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Depositional Environment, Provenance, and Tectonic Setting of the Upper Oligocene Sooke Formation, Vancouver Island, B. C.

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MASTER'S THESIS

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by

Susan Elaine Bream

Accepted in Partial Completion
of the Requirements for the Degree
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February 22, 2018

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A Thesis Presented to the Faculty of
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ABSTRACT

The Upper Oligocene Sooke Formation, the uppermost unit of the Carmanah Group, is exposed along the southeastern coast of Vancouver Island, British Columbia, where it is part of the Crescent terrane. The Sooke Formation is generally less than 45 meters thick.

Typically, a basal boulder breccia is overlain by interdigitated layers of cross-stratified, often fossiliferous sandstone and conglomerate. Deposition of the Sooke Formation occurred along a steep coast with abundant cliffs, narrow boulder beaches and sandy beaches, and a nearby fluvial source. The conglomerates and breccias were deposited by debris flows, rock falls, and as storm lag deposits. Sandstones were deposited dominantly on the shoreface under both fairweather and storm conditions.

The Sooke Formation sandstones are lithic arenites. The sandstones are texturally immature, and modal grain size is fine sand. Calcite cement is the most common cement, although pyrite, hematite, zeolite, clay, silica, and K-rich cement are also present, indicating a complex diagenetic history. Petrographic studies indicate that the dominant source area for the Sooke Formation was Vancouver Island. Boulders and cobbles were derived locally from the underlying Metchosin Volcanics and Sooke Gabbro, and adjacent Leech River Complex. Sand-sized clasts contain more diverse lithologies derived from several sources on Vancouver Island.

Deposition occurred soon after major movement on the Leech River fault, which is thought to be a suture along which rocks of the Crescent terrane were amalgamated with southern Vancouver Island in an early Tertiary subduction regime. Movement along the Leech River fault prior to deposition of the Sooke Formation caused uplift of the Leech River Complex. The area was tectonically active during deposition. Facies show

pulses of shallowing-upwards trends superimposed on a general deepening-upward trend.

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INTRODUCTION

The Upper Oligocene Sooke Formation, the youngest unit of the Carmanah Group, is exposed along the southern coast of Vancouver Island, B.C. (Fig. 1). It consists predominantly of fossiliferous cross-stratified sandstone and conglomerate that was deposited in a shallow marine environment. Generally, it is less than 45 meters thick. Southern Vancouver Island has been a site of tectonic activity from the Late Cretaceous to Early Tertiary and has a complex history. The Sooke Formation was deposited unconformably on rocks of the Crescent Terrane which were underthrust beneath Vancouver Island. The aim of this study is to interpret the depositional environment, provenance, and tectonic setting for the Sooke Formation. This study will allow for a more thorough understanding of the relationships between tectonics and sedimentation on southern Vancouver Island during the Late Oligocene. It will also aid in a better understanding of the regional Tertiary tectonic development of southern Vancouver and the northern Olympic Peninsula.

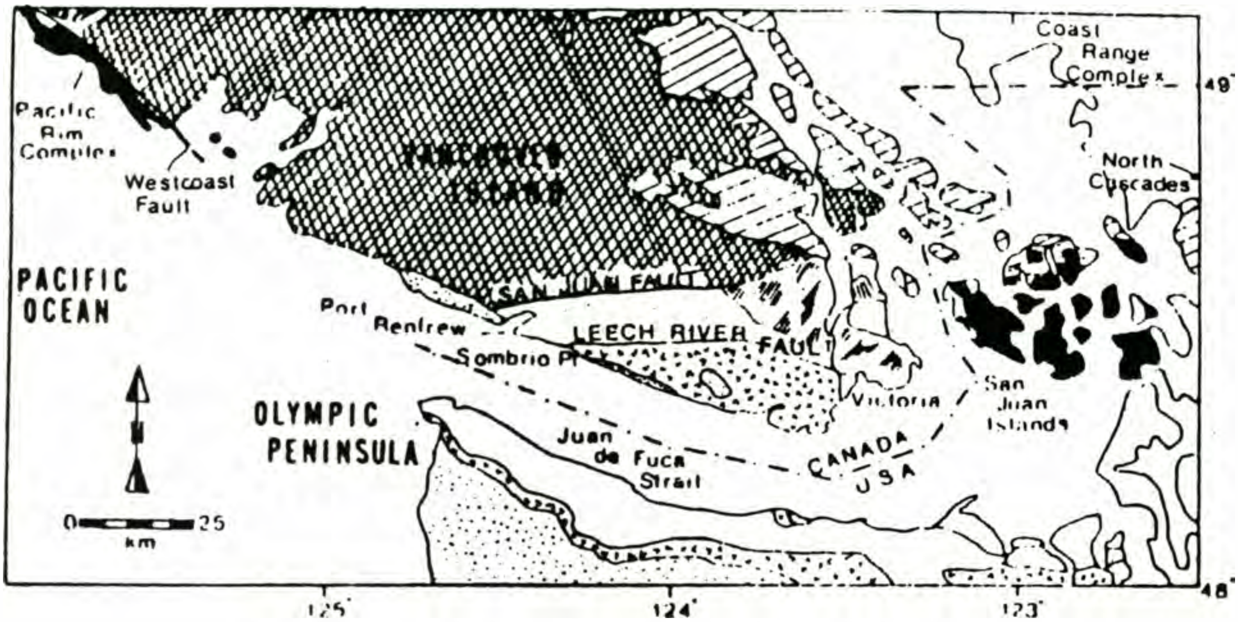
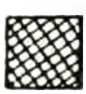


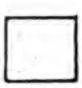
FIGURE 1. Geologic map of southeastern Vancouver Island and part of northwestern Washington (modified from Fairchild and Cowan, 1982; and Brandon, 1985).

Paleozoic and Mesozoic igneous and sedimentary rocks including the Paleozoic Wark Diorite and Colquitz Gneiss, pre-145 Ma metavolcanic rocks, and Jurassic Island Intrusions on Vancouver Island and Turtleback Complex and unnamed Paleozoic volcanic rocks in the San Juan Islands.



Paleozoic to Jurassic strata believed to be part of Wrangellia by Jones et al. (1977); includes metamorphic and igneous rocks of the West Coast Complex, and Lower to Middle (?) Jurassic plutons of the Island Intrusions.

Middle Jurassic to Mid-Cretaceous sedimentary rocks in the San Juan Islands and on the west coast of Vancouver Island that are in part time-correlative with the protolith for the Leech River Complex; includes minor volcanic rocks.



Late Jurassic to Cretaceous rocks of the Leech River Complex; includes metamorphosed pelitic rocks, sandstone, and minor volcanic rocks, chert, and conglomerate.

Upper Cretaceous strata of the Nanaimo Group; includes lower Tertiary strata in mainland Washington.

Lower to Middle Eocene basalts of the Metchosin volcanics on Vancouver Island and Crescent Formation on the Olympic Peninsula.

Tertiary clastic sedimentary rocks; includes Carmanah Group on Vancouver Island and Paleogene rocks on the Olympic Peninsula.

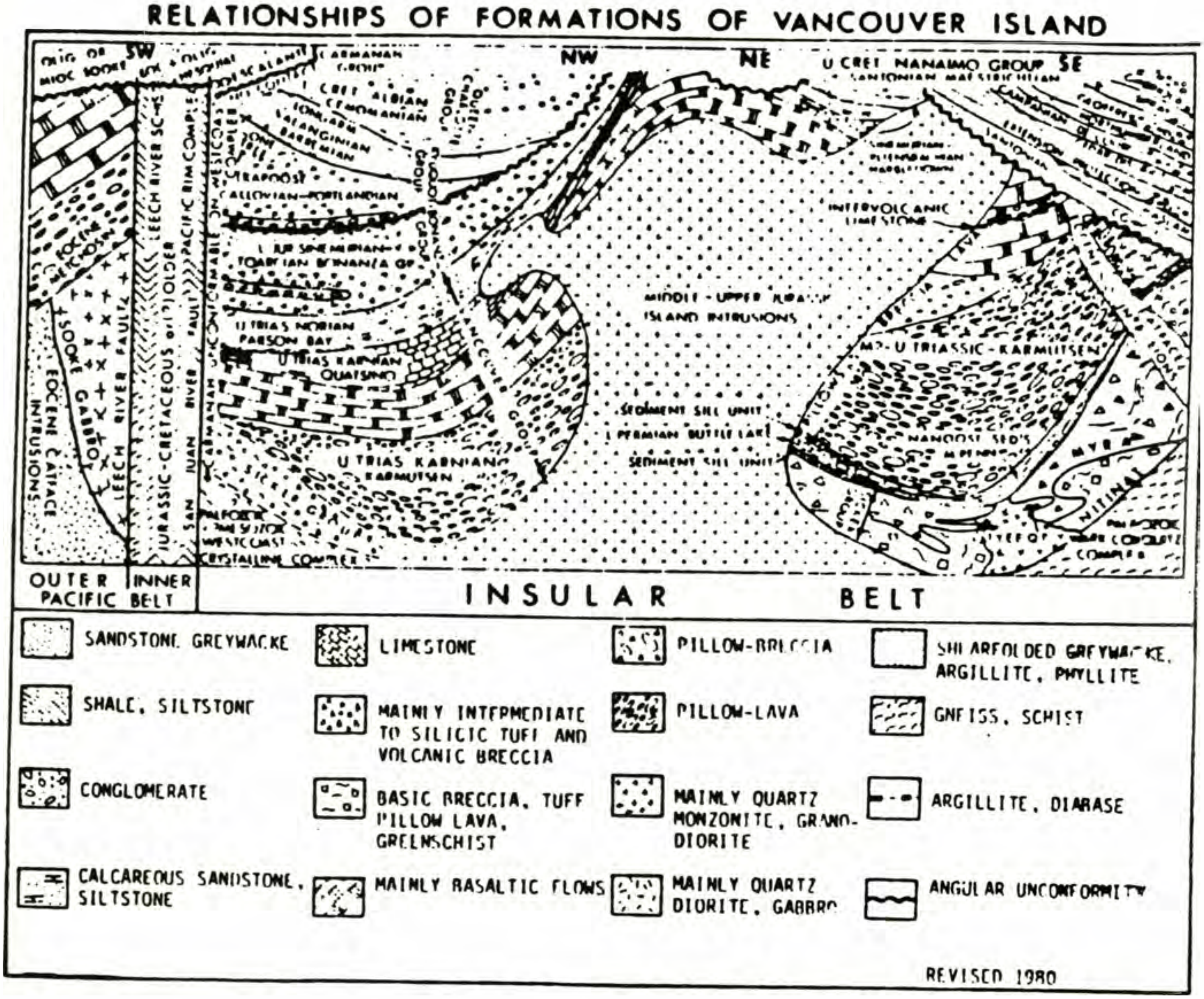


Figure 2. Schematic cross-section showing the relationships of the rocks on Vancouver Island (from Muller, 1983).

REGIONAL GEOLOGY

Vancouver Island is underlain by three of the major tectonic belts of the northern Cordillera (Fig. 2): the Insular Belt, the Inner Pacific Belt, and the Outer Pacific Belt (Muller, 1983). The bulk of the island is part of the Insular Belt, which extends north to Alaska. The Insular Belt on Vancouver Island is bounded by the Malaspina fault (not shown) on the east and the San Juan fault (Fig. 1) to the south. This belt is composed of Paleozoic volcanic, plutonic, and sedimentary rocks of the Wrangellia Terrane (Muller, 1983) overlain by sedimentary rocks of the autochthonous Nanaimo Group (Pacht, 1984).

The Wrangellia Terrane records a history of arc-related volcanism, plutonism, and sedimentation with oceanic-rifting-related volcanism and sedimentation. The Sicker Group encompasses all of the known Paleozoic rocks on Vancouver Island, which range from pre-Devonian (?) to Pennsylvanian-Permian(?). Muller (1977a, 1982) has subdivided it into three to four units. The lowest unit, the Nitinat Formation, consists of Permian or lower rhyolitic to basaltic fine grained tuffs, breccia, and agglomerate (Muller, 1977a) with rare pillows (Muller, 1982). They have been metamorphosed and locally foliated to chlorite-epidote-actinolite-albite greenschists. The Myra Formation, which overlies the Nitinat Formation, consists of black argillite and graywacke interbedded with silicic tuff and breccia and is largely metamorphosed to chlorite-sericite schist (Muller, 1982). Transitional between the Myra Formation and the uppermost member, the Buttle Lake Formation, is a sequence of pelitic and cherty sediments interlayered with diabase and gabbro (Muller, 1982). The Buttle Lake Formation consists of a mid-Pennsylvanian crinoidal limestone with interbedded chert (Muller, 1977a,b). The Sicker Group rocks are the sequential layered rocks — crystalline rocks

	PERIOD	STAGE	FORMATION	SYMBOL	NAME	SYMBOL	ISOTOPIC AGE (Ma)
CENOZOIC		Eocene to Oligocene	SOOKE	mpTsb	SOOKE INTRUSIONS -silicic-	Tg	(K/AR) 32-59
					-basic-	Tgb	(K/AR) 31-49
			HESQUIAT	eoTc	METCHOSIN SCHIST, GNEISS	Tms	(K/AR) 47
		early Eocene	METCHOSIN VOLCANICS	eTm			
MESOZOIC					LEECH RIVER COMPLEX	JKL	(K/AR) 38-41
PALEOZOIC	Devonian or earlier				COLQUITZ GNEISS	Pzs	(U/Pb) 390

note: symbols mpTsb and eoTc conform to earlier names (Sooke Bay and Carmanah Formations).

SYMBOLS
- contact - - - -
- fault (approximate) ~ ~ ~
- road ═══
- post office o

Figure 3a. Key to geologic map for study area (from Muller, 1977a).

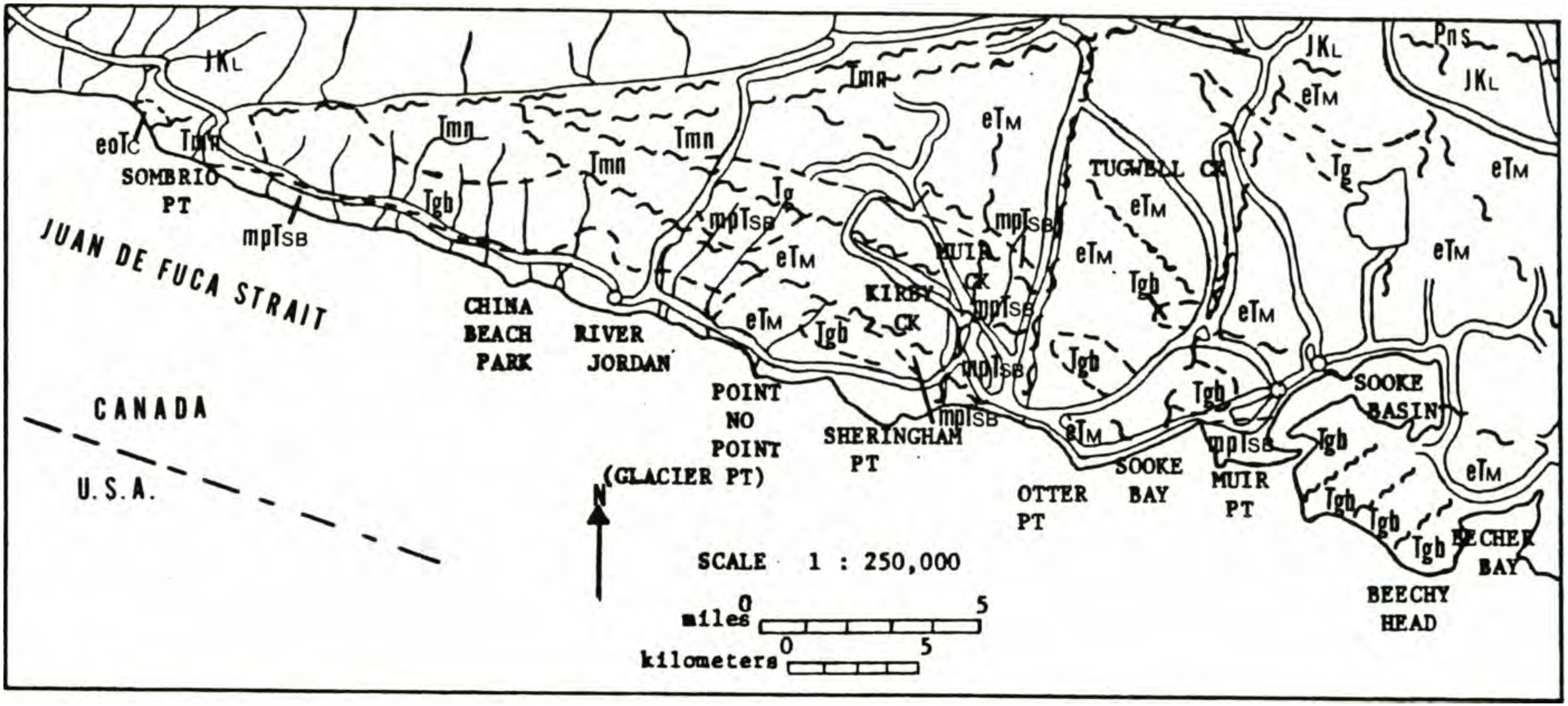


Figure 3b. Geologic map for study area (from Muller, 1977a).

remnant of a mid-Paleozoic volcanic arc with volcanic rocks covered by clastic sediments deposited as turbidites and later by carbonates (Muller, 1977a; Muller et al., 1981).

In some areas, the Sicker Group metavolcanics and metagraywackes are intruded by the apparently Early Devonian or pre-Devonian Tyee Intrusions, in those areas the Sicker Group must be pre-Devonian also (Muller, 1977a). The Tyee Intrusions consist of highly altered granitoid rocks with sericitic albite and microcline perthite, minor epidote and chlorite, and sills of sericitized schist (Muller, 1977a).

The Upper Triassic Vancouver Group is an extensive sequence of rocks on Vancouver Island which extends into the rest of the Insular Belt. It disconformably overlies the Sicker Group and is composed mainly of tholeitic basalt with overlying clastics and carbonates. It is divided into the Karmutsen, Quatsino, and Parson Bay Formations (Muller, 1977a). In some places there is a basal Middle Triassic unit of thin-bedded black argillite intruded by diabase sills. According to Muller et al. (1981), the Karmutsen Formation is the thickest and most extensive formation on Vancouver Island. It consists of pillow basalt of tholeitic composition, pillow breccia with aquagene tuff and layered amygdaloidal basalt and minor upper sedimentary layers (Muller, 1977a, 1982) in a shallowing-upward sequence from deep marine pillow lavas to subaerial flows (Muller, 1977a). Several paleomagnetic studies (Irving et al. and Schwartz et al., as reported in Muller et al., 1981) have inferred a subequatorial position for the Karmutsen Formation. The upper Vancouver Group consists of Upper Triassic sediments of the Quatsino and Parson Bay Formations. The Quatsino Formation consists of limestone with common layers of shell debris interbedded with shale and siltstone in its upper part (Muller et al., 1981). The Parson Bay Formation is in diachronous contact with the Quatsino Formation and directly overlies the Karmutsen volcanics in some places (Muller, 1977a). It consists of interbedded black argillite, graywacke, and limestone. The Vancouver Group rocks are inferred to have formed in an oceanic rift zone similar to that in the Gulf of California. Both sedimentary formations were deposited in near- and off-shore basins during quiescent times in the rift zone (Muller, 1977a).

Overlying the Vancouver Group is the Lower Jurassic Bonanza Group volcanic arc sequence, which is coeval with batholithic intrusions and migmatite complexes of the Island Intrusions, West Coast Complex, and Wark -Colquitz Complex (Muller, 1983). The Bonanza Group is mainly exposed on the northwest and southwest parts of Vancouver Island. Its tholeitic basaltic to rhyolitic tuff, volcanic breccia, and lava flows are intercalated with marine argillite and graywacke and minor conglomerate (Muller, 1977a). It is interpreted as originating from several eruptive centers of a volcanic island arc (Muller, 1977a).

The Island Intrusions and Westcoast Complex, which intrude Sicker, Vancouver, and Bonanza Group rocks on Vancouver Island, are genetically related to the Bonanza Group volcanics (Muller, 1977a). The Island Intrusions consist of Lower to Middle (?) Jurassic granitoid stocks and batholiths (Muller et al., 1981). These rocks have undergone low-grade metamorphism. The Westcoast Complex consists of a heterogeneous assemblage of plutonic and metamorphic rocks such as hornblende-plagioclase gneiss, amphibolite, agmatite, and quartz diorite or tonalite, (Muller, 1977a). Gradational contacts have been observed between it and the Karmutsen and possibly Sicker volcanic rocks, which are considered to be its protolith. Minor metasedimentary rocks, including recrystalized limestone derived from the Quatsino Formation and Buttle Lake limestone, are also present. The Westcoast Complex is derived from migmatization of pre-existing volcanic and sedimentary Sicker and Vancouver Groups during Early to Middle Jurassic plutonism (Muller, et al., 1981).

The Wark-Colquitz Complex (referred to as Wark and Colquitz Gneiss in Muller, 1977a) is exposed near Victoria, B. C.. The Wark Gneiss consists of massive to gneissic biotite-hornblende diorite and quartz diorite. The Colquitz Gneiss is a biotite-hornblende quartz diorite to granodiorite gneiss. In places the two units are interlayered and thought to have originally been clastic sediments and basaltic sills or flows, perhaps part of the Sicker Group. A single K-Ar date suggests an early Jurassic metamorphism of a Paleozoic protolith (Muller, 1977a). The gneisses may be unconformably overlain by the Bonanza Group volcanics.

Finally, the rocks of the Insular Belt of Vancouver Island are overlain by rocks of four different clastic wedges of Mesozoic to Tertiary age. Overlying the Bonanza Group, unconformably and of limited extent, is the Kyuquot Group, a composite clastic wedge of Middle Jurassic to mid-Cretaceous age (Muller et al., 1981). The Kyuquot Group consists of three clastic sedimentary formations. These units consist of conglomerate, lithic sandstone, siltstone, sandy limestone, and calcareous sandstone which are inferred to have been deposited in a neritic continental-shelf environment as an unconformable clastic wedge shed westward on an eroded basement of the Lower Jurassic volcanic-plutonic terrane (Muller, 1977b; Muller et al., 1981). The Queen Charlotte Group is a middle Upper Cretaceous marine sequence of limited extent consisting of graywacke, siltstone, and conglomerate.

The Nanaimo Group is an Upper Cretaceous coal-bearing molasse (Muller, 1983) that unconformably overlies older formations on the northeast side of Vanacouver Island and is considered autochthonous (Pacht, 1984). The Nanaimo Group also is exposed on the adjacent Gulf and San Juan Islands. These sediments consist of cyclical fluvial to deltaic fining-upward sequences of conglomerate, sandstone, shale, and coal and marine sandstone, shale, and thin-bedded, graded shale-siltsone sequences (Muller, 1977a). According to Muller (1977a), the Nanaimo Group was deposited in a fore-arc basin between the Coast Plutonic Belt, which was an active volcanic arc at the time, and the Insular Belt. Alternatively, according to Pacht (1984), it may have been deposited in a pull-apart basin in response to oblique convergence or transform faulting between the Kula (?) plate and the Pacific margin of Washington and B. C..

The fourth clastic wedge, also autochthonous, consists of the Carmanah Group: the Escalante Formation, Hesquiat Formation, and Sooke Formation (oldest to youngest, respectively). These units are exposed on the southern coast of Vancouver Island and most of the continental shelf (Muller, 1977a) with the two older formations overlying Insular Belt rocks. These rocks will be discussed in more detail below.

The Inner Pacific Belt on Vancouver Island is separated from the Insular Belt by both the San Juan fault (Fig. 1) and the Westcoast fault (Fig. 1). In general, this belt represents rocks that were formed in a Late Jurassic to Cretaceous trench (Muller, 1977a). On Vancouver Island, this belt consists of Mesozoic rocks of the Pacific Rim Complex and Leech River Complex (Leech River Formation of Muller, 1977a and 1982, and referred to as Leech River Complex by Fairchild and Cowan, 1982) (Muller, 1983) and correlative Jura-Cretaceous rocks of the Pandora Peak unit (Rusmore and Cowan, 1985).

The Pacific Rim Complex is exposed mainly in the western coastal areas as a fault-bounded slice (Brandon, 1985). According to Brandon (1985), it is composed of a sequence of Lower Cretaceous melanges which depositionally overlie an older igneous basement, which he refers to as the Ucluth Volcanics. The melanges are both mudstone-rich and sandstone-rich with generally highly contorted bedding containing some ribbon cherts, turbidite sandstones, and conglomerate. The Ucluth Volcanics are a lower Mesozoic calc-alkaline arc sequence of fragmental volcanic rocks with subordinate diorite intrusions and interbedded limestone (Brandon, 1985). The rocks are in part coeval with Upper Jurasssic sediments and of the Longarm Formation and possibly with part of the Queen Charlotte Group. The Pacific Rim Complex is inferred to have an origin similar to that of the Fransiscan Complex of California, both forming along the extensive subduction zone on North America's western margin (Muller et al., 1981), although no blueschist metamorphism has been found in the Pacific Rim Complex. A recent study by Brandon (1985) concluded that the Pacific Rim Complex is not a late Mesozoic accretionary wedge, but that it originated by down-slope mass movement processes, such as submarine slides, rock falls, debris flows, and in-situ liquefaction. He favors emplacement against Wrangellia by a large transform fault system (the Westcoast fault), which Brandon and Cowan (1983) claim truncated the west coast of Vancouver Island in the latest Cretaceous or early Tertiary.

The Leech River Complex of probable Late Triassic to Cretaceous age (Fairchild and Cowan, 1982) is exposed between the San Juan and Leech River faults (Fig. 1) on southern Vancouver Island. Like the Pacific Rim Complex, the Leech River Complex consists of graywacke, argillite, minor chert, and volcanic rocks, but the majority of these are metamorphosed to schist (Muller, 1977a). Muller (1982) has subdivided these rocks into three units. The chert-argillite volcanic units (ribbon chert, pelitic rocks, and minor basaltic volcanics) are converted to chlorite- and sericite-schist. The chert has been determined from radiolaria to be Upper Jurassic (Tithonian), but the basalt and limestone could be Upper Triassic (Muller, 1982). The argillite-metasiltstone units are mainly turbidites with beds of graywacke and minor conglomerate and have been metamorphosed to phyllite, slate, and quartz-sericite schist. The metagraywacke-schist unit is the southernmost part of the Complex and consists predominantly of graphitic quartz-sericite (chlorite) phyllite to quartz-feldspar-biotite schist with garnets common and andalusite locally present (Fairchild and Cowan, 1982). These rocks are considered to be higher-grade metamorphic equivalents of the argillite-metasiltstone unit and of the Pandora Peak unit, which is discussed below (Muller, 1982). Large gneissic or unfoliated trondhjemitic composite sills and related smaller pegmatite dikes and sills have been intruded into the Leech River Complex (Fairchild and Cowan, 1982). The age of deformation, synkinematic metamorphism, and intrusive activity is determined by K-Ar dating to be 39 to 41 Ma (Fairchild and Cowan, 1982).

As previously mentioned, Muller (1977a,b) favors an origin for both the Leech River Complex and Pacific Rim Complex coincident with that of the Fransiscan Complex in California; all formed in a late Mesozoic trench. Muller (1983) states that the Leech River Complex was thrust against the Insular Belt on Vancouver along the San Juan Fault in a subduction zone. Alternatively, Fairchild and Cowan (1982) prefer left-lateral strike-slip emplacement along the San Juan Fault for at least 50 kilometers after culmination of metamorphism and intrusion. Recent Lithoprobe Phase 1 seismic reflection data showed the San Juan Fault to be probably very steeply dipping (Yorath et al., 1985). Fairchild and Cowan

(1982) also state that the Leech River Complex is allochthonous with respect to rocks on Vancouver Island immediately to the north.

On the basis of similarities in age, lithology, and metamorphic grade, Rusmore and Cowan (1985) correlate the Pandora Peak unit with the Pacific Rim Complex and with rocks of the San Juan Islands. The Pandora Peak unit is juxtaposed against Wark-Colquitz Gneiss of the Wrangellia Terrane along the Survey Mountain-Trial Island fault on southeastern Vancouver Island. It consists of mudstone, volcaniclastic sandstone, chert, volcanic flows and tuffs, pebbly mudstone, and minor limestone olistoliths, which have undergone low-temperature, high pressure metamorphism (Brandon, M.T. and Massey, N.W.D., written communication, 1985).

The Outer Pacific Belt (Fig. 2) is represented by the Paleogene Catface Intrusions and Sooke Intrusions, the Eocene Metchosin Volcanics, and the fringing sediments of the Upper Oligocene Sooke Formation (Muller, 1983). A clarification must be made regarding some of the nomenclature involved. According to Muller et al. (1981), small stocks of early Tertiary age and of generally quartz-dioritic composition are known in many parts of Vancouver Island. Those that intrude Eocene Metchosin Volcanics have been called the Sooke Intrusions by Clapp and Cooke (1917). That name is also used for Sooke Gabbro, the plutonic substratum to the Metchosin Volcanics. Muller et al. (1981) proposed that the name of these small stocks be changed to Catface Intrusions.

The Catface Intrusions cut Jurassic and older rocks and in one locality intrude Nanaimo Group sediments. The Intrusions generally consist of granitoid rocks, some of which are very difficult to distinguish from similar porphyritic dikes associated with Bonanza Volcanics or Sicker volcanics. Some of the associated stocks are related to gold and copper deposits. The age of the Catface Intrusions has been determined by K-Ar dating to be Late Eocene to Early Oligocene (Muller et al., 1981). Since they have not been found to intrude the Carmanah Group of the same age and are not associated with any volcanic rocks of the same age, it is inferred that intrusion occurred simultaneously with uplift, erosion, and deposition of the older Carmanah Group sediments (Muller et al., 1981) with no volcanic activity produced at the surface. These intrusive rocks appear to represent major fractures of the lower lithosphere (Muller et al., 1981). In the Sooke region, where no pre-Tertiary crustal rocks are present, it is inferred that small plutons of quartz diorite are the result of late phase differentiation of the source magma for the Metchosin Volcanics (Muller et al., 1981).

The Sooke Gabbro (Muller, 1982), also referred to as Sooke Intrusions (Muller, 1977b), as explained above, underlies and intrudes the Metchosin Volcanics. Massey (1985) has proposed that the gabbroic and diabasic Sooke Gabbro is the lower part of an ophiolite sequence that includes the Metchosin Volcanics. The gabbro is commonly a coarse-grained bytownite diopside olivine gabbro with some dikes of leucogabbro (Muller, 1977a, 1982). Gneissic amphibolite, hornblende gabbro, agmatite, and small stocks of tonalite are also associated with these intrusions (Muller, 1977a). The Sooke Gabbro crops out in several locations in the thesis area (Fig. 3).

The Early Eocene Metchosin Volcanics can be subdivided into two units (Muller, 1977b, 1983). The lower, submarine unit includes pillowed and massive flows of tholeitic composition with interbedded tuff, breccia, and volcaniclastic sediments. It is intruded by diabase and gabbro sills and diabase dikes. Above this lie well-bedded tuff and breccia that pass upward into massive amygdaloidal subaerial flows with minor intra-flow chert and limestone (Massey, 1985). Where unaffected by major shearing, these rocks show low- and medium-grade metamorphism up to epidote-amphibolite facies. Where affected by shearing, Metchosin Volcanics are schistose. This schistosity is particularly evident in the vicinity of the Leech River fault. The Metchosin Volcanics have been intruded by stocks of the Catface Intrusions and overlie sheeted dikes and gabbro (Muller, 1982).

From this shoaling-upward, emergent sequence, Massey (1985) infers a ridge-centered ocean-island origin for these rocks, which fits with interpretations for other Coast Range basalts (Snavely et al., 1968; Cady, 1975). Based on trace element analyses, Muller (1980) has concluded that the Metchosin Volcanics and Crescent Formation best fit an Iceland-type ridge-island setting. Massey (1985) referred to the Metchosin Volcanics and the sheeted dike complex and gabbroic stocks as the Metchosin Igneous Complex.

The Metchosin Volcanics are considered correlative with the Crescent Formation of the Olympic Peninsula, Washington (Muller, 1977a, 1980, 1983) (Fig. 1), which, like the Metchosin Volcanics and Sooke Gabbro, is composed of basalt, diabase dikes, and gabbro. Both are considered part of the Crescent Terrane, which is made up of Tertiary volcanic and sedimentary rocks. The origin of the Crescent Formation has been interpreted diffently by various authors. Tabor and Cady (1978a) and Cady (1975) interpreted it as an accreted seamount province. Glassley (1974) initially favored a mid-ocean-ridge origin and later (1976) suggested the possibility of a non-hot spot intra-plate volcanic center. An island arc environment was suggested by Lyttle and Clarke (1975, 1976), but this is quite unlikely considering the overall geochemistry of the unit.

The Escalante and Hesquiat Formations of the Carmanah Group unconformably overlie the Leech River Complex of the Inner Pacific Belt and the Westcoast Complex, the Bonanza Volcanics (Cameron, 1980), and the Island Intrusions of the Insular Belt (Muller, 1977a, 1982). The Sooke Formation unconformably overlies the Metchosin Igneous Complex of Massey (1985) of the Outer Pacific Belt (Muller, 1977b). The Upper Eocene Escalante Formation is the basal member of the Carmanah Group. The Escalante Formation (Cameron, 1971, 1972, 1973) is the same as Jeletzky's Divion "A" (Jeletzky, 1954, 1973) and is correlated with the Lincoln stage of Weaver et al. (1944). The Hesquiat Formation, the middle member, is the same as Jeletzky's Divisions "B" and "C" (Jeletzky, 1954, 1973), and is correlated with the Blakeley stage of Weaver et al. (1944). The youngest member, the Sooke Formation, is the same as Jeletzky's Division "D".

The Escalante Formation consists of a diachronous basal conglomerate (Muller, 1977a), sandstone (Cameron, 1980) with minor shelly conglomerate lenses, argillaceous sandstone with disseminated carbonaceous material, rare fossil leaves, and nodules and concretions (Muller et al., 1981). It is in gradational contact with the Hesquiat Formation (Muller et al., 1981). The depositional environment of the Escalante Formation has been described differently by different authors. Based on foraminifera, Cameron (1980) favors deposition at lower neritic to upper bathyal depths. Based on molluscan fauna, Jeletzky (1975) interprets inner neritic to supratidal depths at the base and inner neritic or outer littoral depths in the upper parts of the formation.

The Hesquiat Formation consists of two distinct lithofacies: 1) a recessive shale-clayey sandstone lithofacies and 2) a resistant sandstone-conglomerate lithofacies. Jeletzky (1975) interprets the shale-clayey lithofacies to be mostly a suspension-settled deposit and the sandstone-conglomerate lithofacies to result from a plastic mass flow deposited in the neritic zone close to the source area. He claims that all evidence points to deposition of the Hesquiat as channel fills on a shallow-water submarine fan. Cameron (1980) interprets the Hesquiat Formation to be an exclusively slope (bathyal depth) deposit with proximal and distal facies deposited on a bathyal water fan.

The Upper Oligocene Sooke Formation has been described as a thin, fluvial or deltaic to shallow marine (Muller, 1977a, 1982), mollusc-bearing sandstone and conglomerate (Muller, 1977b) with thin beds of sandy carbonaceous shale and marl (Clapp and Cooke, 1917). The Sooke Formation unconformably overlies the Metchosin Igneous Complex and is reported by Cameron (1980) to be exposed on a small island near Carmanah point where it overlies beds probably of the Hesquiat Formation.

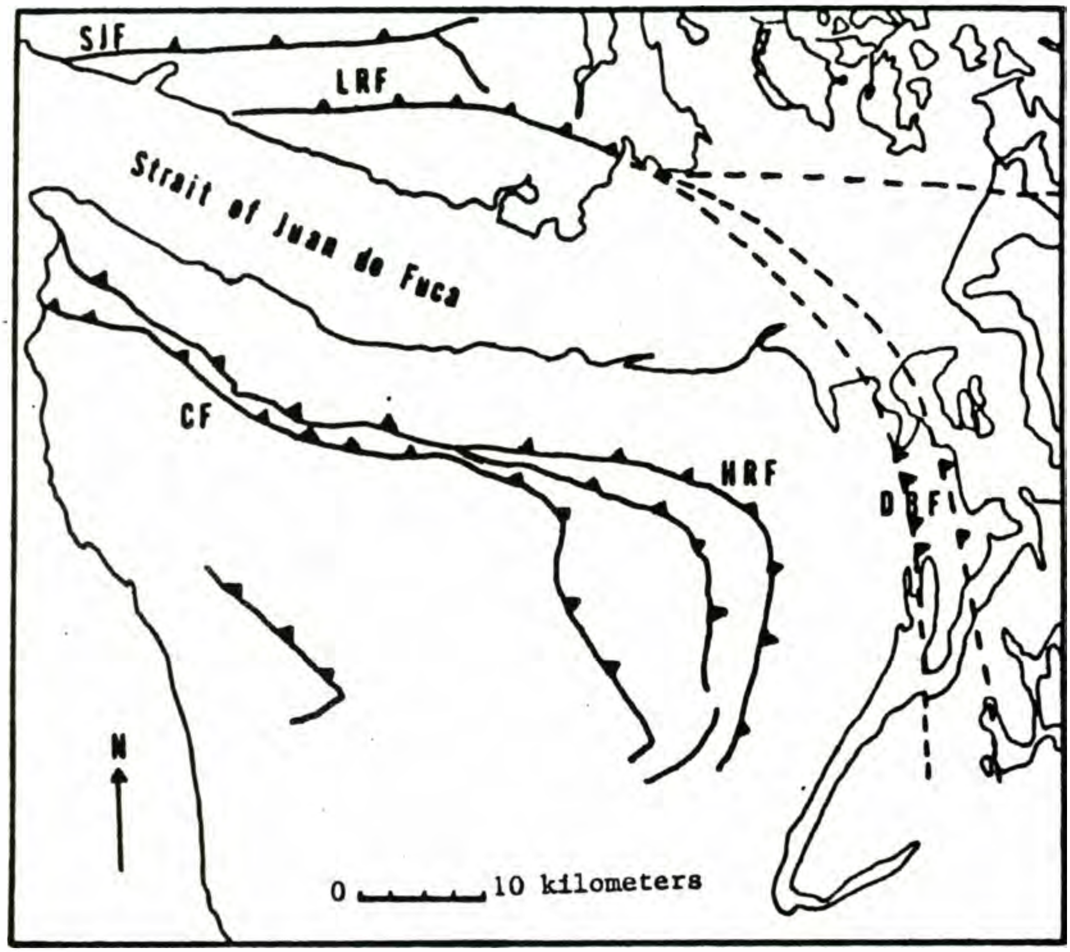


Figure 4. Map showing major structures of southern Vancouver Island and the northern Olympic Peninsula. Faults include San Juan fault (SJF), Leech River fault (LRF), Discovery Bay fault (DBF), Hurricane Ridge fault (HRF), and Calawah fault (CF). Compiled from Tabor and Cady, 1978a; Fairchild, 1979; Yorath et al., 1985; Moyer, 1985; Anderson, 1985.

TECTONIC SETTING

Vancouver Island is composed largely of accreted terranes with rocks spanning the Paleozoic to the Cenozoic and encompassing many tectonic regimes. In most locations, the Sooke Formation unconformably overlies the Metchosin Volcanics and Sooke Gabbro, which, together with the correlative Crescent Formation exposed on the Olympic Peninsula, Washington (Fig. 1), comprise the Crescent Terrane (Muller, 1983; Silberling et al., 1984). The Leech River fault, which intersects the coastline near Sombrio Point (Figs. 1 and 4) is considered to be a terrane-bounding fault (Clowes and Brandon, 1985) separating the Metchosin Volcanics and associated rocks of the Crescent Terrane from the Leech River Complex of the Inner Pacific Belt. It is thought by Clowes and Brandon (1985, p. 10) to represent the "zone of accretion underplating associated with the most recent subduction regime which was initiated in the Late Eocene". According to Muller et al. (1983), the Crescent and Metchosin Formations represent Eocene oceanic crust of the Pacific plate which was accreted to the North American plate after the subduction zone jumped westward in the middle Eocene. Muller (1977b) described the Leech River fault as probably a transcurrent fault, or, less likely, a thrust fault. Fairchild and Cowan (1982) described the fault as a left-lateral transcurrent fault. Recent results from a Lithoprobe Phase 1 deep seismic reflection study have shown that the Leech River fault dips northward at about 35 degrees and extends to at least 10 kilometers depth, so that the basalts have been underthrust at least 15 kilometers to the north beneath Vancouver Island (Clowes and Brandon, 1985). Therefore, the Leech River fault is considered to be the suture zone across which the Crescent Terrane and southeastern Vancouver Island were amalgamated in an Early

Tertiary subduction zone (Muller, 1983).

On the Olympic Peninsula, Washington, the Crescent Terrane (Silberling et al., 1984) consists of the Crescent Formation and underlying and interfingering mostly marine sedimentary rocks of Middle Eocene to Miocene age and overlying marine sedimentary rocks of Middle Eocene to Miocene age (Tabor and Cady, 1978b). The Crescent Formation forms a striking horseshoe shaped backstop against which the Olympic Core Terrane (Silberling et al., 1984) was accreted. On the northern side of the Olympic Peninsula, the volcanic rocks dip steeply to the north. The Eocene to Miocene (Tabor and Cady, 1978b) sedimentary rocks that directly overlie the Crescent Formation are largely deep-water submarine fan deposits which are in turn overlain by the Lower Miocene shallow marine deposits of the Clallam Formation (Anderson, 1985). Enclosed by the horseshoe of Crescent volcanic rocks are the Olympic Core rocks which consist mainly of slightly metamorphosed, sheared, and folded turbidites and shales of Paleocene(?) or Early Eocene to Middle Miocene age (Cady, 1975) separated from the Crescent Terrane rocks by the Hurricane Ridge fault on the east and northeast and on the northwest by the Calawah fault (Cady, 1975) (Figure 4). The core rocks represent an accretionary prism which has been underthrust eastward beneath the Crescent Formation (Cady, 1975) and possibly caused the apparent doming of the Olympic Mountains.

PREVIOUS WORK

The age of the Sooke Formation is poorly defined. Throughout the last 100 years it has been referred to as ranging from Oligocene to Pliocene. The "Sooke Formation" was first described in a report to the Geological Survey of Canada by James Richardson in 1876, who described two stratigraphic sections and stated that the beds were Tertiary or post-Tertiary in age (Cox, 1962). The term Sooke Formation has been attributed to Merriam (1899), who actually referred to the unit as "Sooke beds". Muller (1977a) referred to the unit as Sooke Bay Formation in order to distinguish it from the Sooke Intrusions. Most recent literature refers to it as the Sooke Formation.

J.C. Merriam, in 1896, was the first to publish a faunal list and to discuss the probable age of the Sooke Formation (Cox, 1962). He concluded that the faunal evidence indicated a middle Neocene (obsolete synomym for Neogene) age and that the rocks must be much younger than those of the Carmanah Point beds of western Vancouver Island. According to Clark and Arnold (1923) and Cox (1962), Merriam republished his earlier work and in 1899 added a checklist of marine invertebrate fauna. Also according to Clark and Arnold (1923) and Cox (1962), Dall and Harris, in 1892, referred to the Sooke beds as Neocene, and then in 1898 Dall assigned them to the Miocene. The next major work on the Sooke Formation was by Clapp in 1912, who described a 164 foot stratigraphic section near Coal (now Kirby) Creek and a 101 foot section near the mouth of Jordan River. Clapp and Cooke (1917) discussed the Sooke Formation in detail, redescribed the previous 164 foot section, and extended its thickness to 497 feet. They considered this to be the type section. Cox (1962) questioned the validity of this type section. Based on work by C.E. Weaver, Clapp and Cooke (1917) correlated the Sooke Formation with the upper part of the

Lower Miocene of Washington. Clark and Arnold's 1923 report was a detailed study of the fauna of the Sooke Formation and included a description of a new coral by T. Wayland Vaughan. They assigned the Sooke Formation to the Upper Oligocene or Miocene. Weaver et al. (1944), in their correlation chart, assigned the Sooke Formation to the Lower Miocene. The Sooke Formation also contains fossil vertebrate remains first described and named Desmostylus sookensis by I.E. Cornwall (1922) and later re-named Cornwallius sookensis by O.P. Hay (1923). R.M. Logie (1929) provided a review of earlier studies of the Sooke Formation in an unpublished M.A. thesis at the University of British Columbia. A detailed classification of the microflora of the Sooke Formation presented by Cox (1962) also covers all of the previous paleontological work done on the Sooke Formation. It concludes that the age of the Sooke Formation is lowermost Miocene (Aquitanian) based on the previous invertebrate faunal studies, but that the microflora indicate a possible Pliocene age. Most recently, Addicott (1981) states that Pectinids from the Sooke Formation are from the Juanian Stage (Upper Oligocene). Various recent authors mention the Sooke Formation (Muller, 1977a,b, 1982, 1983; MacLeod et al. 1977; Drummond, 1979; Cameron, 1980; Addicott, 1981); but, aside from paleontological reports, no further detailed studies have been pursued.

ABBREVIATION	LOCATION
SOM A	Sombrio Point
SOM B	Sombrio Beach (exposure in stream)
SOM C	Sombrio Beach cliffs
SOM D	Sombrio Beach cliffs
SOM E	Sombrio River and nearest cliffs to northwest
COR A	Correction Camp cliffs by basal contact
COR B	Correction Camp cliffs by mouth of Rosemond Cree
COR C	Rosemond Creek
ZOD	cliffs sampled on Zodiak boat ride
MYS A	Mystic Beach cliffs by basal contact
MYS B	Mystic Beach cliffs to northwest of trail
MYS C	Mystic Beach exposure north of road
CHI A	China Beach Provincial Park cliffs
CHI B	China Beach Provincial Park wave-cut ledge
SAN	Sandcut Beach cliffs
BTR	Beach Trail cliffs
FRE	French Beach Provincial Park ledges and cliffs
PNP A	Point-No-Point cliffs
PNP B	Point-No-Point private beach
PNP C	Seaside Picnic Trail
PNP D	Kaffer's (private property)
KIR A	Kirby Creek cliffs
KIR B	Kirby Creek north of road
MUI A	Muir Creek cliffs
MUI B	Muir Creek
TUG	Tugwell Creek
WHI	Whiffen Spit
ESP	East Sooke Park

Figure 5a. Key to abbreviations used on location map.

