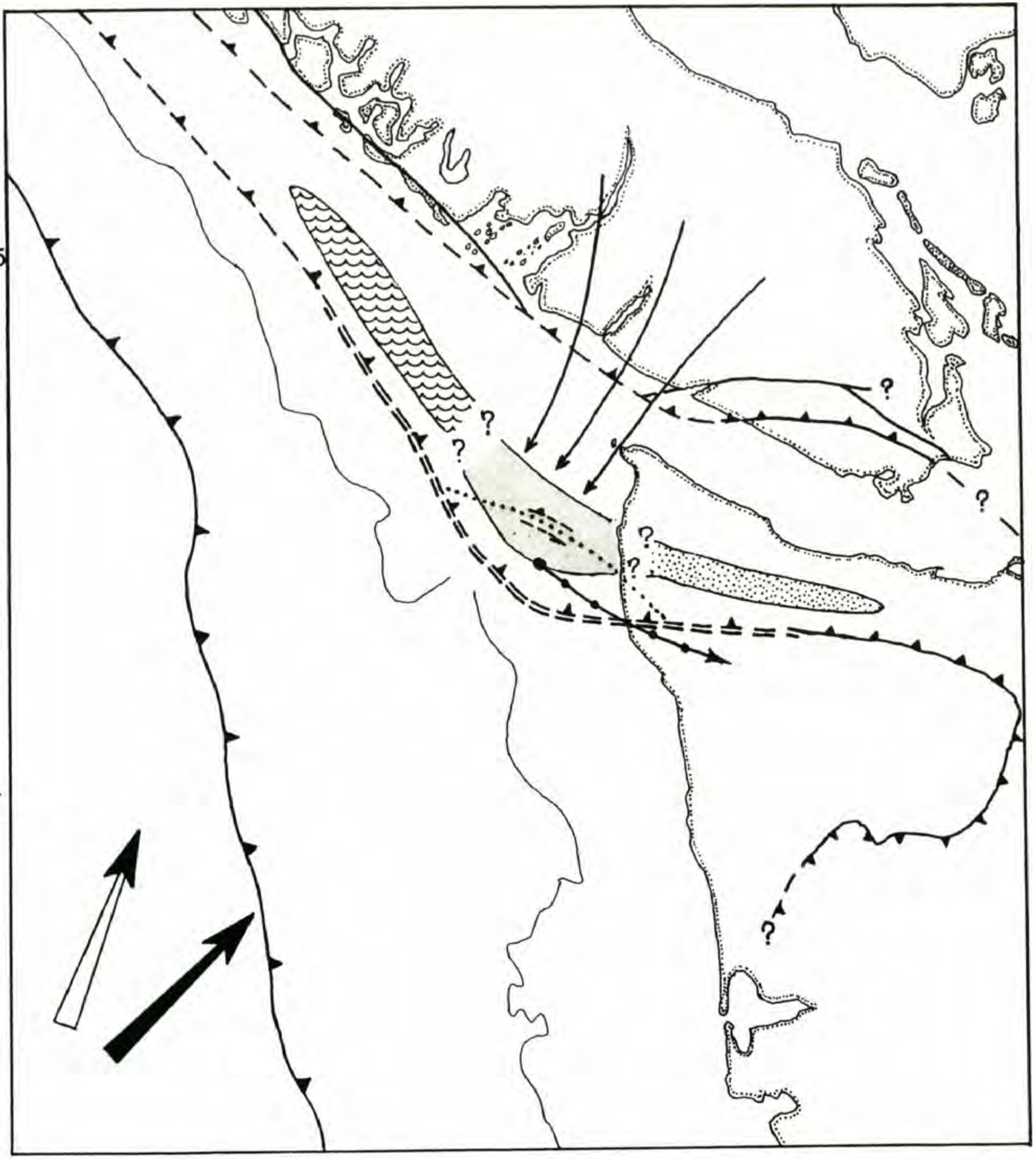
Similarities also exist between the study unit and the Escalante Formation of southwesten Vancouver Island. The Escalante Formation is upper Narizian to Refugian (Cameron, 1980) and is interpreted as upper bathyal to outer neritic sediments derived from Vancouver Island on the basis of foraminifera and stratigraphy (Cameron, 1980; Muller et al., 1980). However, Jeletsky (1975) interprets the Escalante Formation as outer neritic to supratidal on the basis of abraded fossils in shell-lag deposits. It seems probable that these abraded shells were transported from littoral to outer neritic and upper bathyal depths by active shelf processes. Therefore, it is likely that the Escalante Formation and the study unit are coeval and represent similar depositional environments, and probable that they are coextensive.

On the basis of the similarities in age and petrology between the western portion of the Aldwell Formation and the study unit, it is the likely that both sequences were derived from the same source and were possible laterally coextensive. The simplest palinspastic reconstruction that places the study unit in a stratigraphic position laterally equivalent to the western Aldwell Formation (shown in Figure 50) is generated by restoring slivers of the study unit northward along the Crescent thrust fault until they can be placed in lateral continuity with the Aldwell Formation. This position also makes the study unit adjacent

FIGURE 50: Palinspastic reconstruction showing the probable alignment of the Aldwell and Escalante Formations and the study unit, the present coastline, and both present and restored fault orientations. After Clowes et al.,1987;Moyer,1985

EXPLANATION:

- PRESENT COASTLINE
- PRESENT SHELF EDGE
- PRESENT STRIKE-SLIP FAULT
- PRESENT THRUST FAULT
- RESTORED THRUST FAULT (MOYER, 1985)
- INFERRED STRIKE-SLIP FAULT
- PALEOCURRENT DIRECTION
- ESCALANTE FORMATION
- STUDY UNIT
- ALDWELL FORMATION
- INFERRED DIRECTION OF STUDY UNIT TRANSLATION
- SYN-DEPOSITIONAL PLATE MOTION
- POST-DEPOSITIONAL PLATE MOTION



to the present day location of the Escalante Formation. In this model the study unit would have reached its present position, thrust under the Crescent Formation along the Crescent thrust fault, through post-depositional oblique subduction of the Farallon plate (see Figure 1).

Paleocurrent indicators in the study unit also suggest a Vancouver Island source. Measurements of the axes of slump-induced folds, clast alignments, and sparse sole marks in the Bahobohosh and Waatch Point lithofacies by Ansfield (1972) indicate southward- and southeastward-directed paleocurrents. Despite subsequent rotation of the western portion of the Crescent terrane of approximately 40 degrees of clockwise rotation (Moyer, 1985), these paleocurrents indicate that currents depositing the sediments of the study unit were moving generally southward from Vancouver Island.

A Vancouver Island source involves the simplest provenance model. In addition, the probable coextensive relationship between the study unit and the Aldwell and Escalante Formations, the textural and compositional immaturity of the study unit, and the southerly-directed paleocurrent indicators all indicate a proximal Vancouver Island source.

Work on Vancouver Island has led to its division into three main belts of rocks, predominantly on the basis of structural relationships and tectonic origin (Monger et al.,1972). These divisions are the Insular Belt, followed to the southwest by the Inner and Outer Pacific Belts. The Inner Pacific Belt can be ruled out as a potential source for the study unit.

The Inner Pacific Belt consists of the San Juan Island terranes and the Pacific Rim Complex (Monger et al., 1972). The San Juan Islands probably were too far to the east during the middle to late Eocene to have been a likely source for the study unit. The terranes of the San Juan Islands were emplaced between Wrangellia and the Northwest Cascades System by the late Cretaceous (Brown, 1987; Brandon and Cowan, 1985). Such a position would require an excessive amount of littoral transport to move sediment from the San Juan Islands to the shallow marine depositional environment of the study unit. In addition, both the San Juan Island and Pacific Rim Complex contain a distinctive lawsonite-prehnite metamorphic assemblage (Brandon, 1985; 1980) not recorded in the sediments of the study unit and therefore are an unlikely source. The presence of highly unstable detrital grains such as chlorite, pumpellyite, and pyroxene in the study unit suggest that if lawsonite or prehnite were present in the soucre area they would be present in the study unit.

The Outer Pacific Belt is defined by Monger et al. (1972) to be comprised of the basaltic Metchosin Volcanics (assigned to the Crescent Terrane (Cady, 1975)) and the overlying Carmanah Group sediments. Since a significant portion of the lithic clasts in the study unit are basaltic volcanics the basaltic basement of the Outer Pacific Belt could be source for the study unit. Subaerial and submarine flows in the Crescent Formation (Cady, 1975) and sedimentary onlap relationships between the Crescent Formation basalts and overlying sediments (Tabor and Cady, 1978) indicate that portions of the Crescent Formation could have been sloughing basaltic detritus into surrounding basins during the middle to late Eocene (Marcott, 1984). However, since basaltic clasts in the study unit are dominantly altered or metamorphosed, the relatively fresh basaltic detritus derived from the Crescent terrane were of minor importance as study unit sediment.

<u>lithology of the Source Area</u>

The Insular Belt is comprised of the allochthonous plutonic, volcanic, and metasedimentary rocks of Wrangellia and the overlying strata of the Nanaimo Group. Wrangellia on Vancouver Island consists of the late Paleozoic Sicker Group, the Mesozoic Island Intrusions and West Coast Complex, the Wark-Colquitz Gneiss, the Early Jurassic Bonanza Group, the Middle to Late Jurassic Vancouver Group (Muller et al., 1980). The early Paleogene Catface Intrusives penetrate the rock of Wrangellia on Vancouver Island.

The Sicker Group consists of metamorphosed siltstone, argillite, and graywacke deposited as turbidites derived from a granitoid source (Muller et al., 1980) with minor limestone and chert. These sediments are intruded by thick sills of medium-grained meta-diabase. The diabase sills are probably comagmatic with the basaltic Karmutsen Volcanics of the Vancouver Group (Muller et al.,1980). Metamorphism of the Sicker Group generated prehnite-pumpellyite, greenschist, and amphibolite facies metasedimentary and metavolcanic rocks (Muller et al., 1980). Metasedimentary and metabasaltic clasts and chert in the study unit could be derived form the Sicker Group. In addition, monocrystalline grains of quartz, plagioclase, potassium feldspar, chlorite, epidote, actinolite, and amphibole in the study unit could have come from the Sicker Group.

The Vancouver Group is the most extensively exposed of the Insular Belt units. The Vancouver Group consists of the Karmutsen, Quatsino, and Parsons Bay Formations. The Middle(?) to Upper Triassic Karmusten Formation is a thick (6000m) sequence of basaltic volcanics of dominantly tholeiitic composition (Muller et el., 1980). The basalts have been metamorphosed to amphibolite and albite-epidote-actinolite hornfels.

Altered lathwork and microlitic volcanic lithic grains and monocrystalline grains of pyroxene, epidote, actinolite, pumpellyite, and altered plagioclase in the study unit were probably derived largely from the extensively exposed Karmutsen Volcanics.

The Upper Triassic Quatsino and Parsons Bay Formations consist predominantly of fossiliferous limestone with minor amounts of shale and volcanic tuff in the Parsons Bay Formation (Muller et al.,1980). Clearly the lack of limestone clasts in the study unit precludes the Quatsino and Parsons Bay Formations as significant sources of study unit sediments. However, minor quantities of fine-grained sedimentary clasts and the monocrystalline components of volcanic tuffs might have been derived from these formations.

The Middle Jurassic Bonanza Group consists predominantly of basaltic to dacitic effusive to pyroclastic volcanics with minor amounts of clastic and carbonate sediments (Muller et al., 1980). Some of the lathwork, microlitic, and felsic volcanic ltihic grains as well as some sedimentary lithic grains and monocrystalline plagioclase and pyroxene in the study unit could have come from the Bonanza Group.

The Lower Jurassic Island Intrusions and West Coast Complex are cogenetic (Muller et al., 1980). The dominantly granitic and granodioritic plutons of the Island Intrusions grade downward into the quartz diorite, tonalite, granodiorite, migmatite, and greenschist to amphobolite facies metasedimentary and metavolcanic rocks of the West Coast Complex (Muller et al., 1980). The migmatite and intrusives of the West Coast Complex, and by inference the Island Intrusions, are believed to have been derived from the migmatization and melting of the volcanic and sedimentary rocks of the Sicker and Vancouver Groups (Muller et al., 1980). Clearly the Island Intrusions and the West Coast Complex are a likely source for the plutonic clasts and plutonically-derived monocrystalline grains in the study unit. In addition, metasedimentary and metavolcanic clasts and minor chert could also have come from the West Coast Complex.