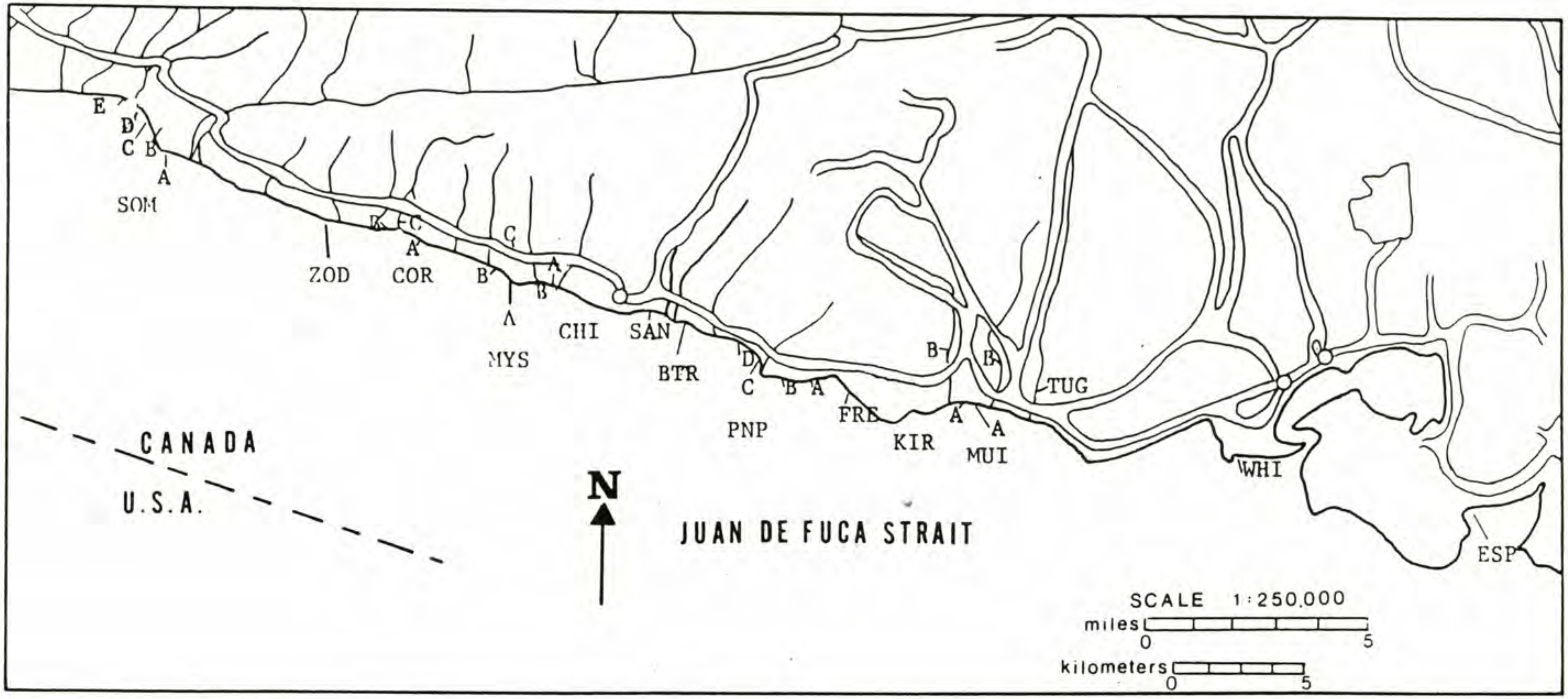


Figure 5b. Location map of study sites.

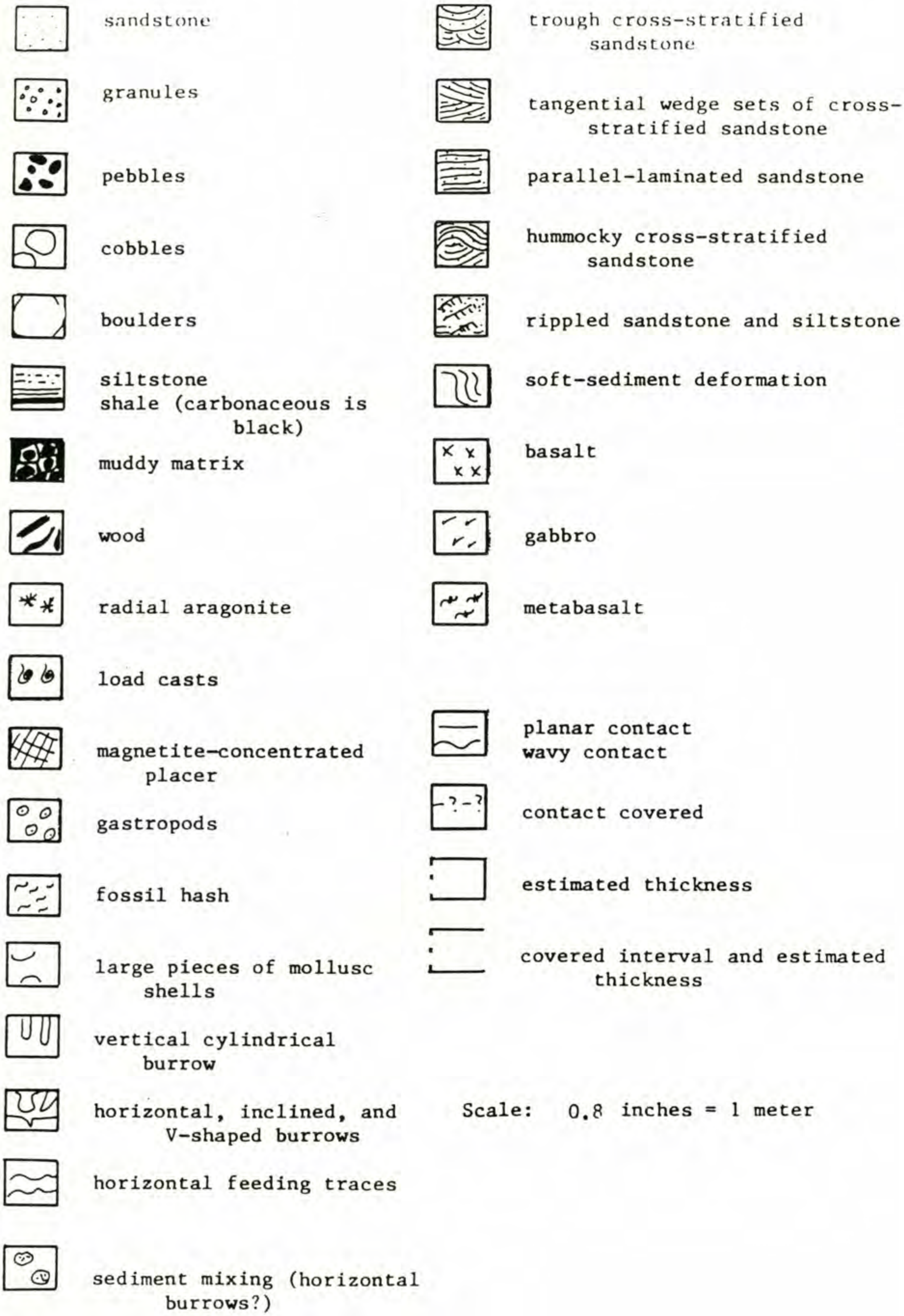


Figure 6. Key to stratigraphic columns.

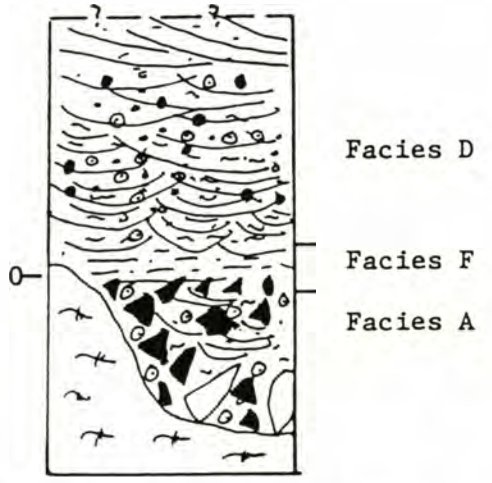


Figure 7. Stratigraphic column of Sombrio Point (SOM A).

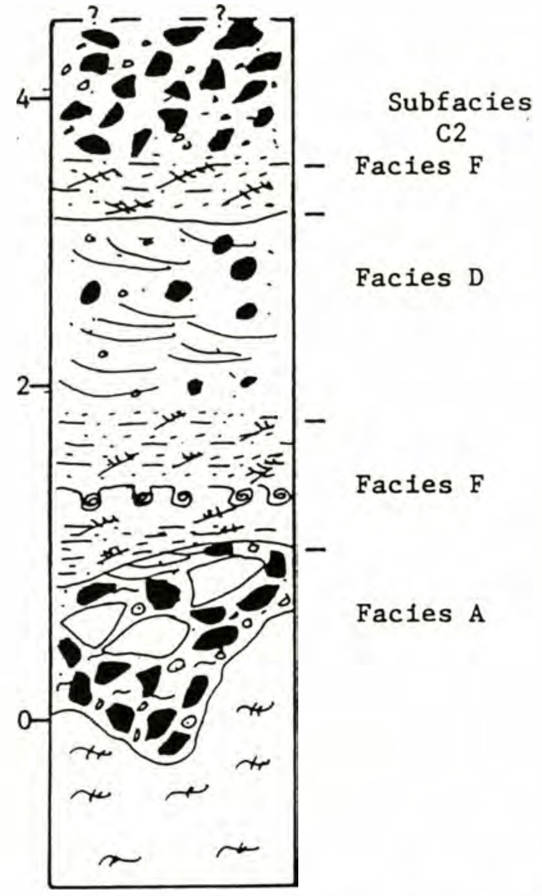


Figure 8. Stratigraphic column of Sombrio Beach (Som B).

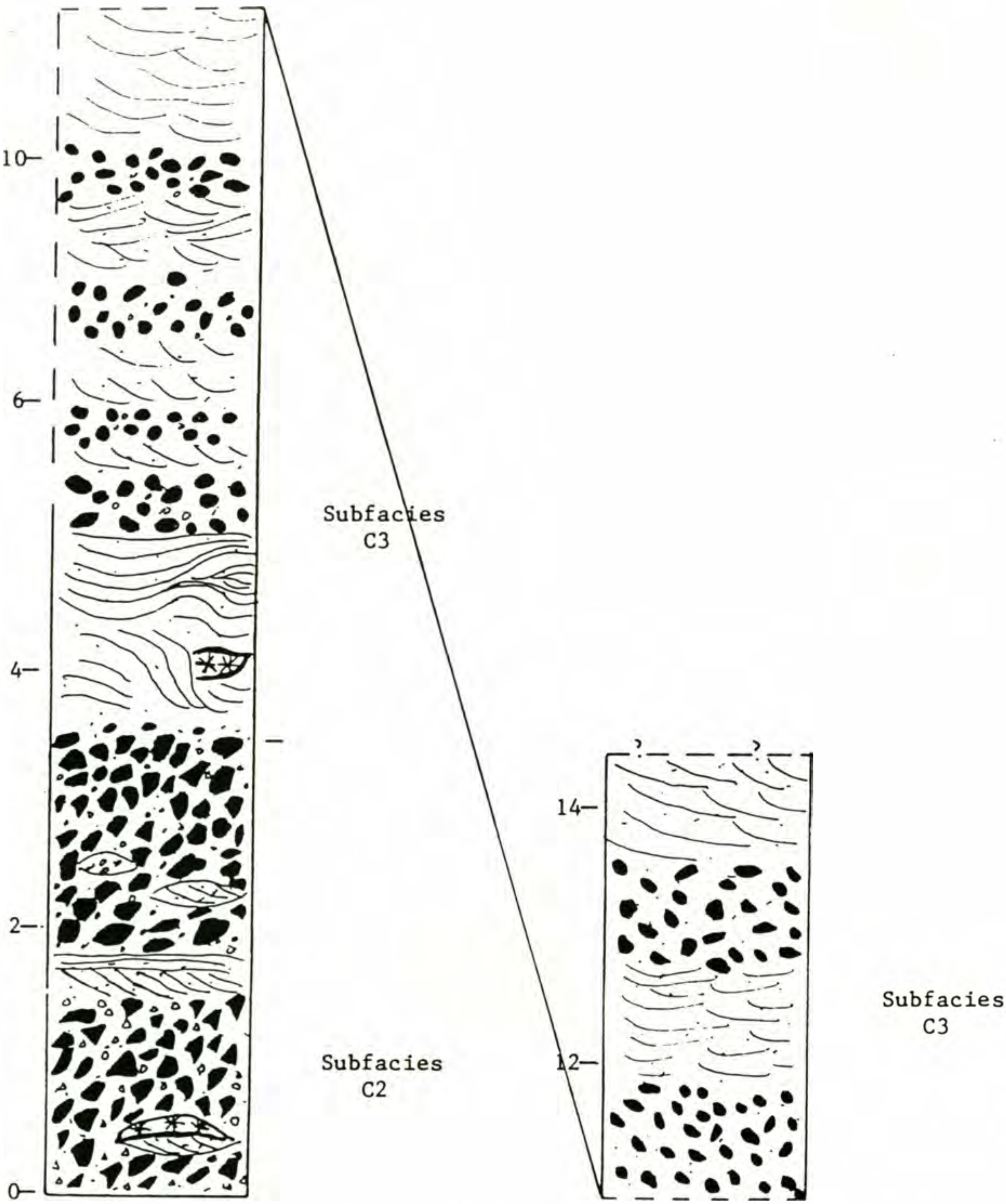


Figure 9. Stratigraphic column of Sombrio Beach (SOM C).

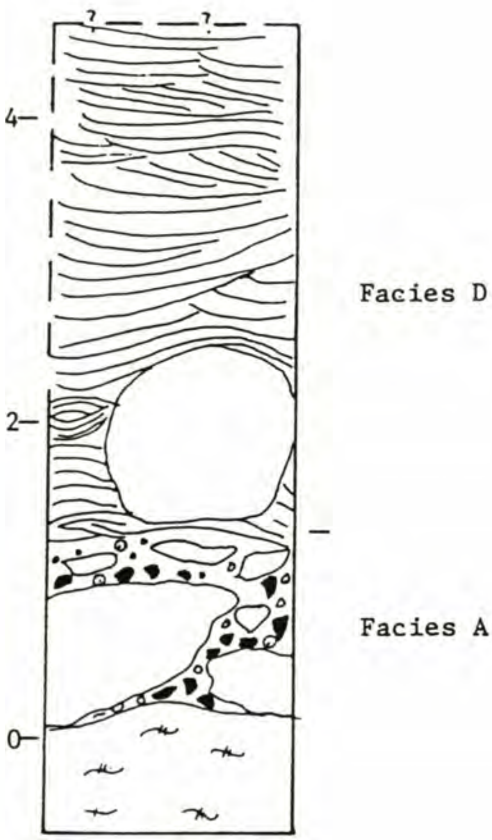


Figure 10. Stratigraphic column of Sombrio Beach (SOM D).

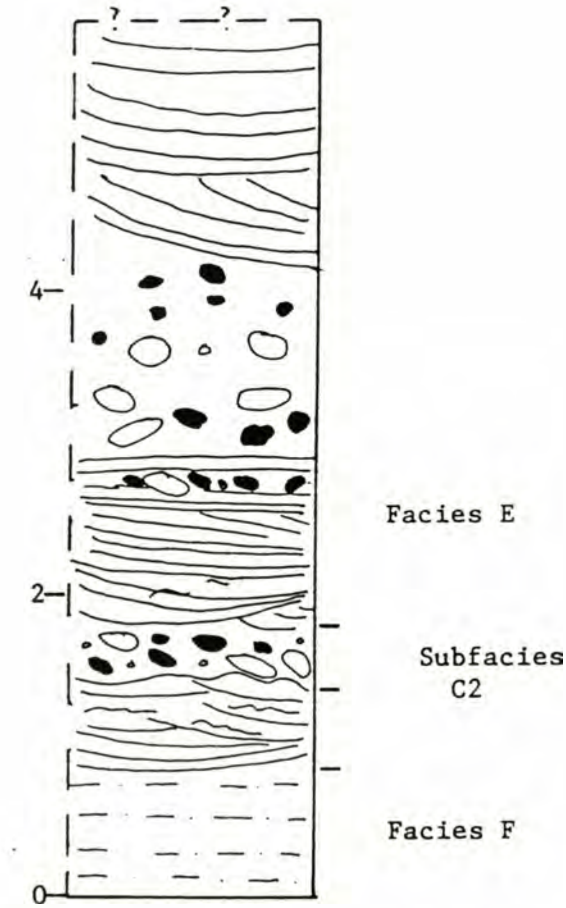


Figure 11. Stratigraphic column of Sombrio Beach (SOM E).

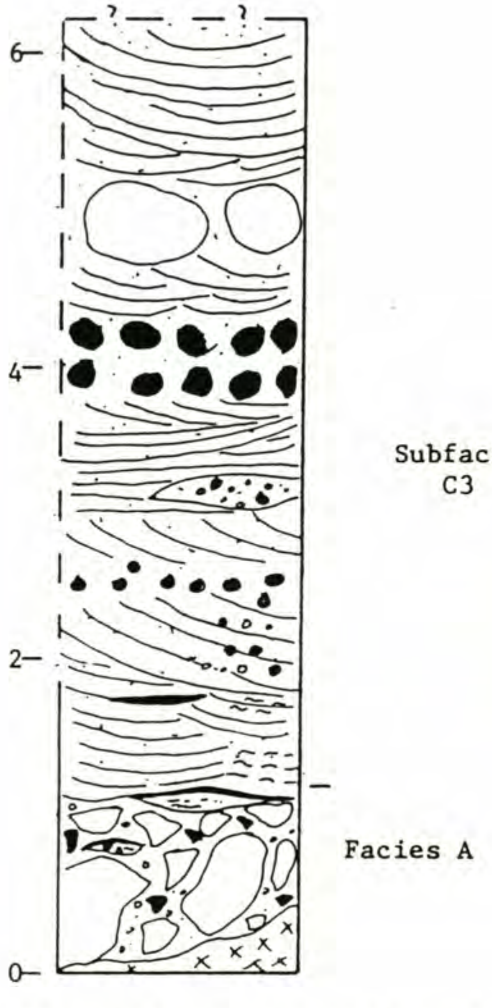


Figure 12. Stratigraphic column of Correction Camp cliffs (COR A).

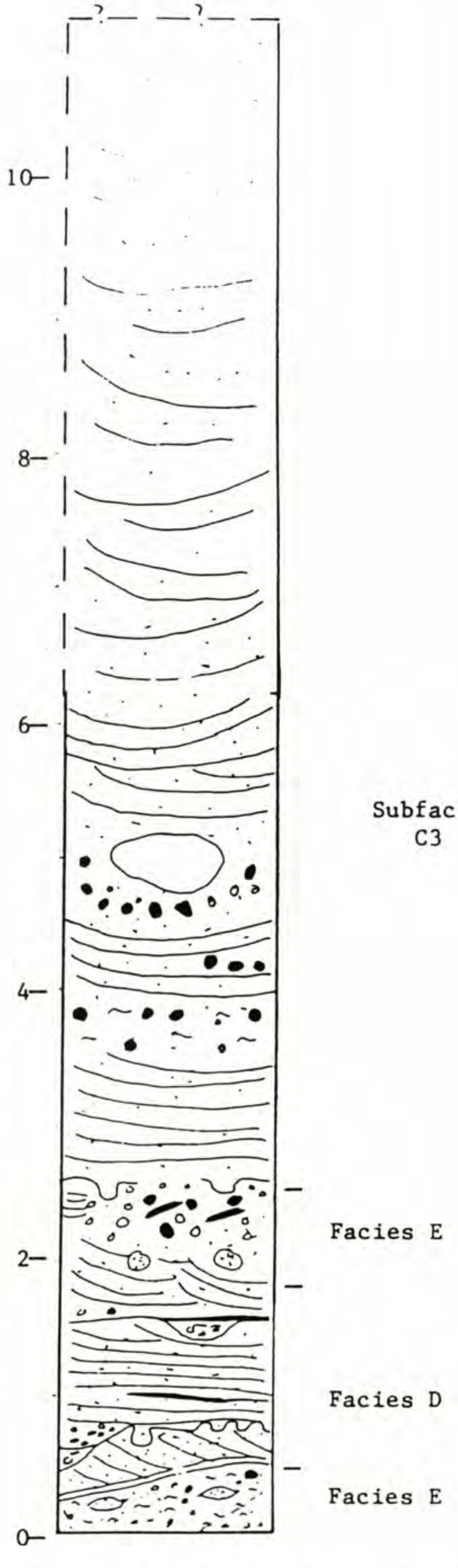


Figure 13. Stratigraphic column of Correction Camp cliffs (COR B).

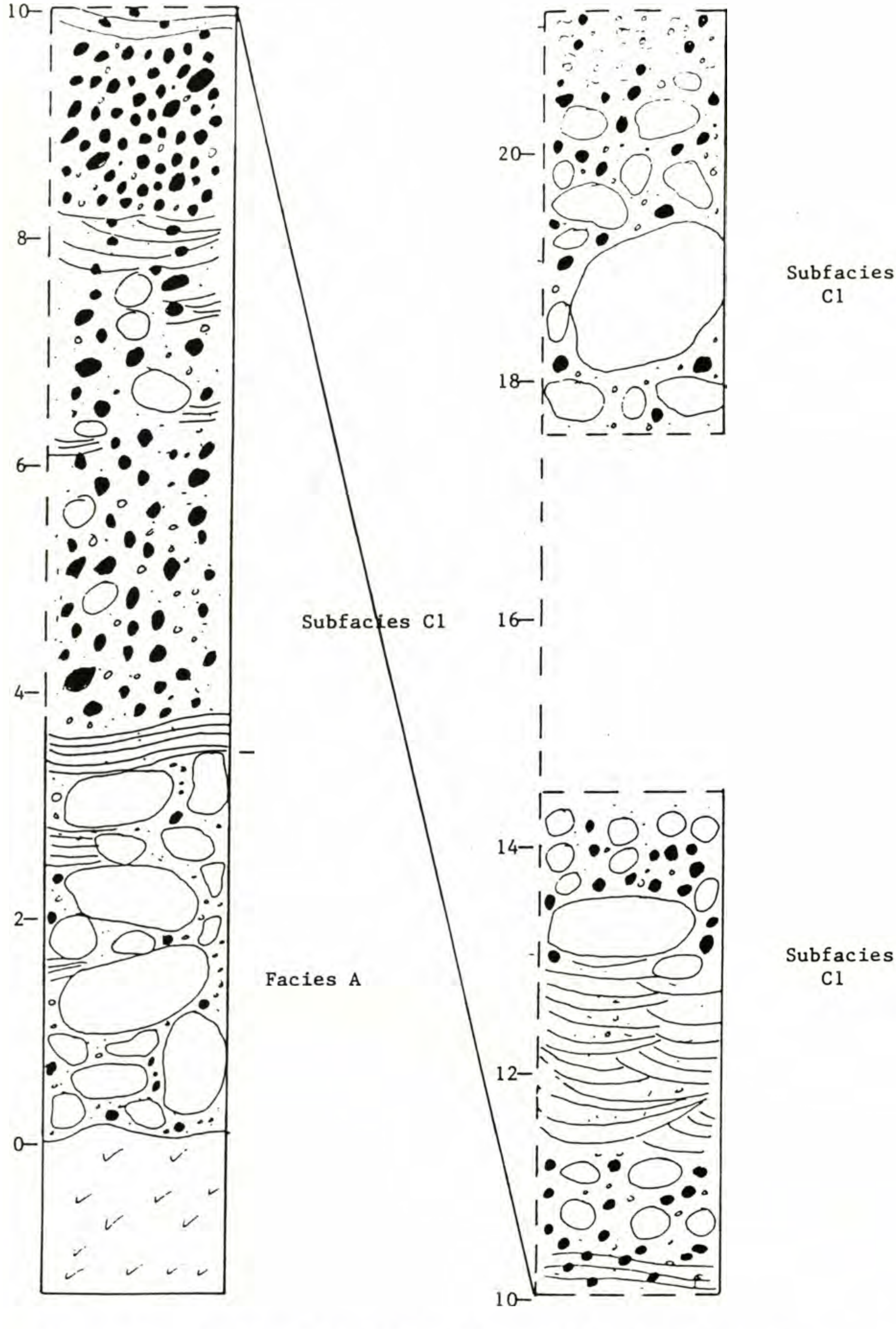


Figure 14. Stratigraphic column of Rosemond Creek at Correction Camp (COR C).

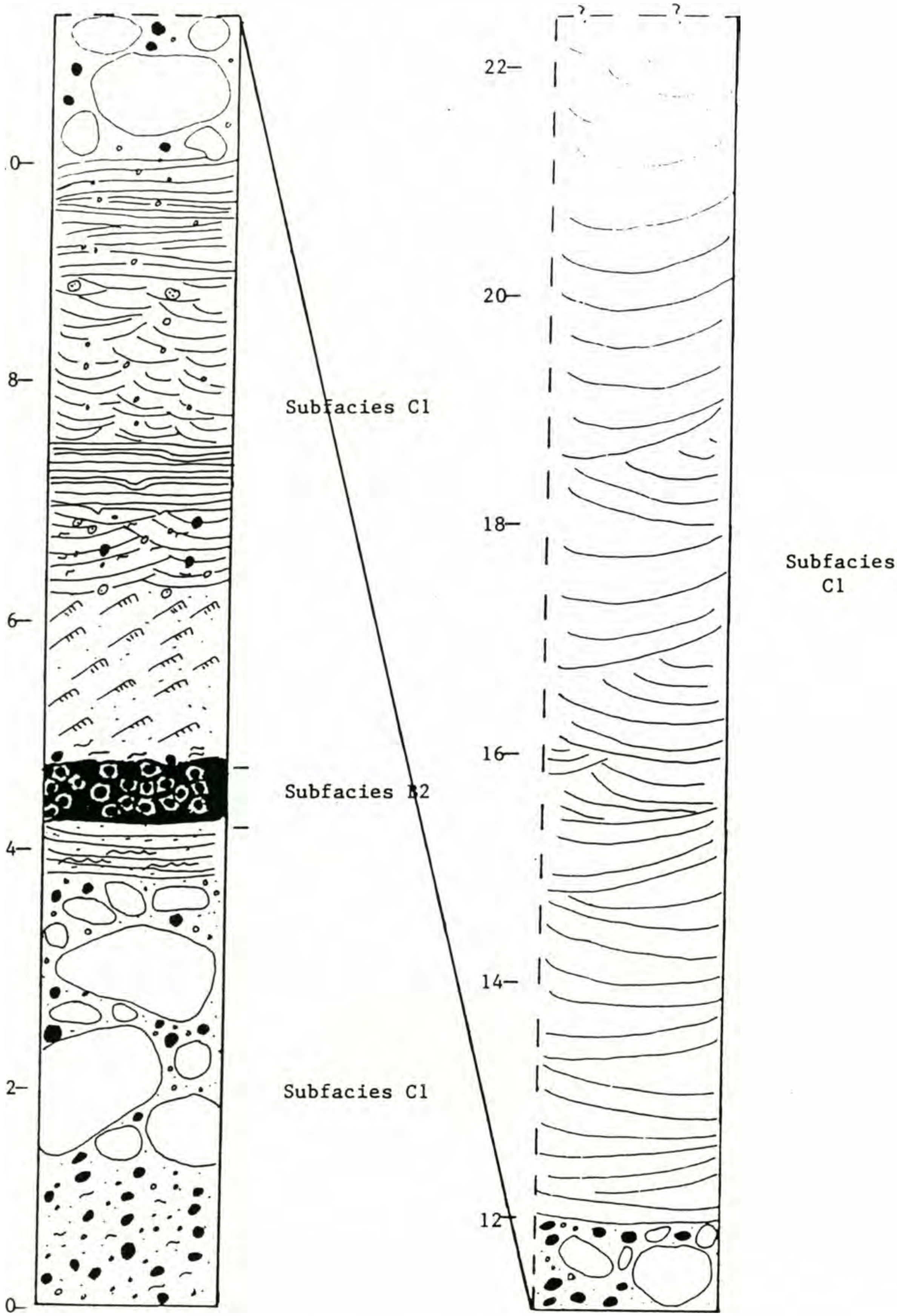


Figure 14. Stratigraphic column of Rosemond Creek continued.

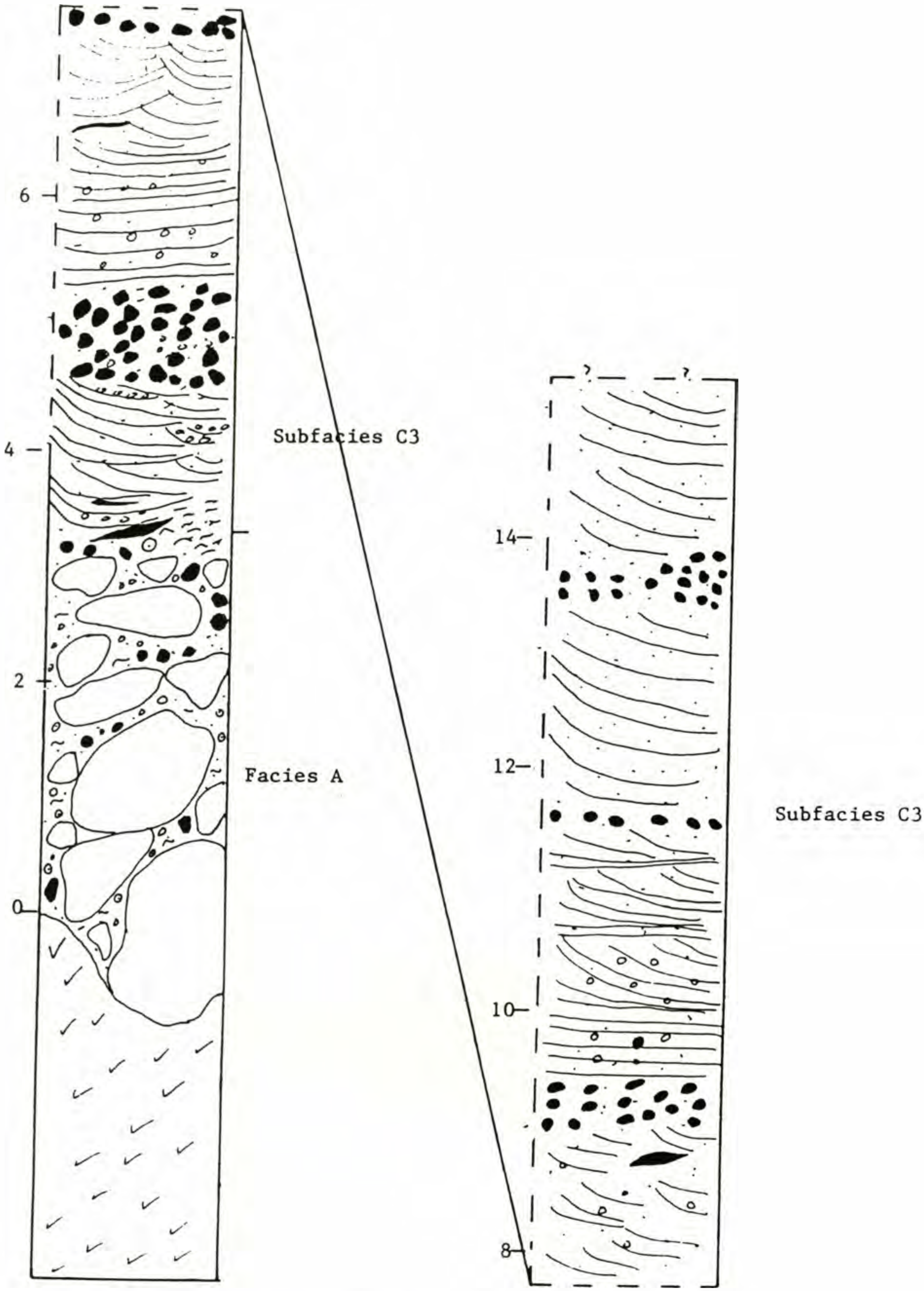


Figure 15. Stratigraphic column of Mystic Beach (MYS A).

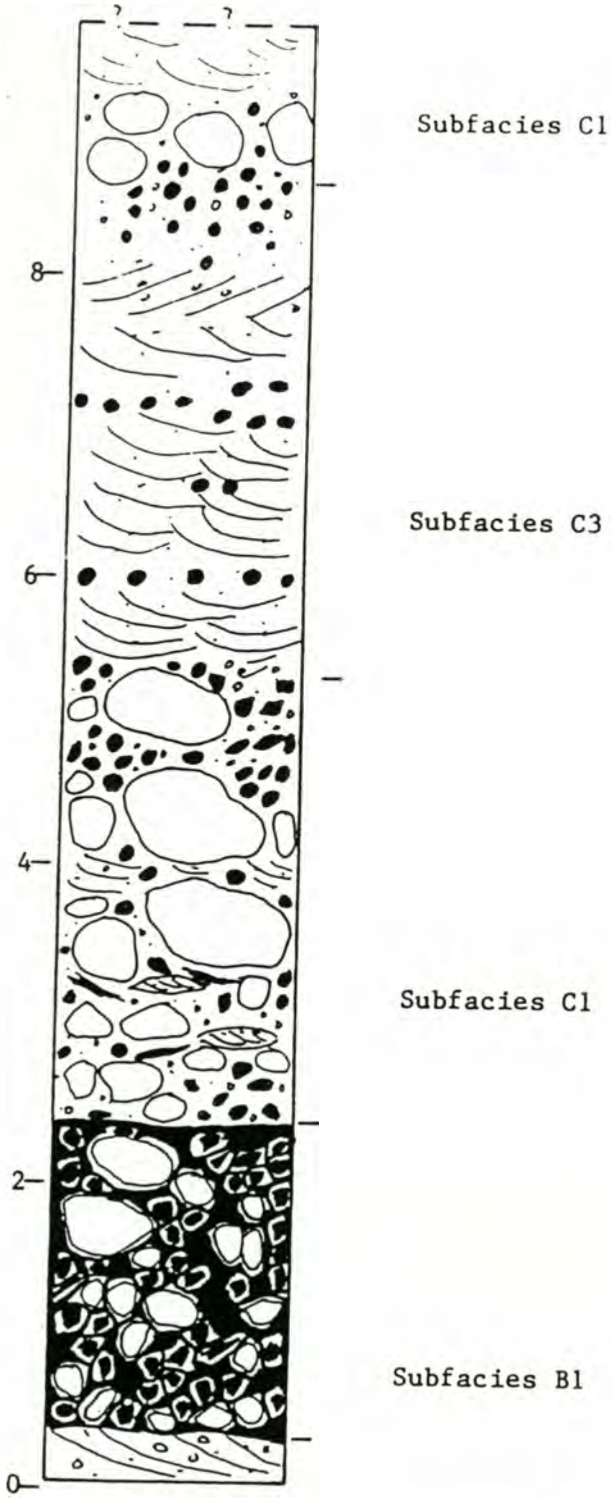


Figure 16. Stratigraphic column of Mystic Beach (MYS B).

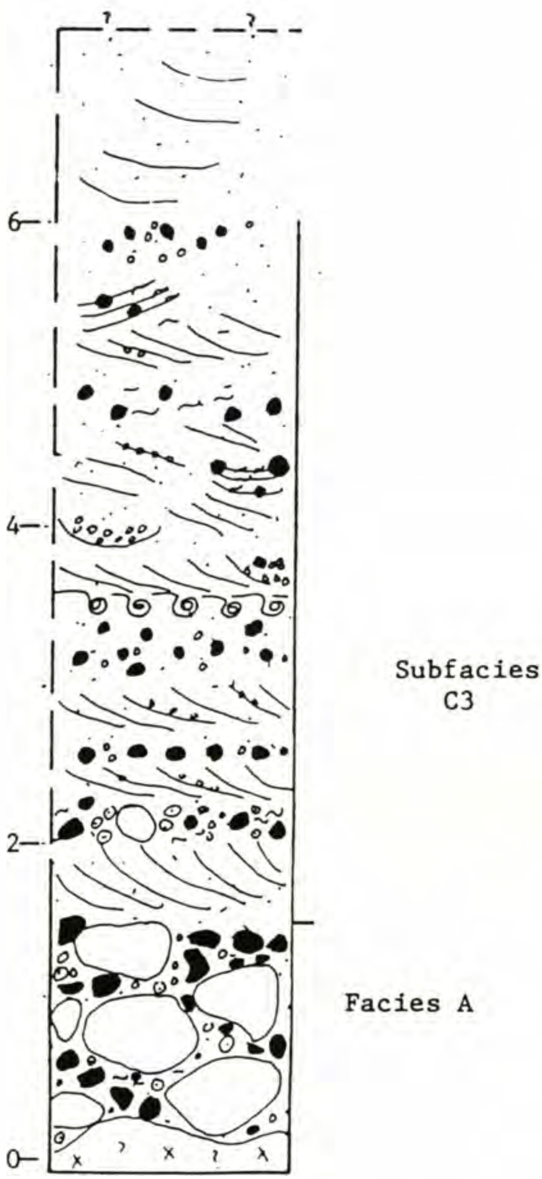


Figure 17. Stratigraphic column of China Beach Provincial Park (CHI A).

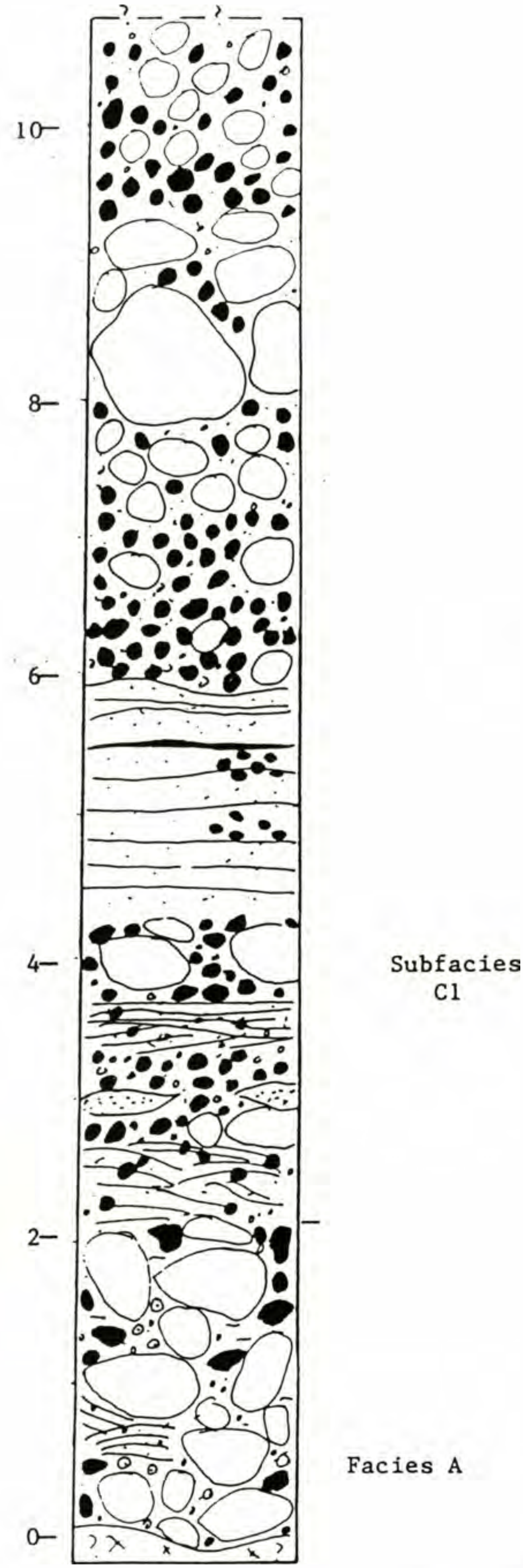


Figure 18. Stratigraphic column of China Beach Provincial Park (CHI B).

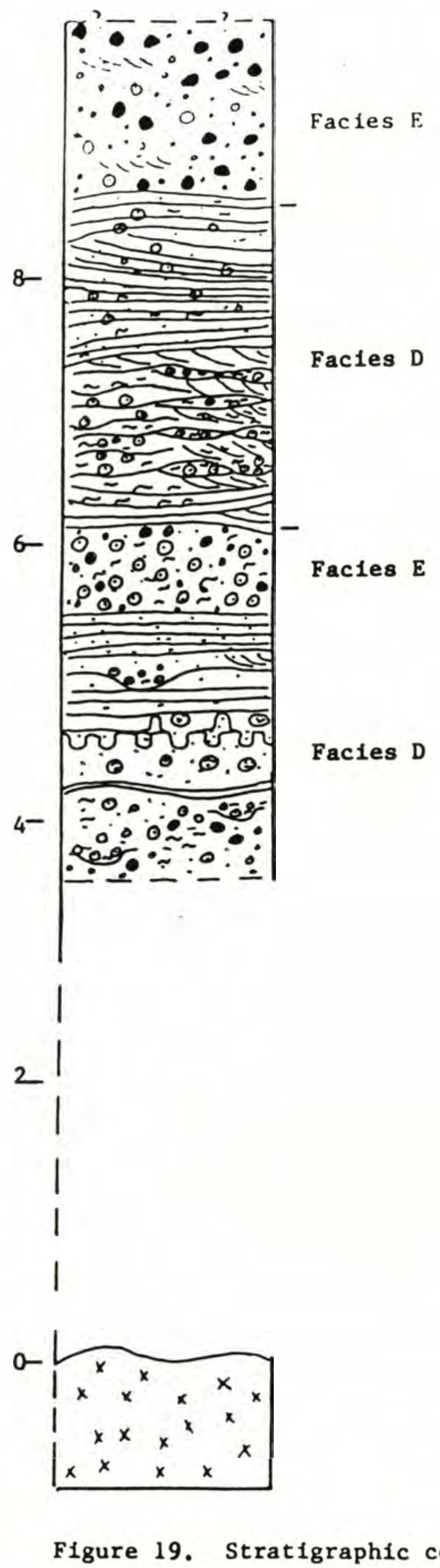


Figure 19. Stratigraphic column of Sandcut Beach (SAN).

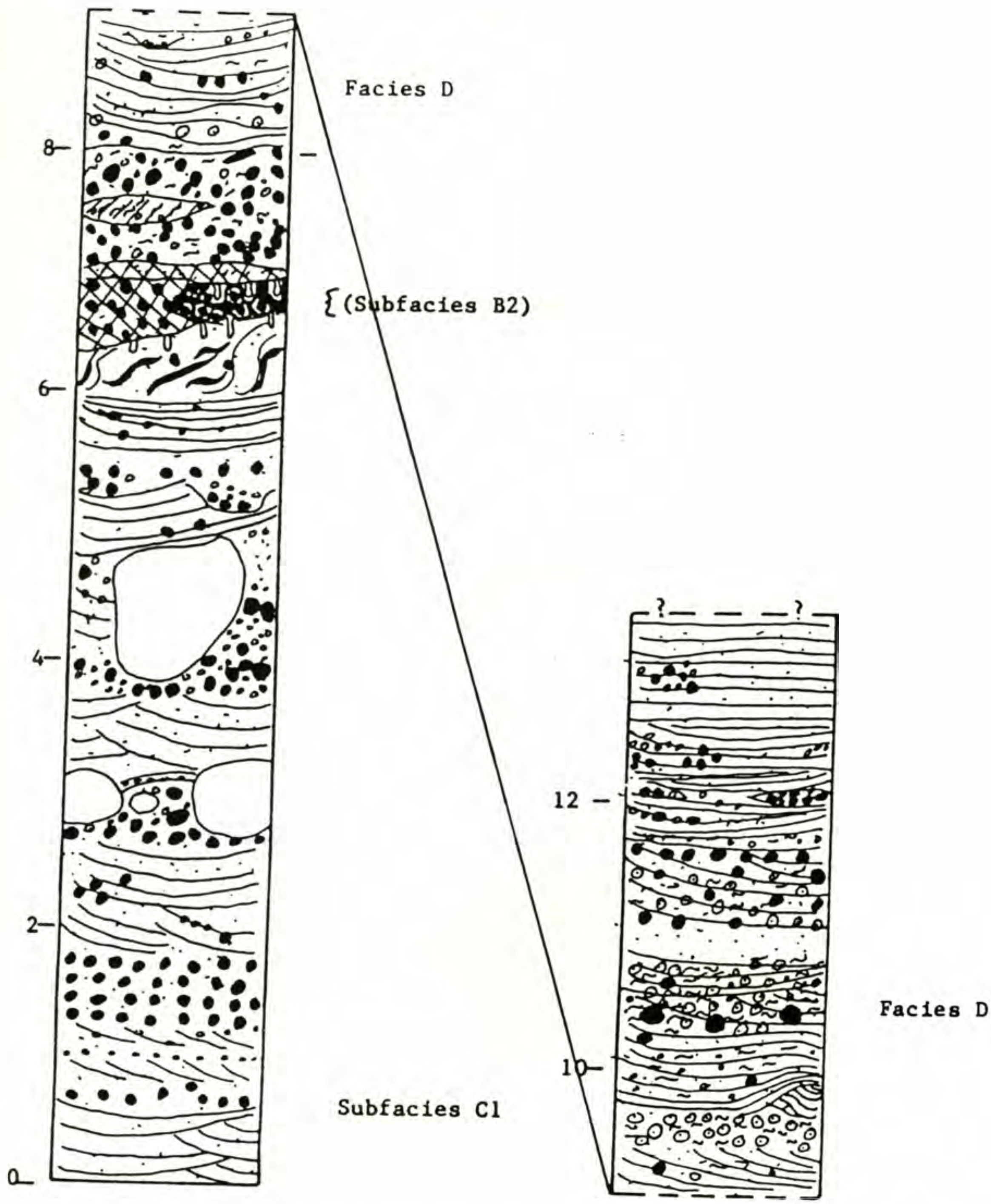
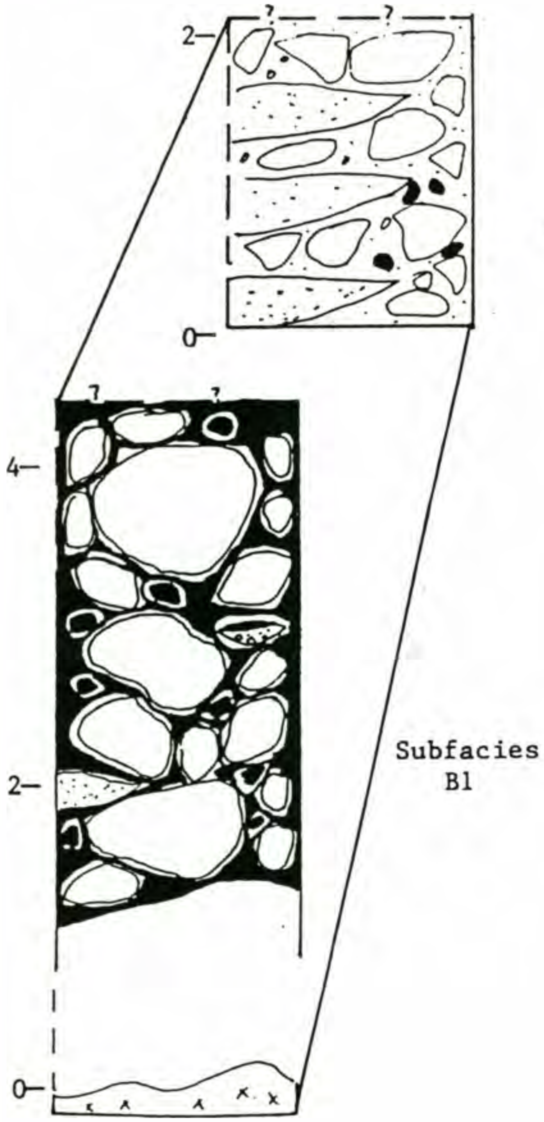


Figure 20. Stratigraphic column of French Beach Provincial Park (FRE).