The partially gneissic diorites and granodiorites of the Wark-Colquitz Gneiss could have supplied gneissic and granitoid plutonic clasts and their moncrystalline derivatives to the study unit. However, due to thier probable eastern position relative to the depositional site of the study unit the Wark-Colquitz Gneiss were probably not a major source. Final emplacment of the Northwest Cascades System, which includes the San Juan Island and the Pacific Rim Complex, prior to the middle Eocene (Brown, 1987) constrains the position of the Wark-Colquitz Gneisses.

The final unit assigned to the Insular Belt by Monger et al. (1972) is the Upper Cretaceous Nanaimo Group. The Nanaimo Group is comprised of arkosic to lithic arenites and associated shales and conglomerates deposited in fluvial, deltaic, shelf, slope, and deep marine environments (Pacht, 1980). Sediment was supplied from Vancouver Island, the Coast Plutonic Complex, and the Northwest Cascade System (Pacht, 1984). The Nanaimo Group extensively overlies the older rocks of Vancouver Island (Figure 46). Sediments of the Nanaimo Group that were derived from Insular Belt sources would be expected to have compositions comparable to those of the study unit if it were derived from the Insular Belt. Shelf sediments in the Nanaimo Group that are derived from the Insular Belt have compositions very similar to those of the study unit (Pacht, 1980). Therefore, erosion of the Nanaimo Group would generate sediments with a composition similar to that of the study unit. However, the textural and compositional immaturity of the study unit and the lack of relict cement overgrowths in the study unit preclude the Nanaimo Group as a potential source. There are too many unstable lithic grains and euhedral to angular grains in the study unit for a significant portion of its sediment to have undergone two sedimentary cycles.

The various rock units of the Insular Belt on Vancouver Island are sufficiently proximal and of adequate diversity to have supplied sediment to the texturally and compostionally varied study unit. One problem with this provenance model is the near absence of hornblende in the study unit. Various sources of hornblende exist among the units of the Insular Belt described above. The Sicker Group, Vancouver Group, Island Intrusions, and West Coast Complex all contain hornblende. This hornblende content should be reflected in the study unit if these Insular Belt units are indeed the source of study unit sediments. Short of citing selective removal of hornblende during transport, failure to recognize hornblende in thin section, or diagenetic attrition of hornblende grains, all of which are unlikely, there is no ready explanation for the scarcity of hornblende in the study unit.

SUMMARY

Despite these problems, a purely Insular Belt source is favored here for reasons presented above. The Sicker Group was a source of basaltic and metasedimentary clasts, chert, greenschist facies minerals (epidote, chlorite, actinolite, and pumpellyite), polycrystalline quartz, feldspar, and minor monocrystalline quartz. The Karmutsen Volcanics provided the majority of basaltic clasts as well as pyroxene and greenschist facies minerals. Minor quantities of basaltic clasts could have come from basalts of the Crescent terrane (Crescent Formation and Metchosin Volcanics). The Bonanza Group was a source of minor basaltic through dacitic volcanic lithics and sedimentary clasts, pyroxene, and plagioclase. The Island Intrusions supplied the variety of plutonic clasts and their monocrystalline components including potassium feldspar, muscovite, and biotite. The West Coast Complex supplied sediment similar to that from the Island Intrusions as well as metasedimentary and metavolcanic clasts and possibly chert.

In conclusion, the textural and compositonal immaturity of the study unit require depostion of its sediments very close to their source. Therefore, the study unit probably formed as a shelf sequence lapping onto and receiving sediment from the southwestern margin of Vancouver Island. It is probable that the study unit was coextensive with the sedimentary environments of the Escalante and Aldwell Formations which also received sediment from Vancouver Island.

TECTONIC INTERPRETATION

INTRODUCTION

The interaction of the Farallon or Kula plates with North America during the middle to late Eocene probably affected the provenance and depositional history of the study unit. Since these effects are recorded in the rocks, it is possible to draw preliminary conclusions about the nature of the interactions of oceanic plates with the North America at Pacific Northwest latitudes and, by extension, the paleogeography of the Pacific Northwest during the Paleogene.

There are three fundamental questions about the Tertiary geology of the Pacific Northwest. First, there is considerable debate over the origin of the basaltic rocks that are the basement of the Washington-Oregon Coast Range. Models ranging from accretion of oceanic crust or an oceanic island chain to the opening of a rift basin in the continental margin have been proposed (see Geologic Setting section). Exactly what tectonic process producted this basaltic basement remains unclear. Second, the post-formation history of this basaltic basement is relatively unconstrained. Sedimentary and minor volcanic rocks overlying the basalt (together termed the Crescent terrane) record rapid changes in bathymetry and lateral changes in provenance and sediment supply. These characteristics suggest that the post-formation history of this basaltic basement and the syn-depositional history of the overlying strata were tectonically dynamic. Stratigraphic and petrographic analysis of the overlying strata allows constraints to be placed on the nature of these dynamics. Third, the location of the Kula-Farallon-North America triple junction and the configuration of the Kula-Farallon ridge during the Paleogene remain largely speculative (Figures 1,2). Any constraints placed on Paleogene tectonic activity through the examination of the stratigraphy and petrology of the study unit might allow some delineation of the Kula-Farallon-North America triple junction and the configuration of the Kula-Farallon ridge.

The study unit has characteristics that have some bearing on these questions. The age of the study unit (upper Ulatizian to upper Narizian; see Figures 10,11) make it coeval with strata overlying basalts of the Crescent terrane. Sediments of the study unit were almost certainly derived from Insular Belts rocks on Vancouver Island. The derivation of these sediments from a proximal area of moderate and high relief and thier deposition in the shallow marine environment constrain the study unit to a position onlapping Vancouver Island. In addition, stratigraphic and petrologic evidence indicates that the study unit was probably coextensive with the western portion of the Aldwell Formation, which overlies the Crescent Formation, and with the Escalante Formation, which overlies Wrangellia. Both these units also probably had a Vancouver Island source. These factors show that the Crescent terrane and Vancouver Island were close together by the middle Eocene. The study unit was deposited as outer shelf sediments derived from and probably onlapping Vancouver Island. If the study unit and the Aldwell Formation were indeed coextensive, then the Crescent terrane, which the Aldwell Formation overlies, must have been in relative proximity to Vancouver Island by the middle to late Eocene. This proximity argues against an allochthonous origin for the Cresent terrane basalts. In addition, this interpretation supports the autochthonous origin of the Cresent terrane indicated by the presence of sediments derived from Vancouver Island interbedded with and underlying the basalts of the Crescent Formation (Einarsen, 1987). The

Crescent terrane is also inferred to have had minimal movement relative to North America after its formation in the early Eocene (Beck, 1984).

Movement that has been documented for the Crescent terrane consists predominantly of approximately 300-400 kilometers of post-middle Eocene northward translation (Beck, 1984) and thrusting under Vancouver Island along the Leech River and associated faults (Clowes et al., 1987; Moyer, 1985; Fairchild and Cowan, 1982; MacLoed et al., 1977). This northward translation and underthrusting of the Crescent terrane are believed by some to be the result of rotation of the Coast Range, either as a whole (Hammond, 1979; Simpson and Cox,1977) or as discrete blocks (Wells, 1982; Moyer et al., 1985) away from the Challis-Absaroka arc towards its present position (see Geologic Setting section, Figures 5,6) during the late Paleogene and early Neogene. The northward translation could have resulted from northeast-directed subduction of the Kula and/or Farallon plates (Beck, 1984; Beck and Engebretson, 1982). The shoaling of the study unit , as well as evidence for rapid sedimentation, and the probable seismic origin of the slumps and debris flows in the study unit could be the result of uplift and thrust related tectonic activity along the southern or southwestern margin of Vancouver Island. Uplift of the southern edge of Vancouver Island caused by underthrusting of the Crescent terrane together with the tropical to subtropical climate of the region during the middle to late Eocene might have resulted in rapid erosion and the delivery of abundant immature sediment to the shelf. Any seismic activity associated with the underthrusting of the Crescent terrane could cause the rapidly deposited sediments to slump, generating olistostromes. Coarse-grained sediments from nearby deltas could also be resedimented onto the shelf by debris flows.

Another possibility is that the rapid sedimentation and probable seismic events recorded in the soft-sediment deformation, slumps, and debris flows of the study unit resulted from the interaction of the Kula-Farallon ridge with North America. Subduction of the young, buoyant, and bathymetrically irregular oceanic crust at or near the ridge would cause uplift of the continental margin and seismic activity indistinguishable in the sedimentary record from that generated by the underthrusting of the Crescent terrane. The Kula-Farallon-North America triple junction might have been located near the latitude of formation of the study unit during the middle to late Eocene (Wells et al., 1984; Engebretson et al., 1986). However, no location for the triple junction or the configuration of the ridge can be defined based on evidence derived from this study.

Although geologic evidence bearing on the origin and subsequent history of the Crescent terrane results from this study, problems do exist in the application of this evidence. Much of the tectonic interpretation presented here hinges on the assumption that the study unit was coextensive with the western Aldwell. The petrologic and time stratigraphic similarities between these units are compelling evidence of their close syn-depositional relationship. However, direct correlation of stratigraphic events in the two sequences is lacking. Such correlation, in conjunction with other evidence, would be strong evidence for the coextensive nature of the two units during depositon.

There is another problem in the application of the results of this study to plate-tectonic questions. Little evidence exists in the study unit that the depositional shoaling of the sequence resulted from anything other than eustatic sealevel fall or build up of the shelf through sedimentation. The presence of olistostromes, debris flows, and soft-sediment deformation suggests that active tectonic uplift of the shelf could have occurred. However, there is no evidence to suggest that these sedimentary structures resulted from anything other than "ordinary" subduction of oceanic lithosphere. Nevertheless, the characteristics and age of the study unit fit into the geologic history for the Crescent terrane and Pacific Northwest that has been developed so far. It is probable that the study unit records some combination of passive (eustatic and basin filling) and tectonic controls on shelf sedimentation that might have been the result of both underthrusting of the Crescent terrane and proximity of the triple junction.

SUMMARY AND CONCLUSIONS

The informally named marine strata examined in this study comprise fault bounded slivers of middle to late Eocene (Ulatizian to Narizian) siltstones, sandstones, and conglomerates exposed on the northwestern Olympic Peninsula. The strata are referred to by Snavely et al. (1986) as the "terrane south of the Crescent thrust fault and north of the Callawah fault" and divided by them into four lithofacies: the sandstone of Bahobohosh, the siltstone of Waatch Point, the siltstone and sandstone of Bear Creek, and the sedimentary and basaltic rocks of Hobuck Lake. Only the first three lithofacies are dealt with in this study. Deposition of the study unit was dominated by sediment-gravity flow and, in the upper lithofacies, by reworking by storm waves. Six facies have been identified consisting of strata deposited by high- and low-density turbidites, storm waves, slumping, tidal or littoral currents, and debris flows. The abundant soft-sediment deformation in the strata imply rapid sedimentation rates. Hummocky stratified horizons appear towards the top of the sequence. Relationships between the facies indicate shallow marine deposition that shoaled from below to above storm wave-base on the outer shelf to shelf-slope break. The presence of coeval shallow marine strata along the western margin of North America that also exhibit a shoaling sequence (the Tyee and Rose Canyon Formations) suggest that the shoaling of the study unit was at least partially eustatically controlled. Persistent non-isostatic effects related to terrane accretion make definitive recognition of eustatic controls to sedimentation along convergent boundaries very difficult.

The sandstones of the study unit are texturally and compositionally immature. Lithic arenites predominate. Textures and compositititions of related conglomerates parallel those of the sandstones. Both are moderately to very poorly sorted. Grains range from rounded to very angular, with sub-angular to angular grains predominating. Quartz and plagioclase are the most common monocrystalline grains, although potassium feldspar and epidote are present in significant quantities. Accessory grains include pyroxene, chlorite, pumpellyite, biotite, actinolite, muscovite, hornblende, zoisite, clinozoisite, zircon, tourmaline, and sphene in decreasing order of abundance. Lithic clasts comprise 35% of all grains. The predominant types are polycrystalline quartz (including chert) followed by intrabasinal sedimentary grains and then basaltic volcanic lithic grains. Plutonic clasts of various types (mostly granitoid) and metamorphic lithics are also present. A diverse plutonic, volcanic, and sedimentary (and their metamorphic equivalents) source consisting of dioritic, granodioritic, and granitic plutonics or gneisses, basaltic volcanics, chert, and greenschist-grade metasedimentary and metavolcanic rocks is indicated by the composition of the study unit. The diagenetic history of the sediments is complex. Early calcite cementation and concretion formation was followed by the growth of clay and zeolite cements.

The provenance of the study unit was most likely Vancouver Island. The lithology of the Sicker, Vancouver, and Bonanza Groups and of the Island Intrusions and West Coast (igneous and metamorphic) Complex, which together comprise Wrangellia on Vancouver Island, could provide all the necessary clast types to generate the sediments of the study unit. In addition, the western position of the study unit argues against sources further east that require large amounts of littoral sediment transport to reach the shallow marine depositional site of the study unit. The probable Vancouver Island source and the shallow marine depositional conditions of the study unit imply that it formed as a sequence onlapping Vancouver Island.

The petrologic similarities between the study unit and the western portion of the coeval Aldwell Formation indicate that the two units probably had the same source and were coextensive. The possibility that the study unit formed as a sequence onlapping Vancouver Island and the probability that it was coextensive with the western portion of the Aldwell Formation have implications regarding the Paleogene tectonics of the Pacific Northwest, as described below.

The Paleogene was a tectonically dynamic period in the northeast Pacific Basin. Subduction rates of the Kula and Farallon plates were very high (> 100 km/my on the average). Major reorganizations of the Kula-Farallon ridge were taking place in response to changes in subduction rates and plate motions, and terrane accretion. In addition, the basaltic basement of the Crescent terrane was generated during the early Eocene. The Aldwell Formation overlies the basalts of the Crescent terrane. The nature of the tectonic setting in which this basement formed is still under debate. Allochthonous (accreted oceanic plate or oceanic island chain) and autochthonous (continental-margin-rift) models have been proposed. Assuming that the study unit developed as a sequence onlapping Vancouver Island that was coextensive with the western portion of the Aldwell Formation, the Crescent terrane basalts, which underlie the Aldwell Formation, would have been proximal to Vancouver Island during the middle to late Eocene. Therefore, a highly allochthonous origin for the Crescent terrane is unlikely.

Consideration of the shoaling sequence present in the study unit allows further speculation about Paleogene tectonics of the Pacific Northwest. Although the presence of coeval shoaling sequences along the western margin of North America allows eustatic control of shoaling in the study unit, the dynamic tectonics of the Paleogene in the Pacific Northwest suggest that tectonic control may also have influenced shoaling. Two end member sources of this tectonic shoaling are possible. First, the shoaling could have resulted from the uplift of the southern edge of Vancouver Island due to the underthrusting of the Crescent terrane. Such uplift would also explain the immaturity of the sediments and the rapid sedimentation rates. Second, the possible approach of the Kula-Farallon ridge to the Pacific Northwest during the Paleogene would have resulted in the subduction of progressively younger, more buoyant, and more bathymetrically irregular oceanic crust. This, in turn, could have caused uplift of the overriding plate, resulting in shoaling of strata deposited during the uplift. Generation of immature sediments and rapid sedimentation rates would also result from this process.

Sedimentary characteristics generated by either of these tectonic processes would be indistinguishable. In addition, both types of tectonic process would generate seismicity, which could produce the olistostromes and debris flows found in the study unit. Therefore, there is no preferred tectonic control to the shoaling of the study unit. Both processes, in addition to eustatic control, could have contributed to this shoaling.

It can be concluded that the petrology, stratigraphy, and structural position of the study unit all reflect the tectonic processes that shaped the Pacific Northwest, although detailed correlation of the features of the study unit to tectonic events is difficult. Nevertheless, this study is one step in developing a better understanding the geologic and tectonic history of the Pacific Northwest. The results of this study suggest research projects that would pursue the questions that this study addresses and that could make more definitive conclusions possible. A project involving the comparison of the study unit with the Escalante and western Aldwell Formations could delineate the relationship between these units. A detailed comparison of the stratigraphy of the three units, including the correlation of catastrophic events, would be especially useful. Analysis of petrologic trends recorded in the three units could also be illuminating. If there is a significant correlation between the stratigraphy and petrologic trends in the units then a strong case can be made for their being coextensive during deposition which has implications for the history of the Crescent terrane. In addition, an analysis of the structural geology of the northern Olympic Peninsula, with special attention to the timing of deformation would be a significant contribution to the understanding of the timing of tectonic events in the Pacific Northwest.

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APPENDIX 1: Stratigraphic Columns

Six stratigraphic sections were measured in the study unit. Two were measured in the Bahobohosh lithofacies (Archawat Creek North and Bahobohosh Point), one in the Waatch Point lithofacies (Waatch Point), one in the Bear Creek lithofacies (Bear Creek Quarry), and one across the contact between the Waatch Point and Bahobohosh lithofacies (Archawat Creek South). The locations of these measured sections are indicated in Figure 12 using the following designations;

A-Archawat Creek North

B-Archawat Creek South

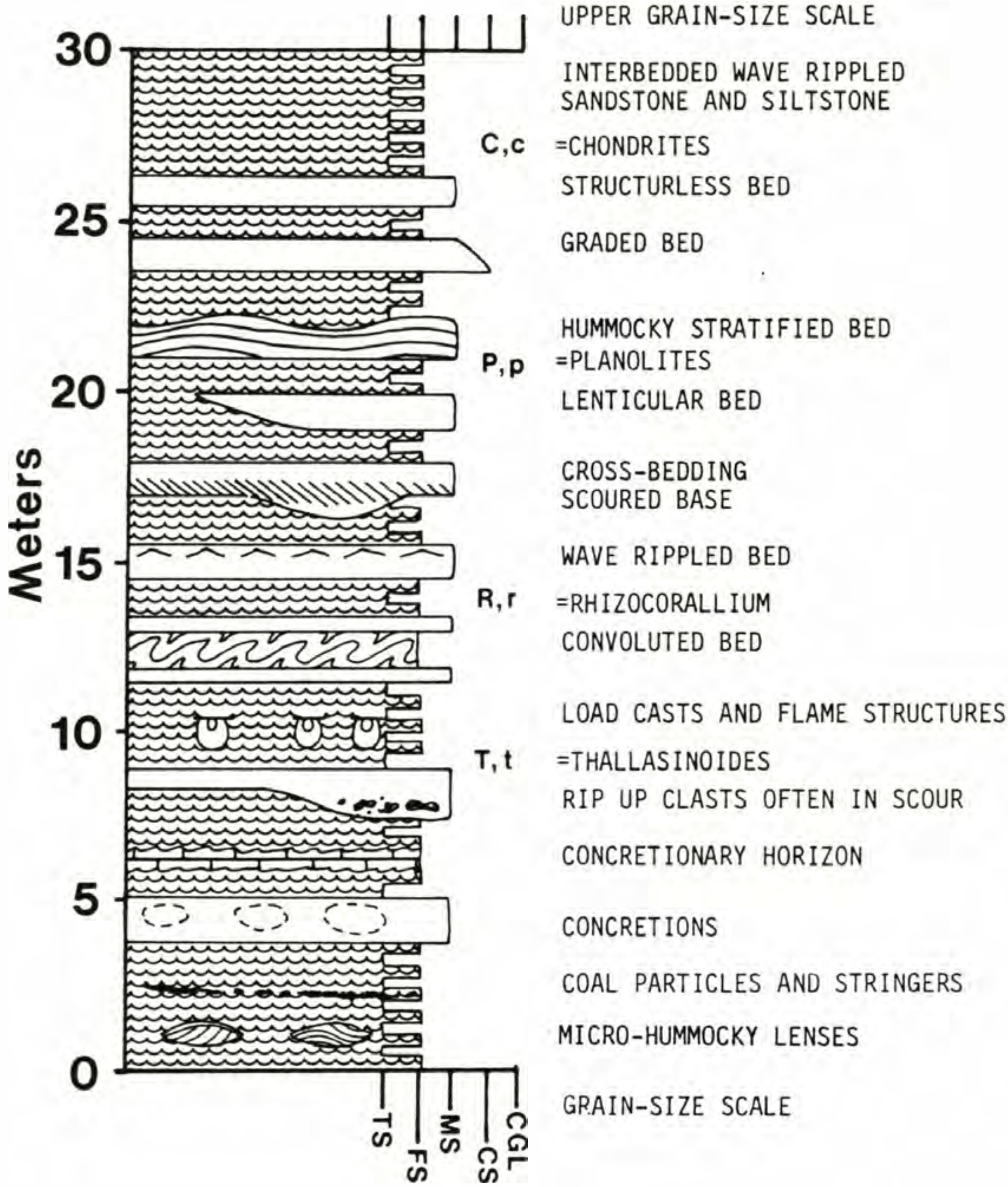
C-Waatch Point

D-Bahobohosh Point

E-Bear Creek Quarry

Representation of the various types of strata present in the study unit are depicted graphically in the stratigraphic columns. The thicknesses of beds in the stratigraphic columns are generally not to scale (conglomeratic and thick sandstone beds are an exception). Bed thicknesses are recorded in the descriptions to the right of each column. An explanation of the graphical representations used in the stratigraphic columns follows this introduction.