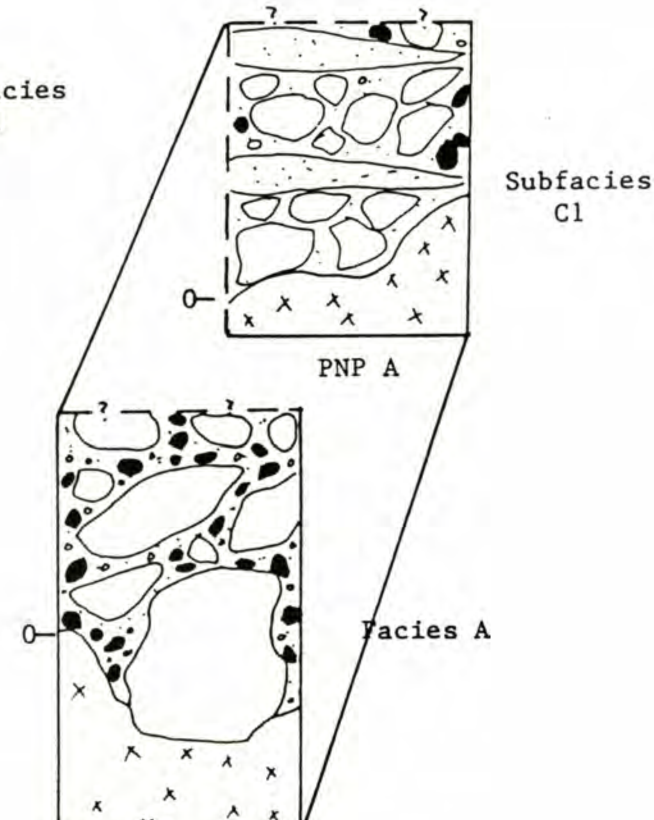


Figure 21. Stratigraphic column of Beach Trail (BTR).

Figure 22. Stratigraphic column of Point-No-Point (PNP A, PNP B).

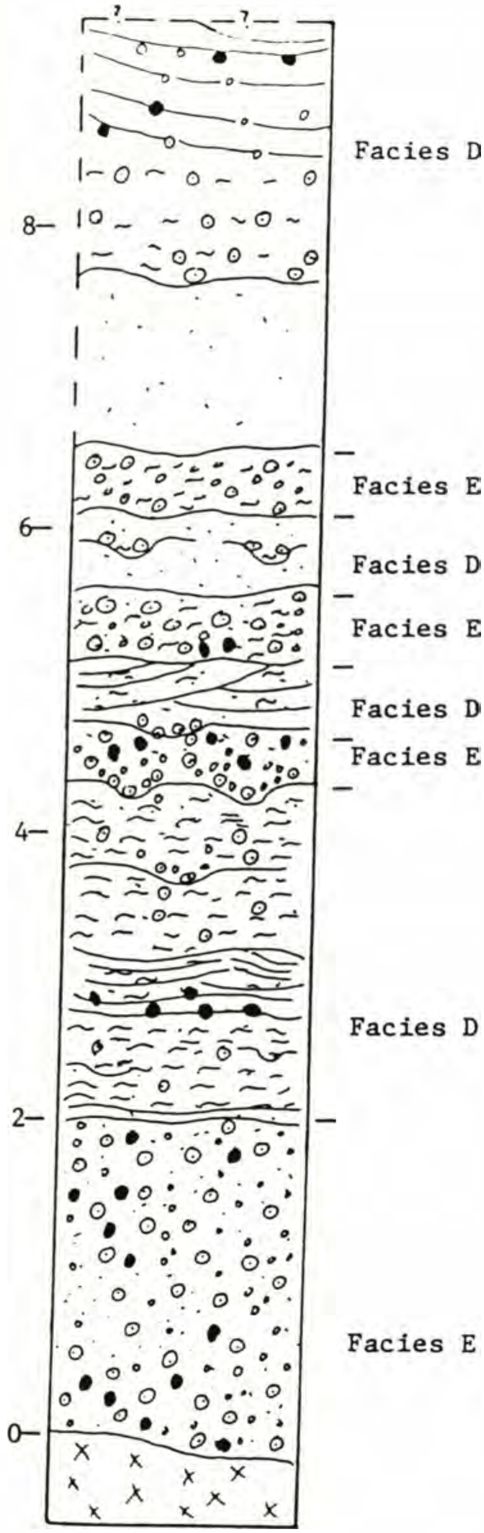


Figure 23. Stratigraphic column of Keffers property near Point-No-Point (PNP D).

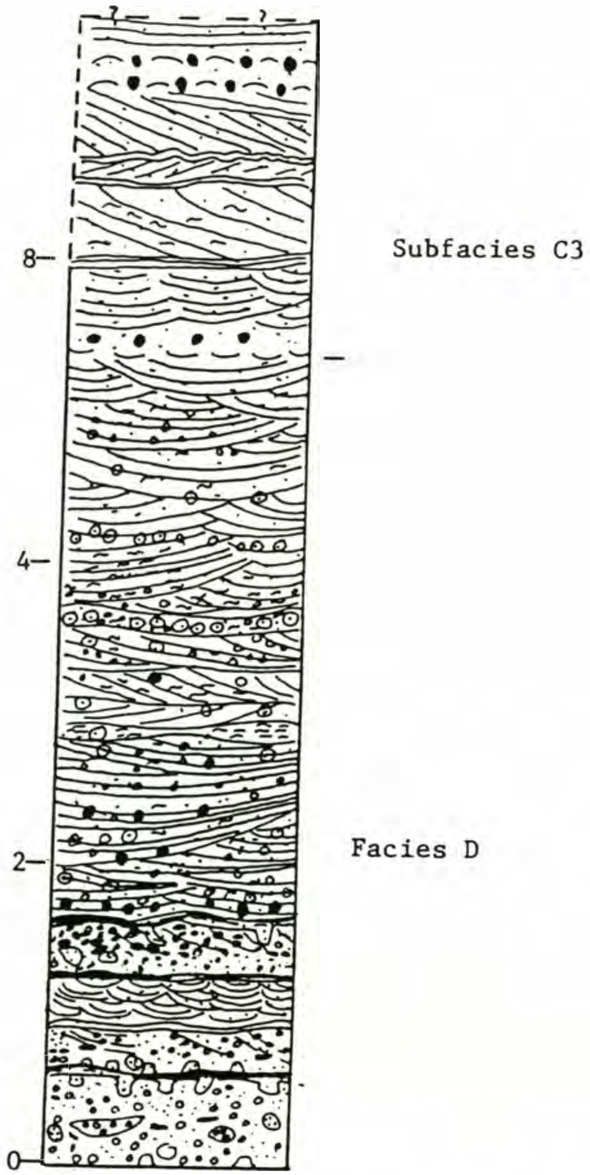


Figure 24. Stratigraphic column of Muir Creek cliffs (MUI A).

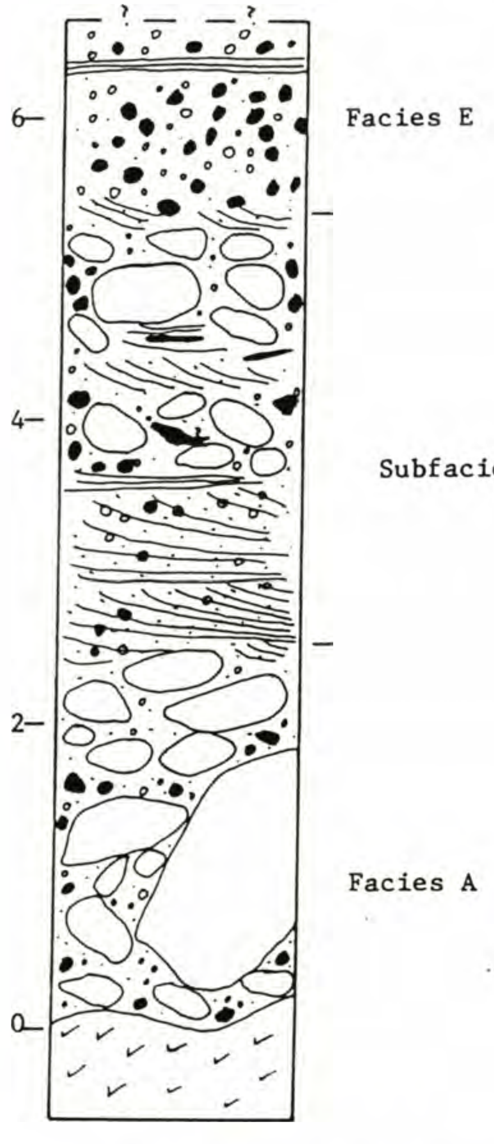


Figure 25. Stratigraphic column of East Sooke Park (ESP).

DEPOSITIONAL ENVIRONMENT

INTRODUCTION

The Sooke Formation is exposed in cliffs and wave-cut ledges on beaches and in several streams. A list of sample locations is given in Figure 5. The beach exposures occur mostly between rocky headlands that are difficult if not impossible to get around. Since the Sooke Formation was deposited unconformably on a very irregular basement, it is not possible to correlate stratigraphic sections from one beach to the next or even from one exposure to the next. The irregularity of the basement rock was one of the controlling factors responsible for the rapid facies changes that occur both laterally and vertically. Because of this difficulty, I have included 12 different stratigraphic columns (Figs. 6 to 25) and have not attempted to correlate them with one another.

The Sooke Formation generally strikes northeast-southwest and on the average dips about 8 degrees to the southeast. Exposures perpendicular to the direction of strike are rare, as most exposures are in cliffs that are roughly parallel to the direction of strike. Because these exposures are two-dimensional, paleocurrent measurements on cross-strata were taken only at one location (Sombrio Beach) (Appendix 1). Although clast imbrication is not pronounced, it is fairly common; and measurements of the direction of pebble and cobble imbrication were taken at several sites. The results of all of the paleocurrent measurements are plotted in Appendix 1. These results indicate a dominant transport direction from the north, but most are quite variable. These results are consistent with the interpretations which are presented in the following section, that these deposits are shoreface and lower foreshore deposits which are formed during storms transporting pebble-sized material seaward.

A significant discrepancy in nomenclature exists at Sombrio Beach.

The outcrops just to the northwest of the Sombrio River have been mapped as Hesquiat Formation (Muller, 1977b). According to B.E.B. Cameron (oral communication, 1986), there are no dates on fossils from these rocks. The outcrops at Botanical Beach, which are dated, are the nearest outcrops of uncontested Hesquiat Formation. Because these outcrops just across the Sombrio River do not differ in any obvious way from the Sooke Formation in terms of lithologies and sedimentary structures, I have included these outcrops in my study.

I have divided the Sooke Formation into 6 major facies and 5 subfacies as follows:

Facies A: boulder breccia

Facies B: dominantly muddy matrix conglomerate

Subfacies B1: muddy to muddy sand matrix boulder conglomerate

Subfacies B2: muddy to muddy sand matrix pebble conglomerate

Facies C: conglomeratic sandstone

Subfacies C1: cross-stratified sandstone with boulder conglomerate

Subfacies C2: thick-bedded cobble to pebble conglomerate and breccia

Subfacies C3: cross-stratified sandstone with parallel- to thick-bedded pebble conglomerate with some small pebble lenses

Facies D: cross-stratified and parallel-laminated sandstones with scattered pebbles, pebble lenses, and sandstone channels

Facies E: thick-bedded pebble grit and conglomerate

Facies F: silty shale and siltstone

The facies are labeled on each stratigraphic column (Figs. 7-25). Figure 5 shows site locations. Table 1 lists the facies and subfacies that are found at each location. Since much of the section is exposed in cliffs or inaccessible coves, bed thickness measurements were feasible only in the

TABLE 1: FACIES DISTRIBUTION (locations listed from west to east)

FACIES:	A	B		C			D	E	F
SUBFACIES:		B1	B2	C1	C2	C3			
LOCATION West half of area:									
SOM A	x						x		x
B	x				x		x		x
C	x				x	x			
D	x						x		
E	x				x		x		x
ZOD							x	x	
MYS A	x					x			
B		x		x		x			
C				x					
COR A	x					x	x	x	
B						x	x	x	
C	x		x	x					
CHI A	x					x		x	
B	x			x					
East half of area:									
SAN							x	x	
FRE		x				x	x	x	
BTR			x	x					
PNP A	x			x					
B	x								
C	x								
D							x	x	
KIR A							x	x	
B		x					x		
MUI A						x	x		
B								x	
TUG			x				x		
WHI							x	x	
ESP	x		x					x	

* note- "x" denotes facies present at specific location - for key
to abreviations refer to table_ lower parts of the cliffs, and on some wav

TABLE 2: MAJOR CHARACTERISTICS OF FACIES

FACIES	MAJOR CHARACTERISTICS
A	Boulder breccia; angular, poorly sorted, boulders to granules; clast-supported in granule sandstone or grit matrix; some fossiliferous; some sandstone lenses and carbonaceous material.
B	Dominantly silty to silty sand matrix.
Subfacies B1	Poorly sorted boulder conglomerate and breccia; mostly clast-supported boulders to granules; some sandstone lenses and carbonaceous material; chaotic arrangement of clasts.
Subfacies B2	Mostly pebble conglomerates; pebbles are rounded to subangular; some vertical cylindrical burrows; sandstone interbeds at one location.
Facies C	conglomeratic sandstone
Subfacies C1	Cross-stratified sandstone with boulder conglomerate; conglomerates are poorly sorted; clast-supported in sandstone and grit matrix; some inversely graded; sandstones mostly trough cross-stratified; contain scattered pebbles and granules; some carbonaceous laminae; some fossiliferous.
Subfacies C2	Thick-bedded cobble to pebble conglomerate and breccia; poorly-sorted; some sandstone interbeds and some carbonaceous laminae; wood replaced by aragonite.
Subfacies C3	Cross-stratified sandstone with parallel- to thick-bedded pebble clast- to matrix-supported conglomerate; laterally continuous; some small pebble lenses; sorting is mostly moderate to well; sandstones dominantly trough cross-stratified with scattered pebbles and granules; many fossiliferous; concretionary.
Facies D	Dominantly trough cross-stratified and parallel-laminated sandstones with scattered pebbles, pebble lenses; some burrows; many small shell- and pebble-lined channels; some beds very fossiliferous.
Facies E	Thick-bedded grit and conglomerate; some very fossiliferous.
Facies F	Silty shale and siltstone; some load casts and deformed ripples; concretionary

lower parts of cliffs, and on some wave-cut platforms. Measured thicknesses are delineated by a solid line on the left-hand side of the stratigraphic columns. Estimated thicknesses are delineated by a dashed line. The following section is a detailed description of the lithologies and sedimentary structures that are found in each facies at the different locations. Table 2 summarizes the major characteristics of each facies. The interpretation of these features will follow in the next section.

FACIES DESCRIPTIONS

FACIES A:

Facies A, a boulder breccia, crops out at many locations along the coast where it unconformably overlies either Metchosin Volcanics or Sooke Gabbro. The basement rock is highly irregular with much vertical relief. The breccia fills in these irregularities and probably was deposited as a basal layer at different times and depths in different parts of the basin. The thickness of the basal breccia is variable, ranging from generally less than 0.6 meters at Sombrio Beach (Fig.26) to approximately 8 meters at Mystic Beach and averaging 1.2 to 1.5 meters. At most locations, large blocks of basement rock protrude up through the basal breccia; and, in a few places, the basement protrusions are hard to distinguish from large clasts within the breccia. The breccia is mostly clast-supported with some matrix-supported pockets. The matrix is a granule-bearing medium-grained sandstone with textural differences depending on location. At Mystic Beach, China Beach Provincial Park, and Sombrio Beach, the matrix is fossiliferous with mostly broken shell fragments and, at Mystic Beach, some large pieces of oyster shells. Bone fragments were found at Sombrio Beach. The sand is generally moderately sorted except at Sombrio, where it is very poorly sorted. Sand grains are generally subangular.

Figure 26. Waterfalls flowing on basal breccia at Sombrio Beach. This breccia is unconformably overlying metamorphosed Metchosin basalt. Arrow denotes contact.

Figure 27. Boulder-sized clasts of Leech River schist and metamorphosed Metchosin basalt at Sombrio Beach.

Figure 28. Facies A basal breccia with sandstone lens at Correction Camp cliffs.

Clasts are randomly oriented, including some vertical boulders, and range in size from granules and small pebbles to large boulders. At East Sooke Park, some blocks of gabbro within the basal breccia are "cadillac-sized" (i.e. up to 4.5 meters long). Clasts are mostly angular to subangular, but exposures along Rosemond Creek have mostly subrounded clasts. The composition of the boulders and cobbles in the breccia usually matches the composition of adjacent or underlying basement rock, except at Sombrio Beach, where many clasts come from a source for which the nearest present exposure is 1.5 to 2 kilometers away. At Sombrio Beach clasts in the basal breccia (Fig. 27) consist largely of Leech River Schist and metamorphosed Metchosin (TM2 of Muller, 1980). At some locations, the sandstone matrix among cobbles and boulders contains pockets of normally graded cobbles and pebbles to granules. At Sombrio, some of the pebbles and granules in such pockets show parallel alignment. Sandstone interbeds within the basal breccia are present at some locations. These are trough to tangential wedge cross-stratified sets that sometimes contain granules and pebbles. They are compositionally and texturally similar to the matrix sandstone. At the Correction Camp cliffs, the interbedded sandstone lenses are carbonaceous (Fig. 28). The basal boulder breccia in places grades upwards into a pebbly granule sandstone and then to sandstone with more scattered granules and pebbles interbedded with conglomerate, and elsewhere it is in sharp contact with cross-laminated sandstone and pebble conglomerate.

FACIES B:

SUBFACIES B1:

This subfacies consists of boulder breccia and conglomerate with a green muddy matrix. It only occurs at two locations, at Mystic Beach and

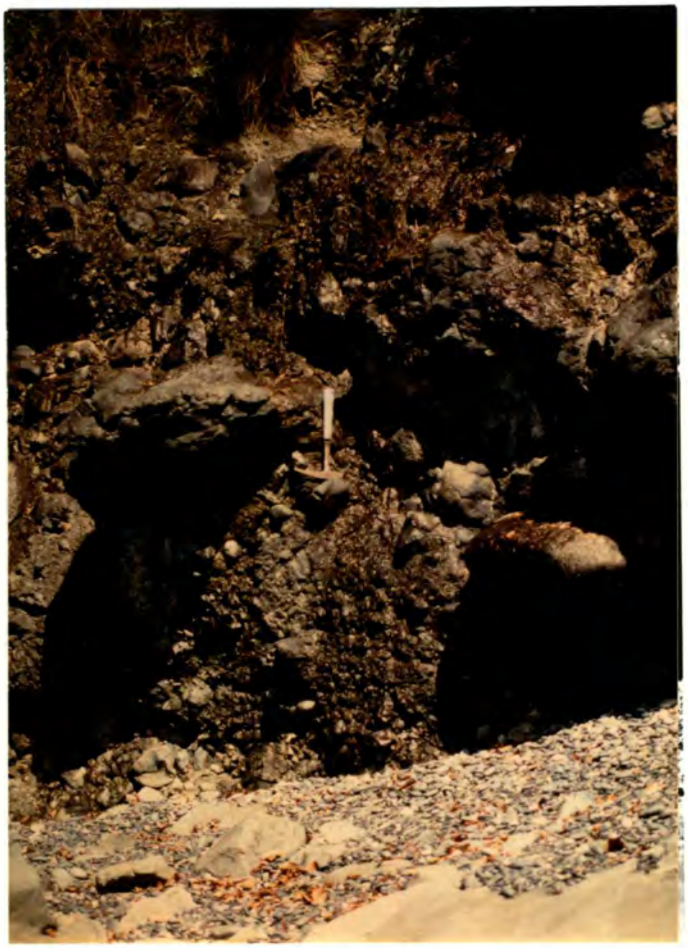


Figure 29. Muddy matrix boulder conglomerate (subfacies B1) at Beach Trail. Note rock hammer for scale.

at Beach Trail (Fig. 29). At Beach Trail this is a basal unit overlying basalt. At both locations it consists of clast-supported boulders to granules in a dominantly silty mud to silty sand matrix. Also at both locations, there are sandy lenses, some crudely normally graded and containing carbonaceous material; and at Beach Trail there are small lenses of carbonaceous shale. No fossils were found at either location. The breccia consists of unsorted, crudely stratified, angular clasts and some wood fragments randomly oriented. Clasts range from boulders to pebbles and granules; they are dominantly cobble-sized at Beach Trail and pebble-sized at Mystic Beach. Boulders are as large as 1.1 to 1.2 meters in diameter and are angular to subrounded. At Beach Trail there is a poorly-developed inverse grading at the base of the exposure with small- to medium-sized pebbles below larger clasts. Normal size grading is found in pockets and at the interface between the breccia and the interbedded sandstone lenses. A pebble count at Mystic Beach shows that the gravel clasts are dominantly basalt and gabbro or their metamorphic equivalents (Appendix 2). At Beach Trail, the compositions are similar.

The basal contact at Mystic Beach is sharp against underlying cross-stratified sandstone which subfacies B1 truncates. The thickness is about 1.4 meters at the point where the underlying sandstone is exposed. The bed pinches out to the northwest in about 0.2 kilometers where interbedded subfacies C1 sandstone and conglomerate predominate.

SUBFACIES B2:

This subfacies resembles subfacies B1 in having a muddy to muddy sand matrix, but this conglomerate lacks boulder-sized clasts. Like subfacies B1, it is nonfossiliferous. At French Beach a pebble conglomerate of this subfacies that is 0.5 meters thick is exposed on wave-cut ledges at low tide. Pebbles are subrounded and moderately sorted. This layer also contains abundant wood and some shale ripups. Stratigraphically it lies between cross-stratified sandstone below and contorted woody sandstone; laterally (to the west) it grades into magnetite-rich subfacies C3 conglomerate. It is burrowed in both the upper and lower parts and across the interface with the underlying sandstone. The burrows are cylindrical and range from 1.3 cm to 33.2 cm in diameter. They are filled with muddy sand that is rich in iron minerals.

In Rosemond Creek there is an 28 cm layer of granule to pebble conglomerate with a muddy sand matrix (Fig. 30). Clasts are rounded to subangular with high sphericity and are poorly-sorted. The upper surface is scoured contact is preserved. It overlies bioturbated sandstone with a planar contact.

A granule to cobble conglomerate with a green muddy to muddy sand matrix is exposed in Kirby Creek, and float of a similar conglomerate was found in Tugwell Creek. The conglomerate is clast-supported and very poorly sorted. Clasts are very well-rounded to subangular. A rounded felsic plutonic cobble was also found in the Kirby Creek exposure. Modal clast size is very coarse pebbles. The sandy matrix is poorly-sorted muddy fine- to medium-grained sandstone. The conglomerate has interbeds of very friable, silty, very fine to fine-grained, poorly-sorted sandstone that contains scattered cobbles, pebbles, and granules.

FACIES C:

SUBFACIES C1:

Subfacies C1 consists of cross-stratified sandstone with boulder conglomerate. It is characterized by a higher percentage of sandstone than conglomerate. The conglomerates are mostly clast-

Figure 30. Subfacies B2 muddy matrix pebble conglomerate below subfacies C1 sandstone along Rosemond Creek. Subfacies C1 sandstone consists of deformed rippled sandstone at the base to trough cross-stratified very fossiliferous sandstone to low angle parallel-laminated sandstone. Note lens cap for scale.

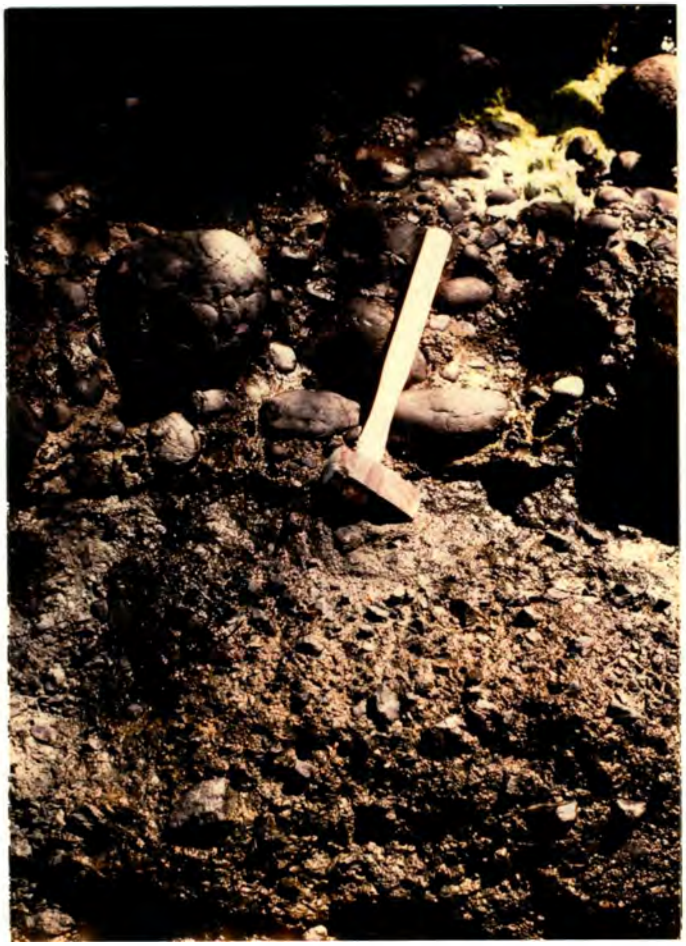


Figure 31. Contact between subfacies B1 breccia and subfacies C1 inversely graded boulder conglomerate at Mystic Beach. Head of hammer is on the contact.

supported boulders often with sandstone lenses. The best exposures are along Rosemond Creek and at Mystic Beach. The sandstones are all cross-bedded and generally contain scattered pebbles. In most places they are not fossiliferous. The boulder conglomerates are generally poorly-sorted and are either clast-or matrix-supported. Clasts are mostly subrounded with some fairly well-rounded boulders up to 1.2 meters in diameter. Boulders are dominantly basalt and gabbro (or their metamorphic equivalents). The bases of the boulder conglomerate beds are erosional but not deeply scoured.

Along Rosemond Creek, sandstones and conglomerates of subfacies C1 overlie the basal breccia. The lowest sandstone is conformable to the underlying breccia. A little further upsection, the sandstone is quite pebbly and gritty. Some of the boulders are huge, on the order of 1.2 to 1.5 meters in diameter. Clasts are better rounded than in the basal breccia and are mostly composed of basalt and gabbro. Between two boulder congomerates there is a sequence of dominantly parallel-bedded sandstone, rippled sandstone, and small- and large-scale trough cross-stratified fossiliferous sandstone. At the base of this cross-stratified sequence is at least 0.8 meters of parallel- to wavy-bedded, very fine to fine-grained, moderately poorly-sorted muddy micaceous sandstone that is thinly bedded and bioturbated. Feeding traces are preserved on bedding planes. Subfacies B1 conglomerate separates this from a sequence of deformed rippled sandstone and large-scale trough cross-stratified very fossiliferous sandstone (Fig. 30). At the base of the rippled sandstone are some pebbles and oyster shells. There are some small V-shaped burrows in the trough cross-stratified sandstone. Beds alternate within the trough set between very fossiliferous sandstone and fine-grained sandstone. The fossils are mostly broken. Above this are wedge sets of tangential cross-stratification and very low angle planar cross-bedding to parallel bedding with some black laminated small troughs or channels. This is a poorly-sorted grit. Next upsection is bioturbated small-scale trough-cross-stratified sandstone with some parallel laminated sandstone with low angle truncations above this. There is some sediment mixing with small clusters of coarse sandstone and granules in this sandstone. More parallel-laminated sandstone with some low-angle truncations is at the top of this sequence. Above the upper conglomerate layer are at least 10.6 meters of cross-laminated sandstone with some trough cross-lamination.

At Mystic Beach, an inversely graded conglomerate overlies a muddy matrix breccia of facies B. Here, the contact between the two is sharp because of the contrast in matrices, but it is not scoured (Fig. 31). The conglomerate grades from mostly subrounded pebbles and cobbles at the base to scattered boulders about 1.2 meters in diameter at the top. In places the boulders poke through the overlying sandstone and conglomerate. There are small lenses of sandstone and carbonaceous material. The matrix is medium-grained, pebbly and granuly, poorly-sorted, nonfossiliferous sandstone. Sand- to small pebble-sized clasts have a variety of lithologies indicating an intermediate volcanic, a metasedimentary, and mafic metavolcanic and plutonic source.

Several other boulder conglomerate layers are exposed above this at Mystic Beach. Directly above the inversely graded conglomerate is a poorly-sorted pebble to boulder conglomerate with minor cross-laminated sandstone lenses. Scattered gravel clasts are mostly rounded to subrounded. This grades into subfacies C3 sandstone and parallel-bedded conglomerate layers. Above this and out of sampling reach is another poorly-sorted slightly inversely-graded boulder conglomerate with rounded to subrounded clasts. Exposures at the northwest end of the beach show parallel-bedded conglomerate with sandstone containing medium-scale trough cross-laminae to large-scale climbing ripples (Fig. 32).

At East Sooke Park, strata of poorly-sorted boulder breccia to conglomerate with lenticular interbeds of cross-stratified sandstone overlie the basal breccia. Each layer is inversely graded at its base (Fig. 33). Boulder- to pebble-sized clasts overlie a layer of cobbles and pebbles 1 to 2 clasts thick, similar to subfacies C1 at other locations. Clasts are slightly imbricated to the southeast. The matrix is a medium-grained moderately-sorted nonfossiliferous sandstone which is the same as the sandstone lenses. Sandstone interbeds consist of trough to tangential wedge sets about 0.2 meters thick. Small wood pieces are scattered in the conglomerate and sandstone.

At both Point-No-Point and Beach Trail, there are exposures of facies C1 that are hard or impossible to reach. These appear to be similar to the exposures at East Sooke Park and so probably were deposited above the basal breccia at these locations. They consist of boulder conglomerate to breccia with interbedded flat-based sandstone lenses.

At China Beach Provincial Park, there is an inversely to normally graded sequence of subrounded to rounded clast-supported cobble and pebble conglomerate with a boulder conglomerate in the middle. As is shown on the stratigraphic column in Figure 18, there are two other clast-supported boulder conglomerate layers separated by trough cross-laminated, pebbly, medium-grained, moderately-sorted sandstone. Other exposures reveal cross-laminated sandstone with scattered pebbles and granules and laterally continuous pebble conglomerates. Small channels are common and have lags of granules or of mixed pebbles and broken shells.

Figure 32. Subfacies C1 sandstone with medium-scale trough cross laminations, interbedded gravels, and large-scale climbing ripples overlain by parallel-laminated sandstone at Mystic Beach.

Figure 33. Cross-stratified sandstone and inversely graded boulder conglomerate of subfacies C1 at East Sooke Park.

SUBFACIES C2

Subfacies C2 is a crudely stratified cobble to granule conglomerate and breccia. It is included in facies C because of the abundant sandstone lenses and its association with subfacies C3 sandstones at Sombrio Beach. Conglomerates and breccias of this subfacies are volumetrically minor components of the Sooke Formation. They are poorly-sorted with mostly angular and some rounded clasts. In wave-cut cliffs at Sombrio Beach, there is a layer at least 3.3 meters thick of angular clast- to matrix-supported breccia and conglomerate with cross-bedded sandy lenses, some graded pockets, and concretions. The sandstone interbeds have unidirectional wedge sets of tangential cross-strata and consist of fine-grained well-sorted angular to subangular sandstone. Sandstone interbeds and lenses are more abundant in the lower part. They contain some dark laminae. Some cross-bedded and cross-laminated layers are interbedded with cross-bedded pebble conglomerates. The matrix sandstone is texturally similar to the sandstone interbeds.

A 0.3 meter-thick parallel to low angle cross-laminated sandstone interbed separates the lower breccia from an upper, coarser conglomerate. Clasts in both the breccia and conglomerate are dominantly composed of schist, quartzite, and metabasalt. Clast sizes in the lower, finer-grained breccia range from very coarse pebbles to small granules. These clasts are mostly subangular, with some very angular clasts. The coarser conglomerate has maximum clasts about 0.3 meters in diameter, but most are very coarse pebble to small cobble-sized. Clasts are mostly subrounded with low sphericity. Associated with the upper surface of the lower breccia layer are radiating aragonite nodules. These are always associated with carbonaceous sandstone lenses and probably replacement of some of the woody material. Other exposures at Sombrio Beach reveal another breccia layer that is at least 1.3 meters thick. This breccia is very similar to the basal breccia, only maximum clast size is cobbles rather than boulders.

Outcrops to the northwest of the Sombrio River may be either Sooke Formation or Hesquiat Formation, as discussed earlier. A cobble-pebble breccia cuts into the underlying cross-stratified sandstone irregularly. The breccia is composed largely of tabular clasts of the Leech River Complex schist and a few rounded metabasaltic clasts. It is clast-supported with a sandstone matrix. Clasts show a tendency toward being imbricated down to the southeast.

SUBFACIES C3

Subfacies C3 is a cross-stratified sandstone with parallel-to wavy-bedded pebble layers and pebbly lenses and occasional scattered boulders. Mystic Beach, Sombrio Beach, and French Beach have the most substantial thicknesses of this facies. Figure 34 shows the cliffs at Mystic Beach with exposures of subfacies C3 sandstone and conglomerate overlying the basal breccia. This sequence of cross-stratified to parallel-laminated sandstone and pebble conglomerate is at least 9.1 meters thick; the top is covered by vegetation. Directly above the basal breccia, the sandstone is medium-grained and moderately-sorted, fossiliferous with broken shells, and contains some carbonaceous lenses. The sandstone is cross-stratified with pebbles and granules lining some foresets and also scattered. Cross-stratification is dominantly trough-type, but some tangential wedge sets are also found. An upward transition from conglomerate to parallel-laminated sandstone to cross-laminated sandstone is common.

The conglomerate layers are clast- to matrix-supported cobble to granule conglomerates, many consisting dominantly of pebbles. These are

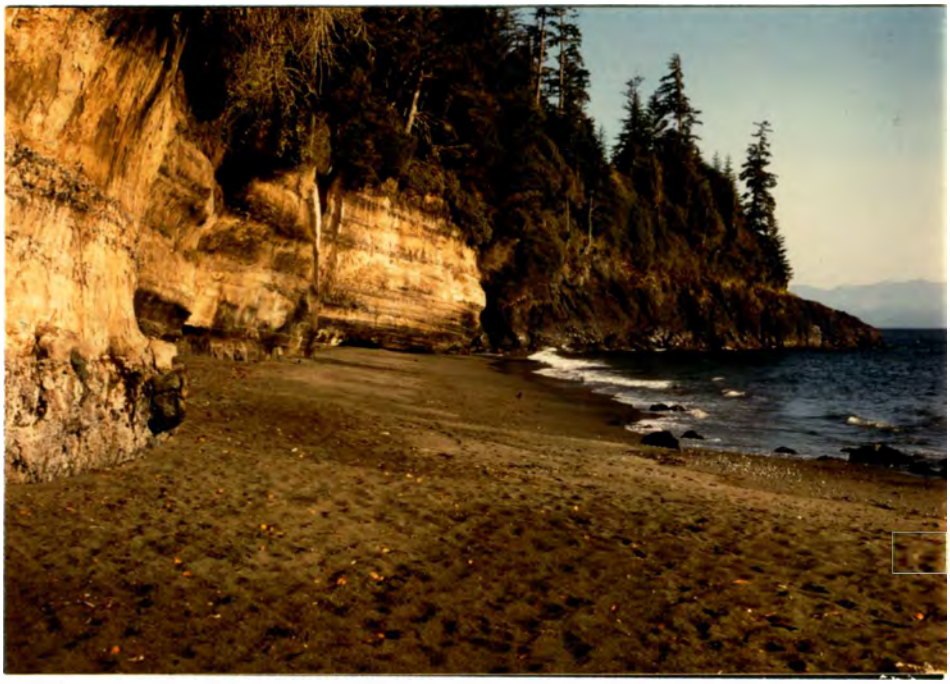


Figure 34. Cliffs at Mystic Beach with subfacies C3 laterally continuous pebble conglomerate and cross-stratified to parallel-laminated sandstone overlying basal breccia in foreground. Cliffs in background are Sooke Gabbro.

Figure 35. Contorted bedding preserved by concretion in subfacies C3 at Sombrio beach. Note the wood to the right of the hammer.

only a few clasts thick but are laterally very continuous. They are generally parallel-bedded with some waviness and bifurcation of layers and a few small lenses. Clasts are sub-rounded to angular and poorly-sorted. Pebbles are moderately spherical with dominantly blocky shapes, some are tabular. Modal clast size is pebbles.

At Sombrio Beach, a sequence at least 7.6 meters thick of interbedded cross-laminated sandstone and tabular conglomerate overlies the basal breccia. The lowest sandstone is medium-grained and moderately well-sorted, concretionary, and contains some contorted bedding (Fig. 35). This contorted-bedded sandstone is associated with woody material and nodules of radial aragonite similar to that in the breccia underlying it. The rest of the sandstone is medium-grained and consists of sets of trough and tangential wedge cross-stratification with rare hummocky cross-strata in the lower part. Honeycomb weathering is well-developed in the upper layers. The conglomerates change from mostly angular and subangular clasts to subrounded ones at the top of the exposure. Imbrication in the mostly tabular clasts is strong in the uppermost layers and is dominantly down to the southeast. Sorting is moderate.

At French Beach low angle trough cross-laminated sandstone onlaps basement rock to the northwest. It contains many concretions, some of which have a distinctive lenticular or tabular shapes. Cross-lamination and pebble- and granule-sand layers can be traced through the concretions. The sandstone is fine- to medium-grained and moderately well-sorted. The interbedded pebble layers fine upward from one layer to the next. Above this is a sequence of 4 parallel-beds of fine to coarse pebbles. The conglomerate contains scattered rounded boulders with predominantly subrounded to rounded cobble- to pebble-sized clasts. It is mostly clast-supported. The bases are erosional and wavy. Conglomerate beds often split and become interbedded with sandstone for a short distance and then join again. The layers of pebbles and cobbles almost pinch out beneath the boulders and thicken adjacent to them, often more so on one side than on the other (Fig. 36). At the bases the conglomerate layers with the boulders are inversely graded. Some layers of conglomerate fine upward from pebbles and cobbles to sand which then coarsens upwards to well-sorted granules and pebbles.

Overlying the pebble conglomerates is concretionary cross-laminated sandstone with both trough and tangential wedge sets, with contorted bedding in the uppermost part. The trough cross-stratification is more abundant. Scattered pebbles are common, and there are some pebble-lined troughs. Some of the small troughs are filled with fining-upward sequences with cobbles and pebbles at the base grading to medium-grained sand at the top. The contorted sandstone is medium-grained and moderately well-sorted. It contains abundant pieces of wood, some as large as one foot long. It pinches out laterally. Above this sandstone is a thick-bedded conglomerate which is unique because it contains a 0.3 meter-thick layer of conglomeratic sandstone rich in magnetite (Fig. 37). It is generally poorly-sorted and shows no clast imbrication or alignment. There is some normal grading, particularly in the magnetite-rich conglomerate and sandstone. There is a 15.2 cm-thick lens of sandstone with foresets lined by shell fragments. This sandstone is fine-grained and poorly-sorted. A pebble count on the upper part of the conglomerate showed a majority of the pebbles to be mafic volcanics. This conglomerate grades laterally into the muddy conglomerate of Subfacies B1.

Two large blocks of float at the beach below the cliffs at Muir Creek are presumed to have fallen off of the upper part of these cliffs. These

Figure 36. French Beach exposure of pebble layers thinning beneath boulders in subfacies C3.

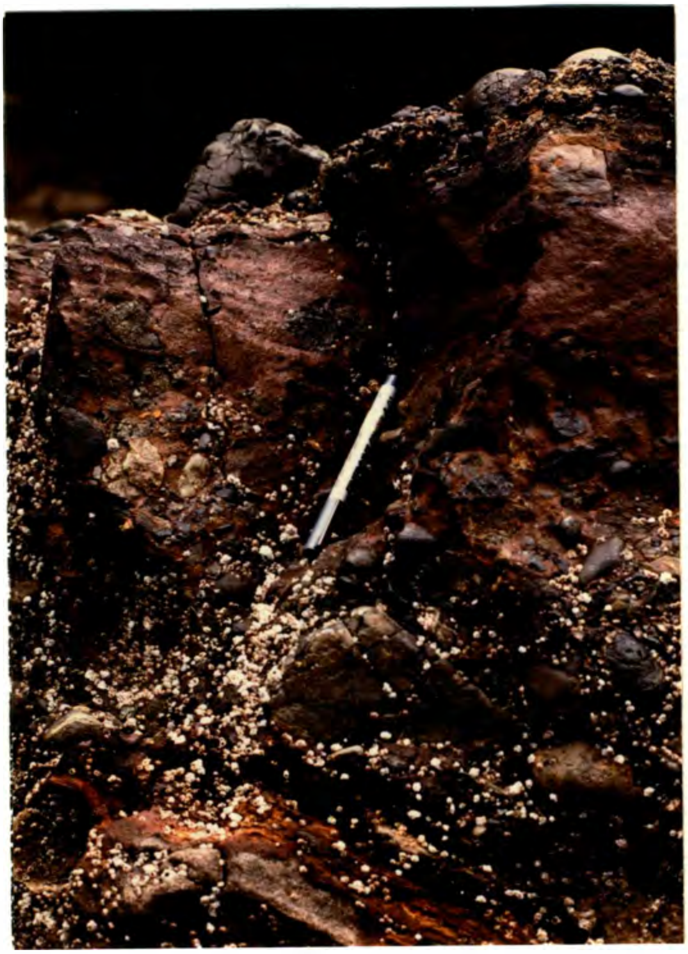


Figure 37. Conglomeratic sandstone with high concentration of magnetite at French Beach. Note woody sandstone in lower part of photo and pen for scale.

contain cross-laminated sandstone, two to three parallel beds of very fossiliferous pebbly conglomerate, and thin silty clay beds. The cross-lamination is two-directional in small tangential wedge sets with some black laminations, shell fragments, and silty clay ripups. The conglomerate layers are distinctive because of the abundant convex-upward mollusc shells (Fig. 38). These are mostly clams with some scallops. The shells are disarticulated, but largely unbroken and fragile. The pebbles are rounded to subrounded. The silty clay layers are contorted and probably rippled and carbonaceous. There are a lot of carbonaceous material and some wavy (probably rippled) black-laminated layers also.

FACIES D

Facies D is the most diverse and also the most abundant (refer to Table 1 and the stratigraphic columns in Figures 7 to 25). It consists of cross-bedded and parallel-bedded and -laminated sandstone with scattered pebbles and granules and grit. It is densely fossiliferous at some locations and sparsely to non-fossiliferous at others. Pebble and granule lenses and small channels are common, as is bioturbation at some locations.

French Beach has easily accessible exposures of this facies. Above the magnetite-bearing conglomerate layer (subfacies C3) is an 2.4 meter thick ledge-forming cross-laminated sandstone containing pebbles, granules, and fossils (Fig. 39). The cross-lamination varies from low angle troughs to tangential wedge sets to wavy-bedding. The sandstone is mostly fine-grained, moderately poorly-sorted, with subangular to subrounded grains. There are some small troughs lined with shells (mostly gastropods). The shells in these troughs are oriented concave-upwards. There are also two distinct very fossiliferous layers. One is about 0.3

Figure 38. Float block of subfacies C3 at Muir Creek cliffs with convex-upward mollusc shell and pebble layer on upper surface.

b

s

a

Figure 39. Facies D concretionary, ledge-forming cross-laminated sandstone (a) below trough cross-laminated very fossiliferous sandstone (b) with round basalt pebbles above scoured surface (s).

Figure 40. Well-bedded very fossiliferous sandstone of facies D at Sandcut Beach. Note the wavy nature of some of these beds.

meters thick and densely concentrated with mostly gastropods and some oyster shells. Thin parting laminations, honeycomb weathering, jointing, and iron-oxide staining are also common.

Above this cross-laminated sandstone is a very fossiliferous pebbly fine-grained sandstone with minor non-pebbly intervals. The fossiliferous sandstone has both broken and unbroken, but disarticulated, shells, including oyster and scallop shells. The base of this sandstone is scoured into the less fossiliferous ledge-forming sandstone. One and three tenths to 5 cm up from the base is a layer of rounded spherical medium-sized pebbles of basalt (Fig. 39). Cross-lamination is in low angle trough and tangential wedge sets. There are some thin beds of well-sorted granules to small pebbles and some beds of poorly-sorted granules to large pebbles all mixed with shells. This is overlain by a thin low angle trough cross-laminated pebble conglomerate to pebbly sandstone with a distinctive yellow-orange weathered color, which is overlain by very low angle cross-laminated sandstone with scattered round, very coarse pebbles and granules, pebble and granule lenses, some pebble-lined laminae and black laminations. At the base of this is an inch of parallel-bedded fossil hash and pebbles. The uppermost sandstone exposed in the cliffs is silica-cemented, very well-sorted, nonfossiliferous, medium-grained sandstone. It contains small pebble lenses and faint parallel bedding.

At the Muir Creek cliffs, Kirby Creek cliffs, Sandcut Beach, and at Keffer's property, cliff exposures reveal well-bedded very fossiliferous pebbly sandstone layers (Fig. 40). At all of these locations, the very fossiliferous sandstone beds alternate with sparsely fossiliferous beds. Shells are mostly broken except for gastropods and are variously oriented. At Sandcut Beach, they are mostly convex-up; while at Keffer's property, they are both convex-and concave-up. The sandstone is generally very fine-grained and poorly-sorted with a lot of granule-sized material. These are concretionary and mostly parallel- to wavy-laminated sandstones with some low angle truncations, trough cross-lamination, small channels with shell lags, and truncated ripple-bedding. Figure 40 shows the wavy lenticular nature of these truncated large-scale ripples at Sandcut Beach. At Sandcut Beach, these beds grade laterally into wavy-laminated sandstone and interbedded fossiliferous fine-grained, moderately-sorted sandstone. Some of the ripples are scoured into by small pebble- and shell-lined channels, while others are truncated by cross-laminations. Some of the small channels have alternating layers of shells and pebbles mixed with shells.