EXPLANATION

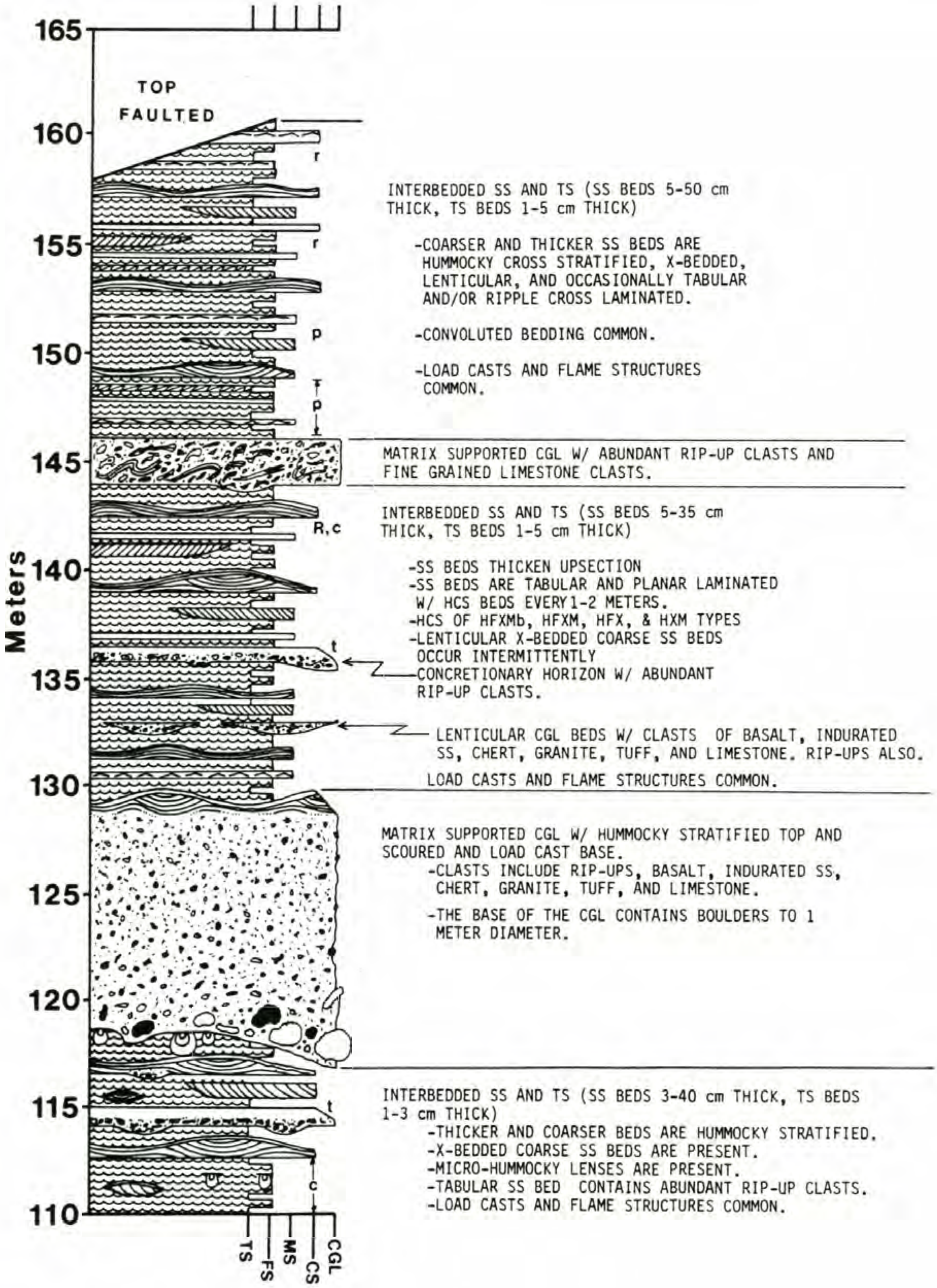


ABBREVIATIONS

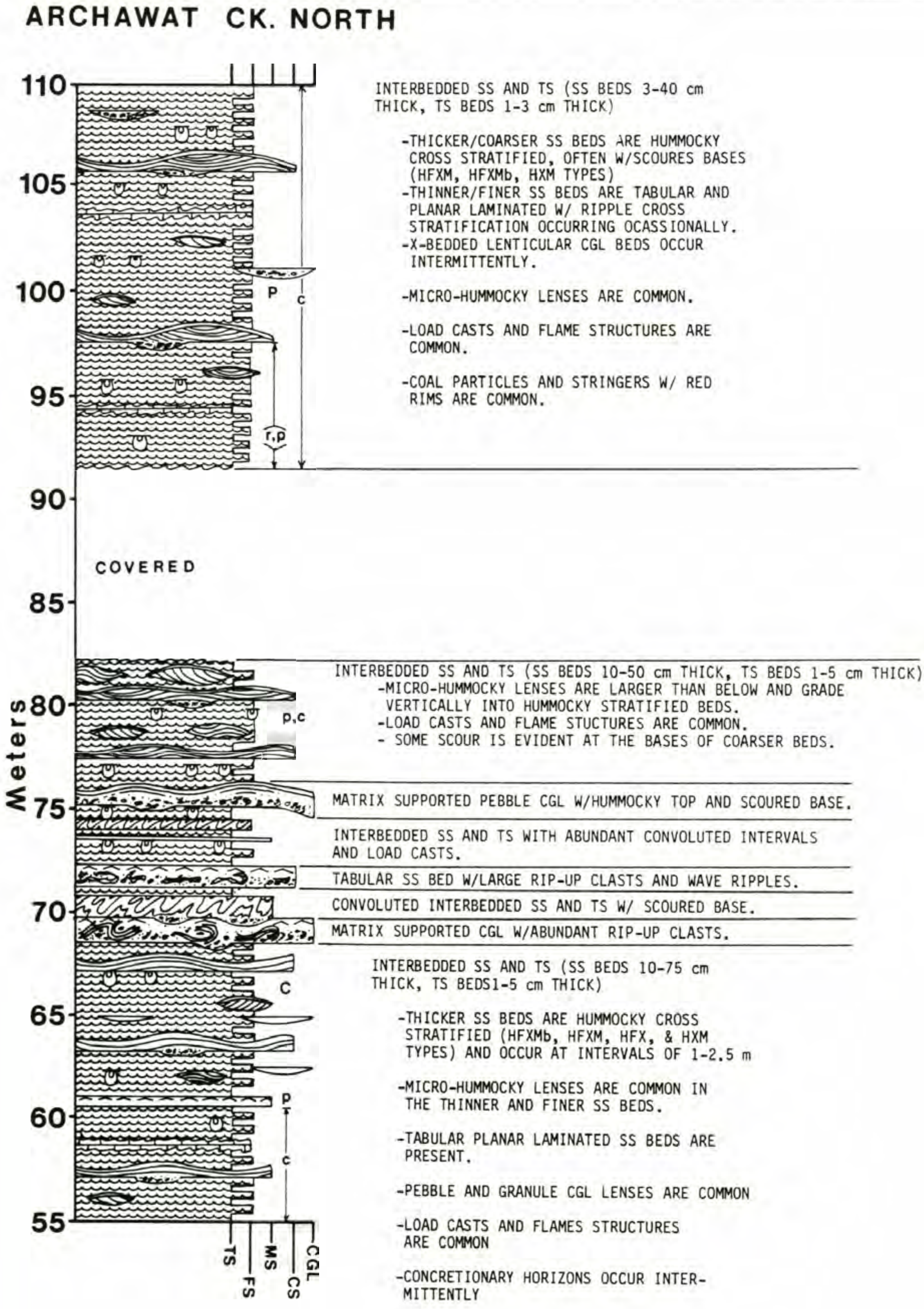
TS	SILTSTONE
FS	FINE SANDSTONE
MS	MEDIUM SANDSTONE
CS	COARSE SANDSTONE
CGL	CONGLOMERATE
c,t,p,r	LOWER CASE TRACE FOSSILS INDICATE LIMITED OCCURRENCES
C,T,P,R	UPPER CASE TRACE FOSSILS INDICATE ABUNDANT OCCURRENCES

SECTION A:

ARCHAWAT CK. NORTH



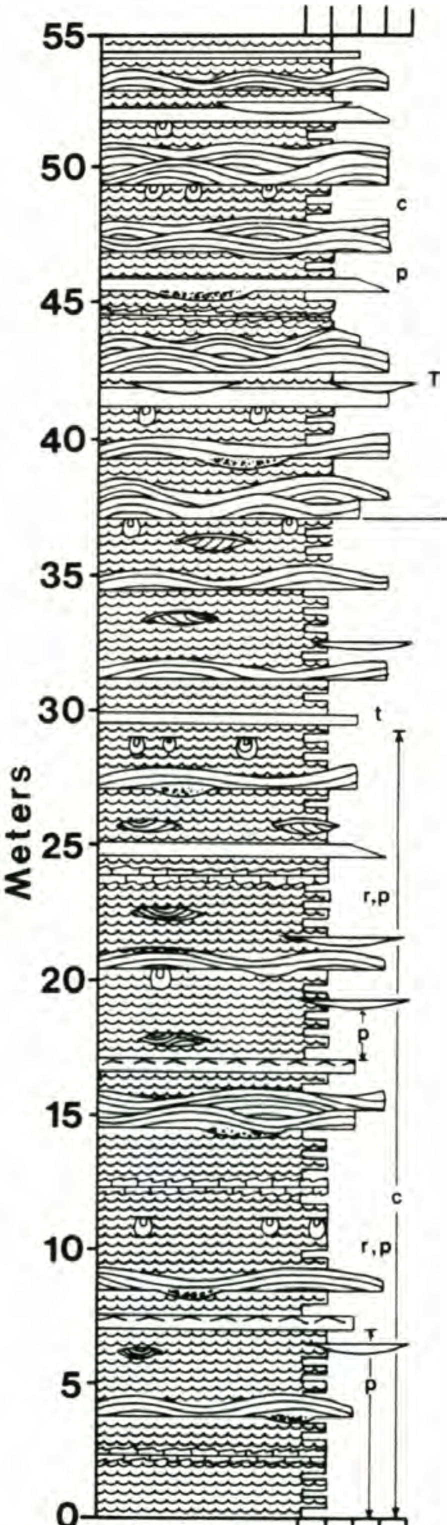
SECTION A:



ARCHAWAT CK. NORTH
110
105
100
95
90
85
80
75
70
65
60
55
Meters
COVERED
P
c
r,p
p,c
C
p
c
TS
FS
MS
CS
CGL
INTERBEDDED SS AND TS (SS BEDS 3-40 cm THICK, TS BEDS 1-3 cm THICK)
-THICKER/COARSER SS BEDS ARE HUMMOCKY CROSS STRATIFIED, OFTEN W/SCOURES BASES (HFXM, HFXMb, HXM TYPES)
-THINNER/FINER SS BEDS ARE TABULAR AND PLANAR LAMINATED W/ RIPPLE CROSS STRATIFICATION OCCURRING OCASSIONALLY.
-X-BEDDED LENTICULAR CGL BEDS OCCUR INTERMITTENTLY.
-MICRO-HUMMOCKY LENSES ARE COMMON.
-LOAD CASTS AND FLAME STRUCTURES ARE COMMON.
-COAL PARTICLES AND STRINGERS W/ RED RIMS ARE COMMON.
INTERBEDDED SS AND TS (SS BEDS 10-50 cm THICK, TS BEDS 1-5 cm THICK)
-MICRO-HUMMOCKY LENSES ARE LARGER THAN BELOW AND GRADE VERTICALLY INTO HUMMOCKY STRATIFIED BEDS.
-LOAD CASTS AND FLAME STUCTURES ARE COMMON.
- SOME SCOUR IS EVIDENT AT THE BASES OF COARSER BEDS.
MATRIX SUPPORTED PEBBLE CGL W/HUMMOCKY TOP AND SCOURED BASE.
INTERBEDDED SS AND TS WITH ABUNDANT CONVOLUTED INTERVALS AND LOAD CASTS.
TABULAR SS BED W/LARGE RIP-UP CLASTS AND WAVE RIPPLES.
CONVOLUTED INTERBEDDED SS AND TS W/ SCOURED BASE.
MATRIX SUPPORTED CGL W/ABUNDANT RIP-UP CLASTS.
INTERBEDDED SS AND TS (SS BEDS 10-75 cm THICK, TS BEDS1-5 cm THICK)
-THICKER SS BEDS ARE HUMMOCKY CROSS STRATIFIED (HFXMb, HFXM, HFX, & HXM TYPES) AND OCCUR AT INTERVALS OF 1-2.5 m
-MICRO-HUMMOCKY LENSES ARE COMMON IN THE THINNER AND FINER SS BEDS.
-TABULAR PLANAR LAMINATED SS BEDS ARE PRESENT.
-PEBBLE AND GRANULE CGL LENSES ARE COMMON
-LOAD CASTS AND FLAMES STRUCTURES ARE COMMON
-CONCRETIONARY HORIZONS OCCUR INTER-MITTENTLY

SECTION A:

ARCHAWAT CK. NORTH



INTERBEDDED SS AND TS (SS BEDS 5-140 cm THICK, TS BEDS 1-4 cm THICK)

-HUMMOCKY CROSS STRATIFIED (HFXM, & HFX TYPES) ARE THICKER AND MORE FREQUENT THAN BELOW. HUMMOCKY BEDS OFTEN AMALGAMATED.

-TABULAR PLANAR LAMINATED SS BEDS ARE COMMON.

-PEBBLE AND GRANULE STRINGERS AND LENSES ARE COMMON.

-LOAD CASTS AND FLAME STRUCTURES ARE COMMON

-CONCRETIONARY HORIZONS ARE PRESENT

INTERBEDDED SS AND TS (SS BEDS 5-100 cm THICK, TS BEDS 1-4 cm THICK)

-THICK SS BEDS (20 cm+) ARE HUMMOCKY CROSS STRATIFIED (HFXM, HFX, HXM TYPES) WITH SHARP, SCOURED, OR LOAD CAST BASES. HUMMOCKY CROSS STRATIFIED BEDS OCCUR AT INTERVALS OF 1-2.5 m.

-THINNER SS BEDS (LESS THAN 20 cm) ARE X-BEDDED, RIPPLE CROSS LAMINATED, AND PLANAR LAMINATED.

-THICKEST SS BEDS (60 cm+) OFTEN HAVE STRUCTURLESS BASES.

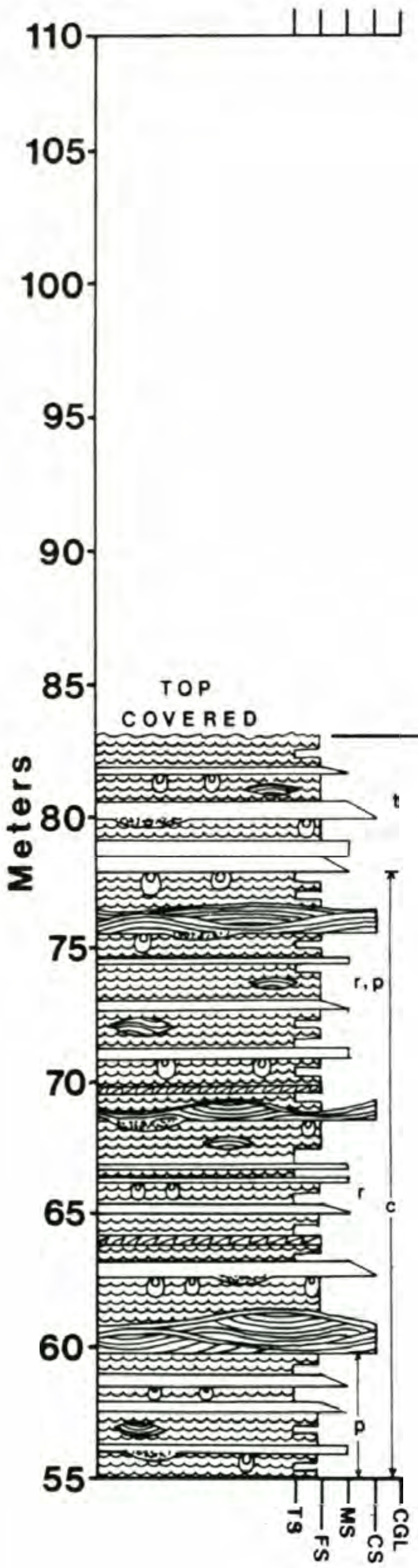
-MICRO-HUMMOCKY LENSES ARE COMMON IN THE THINNER AND FINER INTERBEDDED SS AND TS.

-CONCRETIONARY HORIZONS AND GRANULE TO PEBBLE STRINGERS AND LENSES ARE COMMON

-LOAD CAST & FLAME STRUCTURES COMMON

SECTION B:

ARCHAWAT CK. SOUTH

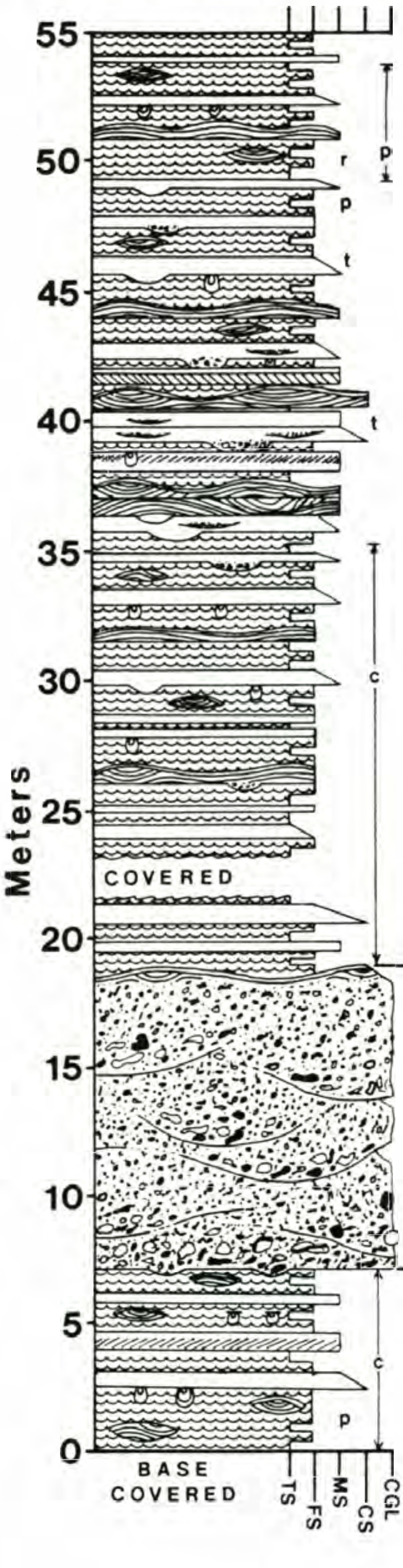


INTERBEDDED SS AND TS (SS BEDS 5-100 cm THICK, TS BEDS 1-10 cm THICK)

- -SS BEDS ARE STRUCTURLESS, GRADED, AND HUMMOCKY CROSS STRATIFIED (HFXMb, HFXM, HFX TYPES)
- -HCS BEDS ARE OCCASIONALLY AMALGAMATED
- -MICRO-HUMMOCKY LENSES ARE COMMON
- -CONVOLUTED BEDDING IS COMMON
- -SCOURED BASES (OFTEN FILLED W/ RIP-UP CLASTS) ARE COMMON
- -LOAD CASTS AND FLAME STRUCTURES ARE COMMON

SECTION B:

ARCHAWAT CK. SOUTH



INTERBEDDED SS AND TS (SS BEDS 3-120 cm THICK, TS BEDS 1-5 cm THICK)

-SS BEDS ARE TABULAR OR HUMMOCKY CROSS STRATIFIED (HFXMb, HFXM, HFX TYPES).

-HCS BEDS ARE OCASSIONALLY AMALGAMATED

-GRADING, X-BEDDING , AND RIPPLE CROSS LAMINATION ARE COMMON IN TABULAR BEDS

-SCOURED BASES (OFTEN FILLED W/ RIP-UP CLASTS) ARE COMMON

-MICRO-HUMMOCKY LENSES ARE COMMON

-THE SEQUENCE EXHIBITS A COARSENING/ THICKENING AND THEN A FINING/THINNING UPWARD PROGRESSION CENTERED AROUND METER 40. HCS, CONVOLUTED BEDDING, LOAD CASTS, AND RIP-UP CLASTS ARE ALL MORE COMMON IN THIS INTERVAL.

-PEBBLE STRINGERS ARE PRESENT WITH IN THE COARSER SS BEDS SUGGESTING AMALGAMATION.

BAHOBOHOSH

MATRIX AND CLAST SUPPORTED CONGLOMERATE W/ MANY AMALGAMATED CHANNELS.

-CLASTS INCLUDE BASALT, INDURATED SS, LAMINATED CONCRETIONARY TS, RIP-UP CLASTS, AND GRANULE CGL.

-BASE IS SLIGHTLY SCOURED AND LOAD CAST IN PLACES.

-TOP OF CGL SET HAS BEEN REWORKED INTO HUMMOCKY-STRATIFIED INTERVAL.

-CHANNELIZED CGL GRADES INTO DIS-ORGANIZED CGL AT THE TOP OF THIS INTERVAL

WAATCH POINT

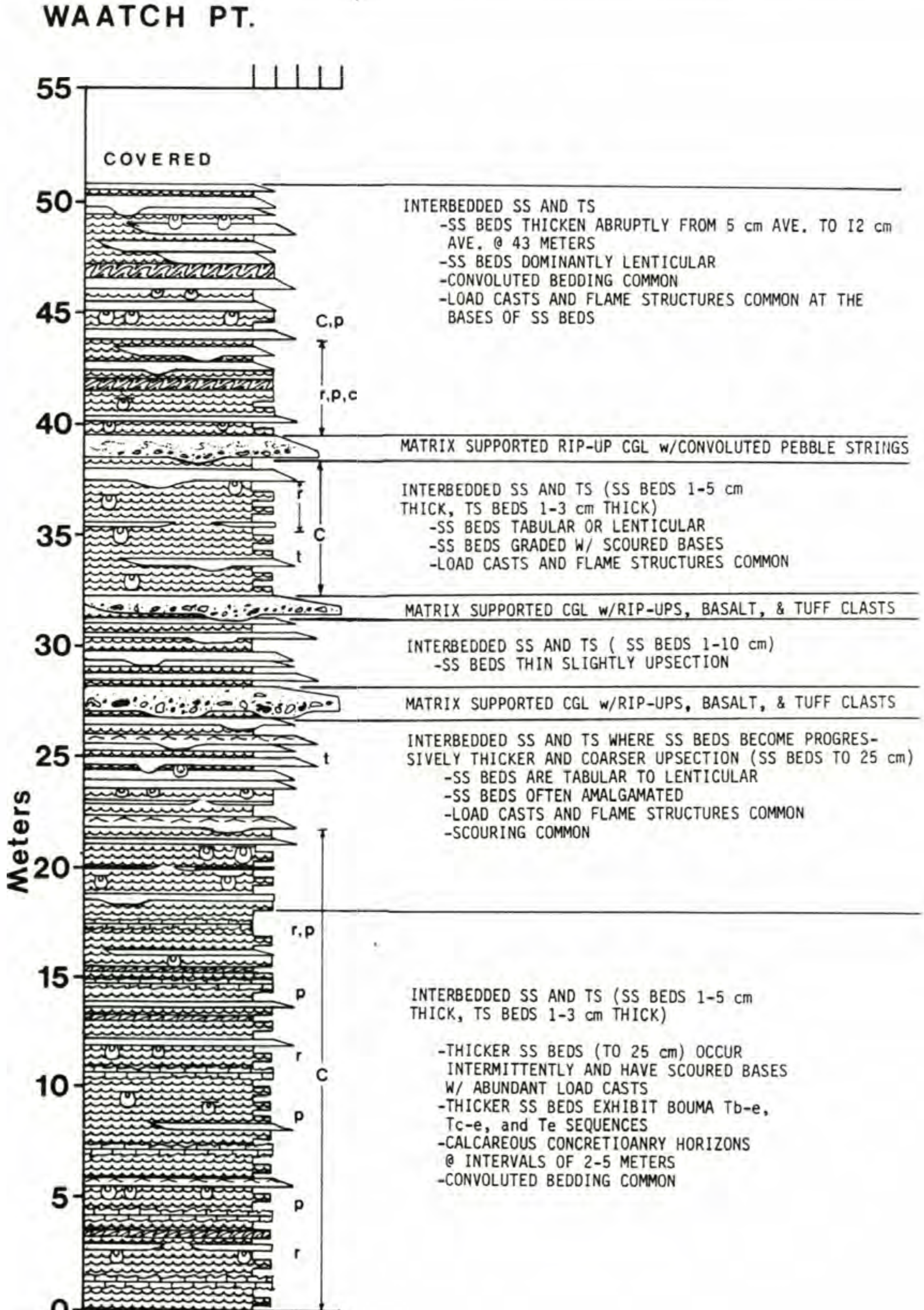
INTERBEDDED SS AND TS (SS BEDS 3-20 cm THICK, TS BEDS 1-5 cm THICK)

-COARSER SS BEDS ARE TABULAR & GRADED. SOME EXHIBIT X-BDG.

-MICRO-HUMMOCKY LENSES ARE COMMON.

-LOAD CASTS AND FLAME STRUCTURES ARE COMMON.