At Sandcut Beach, a sequence of pebbly fossiliferous sandstone has much burrowing and disrupted bedding with mixed pebble and granule clusters. Burrows are mostly horizontal to inclined and about 4 to 5 inches deep; they are filled with sand. Small silty carbonaceous lenses are also assocciated with this horizon. Above and below this are small asymmetrically-filled channels with pebble and shell lags and minor cross-bedded lenses. The sandstone is crudely parallel-bedded and coarsens and becomes more fossiliferous upwards. Above the rippled wavy-bedded fossiliferous sandstone is parallel-bedded pebbly fossiliferous sandstone with broken shells and whole gastropods.

At the Muir Creek cliffs, facies D is similar to that at Sandcut Beach with some rippled wavy-bedded very fossiliferous sandstone, small channels, and a burrowed horizon. The rippled beds are associated with some two-directional tabular sets of tangential cross-lamination with laminae lined with shells and granules and small pebbles. Also, trough cross-lamination with beds lined with pebbles and shells is more common at Muir Creek than at Sandcut Beach, and the burrowed horizon at Muir Creek contains several thin, wavy, carbonaceous muddy siltstone interbeds.

Exposed at the base of the cliffs is a bioturbated grit with some preserved cross-lamination of granules to coarse sand. Thin carbonaceous layers and some wood pieces are found along with small channels and normally graded pockets. One large burrow is inclined and tapers downwards. Many others go right through the carbonaceous siltstone layers and strongly deform the bedding in them; they are inclined to horizontal to the bedding. Some are filled with granules to coarse sand, while others are filled with sand and possibly finer material. The horizontal burrows show on the outcrop as distinctly mottled horizons. There are some small isolated clusters of either coarse sand or granules and wispy patches of fine-grained material within this grit. Above a thin carbonaceous silty layer is a burrowed (Fig. 41), carbonaceous, pebbly, gritty, medium-grained sandstone, crude parallel-lamination and both normal and inverse grading. A distinct 15 cm-thick layer of whole gastropod shells, disarticulated unbroken clam shells, and some shell fragments, with a wavy base occurs high in the section. The sandstone matrix is fine- to medium-grained, gritty, and moderately poorly-sorted.

At Sombrio Beach, facies D conformably overlies the basal breccia. Here it consists of wavy- to trough cross-laminated fine-grained, moderately well-sorted sandstone with isolated hummocks (Fig. 42) and possibly ripples and tangential wedge sets of cross-bedding. The sandstone is concretionary and weathered yellow. Across the Sombrio River, there is quite a bit of cross-bedded sandstone, pebble to cobble conglomerate, and siltstone. The sandstone is concretionary, with mostly low angle tangential wedge sets and some troughs with associated burrows. At Sombrio Point, the basement rock is very irregular, so that the

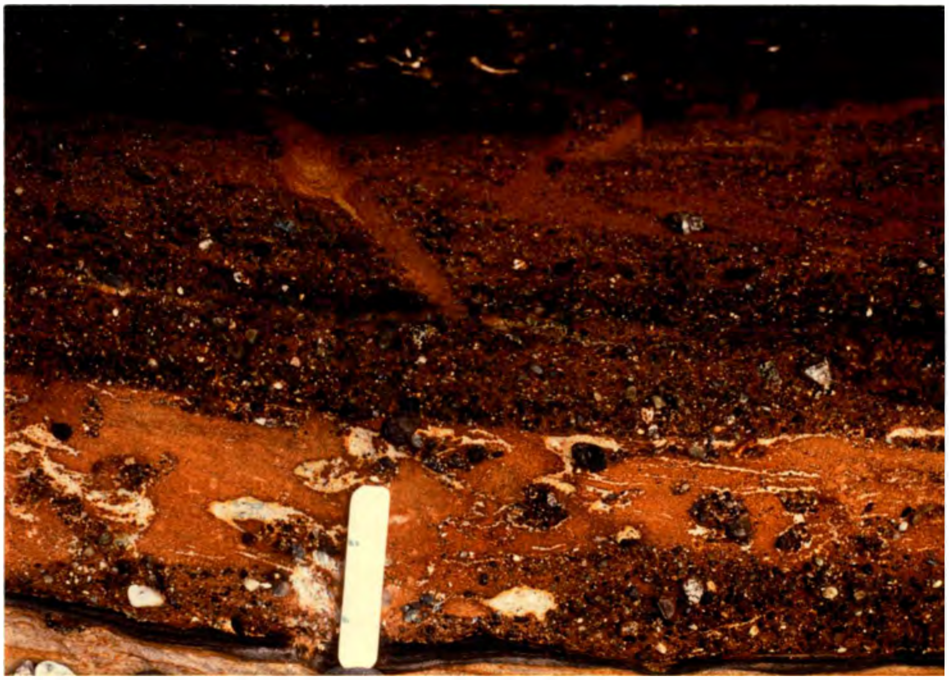


Figure 41. Burrowed horizon in facies D at Muir Creek cliffs. Note trace of cross-bedding preserved in the upper part of the photo. Also note the thin, wavy carbonaceous siltstone layers.

Figure 42. Hummocky cross-stratified sandstone of facies D at Sombrio Beach.

sequence varies somewhat. Overlying the basal breccia is a thin (less than 7.6 cm) thinly-laminated fine-grained sandstone. Above this is trough cross-laminated, fossiliferous, pebbly, gritty, very poorly-sorted medium-grained sandstone (Fig. 43).

At the Correction Camp cliffs, facies D consists of trough cross-laminated sandstones with abundant small channels (Fig. 44) lined with pebbles and granules and filled with parallel-laminated carbonaceous layers. Here there are v-shaped burrows, some of which are nested. There are also some bioturbated mottled horizons which are probably the result of horizontal burrows.

FACIES E

Facies E is a thick-bedded pebbly grit. This facies is present at many locations (refer to Table 1 and stratigraphic columns in Figs. 7 to 25), but constitutes only a small percentage of the Sooke Formation. At some localities, it is fossiliferous; and, at the Correction Camp cliffs, it is burrowed near the top.

At Sandcut Beach, there are two thick-bedded fossiliferous pebbly grit to conglomerate layers. Just below the wavy-bedded fossiliferous sandstone is a layer 0.8 meter thick with whole gastropods, some whole barnacles, and lots of broken shells. Near the top are bone fragments. Pebbles are rounded and moderately-sorted. The grit consists of coarse-grained sand and granules and is poorly sorted. The upper contact is gradational with the overlying beds. The upper thick-bedded grit contains small cross-stratified lenses. This grit is pebbly and has very fine- to fine-grained sand and granules and is fossiliferous. Fossils are broken and rounded. Gravel clasts are subrounded.

Facies E grit is abundant at Keffer's property, where all is

Figure 43. Trough cross-stratified pebbly fossiliferous sandstone of facies D at Sombrio Point.

Figure 44. Sandstone at Correction Camp cliff. Note small channels with gravel lag in one and black-laminated carbonaceous material. Also note nested v-shaped burrow by pen.

fossiliferous. Pebbles and granules are generally subrounded. The lower grit contains mostly moderately-sorted granules and pebbles, while the upper one contains poorly-sorted granules to cobbles. The lower grit has a hint of crude parallel bedding. It is in fault contact with Metchosin basalt. There is a 0.9-meter-wide gouge zone associated with this fault.

FACIES F

This facies only occurs at Sombrio Beach. Along the creek by the waterfalls, nodular, rippled interbedded gray siltstone and fine-grained sandstone overlies the basal breccia. Load casts and convoluted bedding are abundant (Fig. 45). In the Sombrio River, the siltstone is red and gray; the red siltstone is well cemented. Foraminifera have been extracted by B.E.B. Cameron, who is in the process of dating them. Further northwest, in another creek exposure, there is more convoluted rippled siltstone.

Figure 45. Load casts and convoluted bedding in siltstone and fine-grained sandstone of facies F at Sombrio Beach.

FACIES INTERPRETATION

INTRODUCTION

The Sooke Formation was deposited in a high-energy wave-dominated shallow marine environment. Unlike low-energy shallow marine deposits, high-energy deposits are not well-represented in the literature. Studies of modern high-energy nearshore deposits are limited because of difficulties in sampling and observing sedimentological processes in these environments. Significant studies of modern high-energy nearshore deposits include Clifton et al. (1971), Dupre et al. (1980), and Kumar and Sanders (1976); Leithold and Bourgeois (1984); Bourgeois and Leithold (1984); Phillips (1984); Howard and Reineck (1981) studied ancient deposits.

The shallow marine environment has been divided into discrete geomorphological zones, each with characteristic sedimentological processes, many of which overlap. Because the terminology for these zones is confusing, the following discussion defines the terminology used in this thesis and the various sedimentological processes that occur in the high-energy beach and nearshore zones. Figure 46 shows the zones.

The term beach is a general one which encompasses both the backbeach and the foreshore (Davis, 1982). The backbeach is defined as the coastal area above mean high tide (Bourgeois and Leithold, 1984). Eolian and fluvial processes dominate except for periodic washover of the berm crest during storms or swash (Bourgeois and Leithold, 1984). The backbeach is separated from the foreshore by the berm, which is built by deposition from swash, which decelerates as it washes up over the foreshore and onto the backbeach. The foreshore (also referred to as beachface) is defined as the zone extending from mean high water to mean low water and is affected by swash, backwash, surf, rip currents, and longshore currents. Swash and backwash are the dominant processes.

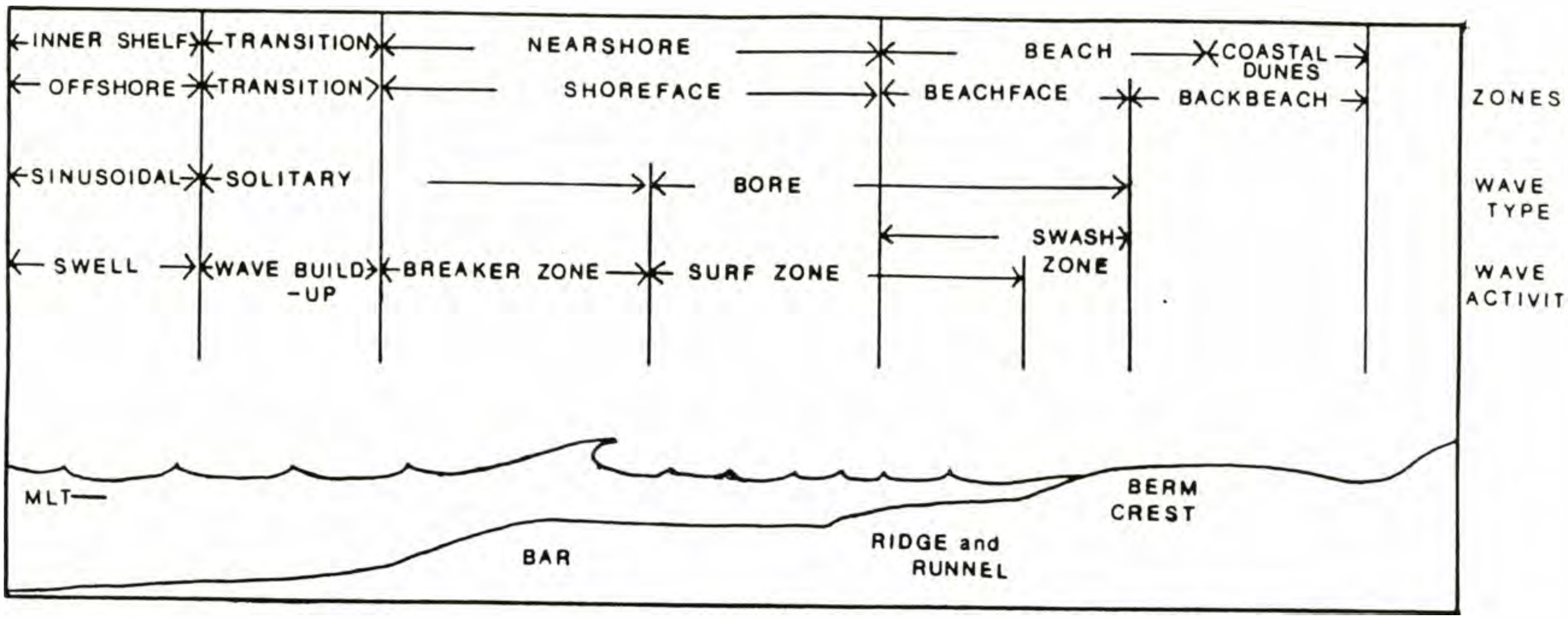


Figure 46. Coastal zones, wave-types, and wave activities (modified from Clifton et al., 1971; Dupre et al., 1980; Bourgeois and Leithold, 1984).

The shoreface is the zone that extends from mean low water to the point where the waves first break (Bourgeois and Leithold, 1984). This area is affected by breaking waves, bore in the surf zone, and longshore and rip currents. The lower depth limit varies because waves break farther out during storms than during fair weather conditions (Bourgeois and Leithold, 1984). The shoreface-offshore transition zone is that zone which is affected by wave build-up and has no clear boundaries (Bourgeois and Leithold, 1984). Burrowing is much more abundant in this zone than in the shoreface zone. The offshore zone is characterized by oscillatory wave motion and by abundant burrowing and fine-grained sediment. The Sooke Formation was deposited in all of these zones, but dominantly in the shoreface and foreshore zones.

Wave activity is the dominant depositional and erosional mechanism in the beach and nearshore zones. As waves approach the shoreline, they are transformed into solitary wave forms and induce sediment transport (Elliot, 1978). They also generate nearshore currents which are capable of transporting sediment. Figure 46 shows the transformation zones for shoaling waves. In the build-up zone, the wave is transformed from a sinusoidal or trochoidal form to a solitary wave form. Each solitary wave transports sediment dominantly shoreward. Figure 47 shows the motion of sediment in the breaker zone, a very high-energy zone that tends to concentrate the coarser sediment. As a wave shallows, its height increases and it steepens and eventually breaks when the water depth is 1.3 times the breaker height.

In the surf zone, the wave consists of a bore which is generated as the wave breaks. This zone has the strongest longshore currents and may have storm-generated rip currents. In the surf zone, sediment movement may be both landward- and seaward-directed. Surf zone deposits are

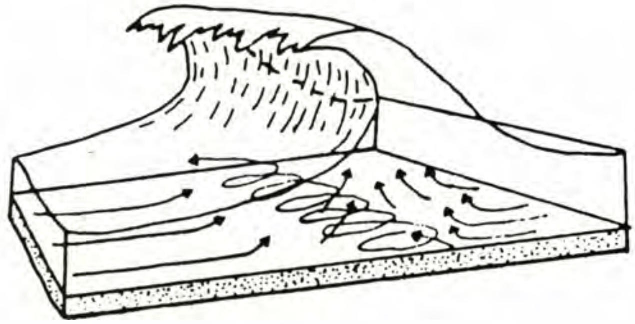


Figure 47. Sediment transport with a breaking wave: Coarse-grained sediment moves as bedload in a series of elliptical paths parallel to the coast, while finer sediment is suspended (modified from Ingle, 1966) (from Elliot, 1978).

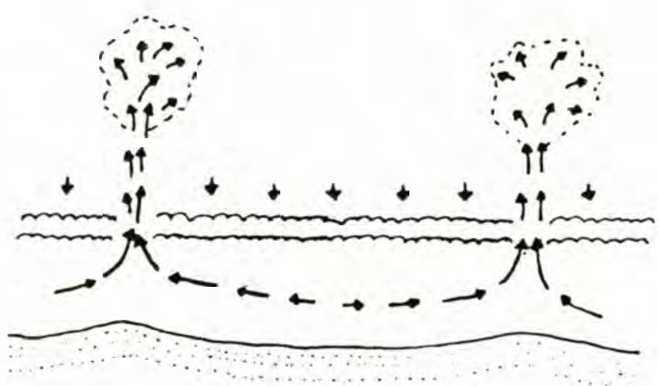


Figure 48. Wave-induced nearshore circulation system (after Shepard and Inman, 1950) (from Elliot, 1978).

variable, but usually consist of trough cross-stratified to parallel-bedded sands and gravels (Dupre et al., 1980; Bourgeois and Leithold, 1984; Clifton et al., 1971). Sands in the surf zone are generally well-sorted.

In the swash zone, each wave produces a very shallow, high-velocity landward-directed swash flow followed by a seaward-directed backwash flow. Swash zone deposits characteristically consist of well-sorted sand and gravel, often micaceous. Parallel laminations with low-angle truncations, inverse grading, and pebble imbrication are common (Dupre et al, 1980; Clifton, 1969).

The two types of wave-induced currents are rip currents and longshore currents. A rip current is a high velocity seaward-directed current formed in response to a hydraulic head generated on the beach by the pile-up of water during a storm (Elliot, 1978); rip currents are more common during winter and spring stormy seasons (Cook, 1970). Figure 48 shows the circulation system that creates rip currents. Rip currents are common along sandy beaches as well as rocky headlands (Cook, 1970). Longshore currents are generated by obliquely approaching waves and flow, usually in troughs, parallel to the shoreline in the surf and breaker zones (Elliot, 1978).

Superimposed on all of these processes is the effect of storms. Storms can severely alter the beach profile by eroding the beachface and carrying sediment into the shoreface and offshore zones. During storms, the waves have shorter periods than the long-period swell that occurs during fair-weather conditions (Elliot, 1978). These short-period waves have higher energy, which lowers wave base, and they transport a lot of sediment compared to fair weather waves.

The nearshore deposits in the Sooke Formation resemble those described by Clifton et al. (1971) for a high-energy non-barred nearshore coastline and those described by (Hunter et al., 1979) for a barred high-energy coastline. Clifton et al. (1971) have interpreted the major features of the bed forms in terms of flow regime, analogous to the flow regimes which apply to continuous, unidirectional currents of a fluvial system. They have divided the non-barred nearshore system into 5 major facies, each related to a particular flow regime. The flow regimes and associated bedforms are shown in Figure 49. Not all of the facies are always present, but they are always consistent in terms of positions relative to one another (Clifton et al., 1971).

The outermost facies consists of asymmetric ripples formed in the innermost offshore. The outer rough facies consists of lunate megaripples that form in the transition zone or shoreface. The outer planar facies consists of nearly horizontally-bedded sandstone produced by sheetflow in the inner part of the wave build-up zone and outer surf zone. The inner rough facies consists of megaripple trough cross-stratification and ripple bedding produced in the inner surf zone in the area where surf and swash processes interact. The inner planar facies consists of swash laminae produced by sheetflow under upper flow regime planar bed conditions. In the barred nearshore (Hunter et al., 1979), the swash-surf transition zone (inner rough facies) is replaced by a swash-trough transition zone and the surf zone (outer planar facies) is replaced by longshore trough and rip channel zones. Since the terminology for all of these zones and processes is easily confused, I will refer to the geomorphological zones and processes operating in them and with the facies of Clifton et al. (1971) in parentheses.

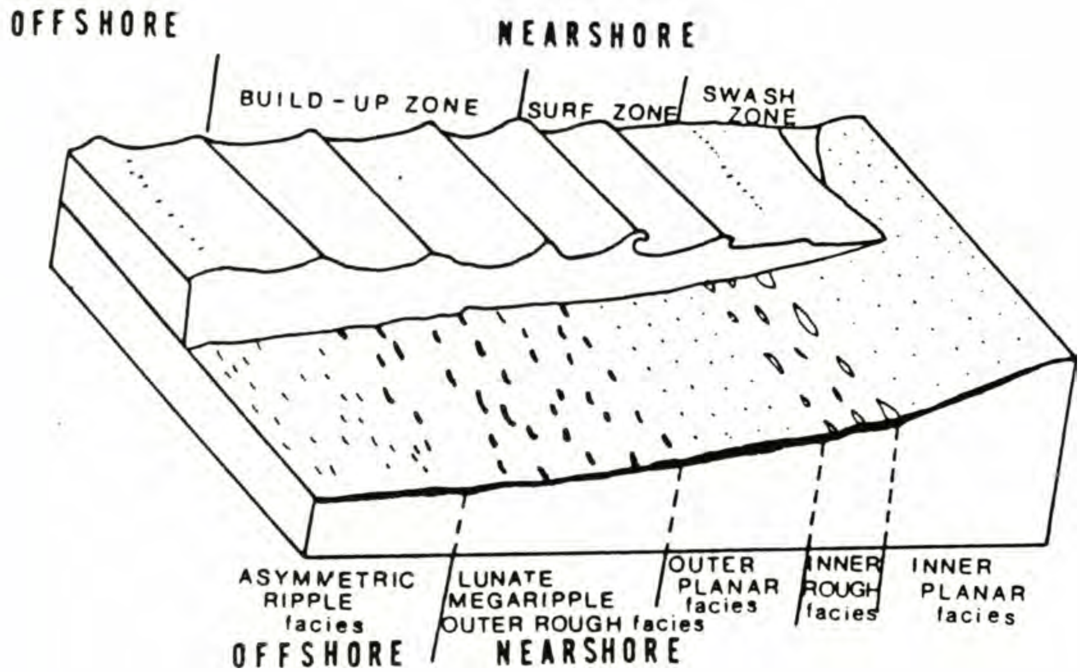


Figure 49. Sedimentary facies and wave activity within and adjacent to the high-energy non-barred nearshore (from Clifton, et al., 1971).

FACIES INTERPRETATION

FACIES A: Boulder breccia

Facies A is unique in that both the coarseness and angularity of the clasts indicate close proximity of the source area to the depositional site. The shelly sand matrix at some locations (Sombrio Beach, Mystic Beach, and China Beach) indicates deposition in a shallow marine environment. The processes that could be responsible for transporting and depositing the boulder-sized (i.e. 0.9 to 1.5 meters in diameter) clasts in the Sooke Formation are debris flows and rock fall from cliffs and sea stacks.

In some locations, the boulders were derived by rock fall or landslides from topographic highs in the basement rock such as adjacent cliffs or sea stacks. At Mystic Beach, China Beach Provincial Park, Point-No-Point, and East Sooke Park, the boulders are of the same compositions as the basement rock and, at Mystic Beach in particular, the basal contact has at least 4.5 to 6.1 meters of relief. In these cases, cobbles and large pebbles are probably also derived from rock-fall and breaking up of large boulders along joints and by crashing against each other in the surf.

The angularity of the clasts suggests that the accumulation occurred adjacent to the stacks and cliffs. The angularity of the sand indicates that it was not reworked by waves or currents for very long, if at all, before it was deposited. Petrographic studies indicate that the sand, granules, and small pebbles were derived from multiple sources, probably by a combination of processes such as fluvial supply, longshore currents, and shoaling waves. Sandstone lenses within the basal breccia at the Correction Camp cliffs were deposited in pockets behind the stacks or beneath cliffs in small coves. The carbonaceous laminations in these lenses are probably a result of one or several flooding events of a nearby fluvial system that carried abundant organic material.

Where shells are present in the matrix, they are broken; the large pieces of oyster and clam shells indicate that they were worked by the waves to some extent before they were deposited. The organisms were probably inhabitants of nearby rocky ledges and sandy shoals. Miller and Orr (1986) describe a Late Oligocene marginal marine sequence in the Scotts Mills Formation in Oregon of conglomeratic debris which was derived from exhumed wave-cut platforms and sea stacks of basaltic basement, a source much like that which I propose for much of facies A of the Sooke Formation.

A debris flow origin is likely for the facies A breccia at Sombrio Beach. The nearest present outcrop of the Leech River Complex is approximately 1.5 to 2 kilometers inland, and rockfall cannot transport boulders that far. Therefore, unless the source for the abundant boulder-sized clasts of Leech River schist has been completely removed by erosion, a debris-flow origin is the most likely. A debris flow could easily transport boulder-sized material for such a distance.

Applying the terminology of Middleton and Hampton (1973), a debris flow is a type of mass sediment flow, equivalent to the slurry flow of Carter (1975). It is a high density, high viscosity, quasi-plastic slurry that contains a significant proportion of large clasts (Shultz, 1984; Fisher, 1971). In order to transport large-boulder-sized clasts, a debris flow must have substantial plastic yield strength (Shultz, 1984). Flow at the base is usually laminar, but evidence for laminar flow was not observed in the Sooke Formation. Deposition is by in situ freezing of the entire mass (Carter, 1975; Shultz, 1984; Fisher, 1971). According to

Rodine and Johnson (1976), debris flows can transport large blocks even on gentle slopes. Surging debris flows are common, and flows often show signs of intersurge reworking of their tops by either fluvial or marine processes (Nemec and Steel, 1984; Fisher, 1971).

If a debris flow was responsible for supplying the coarser sediment in the Sooke Formation, then the paucity of mud in the matrix must be explained. Three possible explanations for the sandy matrix are: 1) winnowing of an original muddy matrix by wave action in the beach to nearshore zones, 2) replacement of mud by calcite cement during diagenesis, and 3) an original sandy matrix from a source area that contributed sand rather than mud.

In order for effective winnowing to take place, the deposit would have had to be relatively thin and wave energy must have been high. The basal breccia at Sombrio Beach is relativey thin (generally less than 0.3 meters). The small pockets of normal grading in the matrix could be the result of infiltration of beach to nearshore gravels, shells, and sand. Alternatively, this grading could be the result of reworking of the upper surface of part of the debris flow deposit by waves or currents which would have winnowed away fine material and deposited sand and gravel. The second possibility, replacement of a small original percentage of mud in the matrix, is also a possibility for the Sooke Formation; since debris flow needs less than 1% mud in order to support large clasts during flow (Wells, 1984). However, petrographic studies indicate that, at Sombrio Beach, replacement of original mud is not likely to have occurred during diagenesis. The calcite cement in this rock is coarse spar and very clear; if it had replaced mud, it would probably be murky. The third possibility, that the original source area provided sand rather than mud is likely. This is the preferred explanation for the sandy matrix because it is the most likely. The debris flow could have originated inland in schistose terrane and picked up basaltic debris as it traveled, both materials contributing sandy material to the matrix. Shells got mixed in as the flow traveled and incorporated beach and nearshore sands. The debris flow was deposited on an irregular bedrock platform. The angularity of the sand grains indicates that the grains did not spend a substantial ammount of time being reworked by waves at the depositional site. The sand matrix was derived from multiple sources. Debris flows are quite common now along the coast in this area and on many other coastlines, and I have observed them after they have flowed onto the beach.

The Sooke Formation basal breccia was deposited along a very rocky coast by two mechanisms, debris flows and rock fall, as is shown diagramatically in Figure 50. The debris flows transported very coarse material from adjacent slopes possibly associated with coastal alluvial fans, as would be expected for a tectonically active area, or fan deltas down stream drainages to the coast, where they deposited the material on the beach and out onto the shoreface. Since there are no associated alluvial channel deposits, the flows were probably triggered by heavy rainfall and followed a stream that only flowed during storms and therefore did not have significant channel deposits other than the debris flows. Slumping could have occurred on nearby slopes as it commonly does along erosional coastlines. Rock falls off steep wave-cut cliffs and seastacks also carried facies A debris onto the beach and shoreface.

FACIES B: Dominantly muddy matrix conglomerate

SUBFACIES B1: Muddy to muddy sand matrix boulder conglomerate

The lack of sorting, indistinct stratification, lack of consistent

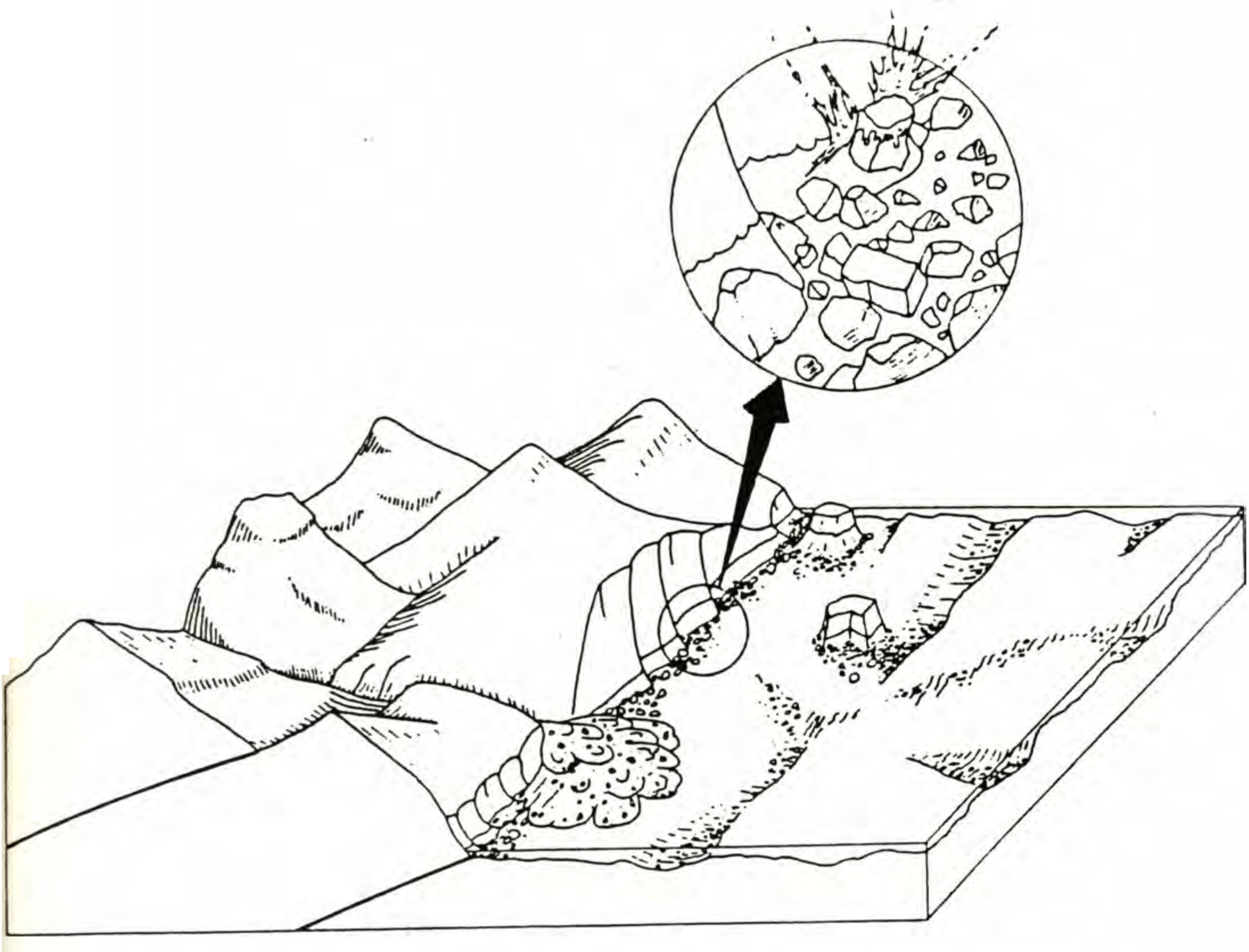


Figure 50. Block diagram showing depositional setting for the basal breccia of facies A.

orientation of clasts, presence of wood, presence of some boulder-sized clasts, and, most significantly, the muddy sand and silty sand matrix that characterize this facies are all features of debris flow deposits (Wells, 1984; Fisher, 1971; Shultz, 1984) and suggest a debris flow origin for these deposits. The presence of the mud in the matrix in these deposits is probably the result of the thickness of the flow and to a source area that supplied mud.

At both localities where subfacies B1 is exposed, the base is either poorly exposed or not exposed at all. At Mystic Beach, the base is erosional, and slightly undulatory, while at Beach Trail, the base is not exposed. At Mystic Beach, there is weak inverse grading at the base. At Beach Trail, there is inverse grading at the base of the exposure. Inverse grading is common at the base of debris flows, suggesting a high dispersive pressure in clast support (Nemec and Steele, 1984). It is also indicative of mass immobilization, or freezing, of the moving slurry, rather than selective, tractive depostion (Shultz, 1984). The small carbonaceous sandstone lenses, which constitute less than about 5% of the deposit at Beach Trail, could represent the waning phases of flows and possibly reworking by waves in a very shallow environment or by streams between surges.

At both Beach Trail and at Mystic Beach, the lateral relationships suggest that the debris flows flowed onto a beach to nearshore environment. At Beach Trail, this occurred early in the depositional history of the Sooke Formation in that part of the basin. These debris flows probably resulted from mass wasting on nearby slopes during heavy rains. At Mystic Beach, the debris flow is overlain by additional probable debris flow deposits, which are in turn overlain by beach to nearshore deposits.

SUBFACIES B2: Muddy to muddy sand matrix pebble conglomerate

Conglomerates of subfacies B2 differ significantly from those of subfacies B1 in having smaller maximum and modal clast sizes, thinner deposits, and the presence of burrowing in subfacies B2 at French Beach Provincial Park. At French Beach Provincial Park, the association of the muddy matrix conglomerate with magnetite-rich conglomerate and woody sandstone and the roundness of clasts suggests that the muddy matrix conglomerate was deposited at the mouth of a small stream that was ponded upon entering the backbeach area, perhaps by a berm deposit. Ponded deposits such as this have been described by Hunter (1980). At French Beach, the pebbles were probably stream bedload material and the muddy sand resulted from settling of suspended material that was being carried in the stream. The burrowing in muddy sediment (Skolithos) suggests a quiet environment where organisms could feed. The deposit of pebble conglomerate with a muddy to muddy sand matrix that is exposed along Rosemond Creek was likewise probably deposited at the mouth of a small stream entering a beach or backbeach area, possibly lagoonal. It overlies bioturbated parallel-laminated sandstone which is interpreted as lower foreshore swash zone deposits. The muddy deposits along Kirby Creek could be associated with a fluvial system similarly to the other subfacies B2 deposits, with the sandstone interbeds representing failure of the berm and deposition of fluvial or swash sediments.

A debris flow or mudflow origin cannot be ruled out for any of these deposits. The subfacies B2 conglomerate that is exposed along Kirby Creek is more likely than the other subfacies B2 conglomerates to be a debris flow deposit because there are sandstone interbeds which could represent intersurge reworking. The matrix is very muddy and the deposit is much thicker than either of the other two subfacies B2 deposits. The roundness and varied lithologies of the clasts indicates that they were transported to some extent by fluvial processes.

FACIES C: Conglomeratic sandstone

SUBFACIES C1: Cross-stratified sandstone with boulder conglomerate

Clasts in these deposits are distinctly better rounded than clasts in the basal breccias. The presence of these boulder conglomerates with cross-laminated sandstone indicates that there were at least two different processes operating in this depositional environment. Debris flows could have transported the large boulders which are present in most of these deposits. The inversely graded boulder conglomerate, which overlies the muddy matrix facies B conglomerate at Mystic Beach is likely a debris flow deposit. The small sandstone lenses result from intersurge reworking of the tops of successive flows. The inverse- to normally-graded conglomerates at China Beach Provincial Park are also likely debris flow deposits, probably from three separate flows, each transporting different sizes of clasts. The roundness of the clasts suggests that they were either fluvially transported or rounded by waves prior to being incorporated into a debris flow. Slumping of older beach deposits (shown diagramatically in Figure 51) could also account for the subrounded boulder-sized clasts and for the sandy matrix. Other boulder conglomerates are debris flow deposits that have been slightly reworked by waves, thus accounting for the greater roundness of the clasts compared to those of the facies A breccias.

The sedimentary structures of the interbedded sandstones indicate that these boulder conglomerates were deposited in a high energy beach-to-shoreface environment. Howard and Reineck (1981) report that, along the

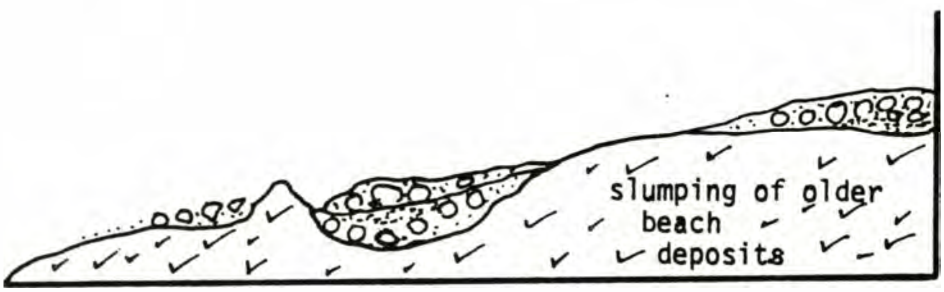


Figure 51. Schematic cross-section showing the origin of some of subfacies C1 boulder conglomerates by slumping of older beach deposits onto basal breccias and sandstones (Modified after Bradley, 1957).

modern California coast, large-scale cross-bedding begins near the low tide line and continues throughout the shoreface. Exposures along Rosemond creek show an extensive thickness of subfacies C1 conglomerate and sandstone, which includes at least 4 boulder conglomerate layers above the basal breccia. The sequence of sandstones between two boulder conglomerates, which was described in detail in the previous section, indicates a general upwards increase in flow regime or wave energy. Following deposition of the boulder conglomerate, the bioturbated sandstone was deposited in a relatively low energy, quiet environment. This was possibly a backbeach environment, perhaps a lagoon, where the mica grains could settle out of suspension. The trace fossils (Macaronichnus segregatis) occur along bedding planes, which suggests that there was sufficient time between deposition of individual laminae for organisms to feed. This sandstone is overlain by additional possible lagoonal deposits of subfacies B1 muddy pebble conglomerates.

Above these quiet water deposits, nearshore deposition of rippled, trough cross-laminated, and parallel-laminated sandstones occurred. This sequence could be the result of everyday processes in the shoreface environment, or it could be related to waning storm events. The base of the rippled sandstone contains a thin storm lag deposit of scattered shells and pebbles. After the storm, the surface became covered with ripples. The sand in these ripples was either deposited by settling out of suspension or brought back in suspension from the foreshore and inner shoreface as the storm waned (Kumar and Sanders, 1976). Rapid deposition is suggested by the deformation of the ripples. The trough cross-laminated sandstone was deposited in response to a subsequent increase in wave energy, which caused megaripples to migrate laterally on the shoreface. According to Hunter et al. (1979), medium-scale cross-bedding formed by migrating megaripples is the dominant bedform in most of the nearshore. Parallel-laminated sandstone with low-angle truncations could be the result of upper plane bed flow conditions (outer planar facies of Clifton et al., 1971) in the surf or breaker zone or of ripple trains migrating on the shoreface; or, alternatively, it could be swash zone deposits (inner planar facies of Clifton et al., 1971) (Clifton et al., 1971; Clifton and Boggs, 1970; Dupre et al., 1980). The small-scale trough cross-lamination at the top of this sequence was deposited during different energy conditions than the parallel-laminated sandstone, as a result of small-scale megaripples migrating. Following deposition of the upper sandstone, there was another event which deposited a boulder conglomerate on the beach or shoreface. This sequence represents the complex interactions of the various nearshore processes.

At Mystic Beach, the sequence of conglomerate to medium-scale trough cross-laminated pebbly sandstone to large-scale climbing rippled sandstone indicates a decrease in flow regime. The conglomerate contains mostly pebbles and cobbles but has scattered boulders and therefore was deposited in a fairly shallow part of the nearshore or on the beach. The overlying sandstones were deposited on the outer shoreface in the surf zone, probably after a storm. The parallel-laminated sandstone that truncates the climbing ripples is probably swash zone deposits and is overlain by another small-boulder conglomerate.

SUBFACIES C2: Thick-bedded cobble to pebble conglomerate and breccia

The breccia and conglomerate of this subfacies were deposited by a process that produced minimal rounding of clasts, as was the basal breccia of facies A. These are also interpreted as debris flow deposits. The difference in clast results either because the source area provided smaller clasts than those of the basal breccia or because these deposits are distal to coarser deposits that are not exposed along the coast. The cross-laminated sandstone lenses which are interbedded with these deposits probably result from intersurge reworking of part of the upper surface of the debris flow by waves. This reworking would have occurred in the nearshore or beach envrionment. Since these deposits have a sandy matrix, the same matrix problem exists for these deposits as for the basal breccia at Sombrio Beach. The better rounding of the conglomerates which lie above one of these breccias suggests that these were fluvial bedload sediment or deposits that became incorporated in a debris flow.

The breccia that is exposed in the cliffs to the northwest of the Sombrio River is more likely to a fluvial channel deposit than a debris flow deposit. The strong scouring at the base and imbrication of clasts are both more characteristic of fluvial deposits than of debris flow deposits. The laminated sandstones above and below it are probably beach-to- nearshore deposits.

SUBFACIES C3: Cross-stratified sandstone with parallel- to thick-bedded pebble conglomerate with some small pebble lenses

Deposition of subfacies C3 sandstones and conglomerates occurred in a high-energy beach-to-nearshore environment which was strongly influenced by storms. The pebble conglomerates are interpreted as lag deposits, mostly from storm events in the upper shoreface or lower foreshore, and as wave-reworked fluvial gravels. Boulders are rare in this subfacies, but exposures at French Beach Provincial Park contain isolated boulders within pebble conglomerate beds. These conglomerates are interpreted as lower foreshore beach deposits. The thin wavy conglomerates could have accumulated at the toe of the beach where coarse material commonly accumulates (Dupre et al., 1980). A fluvial source for these gravels is likely. The large boulders probably were deposited by rock fall from cliffs or terraces, as suggested by the pinched pebble layers beneath some of the boulders, or some may have been left behind by winnowing of debris flow deposits by waves as described by Shultz (1984). Many modern beaches, including several in the field area, have boulders at the toe of the beach that have been rounded by waves. The concentrations of pebbles and cobbles on one side of many boulders is probably a result of backwash moving the gravelly sediment seaward where it gets caught and piles up behind the boulders.

The parallel-bedded thin pebble conglomerates that are found near the base of the cliff exposure at French Beach are probably shoreface storm lag deposits. Lag deposits of this type have been described by Kumar and Sanders (1976). They can be quite variable in thickness. These deposits could be the result of sorting by a rip current, which commonly leaves coarser particles behind as a lag in the surf and swash zones (Cook, 1970). Some lag deposits contain pebbles such as the deposits at French, while others consist dominantly of shells. The successive fining-upward trend of different conglomerate layers could result from differences in storm wave energy. For example, one storm wave could have sufficient energy to transport coarse pebbles and sand, while the next storm wave moves granules and sand.

At French Beach, at the top of this sequence there is a normally graded conglomeratic sandstone that contains a concentration of magnetite; the conglomerate deposited above it contains some ripups of the magnetite-rich sandstone. Heavy mineral concentrations are commonly found in the swash zone. The heavy minerals could have accumulated on the foreshore where heavy mineral concentrations are common (Clifton, 1969; Dupre et al., 1980). Erosion of the foreshore during a storm or a series of storms could have resulted in redeposition of the material on the shoreface. The conglomerate above this magnetite-rich conglomeratic sandstone contains a small sandstone lens with shell-lined laminae. This lens could be from a small sandy bar or on the shoreface.

Sandstones in this facies at French Beach are dominantly cross-laminated and are interpreted as shoreface deposits. They are the result of normal fairweather shoreface processes between storm events. Storm deposits in rip current channels are similar, but generally consist of sand smaller than medium grain size (Cook, 1970). Since these deposits contain scattered pebbles and granules, they are more likely fairweather shoreface deposits.

The contorted sandstone with abundant woody material could have accumulated almost anywhere in the beach to nearshore envrionment. The deformed nature of the sandstone and contorted wood pieces could be the result of dewatering of water-logged wood pieces or the result of burrowing. The pinching out of this deposit suggests that it accumulated by piling up in some sort of a depression against a barrier such as a bar or a berm.

The thin, wavy, pebble conglomerate beds at Mystic Beach were also deposited in the foreshore beach or shoreface environments as lag deposits, probably resulting from high-energy storm waves concentrating the coarser material and lifting finer material into suspension (Kumar and Sanders, 1976). The conglomerates were probably fluvially-supplied and deposited at the mouths of small coastal streams where they accumulated in gravel mouth bars and were subsequently redistributed by wave action. Some of the conglomerates at Mystic Beach are tabular, laterally continuous foot-thick beds which strongly resemble reworked fluvially-supplied conglomerates described by Clifton (1973), Leithold and Bourgeois (1984), and Dupre et al. (1980).

Sandstone interbeds at Mystic Beach indicate rapidly fluctuating wave energy conditions. The transition from a conglomeratic lag deposit to parallel-laminated sandstone to trough cross-laminated sandstone indicates a decrease in flow regime or wave energy. The parallel-laminated sandstone is probably upper flow regime plane bedding deposited as laminae in the swash zone (inner planar facies of Clifton, et al., 1971) or outer surf zone (outer planar facies of Clifton et al., 1971). The overlying trough cross-laminated sandstone was formed by lower flow regime megaripples in the area where swash and surf zones interact (inner rough zone of Clifton et al., 1971) or on the shoreface in the outer surf zone. This whole sequence could be related to a waning storm current and re-establishment of normal shoreface processes.

At Sombrio Beach, the upward increase in the degree of clast roundness in the conglomerates suggests either a change in the mechanism of transportation of the pebbles or a change in the processes that acted on these pebbles at the depositional site. The increase in rounding could indicate a change from debris flow-supplied clasts to better-rounded fluvially-supplied clasts. Alternatively, it could signify that the upper gravels were reworked longer and more thoroughly by waves in the depositonal site. The tabular shapes of clasts and strong imbrication in the upper conglomerate suggest that these gravels were reworked by waves and redeposited on the lower foreshore, where pebble imbrication is common (Dupre et al., 1980; Hunter, 1980).

The float blocks from the Muir Creek cliff present a different picture than the rest of the subfacies in terms of wave energy and water depth. The large unbroken mollusc shells, contorted silty clay beds, and rippled black-laminated layers all indicate low-energy conditions above fairweather wave base. A lagoon or other back-beach ponded water is a likely setting for these deposits. The lagoon would have had periodic flushing in of sand and pebbles during an exceptionally high tide or a storm. The shells were probably derived from within the lagoon itself. Convex-upward orientation of disarticulated bivalve shells is the most hydrodynamically stable position (Clifton and Boggs, 1970). This convex-upward shell orientation suggests the presence of occasional strong currents or waves. The two-directional cross-lamination is a result of changing current or wave directions and probably, in this case, a tidal effect. The associated silty clay ripups indicate periodic influx of a stronger current or wave than normally occurs there. Carbonaceous black-laminated, rippled sandstone and contorted silty clay layers are probably also lagoonal deposits indicating very quiet, low-energy conditions. Alternatively, this sequence could have been deposited in a shoreface environment where wave energy was periodically lower than normal, such as in a shallow trough.

FACIES D: Cross-stratified and parallel-laminated sandstones with scattered pebbles, pebble lenses, and sandstone channels

Facies D sandstones, grits, and minor conglomerates represent deposition on a high energy shoreface mostly above fairweather wave base. Facies D deposits variable characteristics are evidence for rapidly fluctuating conditions of wave energy.