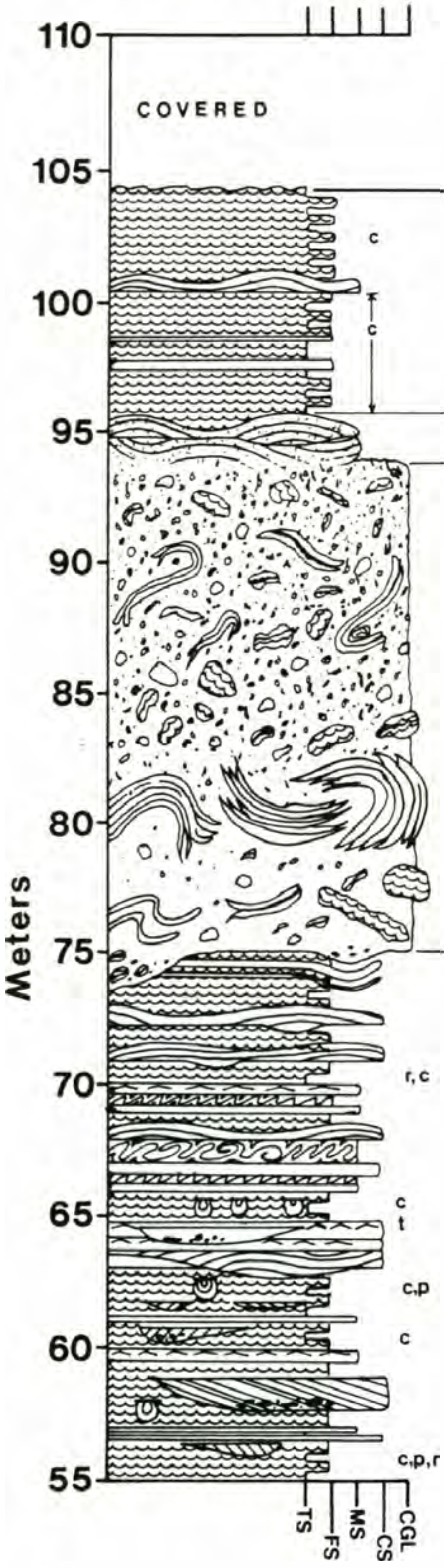
SECTION C:



WAATCH PT.
55
50
45
40
35
30
25
20
15
10
5
0
Meters
COVERED
BASE COVERED
TS
FS
MS
CS
CGL
C,p
r,p,c
r
C
t
t
r,p
p
r
C
p
p
r
INTERBEDDED SS AND TS
-SS BEDS THICKEN ABRUPTLY FROM 5 cm AVE. TO 12 cm AVE. @ 43 METERS
-SS BEDS DOMINANTLY LENTICULAR
-CONVOLUTED BEDDING COMMON
-LOAD CASTS AND FLAME STRUCTURES COMMON AT THE BASES OF SS BEDS
MATRIX SUPPORTED RIP-UP CGL w/CONVOLUTED PEBBLE STRINGS
INTERBEDDED SS AND TS (SS BEDS 1-5 cm THICK, TS BEDS 1-3 cm THICK)
-SS BEDS TABULAR OR LENTICULAR
-SS BEDS GRADED W/ SCOURED BASES
-LOAD CASTS AND FLAME STRUCTURES COMMON
MATRIX SUPPORTED CGL w/RIP-UPS, BASALT, & TUFF CLASTS
INTERBEDDED SS AND TS (SS BEDS 1-10 cm)
-SS BEDS THIN SLIGHTLY UPSECTION
MATRIX SUPPORTED CGL w/RIP-UPS, BASALT, & TUFF CLASTS
INTERBEDDED SS AND TS WHERE SS BEDS BECOME PROGRESSIVELY THICKER AND COARSER UPSECTION (SS BEDS TO 25 cm)
-SS BEDS ARE TABULAR TO LENTICULAR
-SS BEDS OFTEN AMALGAMATED
-LOAD CASTS AND FLAME STRUCTURES COMMON
-SCOURING COMMON
INTERBEDDED SS AND TS (SS BEDS 1-5 cm THICK, TS BEDS 1-3 cm THICK)
-THICKER SS BEDS (TO 25 cm) OCCUR INTERMITTENTLY AND HAVE SCOURED BASES W/ ABUNDANT LOAD CASTS
-THICKER SS BEDS EXHIBIT BOUMA Tb-e, Tc-e, and Te SEQUENCES
-CALCAREOUS CONCRETIOANRY HORIZONS @ INTERVALS OF 2-5 METERS
-CONVOLUTED BEDDING COMMON

SECTION D:

BAHOBOHOSH PT.



INTERBEDDED SS AND TS (SS BEDS 3-10 cm THICK, TS BEDS 1-3 cm THICK)

- -OCCASIONAL TABULAR STRUCTURLESS AND HUMMOCKY CROSS STRATIFIED (HFM TYPE) BEDS OF SLIGHTLY COARSER SAND. THESE BEDS UP TO 20 cm THICK

HUMMOCKY STRATIFIED COARSE SS BED (HFM-TYPE) THAT HAS A GRADATIONAL CONTACT WITH THE CGL INTERVAL BELOW

THICK MATRIX SUPPORTED CGL (CLASTS TO 0.5 m) CONTAINING LARGE RIP UP CLASTS OF INTERBEDDED SS AND TS AS WELL AS EXTRACLASTS.

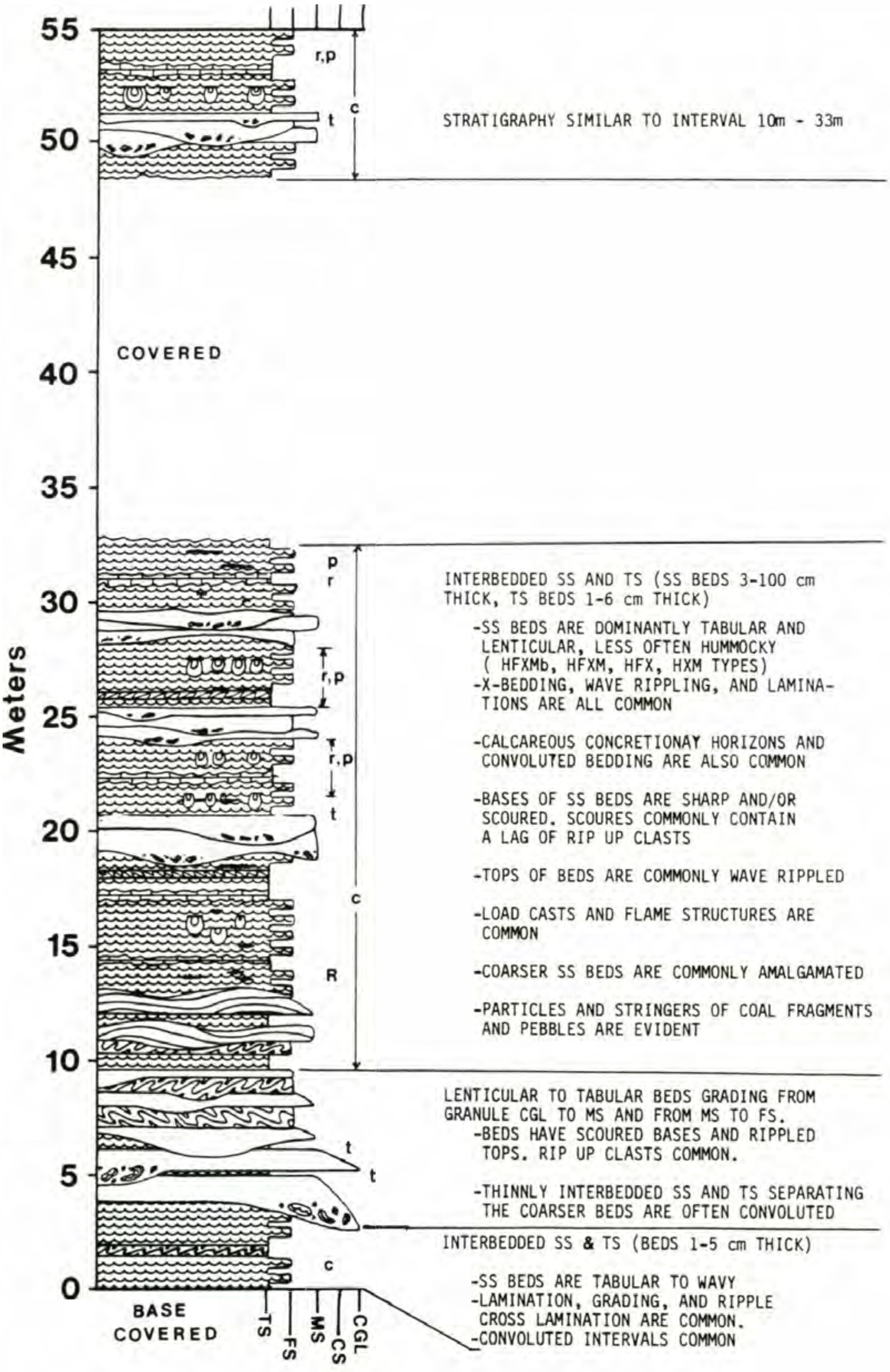
- -LARGE LATERALLY CONTINUOUS ZONES OF CONVOLUTED BEDDING ARE PRESENT TOWARDS THE BASE OF THE INTERVAL.
- -THE BASAL CONTACT OF THE CGL WITH THE UNDERLYING INTERBEDDED SS AND TS IS SCOURED AND HAS AREAS OF LARGE SCALE LOADING.

INTERBEDDED SS AND TS (SS BEDS 3-50 cm THICK, TS BEDS 1-5 cm THICK)

- -SS BED FORMS ARE TABULAR, LENTICULAR, AND HUMMOCKY
- -X-BEDDING, WAVE RIPPLING, AND HUMMOCKY STRATIFICATION (HFX, HFM, AND HFXMb-TYPES) ARE ALL COMMON
- -SS BEDS HAVE SHARP AND/OR SCOURED BASES
- -SS BED TOPS ARE COMMONLY WAVE RIPPLED
- -CONVOLUTED BEDDING COMMON
- -COARSER SS BEDS COMMONLY AMALGAMATED
- -LOAD CASTS AND FLAME STRUCTURES COMMON

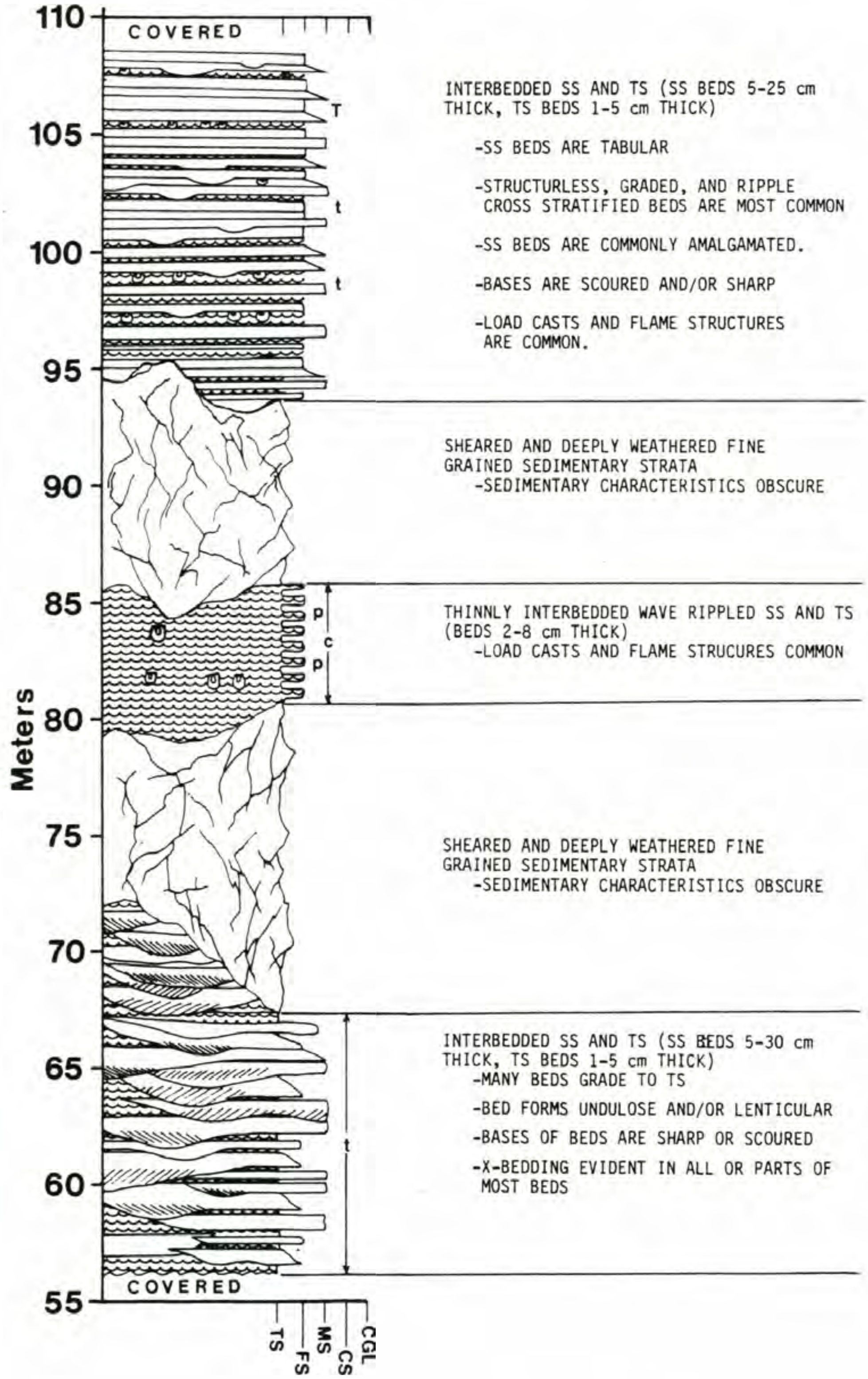
SECTION D:

BAHOBOHOSH PT.



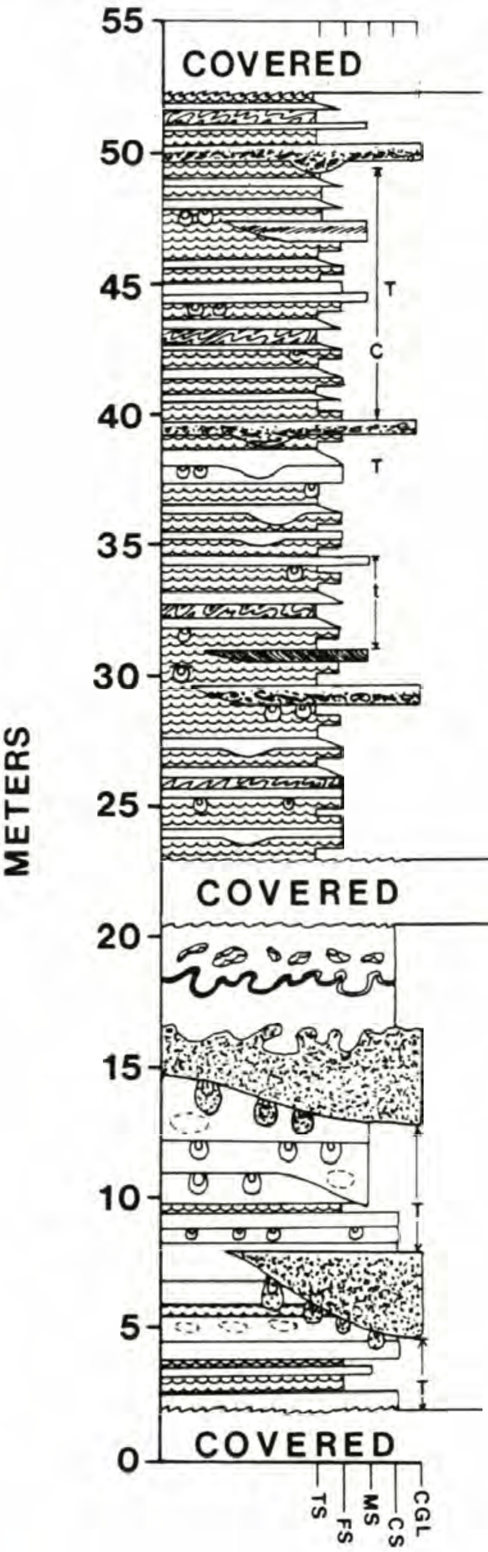
SECTION E:

BEAR CREEK QUARRY



SECTION E:

BEAR CREEK QUARRY



INTERBEDDED SS AND TS (SS BEDS 5-30 cm THICK, TS BEDS 1-3 cm THICK)

- -SS BEDS ARE TABULAR AND LENTICULAR
- -X-BEDDING, GRADING,&RIPPLE CROSS STRATIFICATION ARE THE DOMINANT STRUCTURES. STRUCTURLESS BEDS ARE ALSO PRESENT.
- -BEDS HAVE SHARP AND/OR SCOURED BASES.
- -TS BEDS ARE LAMINATED TO RIPPLED.
- -LOAD CASTS AND FLAME STRUCTURES ARE COMMON.

INTERBEDDED COARSE SS AND GRANULE TO PEBBLE CGL (SS BEDS 30-200 cm THICK, CGL BEDS 50-300 cm THICK)

- -CONTACTS BETWEEN SS AND CGL BEDS ARE COMMONLY CONVOLUTED, LOAD CAST, AND/ SCOURED.
- -TS RIP-UP CLASTS ARE COMMON WITHIN THE SS BEDS.
- -OBLATE CONCRETIONS ARE COMMON IN BOTH THE SS AND CGL BEDS.

APPENDIX 2;--Procedures used in the geochemical investigation.

INTRODUCTION

Geochemical samples of siltsones and shales from the study unit were collected on the basis of the freshness of the rock, lack of apparent bioturbation, and dark "organic" appearance of the sample. Sample locations are shown in Figure 51. Three types of analyses were performed on 15 samples of siltstone and shales from the study unit. Determination of the weight percent of sulfide minerals in the samples and of the sulfur-isotope compositions of pyrite from the samples were performed by Global Geochemical Corporation, Canoga Park, California. Sulfur-isotope values are reported relative to the isotopic ratios in triolite from the Canyon Diablo meteorite. Determination of the amount of organic carbon present in the samples was performed using the carbon wet-oxidation method (described below) on a Oceanography International Corporation (OIC) 0524B Total Carbon System. This system as employed measures the amount of CO_2 generated by the oxidation of organic matter in sediments. The results these three analyses are reported in Table 4.

PROCEDURES USED IN THE GEOCHEMICAL ANALYSES

1. Sediment was ground to 100 mesh in a ball mill. Care was tken to prevent contamination by organic matter.
2. Samples were dried for 24 hours in an oven at 105 ^{o}C and then stored in glass sample jars.
3. Sixteen precombusted ampules for each sample were weighed to the nearest 0.00001 gram.
4. Preweighed sediment from each sample in four weight ranges (10,20,30, and 40 mg) was added to the ampules. Four ampules were prepared for each weight range for a total of 16 ampules per sample.
5. Ampules with sediment were reweighed to determine exact weight of each sample.

6. 1.0 ml., 6% v/v Phosphoric Acid was added to each ampule.

7. 2.0 ml. distilled water was added to each ampule. Water was injected with a pipette in order to wash any clinging sediment down the walls of the ampule.

8. Ampules were covered loosely and allowed to sit for at least 30 minutes. This allows adequate time for the reaction

$$HCO_3^- + CO_3^= \rightarrow CO_2$$

to take place removing any carbon dioxide associated with the carbonate system.

9. 0.6 g $K_2S_2O_8$ (oxidant) were added to each ampule with a dipper measure.

10. 2.0 ml distilled water were added to each ampule so as to wash oxidant to the bottom.

11. Ampules were purged of inorganic carbon for six minutes each using a stream of dried air.

12. Sediment adhering to the purge tube and ampule walls was washed down using a few drops of CO_2-free distilled water.

13. The ampules were sealed.

14. The aampules were heated in a pressure vessel at 175 ^{o}C for no less than four hours. This step allows organic matter in the samples to be converted to CO_2 through the action of the oxidant.

15. CO_2 content of the ampules was determined using the OIC analysis unit. The ampules are broken and evacuated in the intake tube of the unit which analyses the CO_2 content of the evolved gas with an infrared spectroscope. Blank ampules (with out sediment) are also analysed at this time as an internal check of the system.

16. Samples values for total organic carbon are compared to a curve developed through the preparation and analysis of samples with known organic carbon contents.

Averages of the four runs for each sample are reported in Table 2. Values from individual samples were averaged due to negligible variations between runs.

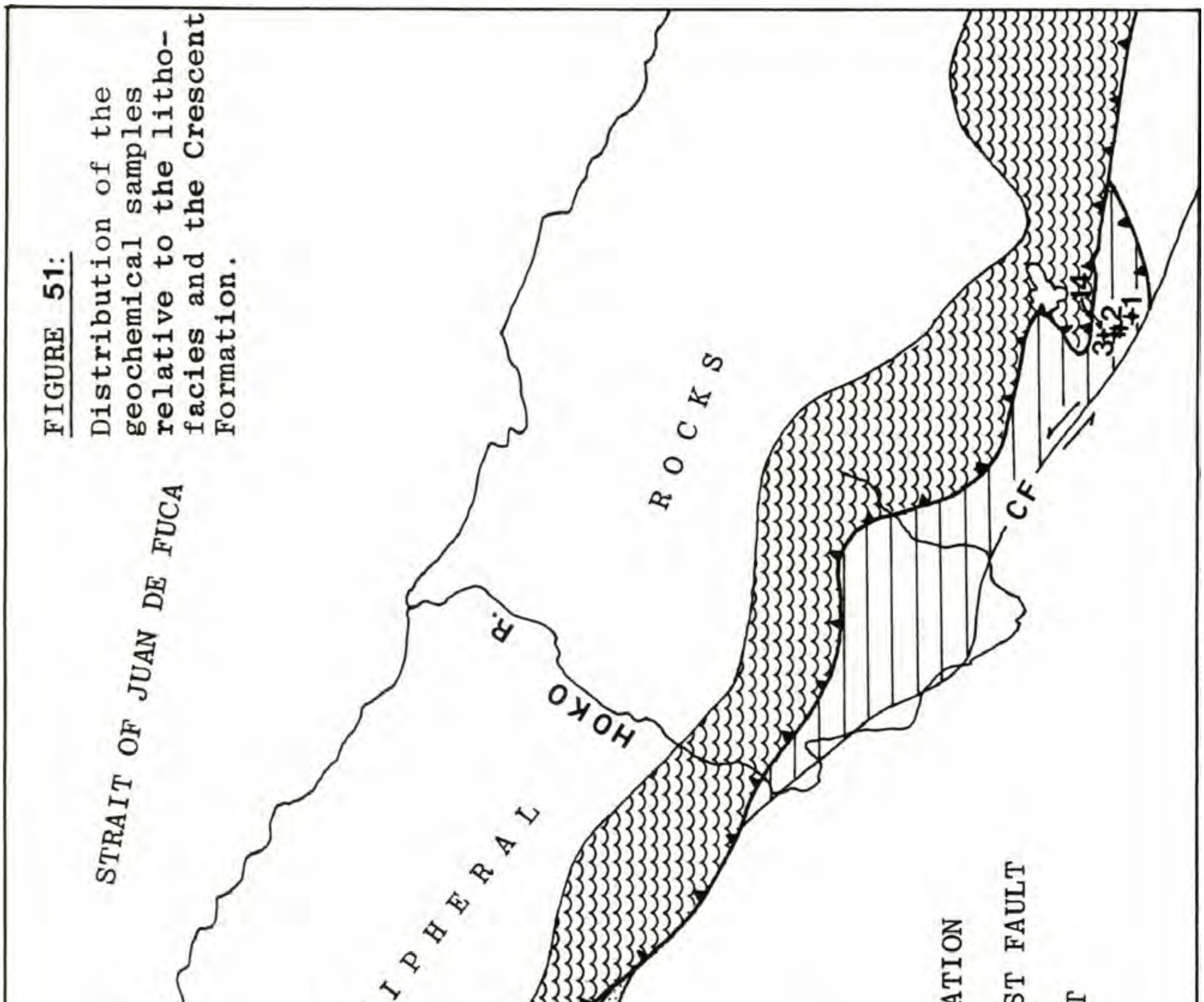


FIGURE 51: Distribution of the geochemical samples relative to the lithofacies and the Crescent Formation.

APPENDIX 3: Point Count Categories

Qm: Monocrystalline quartz grains, including individual grains very fine sand-size or larger, and grains of sand-size monocrystalline quartz within lithic clasts.

Chert: Grains of microcrsytalline quartz (sub-grains are smaller than very fine sand) with up to 15% impurities. Sand-size chert grains within sedimentary lithic clasts are counted here.

Qp: Polycrystalline quartz grains, including non-foliated polycrystalline quartz and heavily recrystallized chert clasts of sand-size. Recrystallized chert is counted.

P: Plagioclase feldspar grains, including individual sand-size grains and sand-size grains within the lithic clasts.

K: Potassium feldspar grains, including individual sand-size grains, and sand-size grains within lithic clasts.