The facies D deposits at French Beach Provincial Park overlies shoreface and possible foreshore deposits. These deposits contain low angle trough and tangential wedge sets of cross-laminated sandstone and wavy-laminated sandstone which are associated with rare isolated hummocky cross-strata. Hummocky cross-strata have been described in the literature by many authors (Hamblin and Walker, 1979; Wright and Walker, 1981; Bourgeois, 1980; Dott and Bourgeois, 1982; Hunter and Clifton, 1982) and indicate storm-wave deposition (Fig. 52). Hummocky cross strata usually occur on the inner shelf just below fairweather wave base, but they have also been reported from shoreface to lagoonal deposits (Dott and Bourgeois, 1982). Since the hummocky cross-strata at French Beach are not abundant and are associated with wavy-laminated sandstone, and not with mud or siltstone, they probably formed on the lower shoreface. After a storm wave passed, normal shoreface megaripple migration resumed, forming the trough and tangential wedge sets of cross strata. Other storms are indicated by the shell lags (Kumar and Sanders, 1976). The gastropods in these lags were resistant to abrasion and acted like pebbles rolling under the waves while finer material was lifted into suspension.

The upper surface of this shoreface sandstone at French Beach has been scoured by a high-energy storm event leaving a layer of scattered round pebbles above a thin veneer of fossiliferous sandstone. This storm event affected fairly shallow depths because there are both broken and disarticulated and unbroken shells. Oyster shells are common in this sandstone as are gastropods, barnacles, scallops, and clams: a mixture of organisms that lived on a rocky substrate with those that burrow in sandy substrates. Thus, some shells were probably derived from rocky cliffs and sandy coves adjacent to the depositional site, while others had been battered around more by the waves. The distribution of pebbles and granules within these beds reflects both the supply of material and the wave energy. Low-angle cross-lamination results from migrating

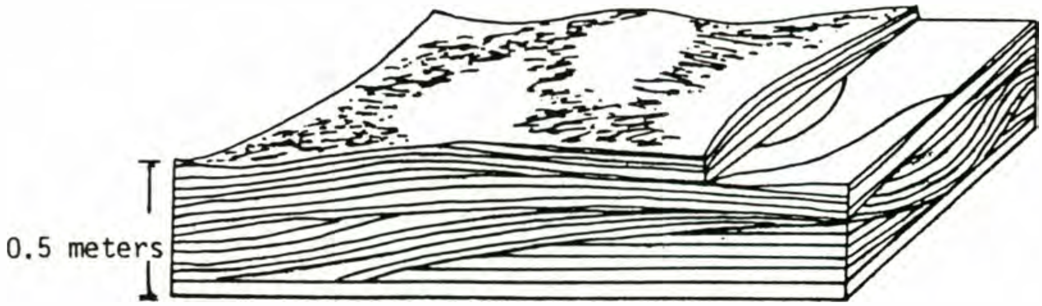


Figure 52. Hummocky cross-stratification (Harms et al., 1975).

megaripples on the shoreface (Clifton et al., 1971; Dupre et al., 1980; Bourgeois and Leithold, 1984). Migrating low-amplitude megaripples formed the pebble conglomerates to pebbly sandstones and conglomerate lenses above the fossiliferous sandstone. These megaripples formed in longshore bars and troughs or possibly in rip current channels. The black laminations may have formed in the troughs between bars. Wave energy was high enough to transport pebbles and granules along with the sand. The thin deposit of parallel-bedded fossiliferous hash and pebbles resulted from either outer surf zone or swash zone deposition of high-energy plane bed transport. The upper sandstone at French Beach Provincial Park is also either outer surf zone or swash zone plane bed deposition from sheet flow under upper flow regime conditions.

The exposures of facies D at the Muir Creek cliffs, Kirby Creek cliffs, Sandcut Beach, and at Keffer's property were all formed in a high-energy environment with a complex interplay of wave activities. The well-bedded, very fossiliferous sandstone layers (Fig.40, p. 67) at all of these localities resemble deposits in the Elk River beds, which are described by Armentrout (1980) and Clifton and Boggs (1970). The well-bedded sandstones in the Sooke Formation were formed under very rapidly fluctuating conditions, probably under "rapidly alternating planar and rippled bed phases" such as those described by Dupre et al. (1980), perhaps in the surf zone with a breaker zone relatively nearshore. The diversity in orientations of shells and shell fragments suggests that the processes varied at different locations within the basin. A mixture of both concave- and convex-up shells has been explained by Clifton and Boggs (1970) as resulting either from currents or waves that are too weak to produce a pronounced shell orientation, or from rapid deposition in sediment traps, penecontemporaneous deformation, or from disruption by burrowing organisms. Because of a lack of evidence which would suggest otherwise, these random orientations in the Sooke Formation were most likely produced by rapid deposition. A dominantly convex-upward shell position, the hydrodynamically most stable position, such as is found at Sandcut Beach, is commonly found in the central part of the surf zone (Clifton and Boggs, 1970).

In all of these locations, very fossiliferous sandstone beds alternate with less fossiliferous sandstone beds. This alternation suggests that there were a series of large wave surges that carried in the shells and granules alternating with weaker surges that moved mostly sand. The trough cross-laminae result from megaripple migration. Surges of different waves capable of moving different sized particles are also evident from the layering in the small channels. These channels probably formed due to a bed irregularity, perhaps initiated by organisms, and subsequent scouring. Squires (1981) describes small channels in Eocene shallow marine deposits in southern California, which he attributes to surge channels cutting through the shoreface. Similar interpretations are made by Brenner and Davies (1973) for Upper Jurassic sandstones in Wyoming and Montana.

At both Sandcut Beach and at the Muir Creek cliffs, the burrowed horizons indicate that there was a period of fairly quiet waves probably between storm events, when organisms were actively feeding in the sediment. At both locations, the burrowed horizons (Skolithos) are associated with either thin (some rippled) carbonaceous silty beds, more common at the Muir Creek cliffs, or with small silty carbonaceous lenses. These also indicate low wave-energy, and probably supplied some of the organic material that the organisms were feeding on. At both locations, bedding is disrupted by burrowing, with some sediment mixing, but not everywhere completely destroyed. Campbell (1971) describes burrows from shoreface sandstones in the Upper Cretaceous Gallup Sandstone that commonly destroyed all original laminae. The burrows in the Sooke Formation were probably formed by organisms feeding or dwelling in the tops of migrating gravel and sand bars or megaripples during times when fairweather conditions prevailed. At Sandcut Beach, the carbonaceous lenses that are associated with the burrowed sandstone were probably deposited in troughs between bars or depressions on tops of bars during fairweather conditions. At the Muir Creek cliffs, the thin carbonaceous layers were also deposited during fairweather conditions. The slightly rippled nature of these suggests that they were deposited as lower flow regime ripples, perhaps on the lowermost shoreface or that they were deposited out of suspension and later molded into ripples by a passing wave. At Muir Creek, most burrows were passively filled mostly before the carbonaceous material was deposited, but the deformation of some of the silty carbonaceous laminae indicate that the organisms made their escape after that sediment was deposited. The upper part of the burrowed section at the Muir Creek cliffs is less intensely burrowed and has better preservation of original trough cross-bedding than the lower part. Small channels in this burrowed zone at Muir Creek were probably caused by small rivulets or surge channels eroding into the tops of bars.

At the Muir Creek cliffs, the burrowing and quiet deposition of the uppermost silty carbonaceous layer was followed by an event on the shoreface that left a lag deposit of gastropod shells. The wavy base to this shell bed indicates that the waves that formed it scoured the surface slightly, but not enough for it to have been a major storm event. Also, the moderately poor sorting of the sandstone matrix of the bed indicates that deposition was rapid and allowed no time for winnowing of the sand. Succeeding waves were even less effective at sorting and winnowing and deposited much more sand mixed with broken shells, pebbles, and whole gastropods. Trough cross-laminated sandstone with some broken shells and granules was deposited by weaker waves which could not move whole gastropods and pebbles.

At Sandcut Beach, the rest of facies D above the burrowed horizon consists of rippled sandstone overlain by parallel-bedded pebbly fossiliferous sandstone, which was probably deposited on the lower shoreface in the outer surf zone during a storm (Dupre et al., 1980). The waves were effective at transporting pebble-sized material including whole gastropods.

At Sombrio Beach, facies D also represents shoreface deposition. The basal breccia of facies A is overlain by wavy-laminated to hummocky cross-laminated fine-grained sandstone resembling deposits at French Beach Provincial Park. These could have been deposited in the transition zone, which is the intermediary zone between lower shoreface and offshore zones. Above the wavy-laminated sandstone are trough and tangential wedge cross-laminated sets of sandstone which were deposited by megaripple migration on the shoreface.

At Sombrio Point, above the basal breccia, a very thin bed of facies F siltstone was deposited in a quiet environment. Overlying the siltstone, trough cross-bedded pebbly sandstones were deposited on the shoreface as megaripples migrated either in longshore troughs, rip current channels, or on the open shoreface.

FACIES E: Thick-bedded pebble grit and conglomerate

Facies E consists of thick-bedded pebbly grit and conglomerate, which is fossiliferous at most localities and burrowed at one locality. The poor sorting of these deposits indicates that they formed by a process which could not effectively sort and winnow away fine material. These deposits are probably all laid down on the lower foreshore and shoreface during storms. The burrowing at the top of one bed at the Correction Camp cliffs is analogous to modern storm lags found on the lower shoreface and inner-shelf, which typically have a sharp base and a burrowed upper contact (Kreisa, 1981). The shapes of some of the pebbles suggests that they were fluvially-supplied. Rip currents associated with a storm event could transport the fluvially-supplied gravels out onto the shoreface. The scoured bases of most of these beds are also indicative of a high-energy event such as a storm. These deposits do not contain much silt-to-clay-sized sediment, which would would have been carried further in suspension.

FACIES F: Silty shale and siltstone

Facies F was deposited in quiet, low-energy waters. Fine-grained deposits such as these are found either in very shallow waters, such as backbeach lagoons (or other ponded water), lakes, or overbank deposits or at depths greater than approximately 5 to 15 meters (Reineck and Singh, 1975) in the offshore zone. Evidence for offshore deposition, which usually consists of HCS and abundant bioturbation, is lacking for these deposits. Because of the associated debris flow deposits of subfacies C2 and facies A at one site at Sombrio Beach, and shoreface deposits at the other Sombrio sites, a shallow marine environment is favored. It is possible that these deposits formed in a local shallow area behind a sea stack or that they formed in a backbeach ponded area. The siltstones that are exposed along the Sombrio River and contain foraminifera are possibly deeper marine deposits, perhaps inner offshore.

PALEOCOLOGY OF MARINE FAUNA

The fauna of the Sooke Formation is fairly well preserved and was studied in detail by Clark and Arnold (1923). The faunal list published in their report is given in Appendix 3. They state that

> "the molluscan assemblage as a whole represents temperate conditions and if living today would be found in shallow waters of the Pacific coast from Vancouver Island to northern California. The presence of such genera as Goniobasis, Lyrena (Corbicula), Ostrea, and the extinct sea-cow Desmostylus indicates brackish water, at least in certain localities" (Clark and Arnold, 1923, p. 125).

Shell accumulations in the Sooke Formation could represent actual communities of organisms coexisting in the same environment, or they could be the result of faunal mixing by waves. Transported and mixed faunal assemblages are common in the shoreface, beach, and intertidal zones (Kreisa, 1981). Shells may also be sorted by waves (Bourgeois and Leithold, 1984).

Particular species that are referred to in the following discussion are taken directly from the list by Clark and Arnold (1923). The Sooke fauna represents a variety of organisms that were adapted to life on both rocky and sandy substrates. Several species of Mytilus (mussels) and Balanaus (barnacles) have been found in the Sooke Formation (Appendix 3). These organisms were suspension feeders that lived on rocky substrates in turbulent waters (Bourgeois and Leithold, 1984). The gastropod genus

Molopophorous and infaunal bivalve genus Yoldia were organisms that lived on a sandy substrate in turbulent water (Bourgeois and Leithold, 1984). Organisms such as these must be able to tolerate current and wave action, desiccation, and rapid fluctuations in temperature and salinity. These animals do so by escaping from the surface into burrows (Crimes, 1975). Trace fossils are important tools in interpretating the sedimentological aspects of the depositional environment because they reflect a direct behavioral response to environmental conditions (Seilacher, 1978). In shoreface conglomerates and associated sandstones, trace fossils are relatively rare; they may be abundant locally, but diversity is generally low (Bourgeois and Leithold, 1984). Trace fossils in the Sooke Formation are of three types: feeding traces, burrows, and borings.

Feeding traces are present at two locations, along Rosemond Creek and at Sombrio Beach. Along Rosemond Creek, they resemble Macaronichnus segregatis, which, in modern sediments, is produced by the marine polychaete, Ophelia limacina (Clifton and Thompson, 1978). They are small (1.5 to 2 mm wide) and sinuous with circular cross-sections. According to Clifton and Thompson (1978), these trace fossils occur in very shallow marine fine- to medium-grained sandstones from Jurassic age to the present. These traces are generally found in nearshore and foreshore deposits (Clifton and Thompson, 1978). In the Sooke Formation, these trails occur in fine-grained sandstones which are inferred to be lower foreshore and possibly nearshore deposits. The feeding traces that are found at Sombrio Beach are wider (1 cm) (Fig. 53) and were formed by larger organisms than those which formed the other traces. These resemble Thalassinoides feeding traces, which are formed by the modern shrimp Callianassa, and were probably formed on the foreshore or shoreface.

Burrows present in shallow marine conglomerates are typically of the

Figure 53. Trace fossils (Thalassanoides) in sandstone of facies D at Sombrio Beach.

Skolithos ichnofacies (Seilacher, 1967; Frey and Seilacher, 1980, both in Bourgeois and Leithold, 1984) (Fig. 54). This ichnofacies is typical of sandy substrates (Frey, 1975). Skolithos ichnofacies burrows are typically vertical cylindrical or U-shaped dwelling burrows which develop mainly in direct response to fluctuations in sedimentation (Frey, 1975). Fluctuations of this type are to be expected in a high-energy nearshore environment. Glossifungites ichnofacies (Fig. 54) are found in semi-consolidated but firm substrates in either somewhat protected, moderately low-energy settings, or omission surfaces in higher-energy settings. Most tracemakers responsible for this ichnofacies are burrowers; some closely simulate borers. Characteristic trace fossils are vertical, U-, or tear-shaped structures (Frey, 1975). As is typical of the burrows in the Sooke Formation, diversity is generally low in both the Skolithos and Glossifungites ichnofacies, although a given type of burrow may be abundant (Simpson, 1975).

There are five basic types of burrows in the Sooke Formation: vertical cylindrical burrows, horizontal, steeply-inclined downward-tapering, v-shaped, and nested v-shaped burrows. Except for the nested burrows, they all lack any internal structure that would indicate active filling.

Although U-shaped burrows are not found in the Sooke Formation, the vertical cylindrical burrows in subfacies B2 at French Beach Provincial Park are possibly dwelling structures of the Skolithos or Glossifungites ichnofacies (Frey, 1975; Frey and Pemberton, 1984) (Fig. 54). They are generally 1 to 3 cm in diameter and 4 to 6 cm long. They also resemble those made by the modern shrimp Callianassa (Weimer and Hoyt, 1964) that uses burrows as domiciles but also feeds within them (Osgood, 1975). Callianassa burrows have been reported in sandy wave-agitated littoral

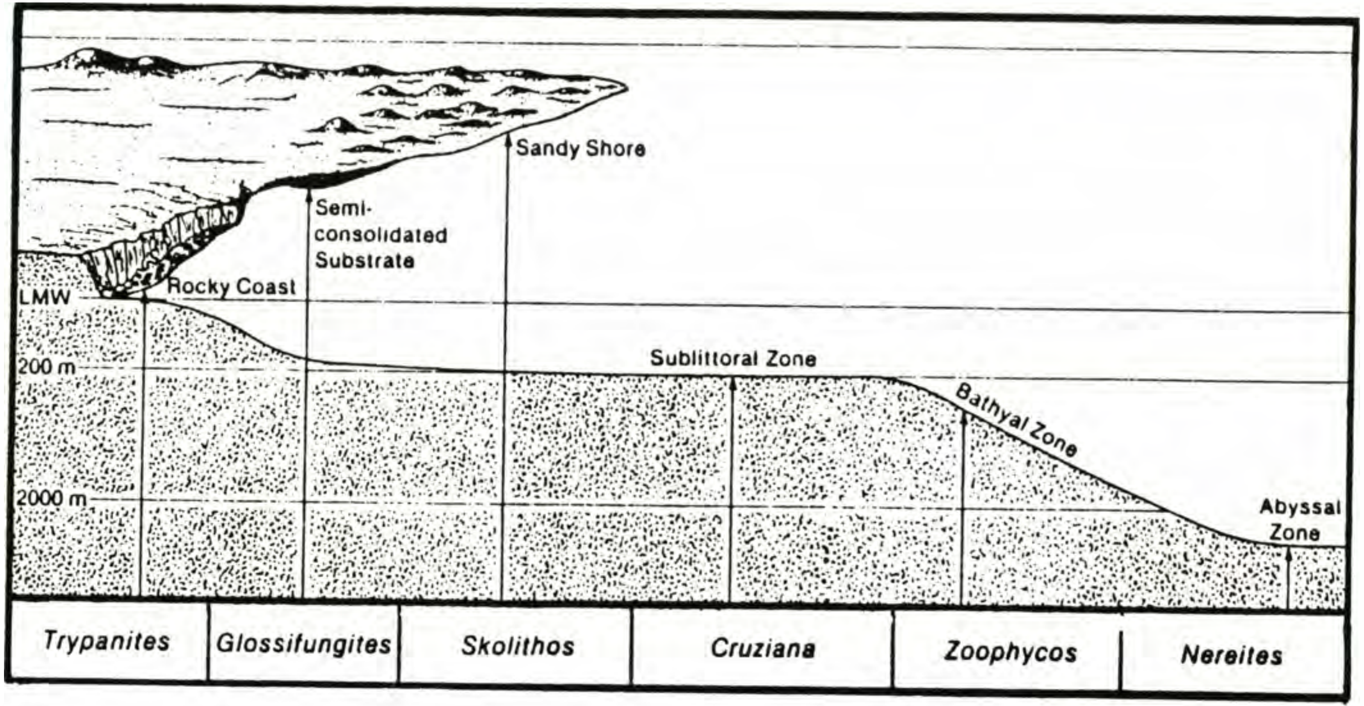


Figure 54. Marine ichnofacies and representative, but not exclusive zones of occurrence (modified after Frey and Pemberton, 1984).

areas by Weimer and Hoyt (1964). Seilacher (1967) states that there is considerable variation in both morphology and environmental distribution of these burrows. He states that the characteristic mud-pellet lining may be missing if the burrows are dug into cohesive muds. The environmental significance of these burrows is compatible with my interpretation of a muddy ponded area in the backbeach or beach environments. The large (8 cm long) downward tapering burrow in facies D at the Muir Creek cliffs (Fig. 41, p.70) is probably of the Skolithos or Glossifungites ichnofacies (Fig. 54), but a specific genus could not be identified. The horizontal burrows which are found at the Muir Creek cliffs, Sandcut Beach, and at the Correction Camp cliffs (Fig. 55) are generally 5 to 8 cm in diameter and resemble those made by deposit-feeding heart urchins. These organisms generally live in the lowermost shoreface to offshore zones (Reineck and Singh, 1975) where turbulence is generally low and the organisms feed on organic matter which settles out of suspension (Frey, 1978). They are probably of the Cruziana ichnofacies, which is typical of this environment (Frey, 1975; Frey and Pemberton, 1984).

The nested v-shaped burrows, such as that shown in Figure 44, p. 74, are escape structures (Fugichnia) similar to those formed by Monocaterion reported by Crimes (1975). These form in direct response to a rapid sedimentation rate. The small v-shaped burrows which are not nested may be shallow escape structures in which the organism escaped rapidly. The clusters of mixed sediment represent bioturbation of some sort, probably horizontal sand- and gravel-filled burrows. They are associated with some swirly and roughly bulbous-shaped traces of finer-grained material, which are possibly burrows or alternatively, they could be sedimentological features.

Wood-boring organisms, such as the bivalve Teredo are commonly

Figure 55. Horizontal burrows in facies D at Muir Creek cliffs.

found along rocky coasts. Many organisms that bore generally do so for protection (Warme and McHurron, 1978). Borings are common in the Trypanites icnhofacies (Frey and Pemberton, 1984) (Fig. 54). One sample of Teredo-bored wood was found in some float at the Muir Creek cliffs and Teredo hard parts were reported in the faunal list by Clark and Arnold (1923).

The fauna and trace fossils of the Sooke Formation yield valuable information regarding the depositional environment. They also reinforce interpretations of the depositional environment that are based on stratigraphy. The Sooke fauna largely consisted of organisms that were adapted to life on both sandy and rocky substrates along high-energy shorelines. Trace fossils were formed in the beach and shoreface environments generally during fairweather conditions. Some traces indicate that sedimentation rates fluctuated rapidly, which is typical of a high-energy nearshore environment.

SUMMARY OF DEPOSITIONAL ENVIRONMENT

The Sooke Formation was deposited in a high-energy shallow marine environment. Rocky headlands, sandy coves, and sea stacks dominated the coastline. Wave activity dominated deposition, while tidal influence was low. Rock fall and slumping from sea stacks, cliffs, and adjacent terraces supplied coarse material to the beach and shoreface. This material accumulated and was reworked to varying degrees by waves. Debris flows also supplied coarse material to the beach and nearshore environments. These debris flows flowed along in stream channels probably associated with alluvial fans and on terraces adjacent to the beaches. Streams supplied thin deposits of muddy conglomerate where they entered the beach and became ponded. Some such conglomerates were subsequently reworked and resedimented by storm waves. Streams also supplied organic material when they flooded.

The sedimentary structures in the sandstones indicate rapidly fluctuating conditions of sedimentation dominantly on the shoreface influenced by passage of storm waves, and thus decreasing flow regimes. A few thin beds of siltstone and shale indicate deposition in quiet waters, either in small ponded areas in the backbeach to beach environments or on the shoreface. The Sooke Formation contains abundant marine fauna, some species of which indicate a shallow marine estuarine environment. Some of the fauna were burrowers into sand and gravel substrates, while others lived on rocky ledges. The burrowing organisms also indicate that conditions of sedimentation fluctuated rapidly. Both faunal and sedimentological evidence indicate that the Sooke Formation was deposited along a coastline which had high wave energy, and both sandy beaches and rocky headlands.

PETROLOGY AND PETROGRAPHY

PETROLOGY METHODS

Samples were collected where variations in mineralogy, color, or texture were observed. Since much of the Sooke Formation is weathered and friable, concretionary layers were sampled more frequently than nonconcretionary layers. Thirty-five whole rock and thirty lithic point counts were done on sand-sized samples coarser than very fine sand. The Gazzi Dickinson point count method was employed. This method allows accurate determination of modal composition independently of grain size and post-depositional changes (Ingersoll et al., 1984). One-half of each thin section was stained for both plagioclase and potassium feldspar. Most commonly four hundred points were counted on the stained portion of each slide in order to determine the whole rock modal compositions. Two hundred points were counted, also on the stained portion, to determine the modal percentages of constituent lithic grains. Point count spacing was usually .5 x 1 mm for the 400 point counts and .4 x 1 mm for the 200 point counts. The results of the point counts are given in Appendices 5 through 8.

Lithic counts were also conducted on pebble to boulder conglomerate layers, both in the field and laboratory. The results of these are presented in Appendix 2. Clasts greater than 1 cm were sampled at regular intervals (usually 5 or 10 cm). The field studies yielded rough estimates of composition, while the detailed laboratory studies allowed accurate descriptions of the coarse-grained sediment in the Sooke Formation. Fifty points were usually counted in the field and one hundred points were counted in the laboratory. Two detailed petrographic studies were made from different locations. Fifteen samples from each were studied and compared with the sand-sized lithic grains for similarities.

One-hundred forty thin sections were analyzed for mineral composition, compositions and textures of lithic clasts, diagenetic history, and textures (grain sizes, sorting, roundness, grain contacts, and fabric).

POINT COUNT CATEGORIES (See Table 3)

Nonlithics:

Qm: Monocrystalline quartz, includes individual quartz grains and grains very fine sand size or larger within lithic fragments; including polycrystalline quartz.

P: Plagioclase feldspar, includes both sodic and calcic plagioclase of very fine sand size and larger, either as individual grains or as constituents of larger lithic fragments.

K: Potassium feldspar, includes potassium feldspar grains very fine sand size or larger as individuals or as constituents of larger lithic fragments.

Am: Amphibole grains that are sand-sized, whether individual or part of a rock fragment.

Pyx: Both orthopyroxene (Opx) and clinopyroxene (Cpx) grains that are sand-sized, whether individual or part of a rock fragment.

Mi: Muscovite or biotite whose short dimension is sand-sized or greater whether individual or part of a rock fragment.

Op: Any opaque minerals sand-sized or greater.

Ce: Calcite cement, zeolite cement, clay cement, pyrite cement, Fe-oxide cement, silica cement, and possibly K-spar cement.

Mtrx: Any interstitial grains smaller than 1/16 mm.

Acc: Accessory minerals including epidote, zoisite, clinozoisite, pumpellyite, chlorite, prehnite, staurolite, and garnet grains, either as detrital fragments or as megacrystalline grains larger than very fine sand size in lithic fragments.

Fos: Any fossils.

Misc: Any grains that cannot be identified or that do not fit any of the other categories.

Lithics:

Qp: Polycrystalline quartz, including nonfoliated polycrystalline quartz and chert fragments smaller than very fine sand size.

Qpf: Polycrystalline quartz, foliated.

Lvm: Volcanic and metavolcanic lithics, including all varieties of volcanic rocks and fine-grained plutonics.

Ls: Sedimentary lithics; shale, siltstone, sandstone, organic material, and grungy chert or polycrystalline quartz with greater than 15% impurities.

Lm: Metasedimentary lithics; slate, phyllite, and schist.

Lmisc: Miscellaneous lithics, including all lithics that are unidentifiable.

Lvo: Meta-igneous assemblages of epidote, quartz, plus or minus pumpellyite, chlorite, and amphibole.

Lpm: Miscellaneous aggregates of plutonic and metaplutonic rocks other than basalt and gabbro.

TABLE 3: GRAIN PARAMETERS (modified from Ingersoll and Suczek, 1979)

Q = Qm + Qp	Q = total quartzose grains
	Qm = monocrystalline quartz grains
	Qp = polycrystalline quartz grains
F = P + K	F = total feldspar grains
	P = plagioclase feldspar grains
	K = potassium feldspar grains
Lt= L + Qp	L = total unstable lithic grains
Lv = Lvl + Lvmi + Lvmisc. + Lvo	Lv = total volcanic lithics
	Lvl = lathwork volcanics
Lsm = Ls + Lm	
L = Ls + Lm + Lv + Lmisc + Lpm	Lvmi = microlitic volcanics
	Lvmisc = miscellaneous volcanic lithics
	Lpm = miscellaneous plutonic and metaplutonic aggregates
	Lvm = meta-igneous assemblages
	Ls = sedimentary lithics
	Lm = metasedimentary lithics
	Lmmisc = miscellaneous metasedimentary lithics
	Lmisc = miscellaneous lithics

DESCRIPTIVE PETROGRAPHY

The Sooke Formation sandstones are lithic arenites, according to the classification system of Dott (1964) (Fig. 56). The sandstones are mostly calcite cemented in both the more resistant concretionary layers and also the noncretionary layers. Nonconcretionary layers, however, are often friable and weathered. Other cements include pyrite, hematite, zeolite, clay, K-feldspar or K-rich zeolite, and silica. Replacement of framework grains by calcite, pyrite, and hematite is common. The Sooke Formation is generally fossiliferous and in places it contains layers of coquina. Fossils are commonly replaced by calcite and less commonly by pyrite or silica.

Grain sizes range from very fine sandstone to coarse sandstone. Granule and pebble sandstones and grits are common and comprise the sandy matrix for the boulder breccias and conglomerates. Siltstone and shale are present, but neither is common. Modal grain size is fine-grained sandstone. Texturally, the Sooke Formation is immature. Sand grains range from angular to well rounded. Angular to subangular grains, especially quartz and plagioclase, are by far the most common. Lithic grains are commonly subrounded to rounded, but are in places subangular. The sandstones are mostly well- to moderately well-sorted.

Monocrystalline quartz is abundant in the Sooke Formation. It is usually angular to subangular. Quartz derived from plutonic rocks is vacuoled and sometimes rutilated. Undulose quartz is probably derived from a metamorphic source, while clear monocrystalline quartz is presumably derived from a volcanic source.

The ratio of plagioclase feldspar to potassium feldspar in the samples point counted varies between 0.69 and 1.00. Both sodic and calcic plagioclase are present in the Sooke Formation. The two most common

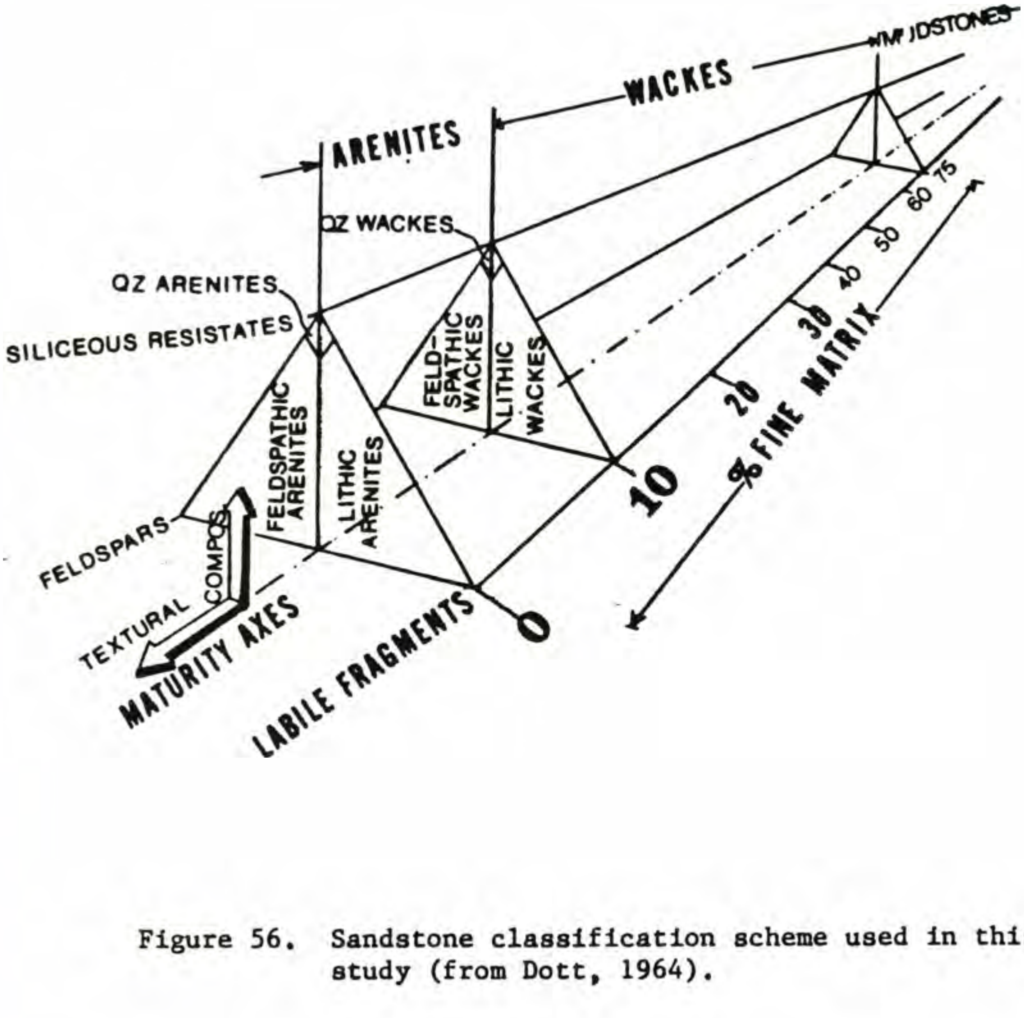


Figure 56. Sandstone classification scheme used in this study (from Dott, 1964).

compositions are oligoclase and bytownite, as determined by the A-normal method. Albite twins are common; combined albite and Carlsbad and Carlsbad twins alone are also present. Some volcanic plagioclase has normal and oscillatory zoning (Fig. 57). Plagioclase ranges from fresh to very altered. Calcite and sericite alteration are common. Pumpellyite and prehnite are common metamorphic minerals. Potassium feldspar is present in some samples as determined by staining methods and by the presence of tartan twinning (Fig. 58) in microcline. Both orthoclase and microcline occur as subangular to subrounded monocrystalline grains and in plutonic aggregates. Potassium feldspar cement is rare.

Mafic minerals include amphiboles, micas, and pyroxenes. Amphibole, predominantly hornblende (Fig. 58), occurs abundantly in some samples both as individual subrounded to subangular grains and in plutonic and metamorphic lithics. Oxyhornblende and actinolite are also present. Muscovite and biotite occur as shreds and as sheets. Biotite is partially replaced by pyrite or altered to chlorite. Both micas are common constituents in metasedimentary lithics. Orthopyroxenes and clinopyroxenes are uncommon in the Sooke Formation, both as detrital grains and as unaltered constituents of lithics. Either pyroxenes were not commonly deposited in the Sooke Formation, or most original pyroxene has been replaced by epidote, calcite, or other calcium-rich minerals.

Epidote constitutes a large proportion of the accessory minerals in the sandstones. It occurs as rounded individual crystals, as aggregates in meta-igneous and metaplutonic lithics, in amygdules, and in veins. It sometimes displays a radiating bladed habit. Clinozoisite and zoisite are also present in veins, in metasedimentary, metavolcanic, and metaplutonic lithics, and as detrital grains. Pumpellyite and chlorite are also common accessory minerals. They occur in amygdules, ground-mass, veins, as

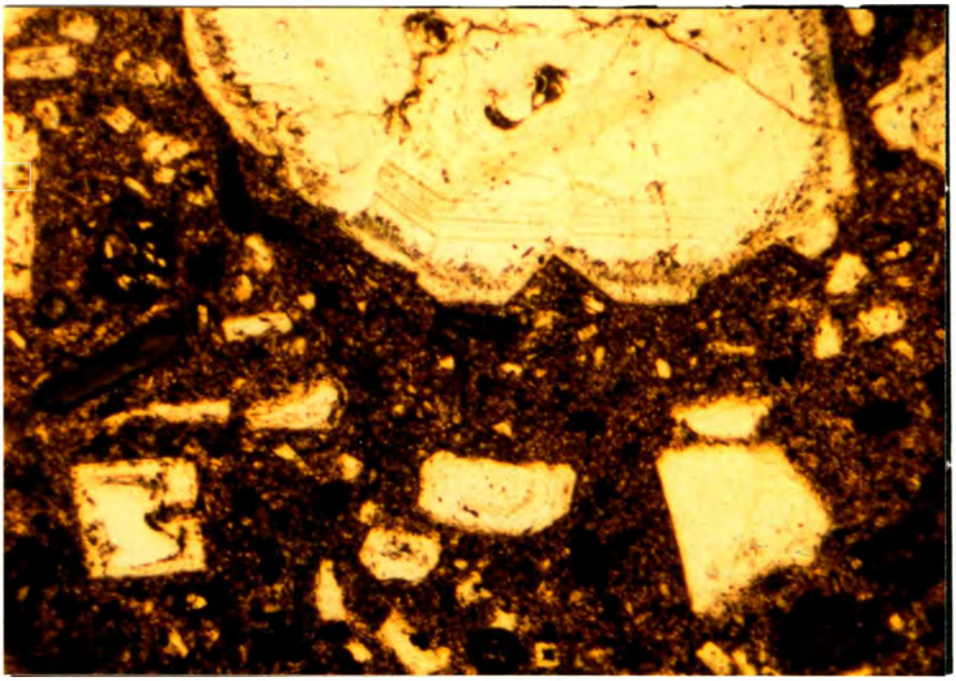


Figure 57. Oscillatory zoned plagioclase in volcanic lithic fragment. Polarized light. Field of view: 2.1 x 1.5 mm.

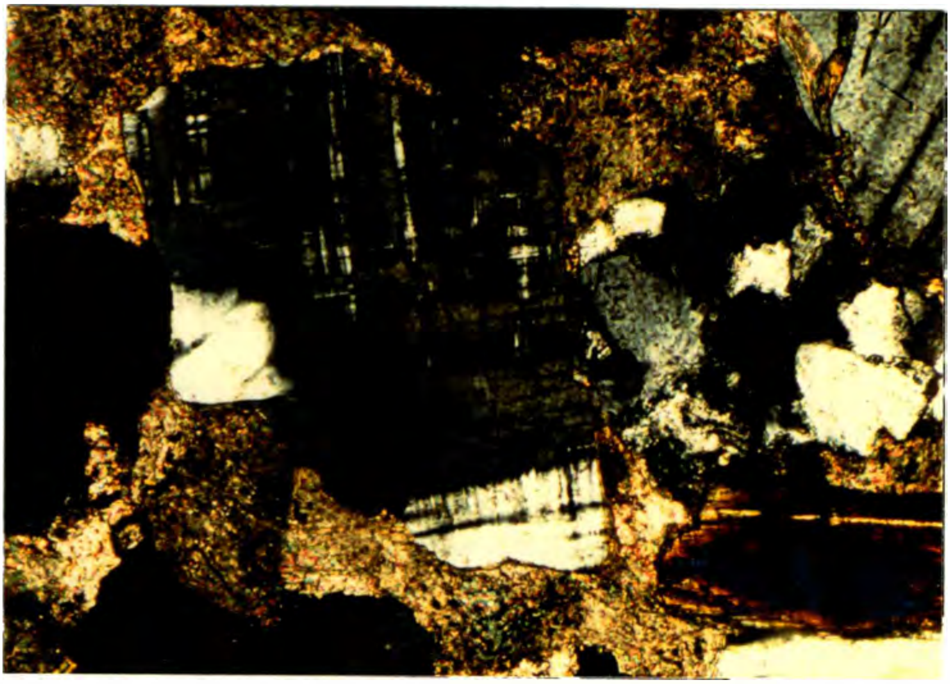


Figure 58. Tartan twinned microcline, polycrystalline quartz, and amphibole surrounded by calcite cement. Polarized light. Field of view: 0.85 x 0.58 mm.

replacement of mafic phenocrysts in metavolcanics and metaplutonics, and as detrital grains. Both chlorite and pumpellyite sometimes show a radiating habit. Subordinate prehnite and staurolite, and rarely garnet and zircon are also present.

Lithic grains constitute a large proportion of the framework grains in the Sooke Formation. Volcanic and metavolcanic grains dominate. Basalt is the most common volcanic lithic type; andesite is subordinate. Textures in the basalt range from microlitic to lathwork. Lathwork volcanics contain plagioclase laths set in a felted, trachytic, subophitic, or intergranular groundmass. Seriate, ophitic, and vitric textures are also present. Both unaltered and altered volcanic grains are common. Epidote, chlorite, pumpellyite, and quartz are significant constituents of the metavolcanic lithics, commonly in veins and amygdules. A minor amount of welded tuff is found in pebbles.

Metaplutonic and plutonic aggregates are also very common. They range in composition from metagabbros to amphibolites to felsic to intermediate compositions. Metagabbros contain epidote, quartz, pumpellyite, and chlorite, some hornblende, and subordinate actinolite, and are extensively veined. Unmetamorphosed gabbro lithics, containing coarse-grained pyroxene, are rare. Amphibolites and gneissic lithics are composed of foliated calcic plagioclase (as determined by pink amaranth stain) and amphibole with opaques and sometimes quartz. The nonfoliated plagioclase and amphibole aggregates are interpreted as hornblende gabbro, tonalite, or amphibolite or gneiss which are cut at an oblique angle to the foliation. Felsic plutonics display some granophyric, graphic, and possibly myrmekitic textures.

Polycrystalline quartz (Fig. 58) is commonly present as both detrital grains and in veins within metavolcanic and metaplutonic lithics. Chert occurs in some samples. Sutured contacts commonly occur in foliated polycrystalline quartz, while concavo-convex contacts are common in non-foliated polycrystalline quartz. Foliated polycrystalline quartz occurs mostly in metasedimentary lithics. Impurities, such as clays, chlorite, mica, and pyrite, are common. Calcite replacement is also common.

Metasedimentary lithics are predominantly quartz-mica phyllites and schists. In these lithics, either muscovite and biotite or a single mica are aligned with foliated polycrystalline quartz and commonly with graphite and pyrite masses. Aggregates of nonfoliated quartz and mica are also common. Other metasedimentary lithics include chlorite, mica, clinozoisite, zoisite, and plagioclase-mica schists.

With the exception of organic material, sedimentary lithics are uncommon in the Sooke Formation. Organic material is conspicuous in some horizons, but did not show up significantly in the point counts.

POST-DEPOSITIONAL CHANGES

Diagenetic changes are important factors in interpreting the burial history of the Sooke Formation. The Sooke Formation has been affected by several diagenetic processes. The net effect of these processes was compaction and cementation, and thus an overall reduction in porosity. Many beds within the Sooke Formation contained original porosities on the order of 25 to 40%, based on the percentage of cement and framework grain replacement. The abundance of floating and point contacts between grains for some beds suggests that either cementation occured fairly early during the diagenetic history of the Sooke Formation or that the amount of grain replacement was more substantial than estimated. All of the 100 samples were studied for diagenetic changes, which include pore-filling cements, fossil and framework grain replacement, alteration of volcanic glass and other groundmass material, cementation of concretionary layers, wood replacement, and coal formation.

Several different stages of cements are present in the Sooke Formation. Sparry calcite cement is the most abundant. Mosaic and partially to completely poikilitic textures are common. Equally common is a murky sparry calcite cement. The murkiness is probably due to impurities, such as clays. In some samples, the sparry calcite displays a fanning habit. Drusy spar cement is sometimes associated with sparry mosaic cement. The drusy cement occurs along the edge of the pore space with mosaic crystals filling the center. This texture is common to some replaced fossils. Calcite veins are also found in some samples. Dissolution of shell material in the Sooke Formation probably supplied the calcium carbonate. Since many lithic grains are either partially or entirely replaced by calcite, it is reasonable to assume that additional calcite was supplied by dissolution of calcic plagioclase and perhaps of mafic minerals, such as calcium-rich pyroxenes. Volcanic lithics and polycrystalline quartz are the most commonly replaced lithics.

Pyrite cement occurs as cubic crystals or as clusters of crystals, either as pore-filling cement or as a replacement cement in fossils and other framework grains. Pyrite occurs in volcanic, meta-igneous, and metasedimentary lithics. It also commonly partially or entirely replaces unstable biotite or amphibole grains. Diagenetically precipitated pyrite implies reducing conditions in a deoxygenated, slightly alkaline environment (Fairbridge, 1967) and is often associated with organic or carbonaceous material (Fairbridge, 1967; Phillips and Griffen, 1981). Pyrite cement is often an early diagenetic phenomenon (Fairbridge, 1967). Pyrite readily oxidizes to limonite or to hematite, which may account for some of the hematite cement in the Sooke Formation.

Iron oxide cements are pervasive in some samples. Hematite (Fig. 59), and less commonly limonite, occurs as coatings (some needlelike) on grains, including fossils, and as grain replacements. It also occurs as small clumps or individuals in pore spaces, where it may be pseudomorphic replacements of an earlier pyrite cement. Authigenesis of iron oxide cement requires a source of iron atoms and oxidizing conditions (Blatt, 1979). Oxidation of pyrite cement or dissolution of mafic minerals or Fe-rich clay minerals is a probable source for the iron. Shallow marine to nonmarine environments, such as those postulated for the Sooke Formation, are generally well oxygenated. The fact that both pyrite and iron oxide cements occur in the Sooke Formation, often in the same bed, indicates that different oxidation conditions existed in different parts of the basin.

Fringing clay cement most commonly occurs as thin coatings on

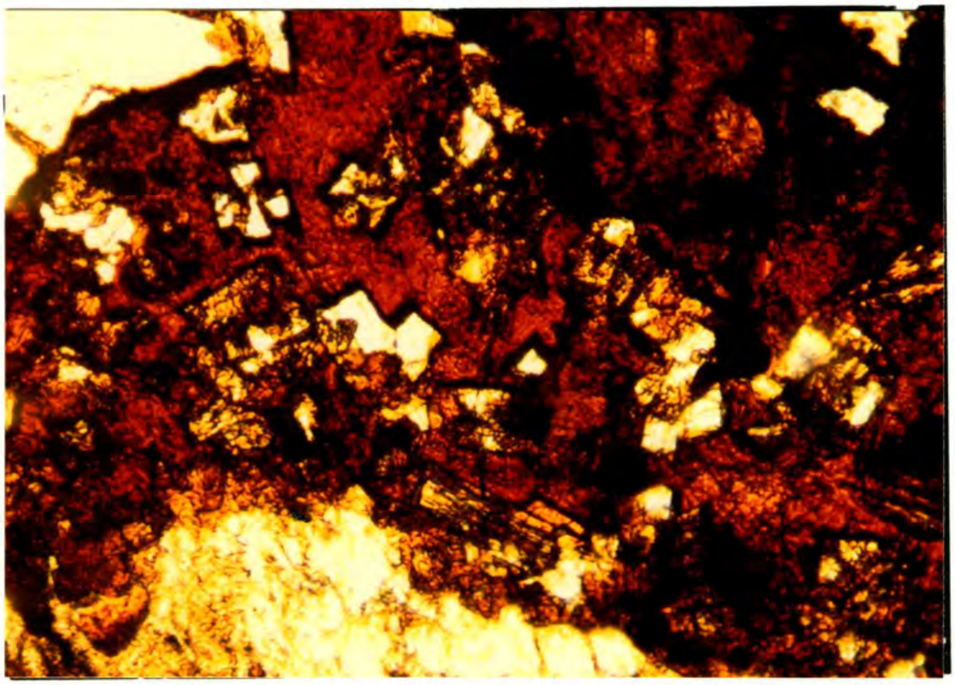


Figure 59. Zeolite and Fe-oxide cements in sandstone. Plane light. Field of view: 0.53 x 0.36 mm.

framework grains, including fossils. Clay is also a diagenetic alteration product of some groundmass material, including volcanic glass, in volcanic lithics. Clay cement is often associated with zeolites of similar compositions (Blatt, 1979). The association of clay cement with zeolite cement is observed in the Sooke Formation.

Calcium-rich zeolites occur both as a pore-filling cement (Fig. 59) and as a replacement of volcanic glass and probably groundmass material in volcanic lithics that were rich in calcic plagioclase. Finely crystalline zeolites are sometimes found in amygdules in volcanic lithics, probably as a replacement of glass. Pore-filling zeolite cement occurs as well-developed tabular crystals. In the Sooke Formation, zeolite cement almost always is associated with clay cement and usually postdates it. The formation of zeolites is dependent on several factors, including pressure, temperature, pH, salinity, burial depth, and permeability (Hay, 1966). Alteration of volcanic glass to zeolites is usually a complex dissolution process and is favored by high pH and high salinity (Hay, 1966).

Silica is present as a late-stage cement in trace amounts in a few samples. In these, polycrystalline quartz cement occurs in the center of void spaces. These are possibly replaced fossils. Chalcedony and chert occur together as the major cement along with clay cement in one sample. Pressure solution, silica released during diagenesis of clay minerals and alteration of volcanic glass to zeolites or clays, and surface weathering of silicate minerals have all been proposed as sources of silica cement (Pettijohn et al., 1973; Blatt, 1979). Both chert and chalcedony may also replace interstitial clays (Dapples, 1979).