Lss: Sedimentary lithic grains that contain more than 50% silt-size grains, including those that are within sandstone clasts.

Lsf: Sedimentary lithic grains that contain more than 50% clay-sized particles, including those within sandstone clasts.

Lm: Metamorphic lithic grains of very fine sand-size or larger. Subcategories include quartz-mica tectonites, metasedimentary, and metavolcanic grains. Metasedimentary and quartz-mica tectonite grains are distinguished as follows: Metasedimentary grains are fine grained and have murky clay minerals developing a foliation that produces a sharp extinction under crossed polarizers; Quartz-mica tectonite grains have a well developed foliation and extinction but have mica grains large enough to be distinguished under relatively low power.

Lv: Volcanic lithic grains that are very fine sand-size or larger. Felsic, lathwork, and microlitic grains are distinguished. The sub-category Lv other also includes all volcanics not fitting the first three categories.

Li: Intrusive lithic grains of very fine sand-size or larger within which individual grains are smaller than very fine sand. Sub-categories include grainitic, granodioritic, gabbroic, and other. Grains are assigned to sub-categories on the basis of the presence or absence of potassium feldspar and mafic minerals, and the percentages of plagioclase in each clasts (>50% P = gabbro, <50% P = granodiorite). Included in the Li other sub-category are grains that contain abundant (>5%) potassium feldspar and are polycrystalline. This texture is probably the result of late stage crystallization of aplites associated with pegmatities (R. S. Babcock, 1987, oral communication).

Misc: Miscellaneous grains. A "grab bag" category in which all indentifiable grains that do not fit in the other categories are counted. This category includes detrital calcite, chlorite, pumpellyite, and rare laumontite, as well as organic matter, and porosity.

H: Accessory minerals, including epidote, pyroxene, biotite, actinolite, muscovite, zoesite, clinozoesite, zircon, tourmaline, and sphene in decreasing order of abundance.

O: Opaque mineral grains of sand-size or larger, including opaques within lithic clasts.

Matrix: Protomatrix and orthomatrix as defined by Dickinson (1970). Interstitial material which is determined to have been of primary origin or recrystallized from material of primary origin.

Cement: Here all minerals produced by post-depositional changes are counted including those replacing primary grains. Cement sub-categories include zeolites, calcite, clay, laumontite, chlorite, and pyrite in decreasing order of abundance.

Unknown: All grains that were unidentifiable were counted here.

APPENDIX 4: Point Count Data

Point count data are reported here following the point count category divisions described in Appendix 3. Data is divided into lithofacies (Snavely et al., 1986). Sample numbers indicate the quadrangle and year of collection using the following designations;

-Sample numbers starting with the number two were collected during the 1986 field season. All others are from the 1985 field season.

-Letters in the sample numbers refer to the 7.5 MINUTE quadrangle in which the sample was collected. All quadrangles are in the northwest corner of the Olympic Peninsula. The letter designations are as follows.

H,RC-HOKO FALLS,WA

N-NEAH BAY,WA

E-ELLIS MOUNTAIN,WA

U-UMBRELLA CREEK,WA

L-LAKE PLEASANT,WA

M-MAKAH BAY,WA

RAW POINT COUNT DATA (400 points)

Bahobohosh Lithofacies

Sample #	M14	M14D	M14F	M14G	M14H
Qm	65	73	96	103	93
Chert	12	35	8	22	16
Qp	13	15	14	22	11
P	36	75	57	72	60
K	15	12	27	31	15
Lss	52	25	31	44	33
Lsf	38	14	16	27	24
Lm	5	8	5	5	4
Lv	25	8	17	27	25
felsic	1	0	1	1	0
lathwork	24	8	15	26	25
microlitic	0	0	1	0	0
other	0	0	0	0	0
Li	2	5	3	6	1
Misc	23	10	2	26	8
H	9	8	10	2	12
muscovite	0	0	0	0	0
biotite	2	3	1	0	1
pyroxene	4	2	3	2	4
amphibole	0	0	0	0	1
olivine	0	0	0	0	0
epidote	2	2	5	0	5
other	1	0	1	0	1
O	4	9	3	1	0
Matrix	15	23	7	0	4
Cement	94	69	109	0	85
Unknown	6	11	9	12	7

Bahobohosh Lithofacies

Sample #	M14L	M17A	M17C	M17F	M18B
Qm	88	62	52	61	72
Chert	19	20	38	26	33
Qp	25	41	22	34	26
P	52	68	55	60	64
K	17	8	8	10	13
Lss	44	5	34	15	19
Lsf	32	74	32	54	71
Lm	9	4	4	3	2
Lv	12	8	28	27	22
felsic	0	1	0	0	2
lathwork	12	4	22	17	18
microlitic	0	3	6	10	2
other	0	0	0	0	0
Li	2	2	1	0	1
Misc	4	6	5	8	5
H	7	12	11	10	15
muscovite	1	0	0	0	0
biotite	1	1	1	2	0
pyroxene	0	1	0	1	3
amphibole	0	0	2	0	0
olivine	0	0	5	0	1
epidote	3	10	3	7	9
other	2	0	0	0	2
O	2	5	6	3	3
Matrix	10	19	18	15	14
Cement	66	60	76	70	34
Unknown	11	6	11	3	7

Bahobohosh Lithofacies

Sample #	M19B	2NIA	2UIB	2UIE	2UIG
Qm	69	108	59	47	97
Chert	12	33	39	50	35
Qp	37	34	26	14	45
P	76	37	31	41	44
K	7	32	8	6	16
Lss	23	13	9	3	23
Lsf	58	0	9	7	13
Lm	2	4	4	8	2
Lv	15	41	36	37	31
felsic	0	18	19	13	15
lathwork	9	22	17	18	14
microlitic	6	0	0	4	2
other	0	1	0	2	0
Li	1	15	6	12	13
Misc	6	2	18	20	4
H	18	5	5	10	4
muscovite	0	0	0	0	0
biotite	0	1	1	0	0
pyroxene	5	4	3	3	1
amphibole	2	0	0	0	0
olivine	0	0	1	1	0
epidote	11	0	0	0	0
other	0	1	0	5	2
O	2	0	0	0	2
Matrix	14	24	46	47	22
Cement	55	42	70	81	41
Unknown	6	15	20	16	8

Bahobohosh Lithofacies

Sample #	2M3D	2M3E	2M3F	2M3G	2M3J
Qm	43	54	64	37	89
Chert	22	32	31	30	20
Qp	30	40	28	45	37
P	29	40	35	30	53
K	9	8	14	2	1
Lss	35	31	31	33	25
Lsf	16	28	40	32	76
Lm	17	19	24	20	0
Lv	32	10	15	9	16
felsic	14	3	5	3	0
lathwork	14	6	10	5	12
microlitic	2	0	0	0	4
other	2	1	0	1	0
Li	17	6	5	0	0
Misc	0	12	15	6	1
H	8	27	14	19	19
muscovite	0	0	0	0	0
biotite	0	1	0	0	0
pyroxene	3	10	3	3	6
amphibole	0	1	0	0	0
olivine	1	3	1	2	2
epidote	2	3	5	0	8
other	2	9	4	14	3
O	5	5	9	3	2
Matrix	6	25	19	23	8
Cement	110	52	41	86	48
Unknown	13	13	15	15	8

Bahobohosh Lithofacies

Sample #	2M3K	2M4A	2M4B	2M4C
Qm	58	57	49	27
Chert	22	31	19	32
Qp	38	43	57	44
P	70	36	66	32
K	0	4	2	1
Lss	24	50	22	59
Lsf	60	26	76	44
Lm	0	23	1	19
Lv	19	22	28	44
felsic	1	1	0	2
lathwork	14	10	20	36
microlitic	4	10	8	6
other	0	1	0	0
Li	0	9	0	2
Misc	2	8	1	4
H	26	6	9	22
muscovite	0	1	1	0
biotite	0	1	2	0
pyroxene	12	0	1	0
amphibole	0	0	0	4
olivine	2	0	0	0
epidote	12	2	5	17
other	0	2	0	1
O	11	6	2	6
Matrix	11	22	15	10
Cement	68	46	46	29
Unknown	7	11	7	15

Waatch Point Lithofacies

Sample #	M15A	M15D	M15G	M16A	M16C
Qm	84	54	72	65	66
Chert	26	39	26	41	25
Qp	21	42	22	22	31
P	77	70	86	91	68
K	17	5	11	10	7
Lss	4	3	3	1	0
Lsf	44	36	46	56	54
Lm	3	6	8	7	1
Lv	3	7	9	7	22
felsic	1	0	0	2	3
lathwork	2	7	9	5	13
microlitic	0	0	0	0	6
other	0	0	0	0	0
Li	2	0	3	2	0
Misc	4	22	3	6	8
H	13	17	12	12	18
muscovite	2	1	0	0	0
biotite	3	0	0	0	2
pyroxene	0	2	2	1	0
amphibole	0	1	0	0	0
olivine	0	0	0	0	0
epidote	3	10	6	5	9
other	5	3	4	6	8
O	20	15	9	11	7
Matrix	22	18	18	9	21
Cement	54	55	61	47	63
Unknown	13	14	10	14	10

Waatch Point Lithofacies

Sample #	2M5B	2M5D
Qm	86	79
Chert	16	31
Qp	23	19
P	60	42
K	8	13
Lss	3	14
Lsf	5	20
Lm	11	12
Lv	17	11
felsic	1	1
lathwork	16	7
microlitic	0	3
other	0	0
Li	8	7
Misc	6	6
H	13	11
muscovite	0	2
biotite	1	1
pyroxene	1	1
amphibole	0	0
olivine	0	0
epidote	7	5
other	3	2
O	2	12
Matrix	31	23
Cement	102	85
Unknown	13	15

Bear Creek Lithofacies

Sample #	L1B	L6A	E6H	L7A	L7A conc.
Qm	48	59	96	46	62
Chert	35	48	32	78	61
Qp	40	31	10	12	50
P	30	52	69	58	58
K	2	0	0	0	0
Lss	4	9	14	38	36
Lsf	27	20	10	19	29
Lm	34	12	0	20	22
Lv	14	17	19	47	39
felsic	0	0	0	1	0
lathwork	12	9	18	34	27
microlitic	1	8	0	10	12
other	1	0	1	2	0
Li	5	7	6	4	0
Misc	11	14	6	7	18
H	10	8	17	13	6
muscovite	4	0	0	2	0
biotite	1	1	1	0	1
pyroxene	1	2	6	2	1
amphibole	0	0	0	1	0
olivine	0	0	0	0	0
epidote	3	3	8	7	3
other	1	2	3	2	1
O	32	12	6	4	1
Matrix	14	13	24	11	3
Cement	76	84	87	38	3
Unknown	18	15	11	12	11

Bear Creek Lithofacies

Sample #	L8E	E8E	E8G	H20B	RC
Qm	120	137	81	104	116
Chert	27	10	16	36	38
Qp	23	13	27	17	16
P	69	81	70	44	50
K	0	0	11	13	16
Lss	12	17	12	26	19
Lsf	12	6	11	7	14
Lm	9	0	2	4	0
Lv	13	19	10	30	32
felsic	0	2	0	1	2
lathwork	9	13	9	29	30
microlitic	4	4	1	0	0
other	0	0	0	0	0
Li	10	7	9	7	8
Misc	6	11	19	17	42
H	4	2	19	8	16
muscovite	1	0	0	0	0
biotite	0	0	1	0	0
pyroxene	1	1	3	1	8
amphibole	0	0	0	0	3
olivine	0	0	0	2	0
epidote	1	0	9	3	5
other	1	1	6	2	0
O	0	0	1	6	11
Matrix	15	7	21	10	—
Cement	72	83	86	62	—
Unknown	9	6	8	9	24

Bear Creek Lithofacies

Sample #	2H6A
Qm	142
Chert	24
Qp	21
P	35
K	19
Lss	1
Lsf	5
Lm	5
Lv	12
felsic	0
lathwork	10
microlitic	0
other	2
Li	10
Misc	5
H	9
muscovite	0
biotite	1
pyroxene	1
amphibole	2
olivine	0
epidote	4
other	1
O	10
Matrix	32
Cement	59
Unknown	14