A potassium-rich cement, recognized by the yellow sodium cobaltinitrite stain, is present in one sample. This cement occurs as grain replacement and as pore-rimming euhedral tabular crystals that resemble a potassium-rich zeolite in crystal habit and birefringence. This is either a K-rich zeolite or K-feldspar cement. It is not present in amounts sufficient to determine which by x-ray diffraction methods. Potassium feldspar cement most commonly forms early during diagenesis; K-feldspar authigenesis requires a silica source, moderately elevated temperatures, and ample potassium ions (Pettijohn et al., 1973).

The Sooke Formation, when deposited, contained abundant plant material. Aragonite needles, partially replaced by calcite, have almost completely replaced some wood layers in the Sooke Formation. The presence of aragonite was verified by x-ray diffraction techniques. Worm tubes in the wood have been preserved by the aragonite. Coal and carbonized wood are found scattered throughout the Sooke Formation. Some woody material was either partially or entirely converted to coal during diagenesis.

Sixteen samples were studied in detail in order to establish the sequence of diagenesis. The results are summarized in Tables 4 and 5. Clay cement is an early cement; in most cases it is the earliest. It does not always coat all of the grains in the rock. The next stage of cement is somewhat variable. This consists of either zeolite, pyrite, Fe-oxide, silica, or K-rich cement. It is possible that pyrite and zeolite cements occured simultaneously in some samples. Calcite cement is a late-stage diagenetic event. Silica cement is also a late-stage cement, post-dating calcite cement.

Diagenesis refers to post-depositional processes which alter deposited sediment and is related to depth of burial (Pettijohn et al, 1973). The boundary between diagenesis and metamorphism is of a transitional nature. The Sooke Formation has undergone an intricate diagenetic history.

TABLE 4: DIAGENETIC CHANGES

Diagenetic Change: / Sample:	F	G	Ca	Z	Cl	Py	FeO	Si	K
MUI-155	x	x	x	x	x	x	x		
FRE-18	x	x	?			x	x		
CHI-36	x	x	x	x	x	x			
MYS-147		x	x	x	tr	x			
MUI-27		x	x	x		x	x		
SOM-207	x	x	x	x	tr	x		tr	
PNP-197		x	x		x	x			
SAN-41	x	x	x		x	x		x	
MUI-158		x			x		x		
WHI-110	x	x	?		x	x		x	
MYS-60	x	x	x				tr		
SOM-50	x	x	x	x	tr	x		x	
SOM-87	x	x	x	x	x	x	x	x	
COR-504		x	x	x	tr	x			
SAN-306		x		x	x		x		
MUI-29	x	x	x	?	tr	tr			x

Key to abbreviations:

F Fossil replacement
G Grain replacement
Ca Calcite cement
Z Zeolite cement
Cl Clay cement
Py Pyrite cement
FeO Iron oxide cement
Si Silica cement
K K-rich cement
tr present in trace amounts

TABLE 5: DIAGENETIC SEQUENCE

Sequence:	1st	2nd	3rd	4th	5th	6th	7th
Sample:							
MUI-155	Cl	Z/Py?	FeO	Ca			
FRE-18	FeO	Py	Ca				
CHI-36	Cl	Z	Py	Ca			
MYS-147	Z	Cl	Py	Ca			
SOM-207	Py?	Ca	Cl	Py	Ca	Z	Ca
PNP-197	Cl	Py	Ca				
SAN-41	Cl	Py	Ca	Si			
MUI-158	Cl	FeO					
WHI-110	Cl	Si					
MYS-60	FeO	Py	Ca				
SOM-50	Cl	Py/Z?	Ca				
SOM-87	Cl	Z/Py	FeO	Ca			
COR-504	Z	Py	Ca				
SAN-306	Cl	Z	FeO				
MUI-29	Cl	P/K?/Z?	Ca				

From the zeolites, it can be deduced that the Sooke Formation was not buried very deeply, most likely between 1000 and 5000 meters (Hay, 1966). All of the post-depositional changes in the Sooke Formation were clearly of diagenetic, not metamorphic, origin.

PROVENANCE

INTRODUCTION

Provenance for the Sooke Formation sandstone and conglomerate is determined petrographically. Results of both point counts and detailed petrographic studies are used to determine both tectonic provenance and possible source areas for the Sooke Formation. Although clasts in the Sooke Formation consist of a variety of lithologies, a large percentage of the clasts are derived from volcanic and metavolcanic sources.

TECTONIC PROVENANCE

Dickinson and Suczek (1979) use modal percentages of detrital framework grains plotted on ternary diagrams in order to determine tectonic provenance of sandstones. Modes for the Sooke Formation are plotted on three ternary diagrams (Figs. 60, 61,and 62). All three plots show that the Sooke Formation sandstones appear to come from a magmatic arc source with a subordinate recycled orogen source. The methods employed by Dickinson and Suczek (1979) are only applicable to the Sooke Formation to a limited extent. As is discussed in the succeeding section, most of the sources for the Sooke Formation are primarily allochthonous to North America and may not fit the classic tectonic settings used in the Dickinson and Suczek model.

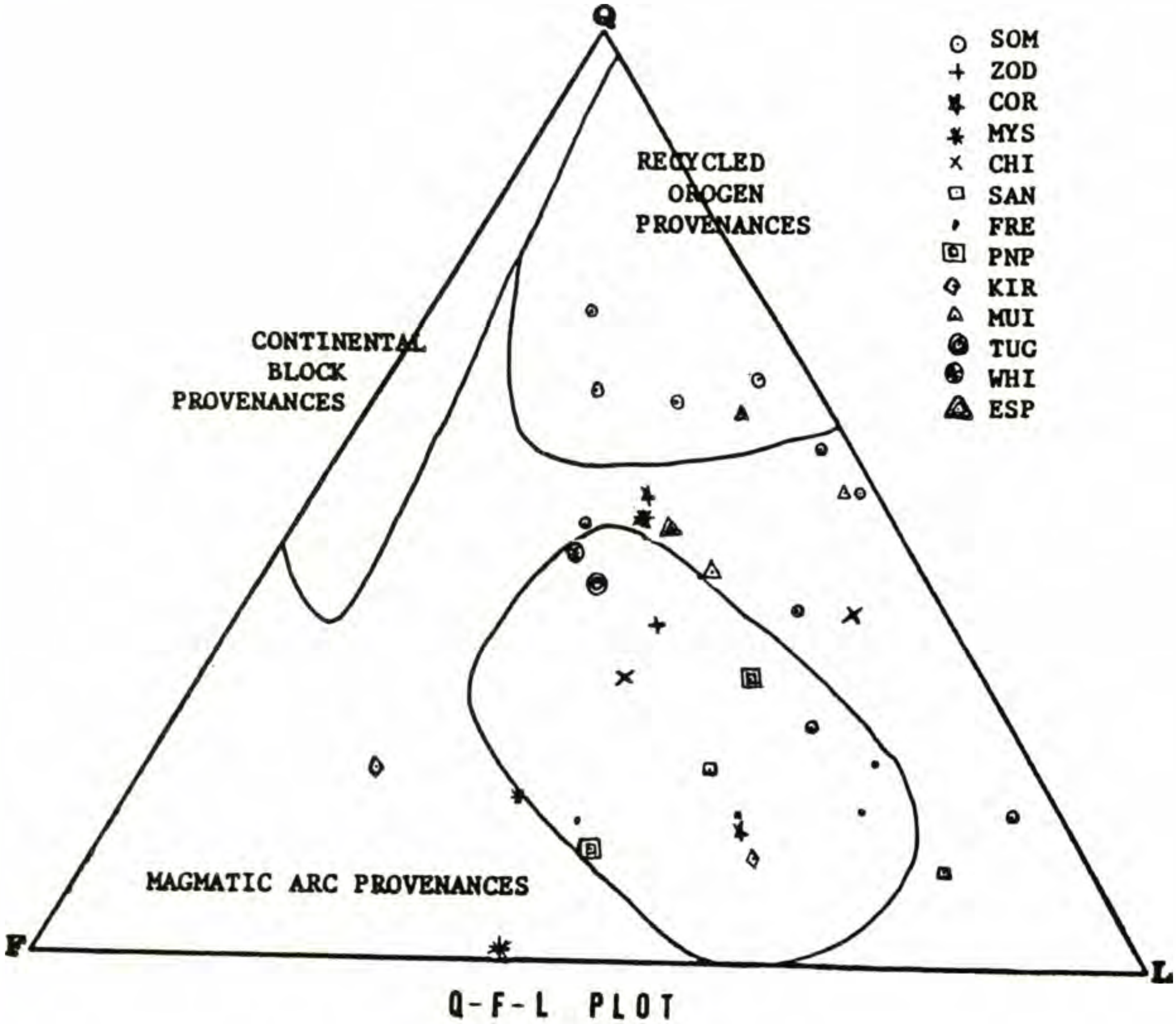


Figure 60. Q–F–L ternary diagram. Sandstone compositions from the Sooke Formation are plotted according to modal percentages. The outlined areas refer to tectonic provenance fields from Dickinson and Suczek (1979).

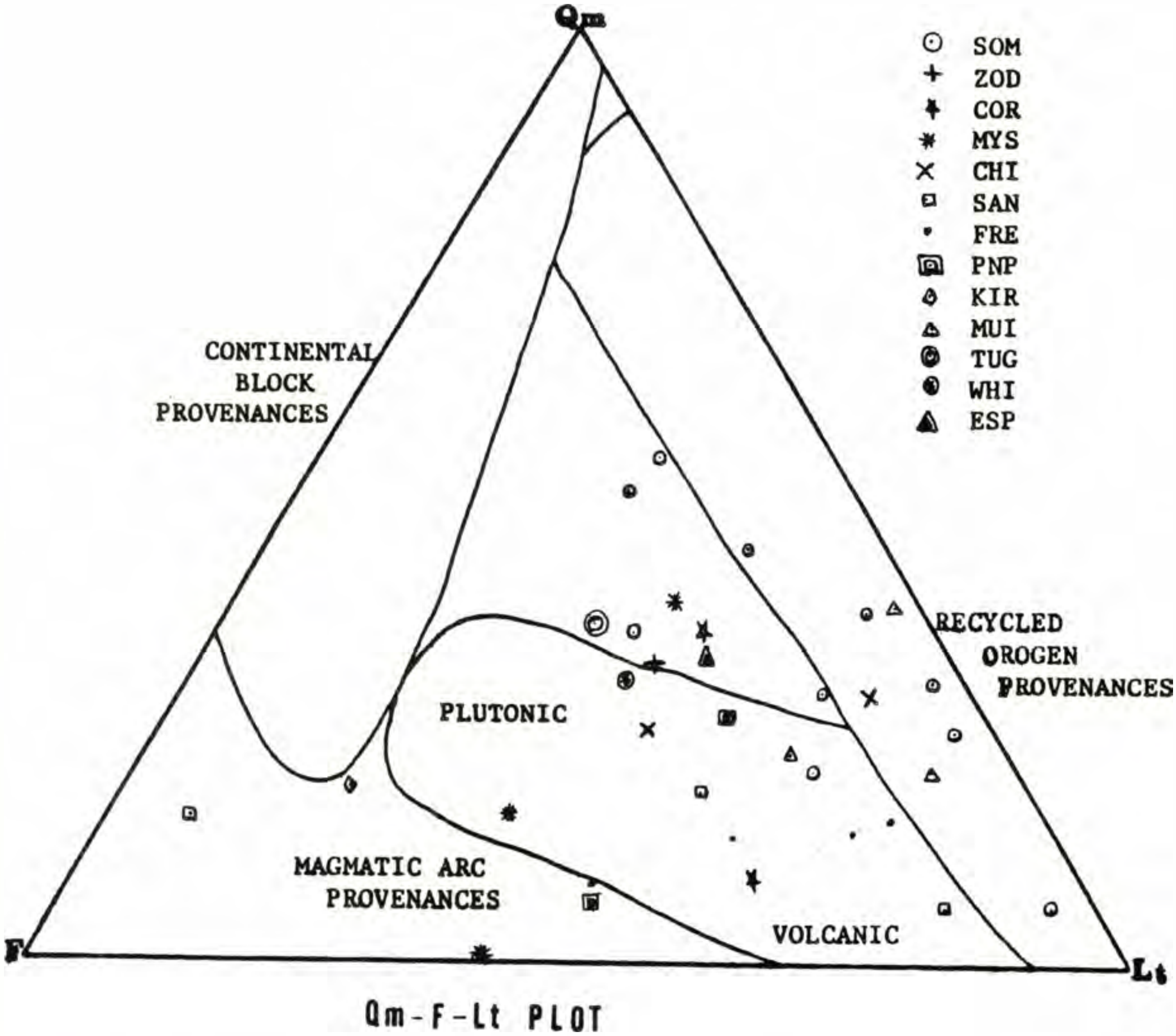


Figure 61. Qm-F-Lt ternary diagram. Sandstone compositions from the Sooke Formation are plotted according to modal percentages. The outlined areas refer to tectonic provenance fields from Dickinson and Suczek (1979).

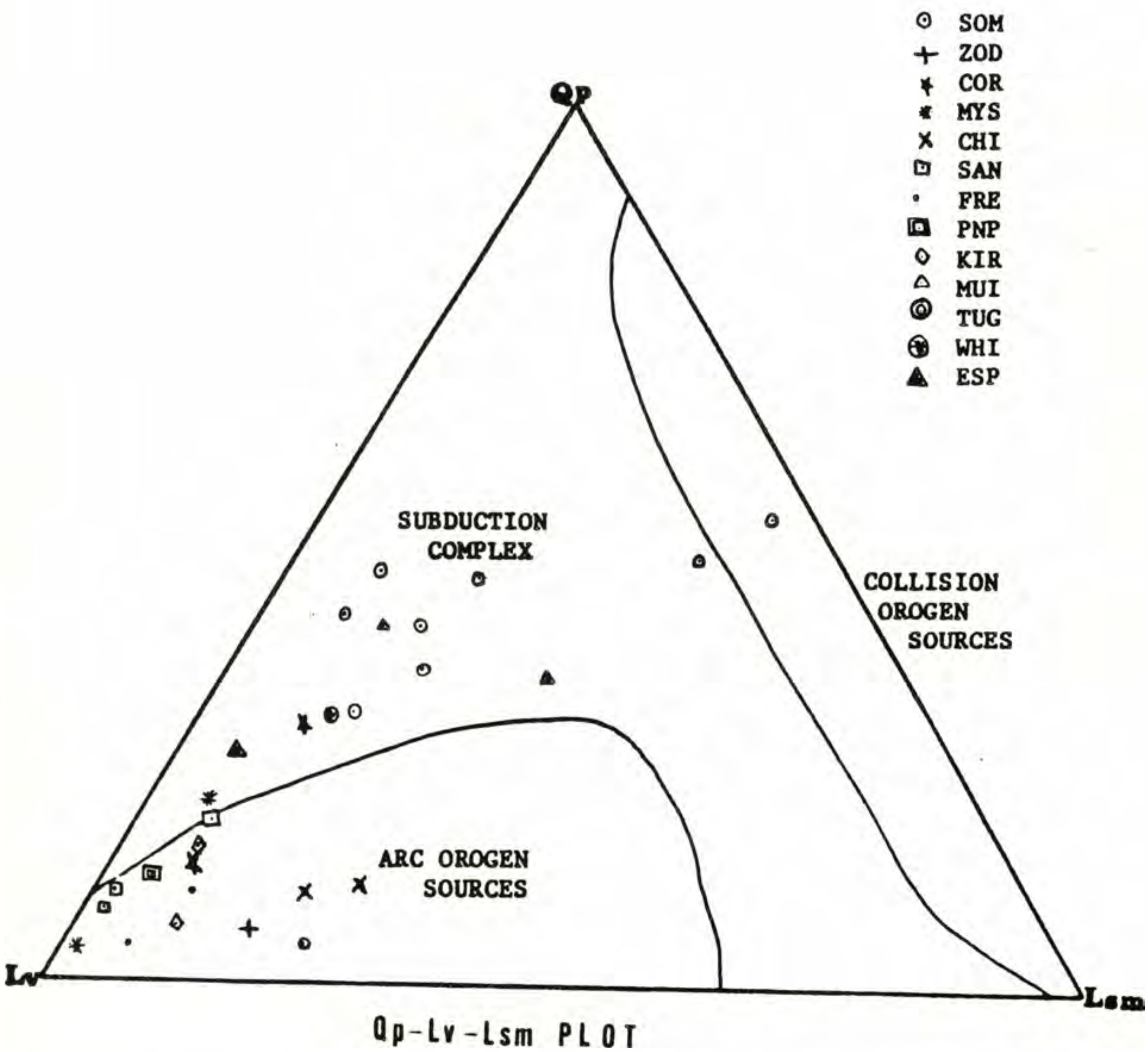


Figure 62. Qp-Lv-Lsm ternary diagram. Sandstone compositions from the Sooke Formation are plotted according to modal percentages. The outlined areas refer to tectonic provenance fields from Dickinson and Suczek (1979).

SOURCE AREAS FOR THE SOOKE FORMATION

The Sooke Formation is texturally and compositionally immature, and the high degree of angularity of monocrystalline sand-sized grains suggests a relatively short transport distance and little reworking. The boulder-sized deposits must have had a local source while the sand-sized deposits could have had a variety of possible sources. Table 6 lists the possible source areas and associated lithologies that are found in the Sooke Formation. Because of the textural immaturity of the Sooke Formation, I have restricted the possibilities considered to nearby sources which include the North and Central Cascades, the Coast Plutonic Complex, the San Juan Islands, Vancouver Island, and the Olympic Peninsula (Fig. 1). By Late Oligocene time, all of these areas that were close enough to serve as possible source areas for the Sooke Formation were in place relative to each other and to North America (Pacht, 1984). Another more local constraint on location of Cascade sources is the Straight Creek Fault. Movement along the Straight Creek Fault had ceased by 37 to 35 Ma (Vance, 1985). The Crescent Terrane, which was emplaced against Vancouver Island along the Leech River Fault, was in place just prior to the time of Sooke Formation deposition. The possible source areas are discussed below in the order of increasing likelihood of an important contribution to the Sooke Formation.

OLYMPIC PENINSULA

The Crescent Terrane on the Olympic Peninsula is not a likely source for several reasons. The peripheral sediments are not recorded as clasts in the Sooke Formation. The basalts and metabasalts of the Crescent Formation contain abundant pyroxenes. Finally, if Vancouver Island is a

TABLE 6: POSSIBLE SOURCE AREAS FOR SOOKE FORMATION

AREA / ROCKS	VANCOUVER ISLAND	COAST RANGE COMPLEX	NORTH and CENTRAL CASCADES	OLYMPIC PENINSULA	SAN JUAN ISLANDS
MAFIC TO INTERMEDIATE VOLCANICS and METAVOLCANICS	Karmutsen Formation Sicker Group Bonanza Group Metchosin Volcanics Pacific Rim Complex	Coast Plutonic Complex	west of SCF: Chilliwack Group Shuksan Greenschist Wells Creek Formation east of SCF: Cascade River Schist Harrison Lake Formation Haystack Mountain unit	Crescent Formation	Garrison Schist Deadman Bay Volcanics Lopez Complex Decatur Terrane Orcas Chert interbeds unnamed rocks
FELSIC PLUTONICS and METAPLUTONICS	Island Intrusions	Coast Plutonic Complex	west of SCF: Mt. Stuart Batholith Chilliwack Composite Batholith other 45 Ma intrusions east of SCF: other 45 Ma intrusions		Turtleback Complex Fidalgo Ophiolite
MAFIC TO INTERMEDIATE PLUTONICS and METAPLUTONICS	Island Intrusions Westcoast Complex Wark-Colquitz Gneiss Catface Intrusions Sooke Gabbro		west of SCF: Yellow-Aster Complex Shuksan Suite east of SCF: Skagit Gneiss Marblemount Meta-Quartz-Diorite Eldorado Orthogneiss		Turtleback Complex Fidalgo Ophiolite
METASEDIMENTS	Leech River Complex Pacific Rim Complex Pandora Peak Unit	Coast Plutonic Complex	west of SCF: Darrington Phyllite Chilliwack Group Nooksack Group east of SCF: Skagit Gneiss Cascade River Schist		Garrison Schist Constitution Formation Decatur Terrane Lopez Complex Garrison Schist
CHERT	Sicker Group Pacific Rim Complex Leech River Complex Pandora Peak unit		west of SCF: Chilliwack Group Wells Creek Volcanics Elbow Lake Unit Cultus Formation recycled from Chuckanut?		Orcas Chert Lopez Complex Decatur Terrane

(Compiled from Misch, 1966; Misch, 1977; Cowan et al., 1977; Hammons, 1979; Muller et al., 1981; Muller, 1983; Blackwell, 1983; Brandon et al., 1983; and Arthur, 1986).

source for some of the Eocene-Oligocene peripheral sediments on the Olympic Peninsula (Ansfield, 1972 ;Snavely et al., 1980; Anderson, 1985; Rauch, 1985), then material would have been transported northward from the Olympic Peninsula to Vancouver Island during this time.

The core rocks on the Olympic Peninsula are not considered a possible source because they do not appear as clasts in the sedimentary record until late Miocene time, where they are one of the sources for the Montesano Formation (Bigelow,P.,oral communiation, 1986).

CASCADES

The North and Central Cascades constitute a complex assemblage of pre-Tertiary oceanic- to arc-derived rocks, upper Cretaceous to Tertiary intrusives and volcanics, Cenozoic volcanics, and Quaternary deposits. They contain many possible pre-Tertiary to early Tertiary contributors of sediment for the sandstones of the Sooke Formation (Table 6). Uplift in the North Cascades may have begun as early as 50 Ma (Hammond, 1979), but the main uplift did not occur until Pliocene-Pleistocene time (Mackin and Cary, 1965). Uplift to produce the Chuckanut, Swauk, and Huntingdon Formations must have occurred in the Eocene (Gresens, 1982; Misch, 1977). Uplift possibly exposed the various pre-Tertiary metavolcanic, metaplutonic, and metasedimentary source rocks by the time the Sooke Formation was deposited.

West of the Straight Creek fault in the Northwest Cascades, there are several possible sources for slate, phyllite, greenschist, polycrystalline quartz and chert, metaplutonic lithics such as trondjehmite, diorite, and gabbro, high-grade metamorphic and igneous lithics, and andesitic volcanic lithics. East of the Straight Creek Fault, in the Cascade Crystalline Core, phyllites, mica schists, impure quartzite, meta-gabbros and -

diorites, amphibolites, and orthogneisses, and various intrusives are possible sources. The younger Tertiary intrusives probably were not emplaced by Late Oligocene time.

Based on textural and lithologic features of the grains in the Sooke Formation, a Cascades source is not likely. Monocrystalline quartz grains and most feldspar grains are not likely to have been derived from these metasediments or other Cascades sources, because most quartz and plagioclase feldspar grains in the Sooke Formation are angular, suggesting a much closer source than the North Cascades which are about 200 kilometers away from the Sooke basin. The angularity of the grains also depends on the type of transport. A combination of fluvial and coastal processes for such a distance would most likely have effectively rounded the grains. The paleogeography and paleo-ocean circulation pattern in the Strait of Juan de Fuca during the Late Oligocene are presumed to be very similar to today's so that the net shore drift during Late Oligocene can be inferred to be from the northwest to the southeast (Schwartz, M.L., oral communication, 1987). This would be the opposite of that which is needed to derive sediment from the Cascades. There are also many lithologies which are present in the Cascades, but which are not represented in the Sooke Formation or which could have been supplied by closer sources, suggesting that they are not a major contributor.

COAST PLUTONIC COMPLEX

The Coast Plutonic Complex was uplifted and exposed to erosion by the Late Cretaceous. Debris shed from the uplifted Coast Plutonic Complex is contained in the Upper Cretaceous Nanaimo Group (Pacht, 1984). The Coast Plutonic Complex consists mainly of Cretaceous to early Tertiary granitic (quartz dioritic and dioritic) rocks, some of which have been metamorphosed to the granulite grade, and migmatites (Pacht, 1984; Roddick, 1963; Hollister, 1975; Monger, 1984; Monger et al., 1982). The granulite facies metamorphic rocks consist of metabasalts, calcium-rich metasediments, and highly aluminous metasediments. These rocks, however, are hundreds of kilometers from the Sooke basin, and uncommon (Roddick, 1983). The Coast Plutonic Complex may have supplied some of the granitic plutonic aggregates and plutonic quartz, K-spar, plagioclase, amphibole, and mica to the Sooke Formation. Potassium feldspar grains are generally more rounded than plagioclase feldspar grains and are more likely to have been derived from a distant source such as this, but is just as likely to have been derived from other sources. Amphibole is not a very stable mineral under sedimentary conditions and could have survived transport from such a distance only if it was very rapid. The granulite facies metamorphic rocks contain various mineral assemblages which would contribute minerals such as illmenite, garnet, orthopyroxene, and sillimanite which are not well represented in the Sooke Formation or minerals such as feldspar, biotite, and staurolite which are common to other closer source areas as well. The magnetite could have been supplied by the Coast Plutonic Complex; it is stable enough to have survived such a transport distance, but there are also closer sources for magnetite on Vancouver Island.

SAN JUAN ISLANDS

The San Juan Islands consist of several terranes with a very complex and controversial tectonic history. Much of the San Juan Islands consists of sedimentary, volcanic, and plutonic rocks which were metamorphosed and deformed during a mid-Cretaceous event. In the northwestern part of the islands there are some unmetamorphosed sedimentary units. The unmetamorphosed sediments are not being considered as source rocks, since sedimentary lithics such as shale, siltstone, sandstone, and conglomerate are rare in the Sooke Formation.

Several possibilities in the San Juan Islands exist for sources of metavolcanics, metaplutonics, metasediments, and chert. These possible sources are listed in Table 6. I consider the San Juan Islands a weak possibility for a source area because of the variety of lithologies and mineral assemblages not represented in the Sooke Formation. The abundance of sedimentary and metasedimentay rocks present in the San Juan Islands but not found as clasts in the Sooke Formation, also suggests that the San Juan Islands were not a dominant source area. Chert is common to both the San Juan Islands and the Sooke Formation, but it could have been derived from many other possible sources.

VANCOUVER ISLAND

On the basis of paleogeography, petrology, and textural maturity, Vancouver Island is the most probable source area for the Sooke sediments, particularly for the pebble to boulder conglomerates. Paleogeographically, Vancouver Island during the Late Oligocene was described by Clapp (1912) and by Drummond (1979) as a steep mountainous coast very similar to today's coastline. Sediment could have been supplied by high-gradient streams and debris flows from a substantial distance inland from the southern coast of the island. Sources on Vancouver Island consist of rocks formed in a wide variety of tectonic settings and comprise three major tectonic belts.

The Insular Belt rocks on Vancouver Island consist of the allochthonous Wrangellia terrane and autochthonous Nanaimo Group sediments. Based on textural maturity and petrology, a Wrangellia source is possible for the sand-sized clasts in the Sooke Formation. Many of the lithic and monocrystalline grains are subangular to subrounded and could have been derived from the Wrangellia rocks. The Sicker Group consists of a diverse range in lithologies only a few of which are represented in the Sooke Formation. Chert, chlorite-sericite schist lithics, diabase, and gabbro all could have been derived from the various lithologies in the Sicker Group. Amphibolite with relict diabase texture containing sodic to calcic plagioclase, epidote, and both hornblende and actinolite may have been derived from interlayers within the Sicker Group. The Tyee Intrusions, which intrude the Sicker Group in some localities, are a possible source for sericitized feldspar, microcline, perthite, minor detrital epidote and chlorite, and sericite schist.

The Karmutsen Formation of the Vancouver Group is a likely source for some of the altered basaltic lithics. The Karmutsen Formation contains masses of epidote, pumpellyite, prehnite, and quartz in amygdules very much like the Metchosin basalts. The Karmutsen basalts are altered and contain sericitized or albitized plagioclase and uralitized pyroxene (to actinolite). Some of the altered lathwork and microlitic volcanic lithics in the Sooke Formation are probably derived from the Karmutsen Formation, especially the subrounded grains.

The Bonanza Group could have supplied amygdaloidal mafic to intermediate volcanics that are found in the Sooke Formation. The oxyhornblende is probably from intermediate volcanics in this group. The Bonanza Group contains abundant pyroxene and plagioclase crystal tuffs which are not represented in the Sooke Formation. The tuffs would not be expected to survive during transport; however, the plagioclase and pyroxene or at least their alteration products would survive transport.

The Island Intrusions and Westcoast Complex are very likely sources for low-grade metaplutonic rocks and associated minerals. The Island Intrusions could have supplied plutonic aggregates ranging from quartz diorite and tonalite to leucogranite or monocrystalline grains derived from the breakdown of these during transport. Such monocrystalline grains include hornblende, biotite (commonly chloritized), plagioclase, quartz, K-feldspar (some granophyric), magnetite, chlorite, pumpellyite, prehnite, and zoisite, most of which are recognized as detrital grains in the Sooke Formation. Mafic to intermediate intrusive clasts in the Sooke Formation and the monocrystalline grains possibly derived from them have several other possible sources. Considering the proximity of the Island Intrusions to the Sooke Formation depositional basin and the abundance of grains common to both, they are a likely plutonic source.

The Island Intrusions grade into the migmatites of the Westcoast Complex. The Westcoast Complex could have supplied a wide variety of lithic grains including greenschist and amphibolite grade metavolcanics and metasediments, migmatites with quartz diorite, tonalite, leuco-tonalite, leucogranite, and plagioclase amphibolites (compositions of diorite, gabbro, quartz diorite, and quartz gabbro). Several minerals are possibly derived from these rocks. Hornblende (commonly yellow-green pleichroic), actinolite, magnetite, epidote, biotite (generally chloritized), plagioclase ranging from oligoclase to labradorite, commonly zoned or cloudy, or altered to sericite, epidote, or prehnite, K-feldspar, and quartz. As with the Island Intrusions, the Westcoast Complex is considered a likely source.

The Wark-Colquitz Gneisses are also probable sources of plutonic and metaplutonic aggregates and monocrystalline grains. These include diorites and granodiorites, some gneissic. These are a likely source for much of the plagioclase-amphibole lithics.

There are several sedimentary units on Vancouver Island and the nearby Gulf Islands. The sediments of the Kuyoquot Group, Queen Charlotte Group are too far away to survive transport and are not represented in the Sooke Formation. Likewise, the sediments of the Nanaimo Group are not represented in the Sooke Formation.

The Inner Pacific Belt on Vancouver Island also contains probable source rocks for the Sooke Formation sediments. The close proximity of these rocks to the depositional basin of the Sooke Formation strongly suggests that these rocks be considered as a potential source. The Pacific Rim Complex, which is correlative to the San Juan terrane (Brandon et al., in press) contains many a variety of lithologies (Table 6), some of which are represented in the Sooke Formation, but many of which are not. The Pacific Rim Complex rocks contain lawsonite and prehnite. These two minerals do not occur together in any clasts in the Sooke Formation and lawsonite is not found at all. Thus, these rocks are not likely sources, and other volcanic and chert sources are more likely.

The Leech River Complex is a definite source for the schistose boulder- to sand-sized clasts found in the Sooke Formation, particularly at Sombrio Beach where the basal breccia in the Sooke Formation contains angular boulders of quartz-mica schist and quartzite. Sand-sized quartz-mica (plus or minus feldspar) schist and phyllite are common in some locations, especially at Sombrio Beach. Slate fragments are less common. Metamorphic polycrystalline quartz is also quite common. These clasts are most likely derived from the southernmost unit, the metagraywacke-schist unit, which also contains common garnets and local andalusite, neither of which are common in the Sooke Formation. It is possible that these minerals were segregated during transport and therefore not deposited in the Sooke Formation. Garnet has a higher specific gravity than staurolite and therefore, could behave differently in transport. Andalusite has good prismatic cleavages, and could have broken down easier than staurolite. Staurolite, which is also common in this unit of the Leech River Complex, is abundant at some locations in the Sooke Formation. Magnetite was possibly derived from some of the metavolcanic rocks (Fairchild and Cowan, 1982). Chert in the Sooke Formation is possibly derived from the chert-argillite volcanic unit. Other foliated clasts in the Sooke Formation could have been derived from the metavolcanics in the Leech River Complex. These include chlorite-quartz-clinozoisite schist and some foliated plagioclase-amphibole-quartz-epidote lithics. Intrusives in the Leech River Schist could have supplied orthoclase, muscovite, quartz, plagioclase, biotite, and zoisite.

The correlative Pandora Peak unit also contains chert, basaltic lithics, rare tuffaceous lithics, mudstone, and volcaniclastic sandstone. The mudstone and volcaniclastic sandstone, which are not found in the Sooke Formation, would not be expected to have survived during transport, so their absence from the Sooke Formation would not be unusual if the Pandora Peak unit was to be considered a possibble source area. Similarly to the Pacific Rim Complex, the Pandora Peak unit contains the lawsonite and aragonite assemblage indicative of high pressure, low-temperature metamorphism (Brandon, M.T. and Massey, N.W.D., written communication) which is not found in any lithics in the Sooke Formation and which is sufficient evidence against a Pandora Peak unit source.

The crystalline rocks of the Crescent Terrane on Vancouver Island are also a very likely and, in many localities, a definite source. Boulders of the Metchosin Volcanics and Sooke Gabbro are contained within some of the conglomerates and make up the basal breccia wherever it is exposed. The variation in composition of these boulders is controlled on a local scale by the outcrop pattern of the basement rock. At the western end of the field area, at Sombrio Beach, boulders of both Leech River schist and green foliated metabasalt are present. At the eastern end at East Sooke Park, where the basement consists of Sooke Gabbro, gabbro boulders are contained within the basal breccia. Based on transport distance and petrologic characteristics, the Metchosin Volcanics are also the most likely source for most of the sand-sized basalt and metabasalt clasts. It is probable that much of the sand-sized metavolcanic and metasedimentary material was derived from mechanical breakdown of the boulders in the depositional area.

Since much of the Metchosin basalt has been altered by low- and medium-grade to amphibolite grade metamorphism, and these types of basaltic lithic grains are common in the Sooke Formation, it is a probable source for much of the epidote, chlorite, pumpellyite, quartz-bearing metabasaltic clasts in the Sooke Formation. This basalt corresponds to Muller's TM2 (1982), exposed in the westernmost part of the field area, which he describes as schistose to amphibolitic or chloritic meta-basalt. Epidote veins are very common. Most of the meta-basalt lithics were probably derived from this meta-basalt. Muller's TM1 (1982) contains abundant pyroxenes which are unusual in the Sooke Formation. It is probable that this largely unmetamorphosed part of the Metchosin, which predominates in the eastern part of the field area, was not actively being eroded to serve as a major source.

The Sooke Gabbro did not contribute as much sand-sized sediment to the Sooke Formation as did the Metchosin basalts. The Sooke Gabbro in the vicinity of East Sooke Park is described by Massey (1985) as mostly a diopside-labradorite-olivine gabbro. The paucity of pyroxenes in the Sooke Formation suggests that the Sooke gabbro did not provide much sand-sized sediment to the Sooke Formation. The olivine in the gabbro is altered to iddingsite, and it would not survive transport. Also associated with the Sooke Gabbro are leucogabbro, gneissic amphibolite, hornblende-gabbro, and small stocks of tonalite (Muller et al., 1981). These do not make up a significant volume of the Sooke Gabbro, however. These are likely sources for some of the mafic to intermediate plutonic and metaplutonic aggregates and monocrystalline grains derived from them, but are not considered to be major sources.

The Eocene Catface Intrusions probably supplied quartz-dioritic plutonic aggregates and monocrystalline grains. Oscillatory plagioclase, perthitic K-feldspar, graphic quartz-feldspar intergrowths, fresh biotite, and green hornblende are all possibly derived from these intrusions.

DISCUSSION OF PROVENANCE

Several possible source areas have been discussed. The Sooke sediments generally are texturally immature arenites, conglomerates, and breccias with minor siltstone and shale. The boulder breccias and conglomerates in the Sooke Formation are obviously derived locally from outcrops of Metchosin Volcanics, Sooke Gabbro, and Leech River Schist that were exposed as sea cliffs and uneven wave-cut platforms during deposition of the Sooke Formation. The cobble- to granule-sized material contains more diverse lithologies but is also mainly derived locally.

Sandstones in the Sooke Formation contain still more diverse lithologies, but these could be derived mainly from the various terranes on Vancouver Island. Consequently, Vancouver Island is interpreted as the dominant source for the Sooke Formation. The Karmutsen Formation, Island

Intrusions, and Westcoast Complex of the Wrangellia Terrane are all very likely sources of detritus that has been rapidly transported a moderate distance. The Leech River Complex of the Inner Pacific Belt is a significant source, as are the Metchosin Volcanics, Sooke Gabbro, and probably Catface Intrusions of the Outer Pacific Belt. These locally derived clasts account for the high degree of angularity of much of the grains in the sandstones. The North Cascades, Coast Plutonic Complex, and the San Juan Islands are considered unlikely possibilities for source areas.

TECTONIC SETTING

DEPOSITION AND TECTONICS

One of the most important factors that affect the depositional environment is the tectonic setting at the time of deposition. A discussion of the tectonic setting of the Sooke Formation is dependent upon the relationships of nearby sedimentary rock units of the same or similar age, on the relative plate motions of the Farallon, Pacific, and North American plates, and on important structural controls.

DEPOSITION

In order to assess the relationship among deposition, tectonics, and paleogeography during Late Oligocene time, nearby sedimentary rock units of the same or similar age must be considered. Time-correlative units are the Pysht, Lincoln Creek, and Blakeley Formations in western Washington. The older Carmanah Group sediments of Vancouver Island will also be discussed as will the younger Clallam Formation of the northern Olympic Peninsula, Washington.

The Escalante and Hesquiat Formations, the older members of the Carmanah Group, are exposed along the west coast of Vancouver Island. The oldest member was first called Division A by Jeletzky (1954, 1973) and renamed the Escalante Formation by Cameron (1971, 1972). The Escalante Formation is Late Eocene in age. The Escalante Formation grades into the Hesquiat Formation (Cameron, 1971, 1972), the middle member of the Carmanah Group, which had earlier been referred to as Divisions B and C (Jeletzky, 1954, 1973) and is Late Eocene to middle Oligocene age.

The Escalante Formation consists mostly of calcareous sandstone with minor, lenticular, shelly conglomerate and argillaceous sandstone (Jeletzky, 1975; Cameron, 1980). The basal contact is very irregular on crystalline basement rocks of the Karmutsen Volcanics (Jeletzky, 1975), the West Coast Complex, and the Bonanza Volcanics (Cameron, 1980). At its upper contact, the Escalante Formation grades into the Hesquiat Formation through calcareous sandstone to argillaceous sandstone and siltstone with shale interbeds (Cameron, 1980).

Based on molluscan macrofauna, Jeletzky (1975) interprets the lower part of the Escalante Formation to have been deposited in a shallow marine environment. Exposures on Hesquiat Peninsula contain well-preserved unabraded mollusc shells which he inferred to have been washed out of a low energy environment during strong storms and deposited and rapidly buried in a surpratidal zone. One location yielded brackish water oysters (Ostrea), which are largely disarticulated and abraded. Jeletzky infers these to have been deposited in a high-energy intertidal (littoral) environment. There is also an abundance of burrows and bioturbation which he infers to have been formed in a relativey low-energy, lowermost littoral, innermost neritic environment. Jeletzky (1975) suggests that a river flowing westward (?) or southwestward (?) drained into an estuarine environment to deposit these sandstones and conglomerates along the coastline. Alternatively, Cameron (1980) states that the slope-type sedimentary structures and the foraminiferal assemblages within the Escalante Formation indicate upper bathyal to lower neritic water depths. He feels that the abraded and disarticulated shallow-water bivalves were transported and redeposited in these environments, largely in conglomeratic lenses and pockets. He states that rapid deepening during Escalante time was necessary to account for the bathyal deposition of the Hesquiat Formation.

The Hesquiat Formation consists of interbedded sandy shale, partly graded cyclic sandstone-silty shale-shale interbeds and pebbly mudstone. The lower contact is gradational with the Escalante Formation (Jeletzky, 1975, Cameron 1980) and unconformable on the Leech River Complex north of the San Juan Fault (Muller, 1977a). The top of the Hesquiat Formation is not exposed in most areas, is faulted in the type locality, and is in contact with the Sooke Formation on a small reef off of Nootka Island (Cameron, 1980). Interbeds of lenticular boulder and pebble conglomerates are characteristically crudely graded, have shale rip-ups, sandstone clasts, reworked fossils, and low clay content (Cameron, 1980). Jeletzky (1975) interprets the fine-grained lithologies to be mostly suspension-settled interchannel deposits, while he interprets the coarser-grained lithologies as channel-fill plastic mass flow deposits on a submarine fan. Based on molluscs and trace fossils he assigns these to outer neritic water depths, even though foraminifera indicate bathyal depths (Cameron, 1980). Jeletzky (1975) suggests that the sediment was shed during pulsating uplifts off of Vancouver Island onto an unstable delta. On the basis of micro- and megafauna, sediments, and sedimentary structures, Cameron (1980) interprets the Hesquiat Formation as being a bathyal deposit of a submarine fan complex.

According to both Jeletzky's and Cameron's interpretations for the depositional environment of the Escalante Formation, the position of the strand line changed radically during the Late Eocene to Late Oligocene times. The older two members of the Carmanah Group were not deposited southeast of the Leech River fault. Sediment was being supplied by uplifted areas and funneled into the Strait of Juan de Fuca northwest of the fault. The Hesquiat Formation had been deposited and uplifted by the time of Sooke Formation deposition.

The Late Oligocene Pysht Formation (defined by Snavely et al., 1977) is the highest member of the Twin River Group of the northern Olympic Peninsula, Washington. It is dominantly composed of massive, semi-indurated mudstone and sandy siltstone with some thin-bedded to massive fine-grained calcareous sandstone beds (Brown and Gower, 1958; Snavely et al., 1977). Channel deposits of pebble to boulder conglomerate with interbedded sandstone and mudstone occur at the base (Snavely et al., 1977). The Pysht is estimated as 1,100 to 1,400 meters (Snavely et al., 1977). Both the upper and lower contacts are gradational with the overlying Clallam Formation and underlying Makah Formation.

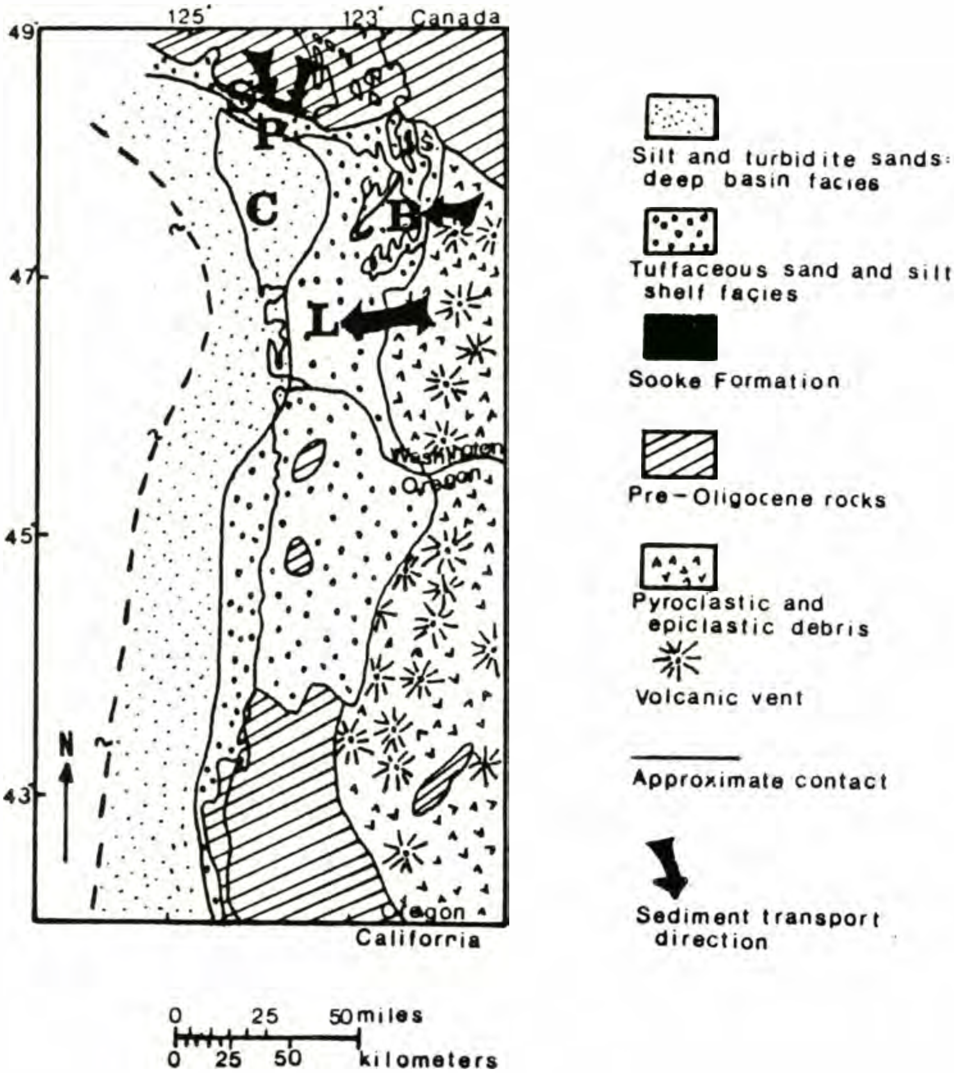
Clasts in the conglomerates are of metamorphic rocks, igneous rocks, and a fine-grained mollusc-bearing sandstone (Snavely et al., 1977). Based on sedimentary structures, the channel conglomerates are interpreted by Snavely et al. (1977) as being derived from an ancient Vancouver shelf and transported through large submarine channels into the basin. The mollusc-bearing sandstone is considered to be derived from nearly coeval but lithified sandstone on the Vancouver shelf (probably Hesquiat Formation).

The Lincoln Creek Formation is exposed along the margins of the Grays Harbor Basin in southwestern Washington (Karachewski, 1983). It is latest Eocene to Late Oligocene in age (Refugian to Zemorrian foraminiferal stages). It was deposited unconformably on Late Eocene unnamed sediments in deeper parts of the basin and on the Crescent Formation where sediments onlapped volcanic highs (Karachewski, 1983). Generally, it is composed of basaltic sandstone interbedded with pyroclastic rocks and tuffaceous siltstones.

Deposition occurred on the continental shelf, which received sediment mainly from an active volcanic arc. Karachewski (1983) interpreted the eastern facies to be representative of continental, deltaic, and nearshore depositional environments and western facies to have been deposited in an offshore marine environment. The eastern facies are represented by the basaltic sandstone and pyroclastics, while the western facies are mainly tuffaceous siltstones. Two types of source areas supplied detritus to the Lincoln Creek Formation. According to Karachewski (1983), a crystalline source area, such as the Okanogan highlands, provided plutonic, metamorphic, and basaltic rocks. Sediment comprising the volcaniclastic sandstone and tuffaceous siltstone beds was supplied by an active, explosive Cascade arc.

The Blakeley Formation crops out along the north shore of the Kitsap Peninsula and on southern Bainbridge Island. Refugian and Zemorrian microfossils indicate a Late Eocene to Late Oligocene age for the Blakley Formation (McLean, 1977). It consists of 2400 meters of volcaniclastic conglomerate, sandstone, mudstone, and shale (McLean, 1977). The turbidite sandstone sequences contain abundant channeling of lenticular strata and mixed shallow and deep water microfaunas. Volcanism in part contemporaneous with deposition is suggested by locally abundant pumice and tuff beds, angularity of plagioclase grains, and presence of unaltered andesite and basalt (McLean, 1977). A westward direction of sediment transport is indicated by paleocurrents and sedimentary structures. This sediment was derived from the active Cascade arc. McLean (1977) proposes turbidity current deposition on part of a submarine fan complex in a deep-marginal basin on the continental shelf.

The Late Oligocene in northwestern Washington was a time of shelf and deep marginal basin sedimentation. Figure 63 shows a Late Oligocene paleogeographic reconstruction for this area. The Blakeley and Lincoln Creek Formations record active Cascade arc volcanism and show that



S = **Sooke Formation**
P = **Pysht Formation**
C = **Olympic Core rocks**
B = Blakeley Formation
L = **Lincoln Creek Formation**

Figure 63. Paleogeographic map of inferred Oligocene shelf and deep water basin facies in southwestern B.C., western Washington, and western Oregon (modified from Snavely and Wagner, 1963; McLean, 1977; Karachewski, 1983).

material was transported westward to the continental shelf where the Lincoln Creek Formation was deposited and sediment of the Blakeley Formation was channeled into a deep marginal basin as turbidity current deposits (McLean, 1977). Conversely, the Pysht Formation derived its material from a northern, Vancouver Island source area, but was also a deep marine deposit. The Sooke Formation also had a dominant Vancouver Island source area for its shallow marine sandstones and conglomerates which delineate the strand line during the Late Oligocene for the northern side of the Strait of Juan de Fuca. These important differences in depths of deposition and in sediment dispersal must reflect tectonic controls on basin geometries during the Late Oligocene.

PLATE TECTONICS

The tectonic setting for the deposition of the Sooke Formation is ultimately related to the relative positions and motions of the Pacific, Farallon, and North American plates during the middle Tertiary. Prior to 43 Ma, the Kula plate was moving northward relative to North America. At about 43 Ma, the demise of the Kula-Pacific spreading system occurred with a reorganization of the Farallon-Pacific system. At this time, the Farallon-Pacific ridge was very close to the edge of continental North America (Engebretson, 1982; Engebretson et al., 1985), possibly close to southern Vancouver Island and the Olympic Peninsula. Figure 64 is a plate reconstruction for the period 37 to 43 Ma. The exact location of the Pacific-North America- Farallon triple junction from about 37 Ma on is not known. Therefore, the triple junction could have been located very close to southern Vancouver Island at this time. The proximity of the ridge means that relatively young and buoyant oceanic crust was being subducted (Anderson, 1985). A convergent subduction regime with the Farallon and

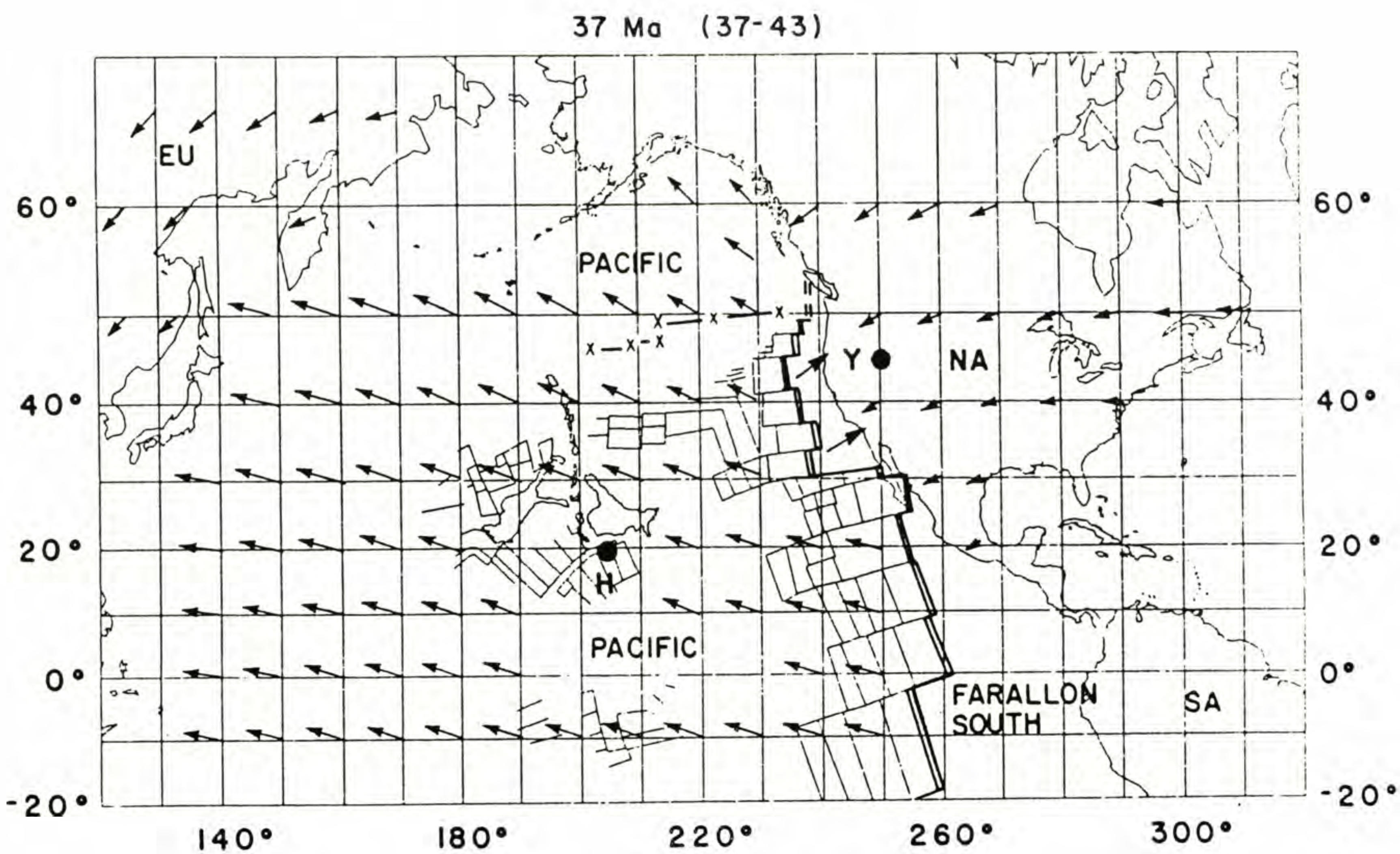


Figure 64. Plate reconstruction for 37 to 43 Ma (from Engebretson, 1982).

perhaps Kula plate descending under the North American plate had been in effect in this area during the entire Tertiary (Engebretson et al., 1985). The trench and subduction zone associated with this convergence shifted from southern Vancouver Island to the Olympic Peninsula about Late Eocene time (Muller, 1977a). Also from 43 Ma until 28 Ma, there was a marked decrease in the rate of Farallon-North America convergence. This decrease is coincident with a shift at about 42 Ma from volcanism and plutonism at the Challis arc to the Cascade arc (Wells et al., 1984).

Figure 65 is a 28 Ma reconstruction, which shows passage of the Aja fracture zone close to the Olympic Peninsula. Figure 65 shows that this fracture zone has migrated north towards southwestern Vancouver Island by about 24 Ma which is just after Sooke deposition ceased. As discussed by Anderson (1985), the passage of a fracture zone could account for uplift as buoyant crust associated with it is subducted beneath the margin. As one can observe from Figure 65, the crust on the north side of the fracture zone, which would affect the continent first, is younger and therefore should be more buoyant than that on the south side. Then, as the fracture zone passed to the north and the ridge moved farther away from the margin, older, denser crust was subducted, which could account for basin subsidence. This passage of a fracture zone could help to explain uplift of the source areas and subsequent basin subsidence which were necessary to the preservation of the strand line facies of the Sooke Formation.

Another possible control on uplift and subsidence could be the passage of the Pacific-Farallon-North America triple junction beneath Vancouver Island. The exact location of the triple junction is not known for the period of Sooke Formation deposition, but it was likely north of southwestern Washington. Numerous small syndepositional normal faults cut

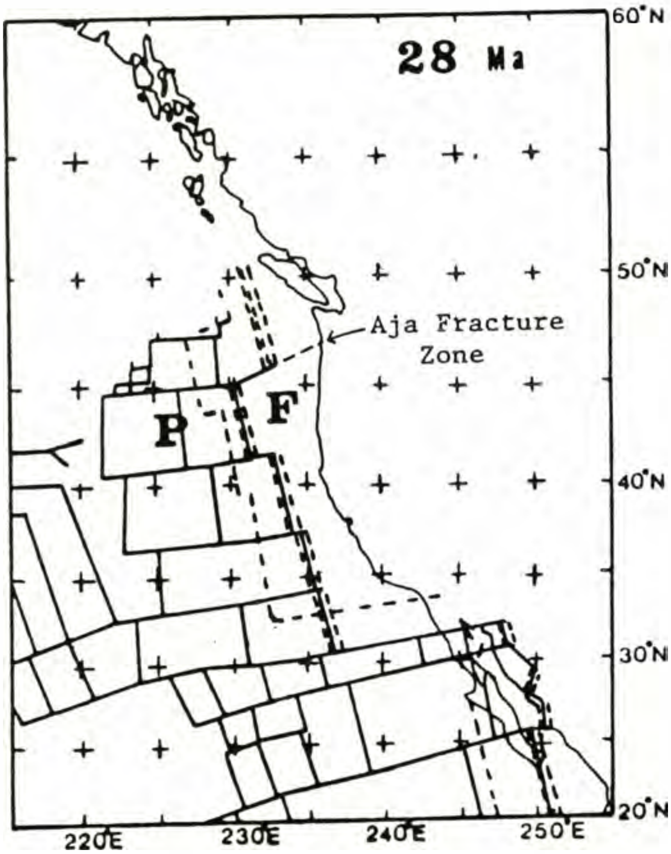


Figure 65. 28 Ma reconstruction for western North America and northeastern Pacific (modified from Engebretson et al., 1985).

the Sooke Formation at the Muir Creek cliffs and at Keffers property. These faults indicate that a tensional regime existed during deposition, which could have been related to the triple junction.

Tectonic movements often have a profound influence on sea level. Vail et al. (1977) noted that there was a global decrease in sea level during the Tertiary. This decrease is reflected in the sediment record for the Strait of Juan de Fuca with a general shallowing-upward of facies from early Tertiary through the Miocene. Vail et al. (1977) also noted that the Late Oligocene was a time of a small-scale global rise in sea level relative to a major drop during the middle Oligocene. The Sooke Formation records a general deepening upwards or transgression possibly with several pulses of either uplift or regression to account for the coarse boulder conglomerates throughout much of the section. If the Pacific-Farallon ridge was offset by a number of fracture zones, then there would possibly have been pulses of uplift of parts of the basin and subsidence of others while different segments of the ridge passed. Thus tectonic movements may have been the ultimate cause of this transgression with pulses of uplift or regression.

STRUCTURAL CONTROLS ON DEPOSITION

The Leech River fault (Fig. 66) is considered to be the suture zone across which the Crescent Terrane and southern Vancouver Island were amalgamated in an early Tertiary subduction zone (Muller, 1983). Regardless of the exact nature of the movement, the timing is fairly well constrained. The oldest possible time for suturing is just after the 39-41 Ma culmination of metamorphism and deformation of the Leech River schist (Fairchild and Cowan, 1982); the youngest possible time is at the Late Oligocene time of deposition of the Sooke Formation (Muller, 1977a;

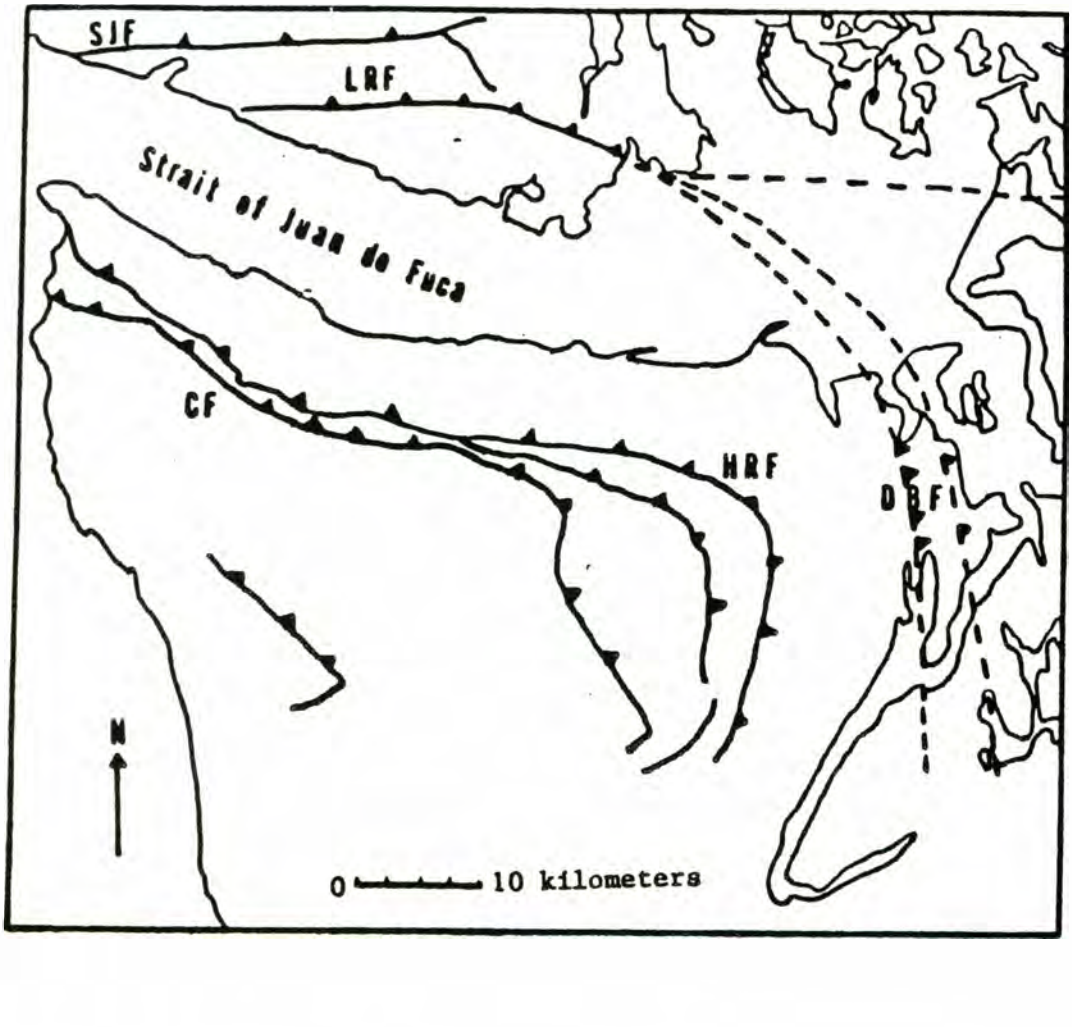


Figure 66. Map showing major structures of southern Vancouver Island and the northern Olympic Peninsula. Faults include San Juan fault (SJF), Leech River fault (LRF), Discovery Bay fault (DBF), Hurricane Ridge fault (HRF), and Calawah fault (CF). Compiled from Tabor and Cady, 1978a; Fairchild, 1979; Yorath et al., 1985; Moyer, 1985; Anderson, 1985.

Fairchild and Cowan, 1982; MacLeod et al., 1977). As reported by Cameron (1980), the Sooke Formation is exposed on a small island near Carmanah Point, well north of the Leech River fault, where it overlies beds probably of the Hesquiat Formation. Fairchild and Cowan (1982) report that the Sooke Formation overlaps the fault on the beach north of Sombrio Point. If the sediments that crop out north of the Sombrio River are Sooke Formation, then it overlaps the trace of the fault at Sombrio Beach.

Muller (1983) interprets the volcanic rocks of the Crescent Terrane to extend across the Strait with the overlying sedimentary rocks pinching out to the north where the basin shallows. They also interpret the core rocks as pinching out beneath the Strait to the north. In the Lithoprobe Phase 1 seismic reflection profile, Yorath et al. (1985) interpret the Crescent Formation to extend across the strait possibly with sedimentary rocks that are equivalent to the core rocks of the Olympic Peninsula beneath it. As reported by MacLeod et al. (1977), seismic reflection data show that sedimentary rocks, interpreted as most likely Eocene and Oligocene (Carmanah Group) and younger, are present offshore of southwestern Vancouver Island overlying rocks interpreted to be equivalent to the Leech River Complex. Gravity and magnetic studies (MacLeod et al., 1977) also show that the Leech River fault extends in a west-southwest trend offshore from Sombrio Point toward Cape Flattery on the Olympic Peninsula and that it extends south of Victoria into the eastern part of the Strait as the Discovery Bay fault (Fig. 66) (MacLeod et al., 1977; Armentrout, 1984).

As discussed in previous chapters, the basal breccia of the Sooke Formation in the vicinity of the Leech River fault contains clasts of both Leech River Complex and of metamorphosed Metchosin Volcanics, thus indicating a very local source for at least part of the formation and a distinct relationship between movement on the Leech River fault and deposition of the Sooke Formation. Uplift prior to deposition of the Sooke Formation would have exposed the Leech River Complex north of the fault, rendering nearby slopes unstable. The pulses of tectonic activity discussed in the previous section are probably related to less dynamic movements that are associated with the Leech River fault system.

The size and distribution of clasts of the Leech River schist in the Sooke Formation are directly related to the proximity to the fault. At Sombrio Beach, the size of these clasts in the basal breccia decreases rapidly away from the fault toward Sombrio Point. Boulder-sized clasts are found only at Sombrio Beach. Throughout the rest of the study area Leech River schist clasts are present as pebbles to sand, but they are much less abundant than at Sombrio Beach (Appendices 2 and 5 through 8). This distribution is most likely related both to streams draining a Leech River source area to the north and to longshore transport locally from the northwest to the southeast.

TECTONIC HISTORY

A discussion of the tectonic setting of the Sooke Formation would not be complete without a summary of the major tectonic events that occurred just prior to, during, and soon after Sooke Formation deposition (Table 7).

The majority of Vancouver Island is composed of rocks of Wrangellia, which collided with North America at about the latitude of Baja California (Packer and Stone, 1974; Muller, 1977a; Jones et al., 1977; Hillhouse et al., 1982; Yole and Irving, 1980; Irving et al., 1985) and were translated up the west coast of North America during the Early Cretaceous (Vallier, 1986) by the motions of the Farallon or Kula plates during oblique subduction (Beck et al., 1981; Jones et al., 1977). Because the Late

TABLE 7

TIMING OF TECTONIC EVENTS

TIMING	EVENT
Before Sooke Formation Deposition:	
90-100 Ma	Amalgamation of Wrangellia and Coast Plutonic Complex at latitude of Baja, California
85-65 Ma	Deposition of Nanaimo Group
55-48 Ma	Basalts of Metchosin and Crescent Formations erupted
45-37 Ma	Strike-slip truncation event in San Juan Islands and western Vancouver Island
43 Ma	Demise of Kula-Pacific ridge and reorganization of Farallon-Pacific system
	Accretion and underthrusting of core rocks of Olympic Peninsula
42 Ma	Shift of volcanism and plutonism from Challis arc to Cascade arc
48-41 Ma	Deposition of Aldwell Formation, Olympic Peninsula
40 Ma	Metamorphism and deformation of Leech River Complex and subsequent movement on San Juan fault
	Beginning of accretion and underthrusting of core rocks of Olympic Peninsula
40-32 Ma	Deposition of Escalante and Hesquiat Formations, Vancouver Island
38-32 Ma	Underthrusting of Metchosin Volcanics along Leech River fault
During Sooke Formation Deposition:	
32-24 Ma	Deposition of Sooke Formation
	Deposition of Pysht, Lincoln Creek, and Blakeley Formations
28 Ma	Passage of Aja fracture zone
After Sooke Formation Deposition:	
25-20 Ma	Deposition of Clallam Formation, Olympic Peninsula

Cretaceous Nanaimo Group onlaps the rocks of Wrangellia that are on Vancouver Island and is partly derived from the Coast Plutonic Complex (Pacht, 1984), these rocks must have been in place relative to each other (and translated together) by Late Cretaceous time. The final time of arrival of the Wrangellia rocks of Vancouver Island to their present position relative to North America is still not definitely known.

Sometime between 55 and 48 Ma, the Crescent and Metchosin basalts were being erupted very close to the continental margin of western North America (Cady, 1975). At this time, the subduction zone between the oceanic (Farallon or Kula) plate and North American plates was probably located west of the Olympic Peninsula and Vancouver Island. Brandon (1985) proposed a strike-slip event from 45 to 37, Ma which truncated part of the San Juan Islands and western Vancouver Island and was responsible for translation of the Pacific Rim Complex rocks northwestward to their present location on Vancouver Island.

At about 43 Ma, the demise of the Kula-Pacific ridge caused a reorganization of the Farallon-Pacific system (Engebretson, 1982; Wells et al., 1984). As previously mentioned, the shift from plutonic and volcanic activity centered at the Challis arc to that centered at the Cascade arc at about 42 Ma was coincident with a decrease in the rate of North America-Farallon convergence (Wells et al., 1984).

Deposition of the oldest peripheral sedimentary rocks on the northern Olympic Peninsula, the Aldwell Formation, occurred between 48 and 41 Ma (Tabor and Cady, 1978a). These were deposited at bathyal depths on two submarine fans (Marcott, 1985). The Leech River Complex was metamorphosed at about 40 Ma and was faulted into place along the San Juan fault (Fairchild and Cowan, 1982). Deposition of the Escalante and Hesquiat Formations followed soon afterwards during the Late Eocene and Oligocene.

Also, beginning at about 40 Ma, the rocks that comprise the core rocks of the Olympic Peninsula began to be accreted in an underthrusting event, which continued at least through the Oligocene (Tabor and Cady, 1978a).

As the basalts of the Crescent Terrane were thrust beneath Vancouver Island along the Leech River fault after the 39 to 41 Ma metamorphic event (Fairchild and Cowan, 1982; Clowes et al., 1985), local uplift of Wrangellia rocks, Leech River Complex, and Metchosin Volcanics occurred. This underthrusting event also caused counterclockwise rotation of the basalts (Moyer, 1985). According to Moyer (1985), a later clockwise rotation of the western portion of the Crescent Terrane on the Olympic Peninsula occurred between 28 and 9 Ma.

A marine regression and strand line deposition of the Sooke Formation followed this underthrusting and uplift between 38 and 24 Ma. Passage of the Aja fracture zone at about 28 Ma and the Pacific-Farallon-North America triple junction may have caused local uplift followed by basin subsidence. At this time, deeper marine deposition of the Pysht Formation was occurring on the Northern Olympic Peninsula. Farther south, deep marine and shelf deposition of the Lincoln Creek and Blakeley Formations were occurring. The deltaic Clallam Formation was deposited between 25 and 20 Ma on the Olympic Peninsula.

CONCLUSION

The Upper Oligocene Sooke Formation is exposed along the coast of southeastern Vancouver Island. It is generally less than 150 feet thick and consists dominantly of sandstone and conglomerate. It was deposited in a setting which was dominated by high-energy beach and nearshore environments. The Late Oligocene coastline on southeastern Vancouver Island consisted of rocky headlands and sandy beaches. Faunal evidence indicates that at least part of the Sooke Formation was deposited in brackish water near the mouth of an estuary. The sediment in the Sooke Formation was derived both locally and from a more distant source inland on Vancouver Island.

The Sooke Formation has been divided into six facies. Facies A consists of a basal boulder breccia, some of which is fossiliferous. The basal breccia was deposited unconformably on the Metchosin Volcanics and Sooke Gabbro by two mechanisms: debris flows and rock fall. The debris flows originated inland. Rock fall occurred off cliffs and sea stacks. Deposition occurred in the beach and nearshore environments. Sandstone lenses are the result of wave activity.

Facies B is characterized by a dominantly muddy matrix boulder conglomerate (subfacies B1) and pebble conglomerate (subfacies B2). Surging debris flows were responsible for depositing the boulder conglomerates. These deposits are very poorly sorted, lack clast orientation, and contain woody material. Backbeach ponding of a stream entering the beach could account for the subfacies B2 pebble conglomerates, in particular the burrowed conglomerate. Alternatively, these could be debris flow deposits.

Facies C is composed of conglomeratic sandstone and consists of three subfacies. Subfacies C1 contains boulder conglomerates and cross-stratified sandstone, some of which is fossiliferous. The conglomerates were deposited by debris flows. Some of these flows may have originated by slumping of uplifted terraces of older debris flow deposits and beach deposits. The sandstones were deposited by wave activity in the beach and shoreface environments. Trough cross-stratification is the dominant bedding type, although tangential wedge cross-stratified sets and parallel-laminated sets are also present. Particular sequences of bedforms indicate rapidly fluctuating conditions. Subfacies C2 consists of more debris flow deposits of cobble to pebble conglomerate and breccia with sandstones deposited by intersurge reworking by waves. Subfacies C3 differs from the rest of facies C deposits because it has laterally continuous parallel- to thick-bedded pebble conglomerates and smaller pebble lenses and cross-stratified sandstone. These conglomerates are interpreted as lower foreshore and shoreface storm lag deposits. The pebbles were supplied by streams and reworked and redistributed by waves. The sandstones are interpreted similarly to subfacies C1 sandstones as mostly shoreface deposits.

Facies D is extremely variable in textures and sedimentary structures but consists largely of cross-stratified and parallel-laminated sandstones with scattered pebbles, pebble lenses, and sandstone channels. It is very fossiliferous in many locations, and some beds are burrowed. Both the stratigraphy and the paleoecology indicate that sedimentation fluctuated rapidly under dominantly high-energy conditions on the shoreface with some quieter fairweather deposition on the lowermost shoreface. The influence of storms on sedimentation is evident by some hummocky cross-stratified sandstones and by shell lag deposits.

Facies E, a thick-bedded pebble grit and conglomerate was deposited by storms. these deposits are poorly-sorted and fossiliferous at some localities and burrowed at one locality. The burrowing indicates quiet fairweather conditions following a storm.

Facies F consists of silty shale and siltstone which were deposited in quiet, low-energy waters. Quiet depositional settings such as local shallow areas behind seastacks or backbeach ponded areas are probable for these deposits.

Boulders and cobbles in the Sooke Formation consist of basalt, gabbro (and metamorphic equivalents), and schist. They are all derived locally from the underlying basement rock of Metchosin Volcanics and Sooke Gabbro except for the schist, which is derived from the Leech River Complex to the north. Pebbles and granules have more variable lithologies, which include volcanic and metavolcanic (basalt and andesite), mafic plutonic and metaplutonic (gabbro and amphibolite), felsic plutonic, and metasedimentary (schist), but are dominantly basaltic and meta-basaltic. Angularity of conglomerate clasts is variable, with debris flow deposits generally more angular than fluvially-supplied shoreface storm lag deposits.

The Sooke Formation sandstones are lithic arenites and are both texturally and compositionally immature. Grain sizes range from very fine sandstone to coarse sandstone, commonly with granules and pebbles and sometimes referred to as grits. Modal grain size is fine-grained sandstone. Angularity ranges from well-rounded to angular, with angular to subangular the most common. Lithic grains show a tendency towards being slightly better rounded than monocrystalline grains. Sediments are mostly well- to moderately well-sorted. Quartz, plagioclase feldspar, and amphibole are the most common monocrystalline grains, with subordinate micas, epidote minerals, staurolite, and K-feldspar, and rare pyroxene, garnet, zircon, and detrital pumpellyite and chlorite. Lithic grains are dominantly meta-basalt and amphibolite, and less commonly polycrystalline quartz and chert, schist, phyllite, and andesite.

Diagenetic changes of the Sooke Formation were relatively complex. The sandstones are mostly calcite cemented and concretionary layers are common. Other cements include pyrite, hematite, zeolite, clay, K-feldspar or K-rich zeolite, and silica. Commonly, several stages of cement are present in one bed. Fossils are commonly replaced by calcite. The Sooke Formation contained abundant woody material, some of which was preserved as coal. The presence of zeolite cement indicates that the Sooke Formation was buried at a relatively shallow depth.

Prior to deposition of the Sooke Formation, the Escalante and Hesquiat Formations were deposited on southwestern Vancouver Island. The Escalante Formation was deposited either in a high-energy littoral environment or in an upper bathyal to lower neritic environment. The Hesquiat Formation was deposited on a bathyal submarine fan complex. Deposition of the Sooke Formation occurred at much shallower depths than the older Hesquiat Formation indicating that there was a significant shallowing of the depositional basin between Late Eocene to middle Oligocene and Late Oligocene times. The strand line facies of the Sooke Formation also contrast with other Late Oligocene sedimentary units in northwestern Washington which were deposited on the shelf and in deep marginal basins.

The tectonic setting was an important control on the deposition of the Sooke Formation and is ultimately related to the relative positions of the Pacific, Farallon, and North American plates during the middle Tertiary. A Farallon (and perhaps Kula)-North America subduction regime has been in effect in this area during the entire Tertiary. It is possible that the Pacific-Farallon triple junction was located beneath southern Vancouver Island during the Late Oligocene. Subduction of the triple junction or passage of one or more fracture zones might have affected uplift and basin subsidence and local sea level during deposition of the Sooke Formation. The Leech River fault is thought to be the suture along which rocks of the Crescent Terrane and the Leech River Complex were amalgamated during subduction. The latest major movement on this fault is constrained by deposition of the Sooke Formation which reportedly overlaps and is undeformed by it. Movement on the Leech River Fault prior to Sooke deposition caused uplift of various source terranes; that uplift was a major control on the composition and distribution of clasts in the Sooke Formation, especially in the basal breccia of facies A. Tectonic setting, depositional environment, and provenance for the Sooke Formation are all interrelated and the effects of these can be seen in this study of the Sooke Formation.

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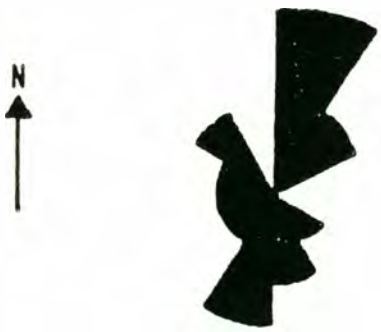
APPENDIX 1: Paleocurrent Rose Diagrams

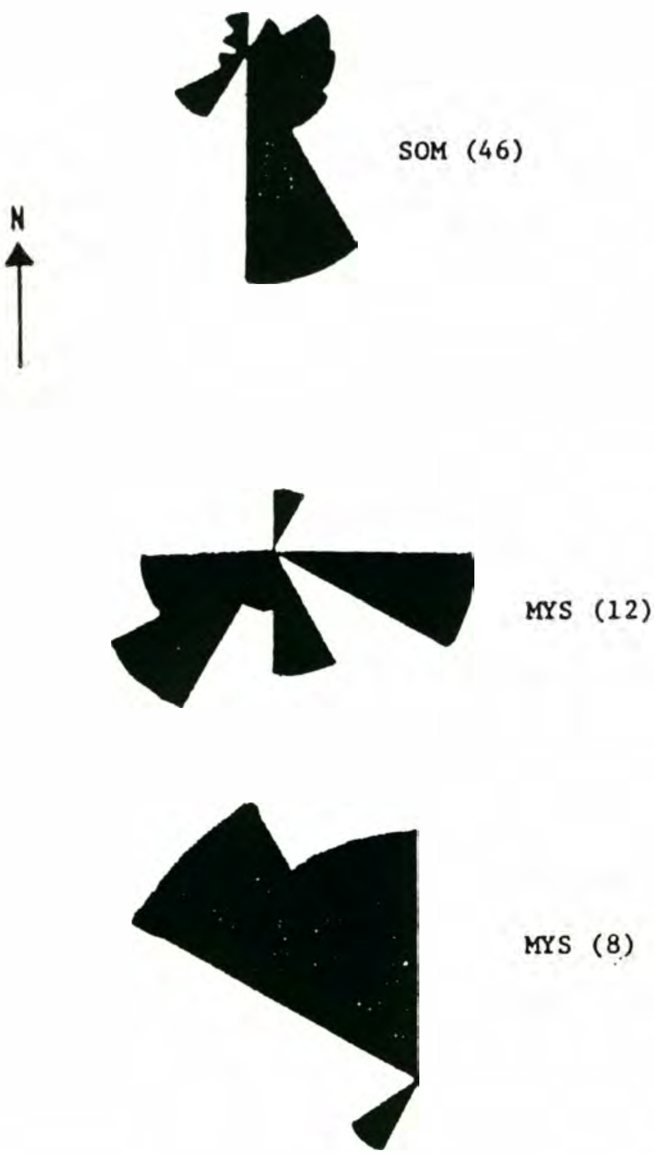
PNP (9)



WHI (17)

ESP (8)

Note: Measurements were taken from lineations of pebbles. The plots use the total number of readings (in parentheses) normalized to 100 %.



Note: Measurements were taken from lineations of pebbles.
The plots use the total number of readings (in parentheses) normalized to 100 %.

(SOM 9)

Note: Measurements were taken on cross-strata. The plots use the total number of readings (in parentheses) normalized to 100 %.

APPENDIX 2: Pebble Count Results

Pebble Count 1: Sombrio Beach (SOM D)

# Points	Lv	Lvm	Lpm	Lms	Lmi
2				x	
2		x			
2		x			
3				x	
1		x			
3		x			
1		x			
1				x	
1				x	
1				x	
4		x			
3		x			
1				x	
1				x	
1		x			
1		x			
1		x			
2		x			
1		x			
1				x	
1				x	
1				x	
2		x			
3				x	
5				x	
4		x			
1		x			
3		x			
1		x			
1		x			
2		x			
1				x	
4				x	

Total Points: 62

Pebble Count 2: Sombrio Beach (SOM C)

# Points	Lv	Lvm	Lpm	Lms	Lmisc
1		x			
1		x			
1					x
1				x	
1				x	
1				x	
3				x	
1				x	
1					x
1		x			
1		x			
1				x	
1					x
1		x			
1				x	
1				x	
1				x	
1		x			
1		x			
1		x			
3		x			
1				x	
1				x	
1				x	
1				x	
1				x	
1				x	
1				x	
1				x	
1		x			
1				x	
1		x			
1				x	
3				x	
1				x	
1		x			
1		x			
1				x	
1				x	
1				x	

Total Points: 50

Pebble Count 3: Sombrio Beach (SOM C)

# Points	Lv	Lvm	Lpm	Lms	Lmisc
1		x			
1		x			
1				x	
1		x			
1		x			
1				x	
1		x			
1		x			
1				x	
1		x			
1					x
1		x			
1				x	
1		x			
1		x			
1		x			
2		x			
1		x			
1		x			
1		x			
1		x			
1				x	
1		x			
1		x			
1				x	
1		x			
1				x	
1		x			
1		x			
1		x			
1		x			
1				x	
1					x
1		x			
1					x
1		x			
1		x			
1		x			
1		x			
1		x			
2		x			
1		x			
3		x			
1				x	
1					x
3				x	

Total Points: 50

Pebble Count 4: Sombrio Beach (SOM C)

# Points	Lv	Lvm	Lpm	Lms	Lmisc
2				x	
1				x	
1				x	
1	x				
1	x				
1	x				
1					x
1				x	
1	x				
1	x				
1	x				
1	x				
1	x				
1	x				
1					x
1	x				
3	x				
1	x				
1				x	
1				x	
2	x				
1				x	
1				x	
1	x				
1				x	
1					x
1				x	
1				x	
1	x				
1				x	
1				x	
2	x				
1				x	
1				x	
1				x	
1	x				
1	x				
2				x	
1				x	
1	x				
1	x				
2				x	

Total Points: 50

Pebble Count 4: Correction Camp (COR B)

# Points	Lv	Lvm	Lpm	Lms	Lmisc
1				x	
1	x				
1				x	
1					x
1			x		
1	x				
1			x		
1	x				
1	x				
1	x				
1	x				
1		x			
1				x	
1	x				
1	x				
1			x		
1			x		
1			x		
1	x				
1	x				
1					x
1					x
1					x
1	x				
1	x				
1	x				
1	x				
1				x	
1				x	
1					x
1	x				
1	x				
1				x	
1			x		

Total Points: 35

Pebble Count 5: Correction Camp (COR A)

# Points	Lv	Lvm	Lpm	Lms	Lmisc
2		x			
5			x		
1		x			
1		x			
5		x			
1			x		
1		x			
1			x		
3			x		
1			x		
1		x			
1		x			
2			x		
1		x			
1			x		
1			x		
1			x		
1			x		
3			x		
4		x			
8			x		
8			x		
1			x		
1			x		
1			x		
1			x		
1			x		
1			x		

Total Points: 50

Pebble Count 8: Mystic Beach (MYS B)

# Points	Lv	Lvm	Lpm	Lms	Lmisc
7	x				
1	x				
1	x				
1	x				
1	x				
1	x				
8	x				
1					x
1		x			
1	x				
1	x				
1	x				
2			x		
1			x		
3	x				
1					x
1			x		
1					x
1			x		
1	x				
1	x				
1					x
1	x				

Total Points: 50

Pebble Count 6: Mystic Beach (MYS A)

# Points	Lv	Lvm	Lpm	Lms	Lmisc
2			x		
1	x				
1	x				
2			x		
1	x				
1			x		
1	x				
1			x		
1	x				
1	x				
1		x			
1	x				
1	x				
1	x				
1	x				
1	x				
1	x				
1		x			
1			x		
1	x				
1		x			
1			x		
1	x				
1	x				
1			x		
1	x				
2				x	
1				x	
1	x				
1	x				
1		x			
1	x				
1	x				
1	x				
1		x			
1				x	
1	x				
1	x				
1	x				
1		x			
2		x			

Total Points: 50

Pebble Count 9: China Beach Provincial Park (CHI A)

# Points	Lv	Lvm	Lpm	Lms	Lmisc
1			x		
2			x		
1		x			
1		x			
2			x		
2			x		
1	x				
1			x		
1	x				
1			x		
1			x		
1			x		
4	x				
1					x
1			x		
1					x
1			x		
4			x		
1	x				
1			x		
1			x		
1			x		
1	x				
1			x		
1	x				
1	x				
1	x				
1			x		
2			x		
5	x				
1	x				
2			x		
1	x				

Total Points: 50

Pebble Count 10: French Beach Provincial Park (FRE A)

# Points	Lv	Lvm	Lpm	Lms	Lmisc
1	x				
1	x				
1	x				
1	x				
1	x				
1	x				
1	x				
1	x				
1	x				
1	x				
1	x				
1		x			
1	x				
1	x				
1		x			
1	x				
1		x			
1	x				
1	x				
1	x				
1	x				
1		x			

Total Points: 22

Pebble Count 11: French Beach Provincial Park (FRE-A)

# Points	Lv	Lvm	Lpm	Lms	Lmisc
1	x				
1	x				
1	x				
1	x				
2			x		
1		x			
2					x
3	x				
2			x		
1			x		
1	x				
2			x		
2			x		
1			x		
1	x				
1	x				
1			x		
1				x	
1	x				
1	x				
1	x				
1				x	
1	x				
1	x				
1				x	
1	x				
1	x				
1	x				
1	x				
1	x				
1	x				
1	x				
1	x				
1	x				
1	x				
1	x				
1	x				
1		x			
1			x		
1	x				
1	x				
1	x				
1	x				
1	x				
1			x		
2	x				
1	x				
1	x				
2			x		
2	x				
2	x				
2	x				

Pebble Count 11 continued

1	x				
1	x				
1			x		
2	x				
2	x				
1	x				
1	x				
2	x				
4			x		
1	x				
1			x		
1	x				
1	x				
2			x		
1	x				
1			x		
1	x				
2	x				
1			x		
1			x		
1			x		
1					x
1		x			
1	x				
1			x		
1	x				
1			x		
1	x				
1	x				
1	x				
1	x				

Total Points: 100

Pebble Count 12: Beach Trail (BTR)

# Points	Lv	Lvm	Lpm	Lms	Lmisc
1					x
1					x
1		x			
1	x				
1	x				
1			x		
1	x				
1	x				
1			x		
1		x			
1		x			
1	x				
1		x			
1		x			
1		x			
1		x			
1	x				
1			x		
1			x		
1	x				
2			x		
1	x				
1	x				
1	x				
1			x		
1	x				
1	x				
1	x				
1	x				
1	x				
1	x				
1	x				
1	x				
1	x				
1			x		
1	x				
1	x				
1	x				
1			x		
1	x				
2	x				
2	x				
1	x				
1	x				

Total Points: 49

Pebble Count 13: Whiffen Spit (WHI)

# Points	Lv	Lvm	Lpm	Lms	Lmisc
1				x	
1				x	
1				x	
1	x				
1		x			
2		x			
1		x			
1	x				
1	x				
1				x	
1				x	
1		x			
1	x				
1	x				
1		x			
1		x			
1	x				
1	x				
1		x			
1		x			
1				x	

Total Points: 23

Pebble Count 14: East Sooke Park (ESP)

# Points	Lv	Lvm	Lpm	Lms	Lmisc
2			x		
1	x				
1			x		
2			x		
1			x		
1			x		
1			x		
2			x		
1			x		
1			x		
3			x		
1	x				
1			x		
1			x		
1			x		
1			x		
1			x		
1			x		
1			x		
2			x		
3			x		
1			x		
1			x		
1			x		
1			x		
1			x		
2			x		
1			x		
2			x		
1	x				
1			x		
1					x
1			x		
1			x		
1			x		
1	x				
2			x		
2			x		

Total Points: 50

APPENDIX 3: Fauna list (from Clark and Arnold, 1923).

PELECYPODA

Antigona vancouverensis (Merriam)
Cardium sookensis n. sp.
Ch one vancouveren is n. sp.
Cryptomya quadrata Arnold vancouverensis n. subsp.
Cyrene sookensis n. sp.
Diplodonta cf. stephensoni Clark
Glycymeris vancouverensis n. sp.
Macoma sookensis n. sp.
Macoma sp.
Metis vancouverensis n. sp.
Modiolus sookensis n. sp.
Mulinia newcombei n. sp.
Myadesma dalli Clark
Mytilus hannibali n. sp.
Mytilus mathewsonii Gabb
Mytilus sammamishensis Weaver
Mytilus vancouverensis n. sp.
Ostrea sookensis n. sp.
Panope cf. generosa Gould
Pecten columbianum n. sp.
Pecten cornwalli n. sp.
Pecten vancouverensis Whiteaves sanjuanensis n. subsp.
Phacoides columbianum n. sp.
Platyodon aff. cancellatus Conrad
Pododesmus newcombei n. sp.
Saxidomus newcombei (Meriam)
Semele vancouverensis n. sp.
Solen clallamensis n. sp.
Spisula hannibali n. sp.
Spisula sookensis n. sp.
Tellina bodegensis Hinds n. subsp.?
Tellina oregonensis Conrad
Tellina vancouverensis n. sp.
Teredo sp.
Venus victoriana n. sp.
Yoldia cf. cooperii Gabb
Zirfaea sp.

GASTROPODA

Acmaea geometrica (Merriam)
Acmaea hannibali n. sp.
Acmaea mitra Eschscholtz vancouverensis n. subsp.
Acmaea victoriana n. sp.
Agasoma accuminatum Anderson and Martin
Ancilla fishii Gabb
Antiplanes muirensis n. sp.
Bursa vancouverensis n. sp.
Calyptraea mammilaris Broderip vancouverensis n. subsp.
Calyptraea sookensis n. sp.
Cerithidea newcombei n. sp.
Crepidula sookensis n. sp.
Eudolium sp.
Fusinus hannibali n. sp.
Gadinia reticulata Sowerby sookensis n. subsp.
Goniobasis sookensis n. sp.
Leptothyra vancouverensis n. sp.
Littorina sookensis n. sp.
Megathura vancouverensis n. sp.
Molopophorus newcombei (Merriam)
Polinices recluziana (Deshayes) vancouverensis n. subsp.
Polinices sookensis n. sp.
Polinices victoriana n. sp.
Puncturella sp.
Rapana perrini n. sp.
Searlesia branneri n. sp.
Thais cornwalli n. sp.

AMPHINEURA

Oligochiton lioplax Berry

ANTHOZOA

Siderastrea voncouverensis n. sp. Vaughan

BRACHIOPODA

Terebratella? sookensis n. sp.
Terebratalia transversa Sowerby n. subsp.?

ECHINOIDEA

Soutella newcombei Kew

VERMES

Serpula sp.

CRUSTACEA

Balanus sp.

VERTEBRATA

Desmostylus? sp.

APPENDIX 4: Grain Category Descriptions

Quartz (Qm)- Monocrystalline quartz is common in most samples. It is usually angular to subangular and less commonly subrounded and rarely rounded. The quartz is often undulose, particularly when it is part of a foliated coarse polycrystalline quartz grain. The undulose quartz is probably derived from a metamorphic source. Metamorphic derived quartz is also present in some metaigneous lithics. Both clear and vacuoled varieties are also common, and some grains have needle-like inclusions. The clear quartz is most likely derived from a volcanic source, while the vacuoled and rutilated quartz is probably derived from a plutonic source. A few samples have poikilitic quartz. Partial replacement by calcite cement is observed in some samples. No overgrowths were observed on any quartz grains.

Plagioclase (P)- Plagioclase is present both as fresh, unaltered grains and as very altered grains, often partially replaced by calcite (Fig. 67), pumpellyite, sericite, or prehnite. Plagioclase crystals with sieve texture are sometimes present. Albite and Carlsbad twins are common, and some combined Carlsbad and Albite twins are present. Plagioclase is mostly angular to subangular. Both calcic and sodic plagioclase are common and are revealed by whether the grains do or do not take the pink amaranth stain for calcium and specifically by the A-normal method. The A-normal method yielded plagioclase ranging from oligoclase to bytownite with oligoclase and labradorite the most common. Normally zoned and oscillatory zoned crystals indicate a volcanic source. The angularity of the plagioclase grains probably indicates a relatively nearby source area. Plagioclase is found as phenocrysts in volcanic lithics, as detrital grains, and also in plutonic and metamorphic lithics.

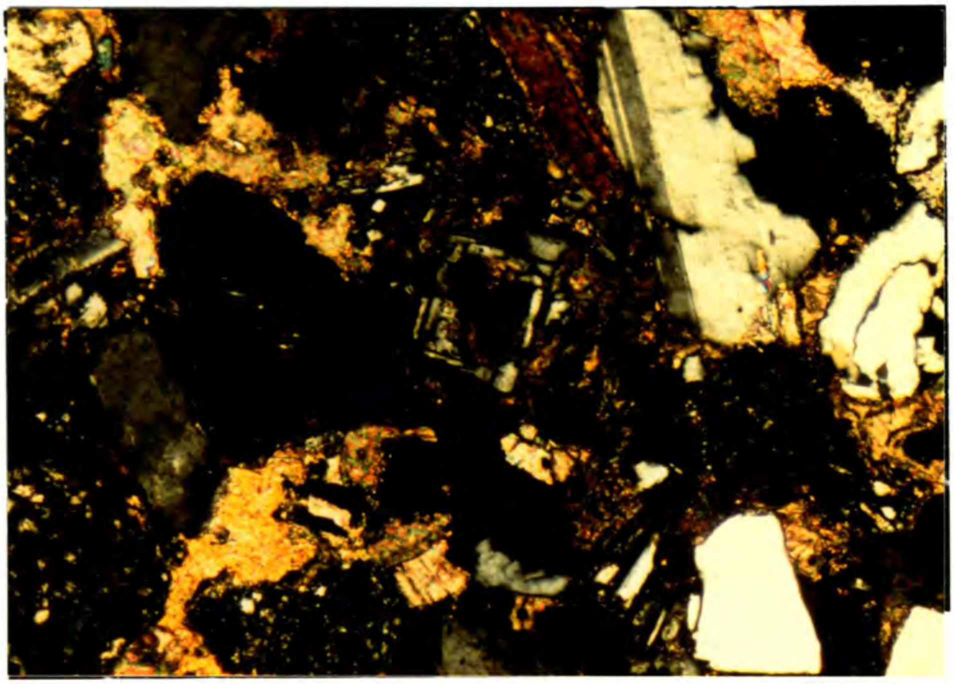


Figure 67. Core of plagioclase replaced by calcite cement in sandstone. Polarized light. Field of view: 2.1 x 1.5 mm.

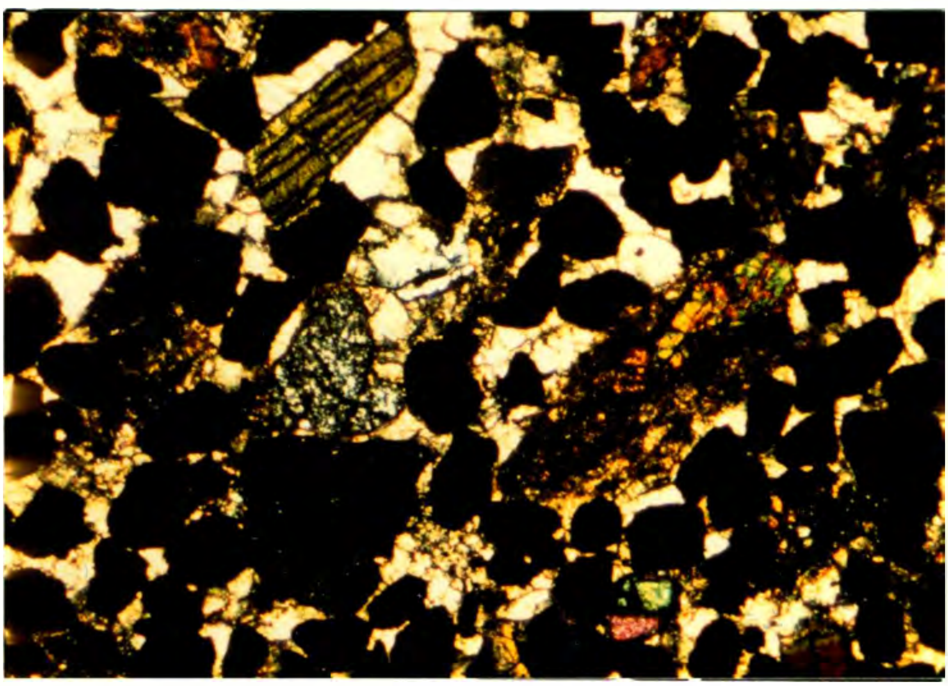


Figure 68. Magnetite placer deposit with epidote, chert, and hornblende. Polarized light. Field of view: 2.1 x 1.5 mm.

Potassium Feldspar (K)- Both orthoclase and microcline are present in the Sooke Formation, but neither mineral is common. In general, potassium feldspar is recognized by the yellow sodium cobaltinitrate stain under plane polarized light and by the presence of tartan twinning for microcline. Most grains are subangular to subrounded. Potassium feldspar is mainly found as individual detrital grains and as plutonic aggregates with quartz. It is rarely observed to be partially replacing plagioclase grains and K-spar cement is equally rare.

Micas (Mi)- Both muscovite and biotite are present as sand-sized grains in a small percentage of most samples. They are often deformed and biotite is commonly "shredded", or stretched and torn and partially filled by calcite cement. Partial replacement of biotite by pyrite or alteration to chlorite is also common. Biotite usually occurs as brown to red-orange and rarely green pleochroic platy detrital grains or as grains in metasedimentary or plutonic aggregates. Muscovite usually occurs as thin detrital strips or as grains in metasedimentary rocks. Fine-grained muscovite (sericite) is a common alteration product of feldspars. It is also common in metasedimentary rocks.

Amphiboles (Am)- Amphibole is a common constituent of many samples. Hornblende is the most common amphibole in the Sooke Formation (Fig. 68), often displaying prismatic end sections which show the characteristic 60/120 degree cleavage and green to blue-green pleochroism. Oxyhornblende and actinolite are also present. The presence of oxyhornblende, both as individual grains and as phenocrysts with plagioclase in volcanic lithics might indicate an andesitic source for at least part of the Sooke Formation. It could also be derived from a hornblende basalt source. Actinolite is found in some metavolcanic lithics as foliated aggregates of amphibole and plagioclase. The actinolite is recognized by its very low extinction angle, lower birefringence than hornblende, and sometimes "frayed" fibrous edges. Hornblende is commonly detrital, but it is also commonly found with calcic plagioclase and sometimes epidote in metaplutonic aggregates, as foliated aggregates, and in lathwork volcanics.

Pyroxenes (Cpx and Opx)- Pyroxenes in general are uncommon, clinopyroxene being more common than clinopyroxene. Clinopyroxene is recognized by its relatively high relief, 90 degree cleavage, inclined extinction, and colorless to light green pleochroism. It is found mostly as individual subangular to subrounded detrital grains and rarely as phenocrysts in basaltic volcanic lithics. Orthopyroxene displays a slightly green pleochroism and is found only as detrital fragments.

Opaques (Op)- Opaque minerals are fairly common throughout the Sooke Formation as a cement, individual detrital grains, or an alteration product or accessory mineral in lithic grains. The most common opaque mineral is pyrite, which occurs in all three of the above-mentioned varieties. Pyrite occurs as cubic crystals, as clusters of crystals, or as fromboidal masses. Hematite is a less common cement. Magnetite is present as a placer mineral (Fig. 68).

Accessories (Acc)- Accessory minerals include epidote, pumpellyite, chlorite, staurolite, prehnite, and garnet. Epidote (Fig. 68) is a very common accessory mineral and is found both as rounded detrital grains, as constituents of various metavolcanic (metabasaltic) lithics, in metaplutonic (metadiabase to metagabbro) aggregates and as veins in the above. Epidote ranges in size from very finely microcrystalline to coarsely crystalline and is usually globular, although a bladed radial habit is sometimes observed. Both clinozoisite and zoisite are also present, but they are less common than epidote. Zoisite frequently occurs with epidote in metavolcanic and metaplutonic rocks and in schists. Pumpellyite is the next most common accessory mineral. Radial pumpellyite (Fig. 69) is found mostly in amygdules and veins, while finely crystalline pumpellyite, often weathered, is common in volcanic lithics. It occurs both as altered groundmass and as altered mafic phenocrysts (probably altered pyroxenes). Chlorite is found either as finely crystalline masses or as radial masses, which often show the anomalous blue interference colors. Chlorite also occurs as an alteration product of mafic minerals or as an amygdule mineral. Staurolite is not very common, but when present is found as individual detrital grains and is usually poikilitic. Prehnite is also uncommon. When present, it occurs as bladed or platy masses in amygdules or as a replacement of plagioclase. Zircons and garnets are present, but they are very uncommon.

Cement (Cem)- Calcite cement is by far the most common in the Sooke Formation. It is mostly sparry calcite cement; both clear and murky varieties are present. Mosaic textures are the most common, but poikilitic and radial spar cement do occur. Impurities in the murky spar cement are probably clay particles. Pyrite, hematite, zeolite, fringing clay, and silica cement are also present. K-spar or K-rich zeolite cement is possibly present in trace amounts. Calcite, pyrite, and silica cement replace some fossils. Calcite, pyrite, and hematite cement replace some framework grains, particularly lithic fragments and plagioclase grains. Calcite veins are present in some samples.

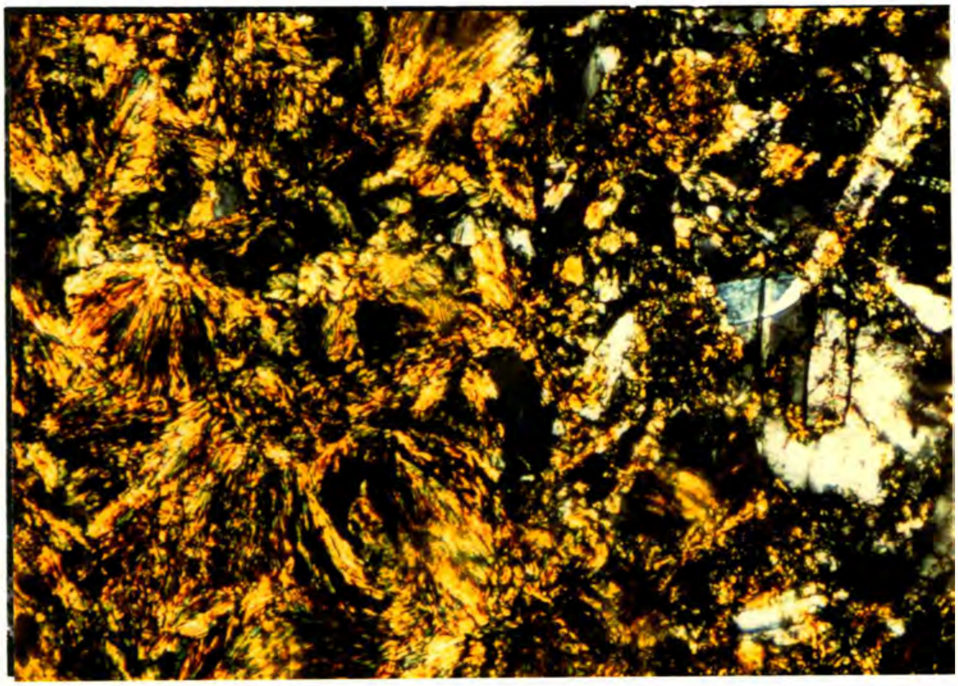


Figure 69. Radial pumpellyite in meta-volcanic lithic. Polarized light. Field of view: 2.7 x 1.8 mm.

Fossils (Fos)- Much of the Sooke Formation is fossiliferous. Fossils are generally broken and rounded to well-rounded. There is some replacement by calcite, pyrite, and silica.

Matrix (Mtx)- Matrix was counted as any interstitial grain smaller than very fine sand size.

Miscellaneous grains (Misc.)- Miscellaneous grains are those monocrystalline grains that are unidentifiable.

Lithics

Polycrystalline Quartz (Qp)- Polycrystalline quartz is very common. It is present both as individual lithic grains and as veins in volcanic and metavolcanic lithics. Polycrystalline quartz ranges from chert to coarse polycrystalline quartz. Polycrystalline quartz is usually undulose and often foliated (Fig. 70), but clear and sometimes rutilated varieties are also present. Grain contacts are usually sutured or concavo-convex. The polycrystalline quartz is often murky and was counted as Qp if the impurities were smaller than very fine sand size and less than 15% of the part of the grain under the cross hairs. Impurities varied from clays to very fine- grained chlorite, mica, graphite, or pyrite. Foliated polycrystalline quartz (Fig. 70) was counted separately (Qpf). Replacement by calcite is common. Much of the polycrystalline quartz is present both in foliated and nonfoliated aggregates. Mica-Qp aggregates and polycrystalline quartz-epidote assemblages will be discussed below.

Lathwork Volcanics (Lvl)- Lathwork volcanic lithic fragments (Fig. 71) are by far the most abundant lithic fragments in the sandstones point-counted. They range from fresh to altered basalts to subordinate andesites. Fresh

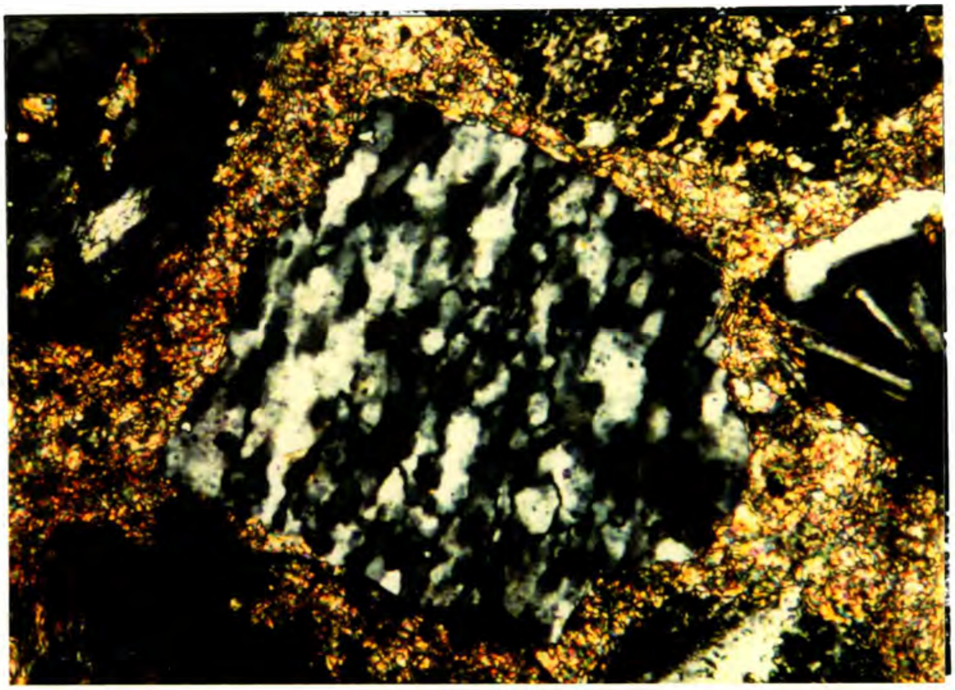


Figure 70. Foliated polycrystalline quartz surrounded by calcite cement. Polarized light. Field of view: 0.53 x 0.36 mm.

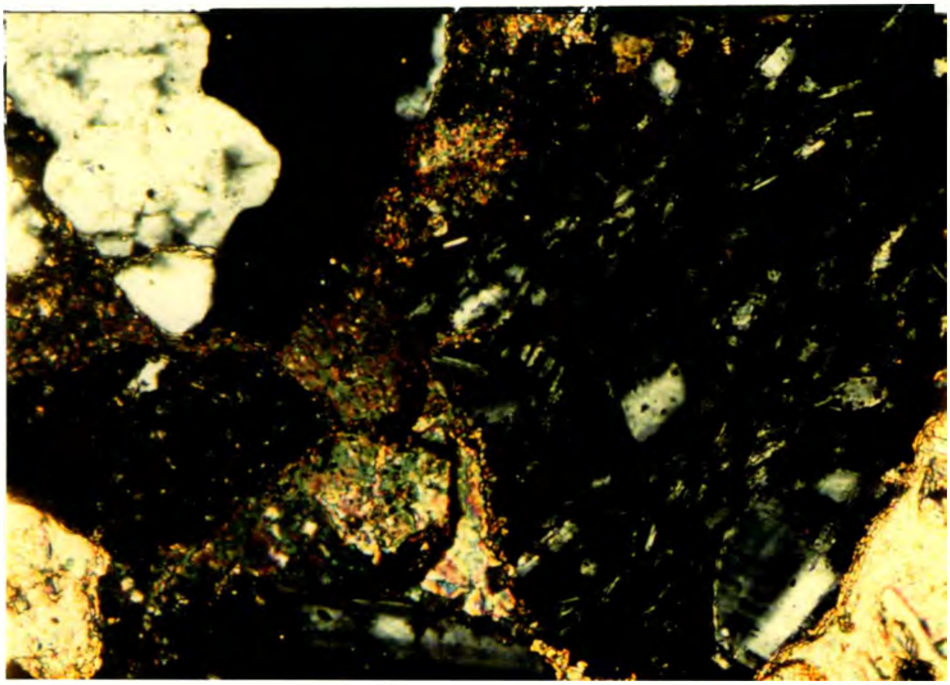


Figure 71. Lathwork volcanic lithic in sandstone. Polarized light. Field of view: 0.66 x 0.45 mm.

lathwork volcanics contain angular, often albite twinned laths of plagioclase (both sodic and calcic) set in a felted, trachytic, subophitic, or intergranular groundmass. Seriate, ophitic, and vitric textures are also common. Altered basaltic lathwork volcanic lithics contain plagioclase laths within an altered groundmass of epidote plus or minus pumpellyite plus or minus chlorite. The grains may contain pyrite and may be almost completely replaced by calcite cement. Other grains have a glassy groundmass that has been altered to zeolite minerals or to brown clay minerals. A small percentage of welded tuffs are found in the Sooke Formation. Pyroxene is a very uncommon constituent of the lathwork volcanic lithics. Green amphibole, being much more common, is often found in an ophitic to subophitic texture, with amphibole crystals surrounding or partially surrounding plagioclase laths. It is also found in an intergranular texture between plagioclase laths. These volcanic textures may also represent a shallow hypabyssal origin. Pyroxene was observed in one sample to be partially altered to epidote; this feature may help explain the paucity of pyroxenes and the abundance of epidote in most basalt grains. Plagioclase may be altered to sericite, epidote, or calcite.

Veins are common in altered basaltic volcanics. The veins consist of either calcite, epidote (Fig. 72), pumpellyite, or quartz. Amygdules occur both within basalt fragments and as individual detrital grains. Most amygdules are filled with pumpellyite, chlorite, quartz, zeolites, or least commonly, prehnite. One sample of altered basalt has an amygdule of coarse polycrystalline quartz surrounded by radial chlorite, surrounded by radial pumpellyite, and with an outer rim of polycrystalline quartz.

Andesitic to dacitic lithics were distinguishable only where they contain oxyhornblende and randomly oriented plagioclase laths and are

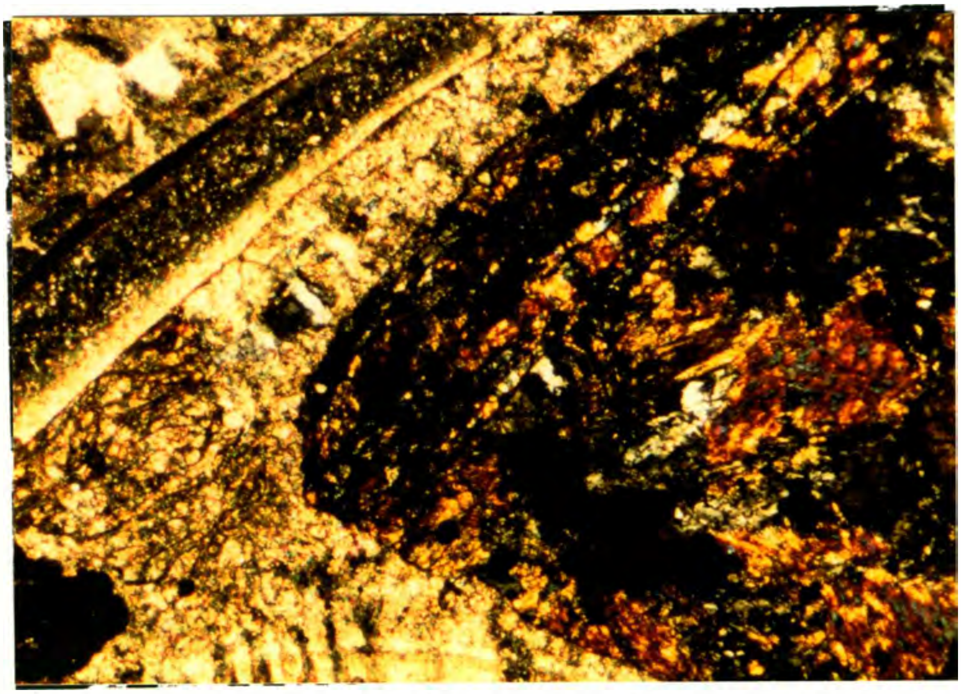


Figure 72. Epidote vein in meta-volcanic lithic. Note fossil fragment in the upper left corner. Polarized light. Field of view: 2.1 x 1.5 mm.

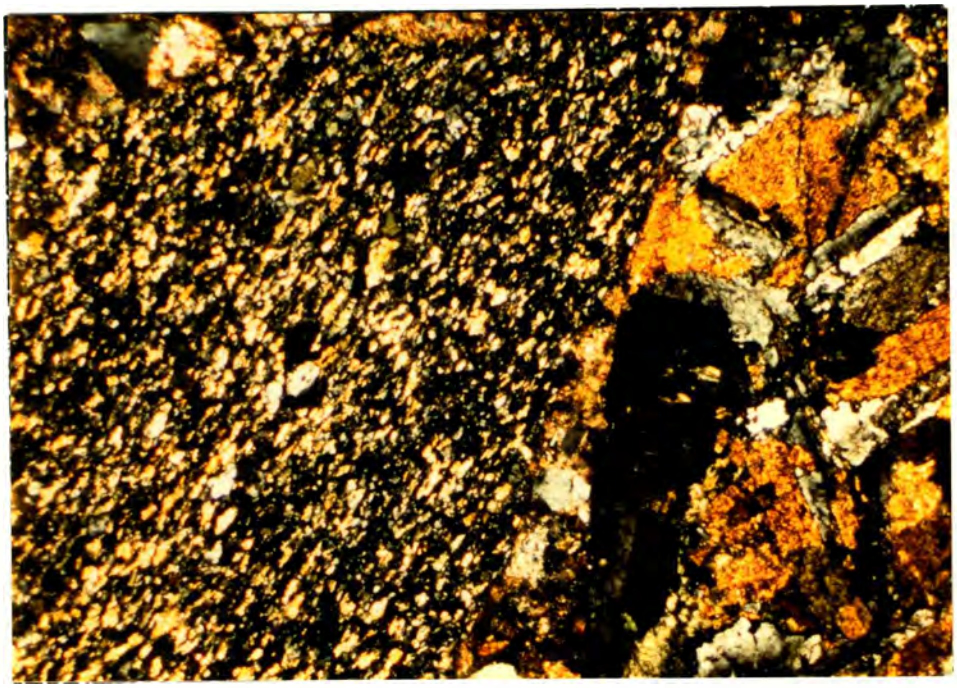


Figure 73. Amphibolite lithic and coarse plagioclase-amphibole lithic. Polarized light. Field of view: 3.4 x 2.3 mm.

generally free of epidote or chlorite.

Microlitic Volcanics (Lvm)- These are not as common as lathwork volcanics. Some samples are fresh , although most grains are altered. The glassy groundmass in many microlitic volcanics is altered to zeolites; less commonly, it is altered to chlorite or fine-grained pumpellyite. Mafic microlitic volcanics were separated from intermediate compositions based on the degree of alteration of the groundmass.

Metavolcanics and Metaplutonics (Lvo)- Metavolcanics and metaplutonics range from metabasalts to metagabbros that are metamorphosed in the prehnite-pumpellyite and greenschist grade. These clasts are composed mainly of fine to coarsely crystalline epidote minerals, metamorphic quartz, often accessory pyrite, pumpellyite or chlorite, and sometimes amphibole. No relict volcanic texture is visible. Veins are common and often complex. The most common vein materials are epidote, quartz, and pumpellyite. The epidote probably originates from calcic plagioclase or from pyroxenes.

Miscellaneous Volcanics (Lvmisc.)- These are unidentifiable grains that are usually extremely altered volcanic lithics. Generally, these grains consist of assemblages of pumpellyite, chlorite, and pyrite. Very weathered fine-grained pumpellyite is common in some clasts.

Miscellaneous Plutonic and Metaplutonic Aggregates (Lpm)- Plutonic and metaplutonic aggregates range in composition from metagabbros to amphibolites (Fig. 73) to felsic to intermediate compositions. These include quartz-sodic plagioclase , K-spar-quartz, amphibole-quartz, and amphibole-calcic plagioclase (plus or minus epidote, quartz, and pyrite) aggregates. Granophyric, graphic (Fig. 74), and possibly myrmekitic textures are sometimes present. Texturally, the amphibole-plagioclase aggregates range in grain sizes from diabasic to coarse gabbroic and a distinction between foliated and non-foliated varieties is evident. The foliated aggregates are often veined with fine-grained epidote or with pumpellyite. Some of the plagioclase-amphibole aggregates contain actinolite as the primary amphibole.

Quartz-Mica Lithics

Quartz-Mica Tectonites (Qmt)- Quartz-mica tectonites (Fig. 75) consist of both schistose and phyllitic aggregates or of polycrystalline quartz and either biotite plus muscovite or of a single mica. They also occur with abundant graphite and pyrite. The polycrystalline quartz in these lithics is usually foliated and ranges from clear to slightly murky with opaque materials. These clasts are often strongly folded.

Quartz-Mica Aggregates (Qma)- Quartz-mica aggregates are nonfoliated assemblages of polycrystalline quartz and both biotite or muscovite or a single mica (usually muscovite) in which the micas are too small to count as monocrystalline grains and are greater than 15% of the lithic fragment.

Miscellaneous Metasedimentary Lithics (Lsmmisc.)- Other metasedimentary lithics include foliated assemblages of chlorite, two micas, epidote minerals, plagioclase-mica assemblages, and other miscellaneous unidentifiable foliated metasediments.

Sedimentary Lithics (Ls)- Sedimentary lithics are not common in the Sooke Formation. When present, these consist of organic material, rare sandstone clasts, shale, or siltstone clasts.

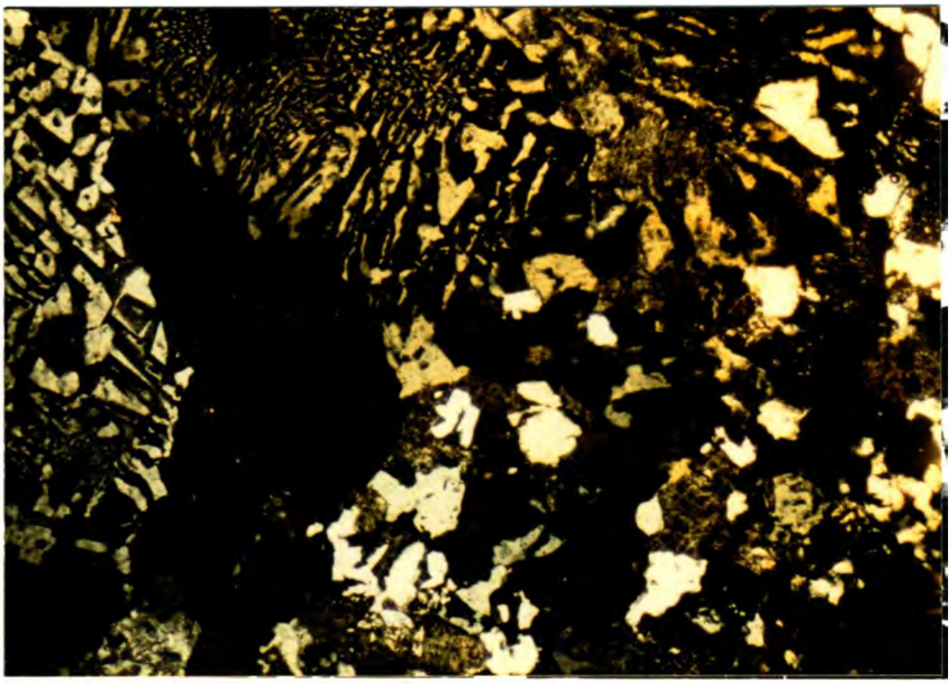


Figure 74. Graphic and myrmekitic textures in felsic plutonic lithic. Polarized light. Field of view: 2.7 x 1.8 mm.

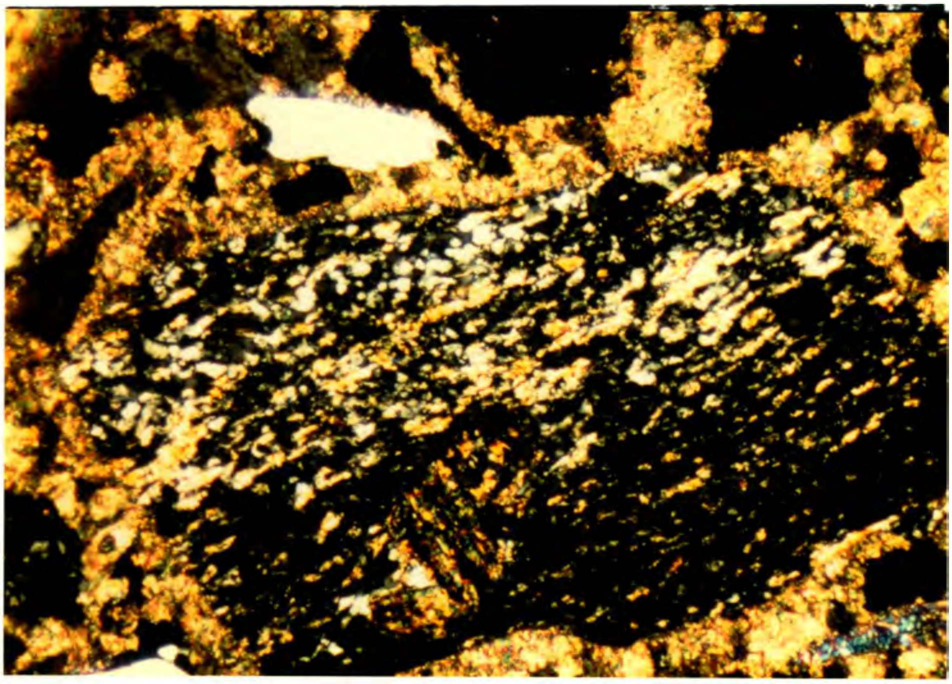


Figure 75. Quartz-mica-tectonite lithic. Polarized light. Field of view: 2.1 x 1.5 mm.

Miscellaneous Lithics (Lmisc.)- These consist of unidentifiable lithic grains.

APPENDIX 5: Point Count Results - East Half of Field Area

Whole Rock Count

Sample:	FRE-134	FRE-65	MUI-27	PNP-140	MUI-29	TUG-211	KIR-82
# Points	400	312	400	400	400	400	600
Qm	27	20	59	57	57	93	20
Qp	3	11	115	8	52	8	4
K	-	2	1	1	5	13	-
P	66	22	27	46	49	66	67
Lith	119	92	99	97	98	74	122
Mi	-	1	-	2	1	1	1
Pyx	-	4	-	2	-	1	1
Op	-	4	2	1	-	-	2
Am	20	15	27	13	11	4	2
Acc	5	19	20	39	1	-	2
Cem	139	114	36	128	100	133	200
Misc	14	5	14	6	3	7	3
Fos	4	3	-	-	23	-	176
Mtx	3	-	-	-	-	-	-

Lithic Count

# Points	none	none	none	200	200	200	200
Qp	-	-	-	22	70	20	9
Qpf	-	-	-	2	3	-	3
Lvl	-	-	-	142	72	58	158
Lmi	-	-	-	6	13	2	1
Lvm	-	-	-	1	4	7	-
Lvmisc	-	-	-	21	1	16	9
Lpm	-	-	-	-	9	-	1
Lmmisc	-	-	-	1	4	7	6
Qma	-	-	-	3	-	9	-
Qmt	-	-	-	1	-	4	4
Ls	-	-	-	-	17	17	7
Lmisc	-	-	-	1	1	2	1

Whole Rock Point Count Results - East Half of Field Area Continued

Sample:	FRE-13	MUI-203	KIR-75	SAN-308	ESP-160	SAN-41	PNP-197
# Points	400	400	400	450	400	500	400
Qm	26	90	40	36	79	36	19
Qp	7	29	2	7	28	5	12
K	1	1	3	-	10	2	2
P	40	5	125	28	43	62	113
Lith	129	111	36	112	74	100	105
Mi	4	22	1	3	-	1	1
Pyx	1	-	2	-	1	1	1
Op	4	1	1	4	1	1	-
Am	17	1	32	23	11	29	7
Acc	22	23	4	6	6	5	4
Cem	128	102	139	90	135	246	122
Misc	15	13	14	9	11	11	7
Fos	6	-	-	128	-	-	4
Mtx	-	1	1	3	1	1	3

Lithic Point Count

# Points	200	200	200	200	200	200	none
Qp	5	36	26	13	48	30	-
Qpf	1	28	3	3	1	3	-
Lvl	39	14	121	143	101	37	-
Lvmi	-	-	7	4	8	4	-
Lvm	53	27	2	19	6	15	-
Lvmisc	76	29	21	19	26	75	-
Lpm	2	-	2	8	1	20	-
Lmmisc	4	36	5	1	-	6	-
Qma	-	-	-	-	9	-	-
Qmt	1	6	1	-	-	-	-
Ls	5	1	5	-	-	1	-
Lmisc	12	14	6	1	5	6	-

Whole Rock Point Count Results - East Half of Field Area Continued

Sample:	FRE-132	WHI-110	SAN-44
# Points	410	400	400
Qm	19	69	11
Qp	13	32	10
K	1	4	-
P	103	66	36
Lith	92	56	185
Mi	1	1	1
Pyx	-	1	1
Op	1	-	3
Am	14	29	29
Acc	3	7	30
Cem	140	122	83
Misc	8	9	6
Fos	2	-	5
Mtx	13	4	-

Lithic Count

# Points	200	200	200
Qp	16	51	14
Qpf	1	5	2
Lvl	44	69	77
Lmi	9	12	20
Lvm	18	9	33
Lvmisc	78	19	19
Lpm	5	4	30
Lmmisc	9	8	1
Qma	-	8	-
Qmt	-	2	-
Ls	5	2	-
Lmisc	15	11	4

APPENDIX 6: Point Count Results - West Half of Field Area

Whole Rock Count

Sample:	COR-127	SOM-207	SOM-54	SOM-50	SOM-87	CHI-40	ZOD-201
# Points	400	600	300	450	400	400	400
Qm	20	14	38	94	32	50	78
Qp	8	24	10	66	6	14	6
K	4	1	-	1	-	-	6
P	62	10	19	13	31	17	63
Lith	120	184	62	81	89	93	90
Mi	-	1	7	14	3	12	3
Pyx	-	-	3	-	3	5	-
Op	4	2	14	-	4	2	-
Am	75	-	1	1	33	2	15
Acc	4	23	25	2	6	7	-
Cem	94	194	91	171	144	144	133
Misc	8	7	4	1	6	6	5
Fos	-	137	27	-	43	41	-
Mtx	1	3	-	6	-	-	-

Lithic Count

# Points	200	200	200	200	200	200	200
Qp	9	11	6	67	72	20	11
Qpf	2	8	2	28	1	1	-
Lvl	71	101	83	11	43	99	119
Lmi	1	-	1	-	4	5	18
Lvm	14	37	47	-	34	1	5
Lvmisc	15	35	17	19	17	25	16
Lpm	38	-	-	-	-	3	-
Lmmisc	5	1	7	5	1	-	3
Qma	-	-	7	3	15	2	6
Qmt	-	-	29	56	7	13	1
Ls	1	1	1	5	5	30	19
Lmisc	6	6	2	4	1	1	-

Whole Rock Point Count Results - West Half of Field Area Continued

Sample:	MYS-147	CHI-36	SOM-49	MYS-303	SOM-208	SOM-88	COR-96
# Points	400	400	400	400	400	400	400
Qm	29	50	77	88	44	125	80
Qp	3	12	51	21	56	27	32
K	1	11	-	6	1	10	3
P	95	58	8	47	6	44	47
Lith	63	78	121	70	77	46	64
Mi	-	6	7	2	29	1	-
Pyx	-	-	-	-	-	-	-
Op	7	4	4	3	7	-	2
Am	131	10	1	34	-	3	16
Acc	12	2	10	10	6	2	8
Cem	53	159	111	106	149	134	127
Misc	6	9	8	10	5	8	10
Fos	-	-	1	-	15	-	-
Mtx	-	1	1	3	5	-	11

Lithic Count

# Points	200	211	200	200	200	200	200
Qp	5	30	16	39	56	74	50
Qpf	1	7	52	1	45	5	6
Lvl	16	118	70	109	5	55	80
Lmi	1	5	1	3	-	5	3
Lvm	171	4	18	15	1	11	9
Lvmisc	3	16	6	19	8	28	26
Lpm	-	2	-	3	-	1	-
Lmmisc	-	18	6	3	25	2	5
Qma	-	2	1	3	2	7	1
Qmt	1	1	29	2	51	1	4
Ls	-	2	1	2	4	6	8
Lmisc	2	6	-	1	3	5	8

Whole Rock Point Count Results - West Half of Field Area Continued

Sample:	SOM-91	MYS-700	SOM-93	SOM-320
# Points	400	400	400	400
Qm	137	-	104	82
Qp	40	-	39	28
K	9	-	9	7
P	35	115	24	61
Lith	37	76	65	57
Mi	1	-	2	3
Pyx	-	-	-	-
Op	-	18	1	-
Am	-	52	1	2
Acc	-	40	5	3
Cem	129	62	143	144
Misc	12	14	5	8
Fos	-	23	-	-
Mtx	-	-	2	5

Lithic Point Count

# Points	200	200	200	200
Qp	92	-	70	50
Qpf	3	-	2	8
Lvl	69	-	38	56
Lvmi	-	-	-	4
Lvm	1	-	7	-
Lvmisc	18	-	33	49
Lpm	-	-	1	-
Lsmmisc	1	-	7	18
Qma	1	-	1	3
Qmt	4	-	6	-
Ls	11	-	12	4
Lmisc	-	-	14	8

APPENDIX 7: Point Count Modal Percentages - East Half of Field Area

Whole Rock Count

Sample:	FRE-134	FRE-65	MUI-27	PNP-140	MUI-29	TUG-211	KIR-82
Qm	6.7	6.4	14.7	14.2	14.2	23.2	3.4
Qp	.7	3.5	28.7	2.0	13.0	2.0	.7
K	-	.6	.2	.2	1.2	3.2	-
P	16.0	7.0	6.7	11.5	12.2	16.5	11.4
Lith	29.7	29.4	24.7	24.5	24.5	18.5	20.7
Mi	-	.3	-	.5	.2	.2	.2
Pyx	-	1.3	-	.5	-	.2	.2
Op	-	1.3	.5	.2	-	-	.3
Am	5.0	4.8	6.7	3.2	2.7	1.0	.3
Acc	1.2	6.1	5.0	9.7	.2	-	.3
Cem	34.7	36.5	9.0	32.0	25.0	33.2	34.0
Misc	3.0	1.6	3.5	1.5	.7	1.7	.5
Fos	1.0	1.0	-	-	5.7	-	29.9
Mtx	.7	-	-	-	-	-	-

Lithic Count

Qp	-	-	-	11.0	35.0	10.0	4.5
Qpf	-	-	-	1.0	1.5	-	1.5
Lvl	-	-	-	71.0	36.0	58.0	79.0
Lmi	-	-	-	3.0	4.0	-	-
Lvm	-	-	-	.5	.2	3.5	-
Lvmisc	-	-	-	10.5	.5	8.0	4.5
Lpm	-	-	-	-	4.5	-	.5
Lmmisc	-	-	-	.5	2.0	3.5	3.0
Qma	-	-	-	.5	-	4.5	-
Qmt	-	-	-	.5	-	2.0	2.0
Ls	-	-	-	-	8.5	8.5	3.5
Lmisc	-	-	-	.5	.5	1.0	.5

Modal Percentages for Ternary Diagrams

Q-F-L	14-31-55	21-16-63	58-9-33	30-23-57	41-21-38	40-31-29	11-32-57
Qm-F-Lt	13-31-56	14-16-70	20-9-71	27-23-50	22-21-57	37-31-32	9-32-59
Qp-Lv-Lsm	------	------	------	12-85-3	40-49-11	10-71-19	6-85-9
P/F	1.00	0.92	0.96	0.98	0.91	0.84	1.00

Point Count Modal Percentages - East Half of Field Area Continued

Whole Rock Count

Sample:	FRE-13	MUI-203	KIR-75	SAN-308	ESP-160	SAN-41	PNP-197
Qm	6.5	22.5	10.0	7.9	19.7	7.2	4.7
Qp	1.7	7.2	.5	1.5	7.0	1.0	3.0
K	.2	.2	.7	-	2.5	.4	.5
P	10.0	1.2	31.2	6.2	10.7	12.4	28.2
Lith	32.2	27.7	9.0	24.6	18.5	20.0	26.2
Mi	1.0	5.5	.2	.7	-	.2	.2
Pyx	.2	-	.5	-	.2	.2	.2
Op	1.0	.2	.2	.9	.2	.2	-
Am	4.2	.2	8.0	5.1	2.7	5.8	1.7
Acc	5.5	5.7	1.0	1.3	1.5	1.0	1.0
Cem	32.0	25.5	34.7	19.8	33.7	49.2	30.5
Misc	3.7	3.2	3.5	2.0	2.7	2.2	1.7
Fos	1.5	-	-	28.2	-	-	1.0
Mtx	-	.2	.2	.7	.2	.2	.7

Lithic Count

Qp	2.5	18.0	13.0	4.2	23.5	15.0	-
Qpf	.5	14.0	1.5	1.0	.5	1.5	-
Lvl	19.5	7.0	60.5	45.8	49.5	18.5	-
Lvmi	-	-	3.5	1.3	3.9	2.0	-
Lvm	26.5	13.5	1.0	6.1	2.9	7.5	-
Lvmisc	38.0	14.5	10.5	6.1	12.7	37.5	-
Lpm	1.0	-	1.0	2.6	.5	10.0	-
Lmmisc	2.0	18.0	2.5	.3	-	3.0	-
Qma	-	-	-	-	4.4	-	-
Qmt	.5	3.0	.5	-	-	-	-
Ls	2.5	.5	2.5	-	-	.5	-
Lmisc	6.0	7.0	3.0	.3	2.4	3.0	-

Modal Percentages for Ternary Diagrams

Q-F-L	16-20-64	50-3-47	20-62-18	24-15-61	46-23-31	20-31-49	12-46-42
Qm-F-Lt	13-20-67	38-3-59	19-62-19	20-15-65	34-22-44	18-31-51	7-46-47
Qp-Lv-Lsm	3-91-6	33-37-30	15-79-6	8-91-1	25-70-5	19-76-5	------
P/F	0.98	0.83	0.98	1.00	0.81	0.97	0.98

Point Count Modal Percentages - East Half of Field Area Continued

Whole Rock Count

Sample:	FRE-132	WHI-110	SAN-44
Qm	4.6	17.2	2.7
Qp	3.1	8.0	2.5
K	.2	1.0	-
P	24.7	16.5	9.0
Lith	22.1	14.0	46.2
Mi	.2	.2	.2
Pyx	-	.2	.2
Op	.2	-	.7
Am	3.4	7.2	7.2
Acc	.7	1.7	7.5
Cem	33.6	30.5	20.7
Misc	1.9	2.2	1.5
Fos	.5	-	1.2
Mtx	3.1	1.0	-

Lithic Count

Qp	8.0	25.5	7.0
Qpf	.5	2.5	1.0
Lvl	22.0	34.0	38.5
Lmi	4.5	6.0	10.0
Lvm	9.0	4.5	16.5
Lvmisc	39.0	9.5	9.5
Lpm	2.5	2.0	15.0
Lmmisc	4.5	4.0	.5
Qma	-	4.0	-
Qmt	-	-	-
Ls	2.5	1.0	-
Lmisc	4.5	4.0	.5

Modal Percentages for Ternary Diagrams

Q-F-L	14-46-40	44-31-25	9-15 76
Qm-F-Lt	8-46-46	30-31-39	5-15-80
Qp-Lv-Lsm	10-82-8	30-59-11	10-89-1
P/F	0.99	0.94	1.00

APPENDIX 8: Point Count Modal Percentages - West Half of Field Area

Whole Rock Count

Sample:	COR-127	SOM-207	SOM-54	SOM-50	SOM-87	CHI-40	ZOD-201
Qm	5.0	2.4	12.5	20.7	8.0	12.5	19.5
Qp	2.0	4.1	3.3	14.5	1.5	3.5	1.5
K	1.0	.2	-	.2	-	-	1.5
P	15.5	1.7	6.3	2.9	7.7	4.2	15.7
Lith	30.0	31.3	20.5	17.8	22.2	23.2	22.5
Mi	-	.2	2.3	3.1	.7	3.0	.7
Pyx	-	-	1.0	-	.7	.7	.2
Op	1.0	.3	4.6	-	1.0	.5	-
Am	18.7	-	.3	.2	8.2	.5	3.7
Acc	1.0	3.9	8.2	.4	1.5	1.7	-
Cem	23.5	33.0	30.0	37.6	36.0	36.0	33.2
Misc	2.0	1.2	1.3	1.2	1.5	1.5	1.2
Fos	-	23.3	8.9	-	10.7	10.2	-
Mtx	.2	.5	-	1.3	-	-	-

Lithic Count

Qp	4.5	5.5	3.0	33.5	36.0	10.0	5.5
Qpf	1.0	4.0	1.0	14.0	5.0	.5	-
Lvl	35.5	50.5	41.5	5.5	21.5	47.5	59.5
Lmi	.5	-	.5	-	2.0	2.5	9.0
Lvm	7.0	18.5	23.5	-	17.0	.5	2.5
Lvmisc	7.5	17.5	8.5	9.5	8.5	12.5	8.0
Lpm	3.0	38.0	-	-	-	1.5	-
Lmmisc	2.5	.5	2.5	3.5	.5	-	1.5
Qma	-	-	3.5	1.5	7.5	1.0	3.0
Qmt	-	-	14.5	28.0	3.5	6.5	.5
Ls	.5	.5	.5	2.5	2.5	15.0	9.5
Lmisc	2.5	.5	2.5	3.5	.5	-	1.5

Modal Percentages for Ternary Diagrams

Q-F-L	13-31-56	16-5-79	37-15-48	62-6-32	24-20-56	37-10-53	35-28-37
Qm-F-Lt	9-31-60	6-5-89	29-15-56	37-6-57	20-20-60	29-10-61	32-28-40
Qp-Lv-Lsm	13-80-7	10-89-1	4-74-22	49-14-37	46-36-18	11-66-23	6-79-15
P/F	0.94	0.91	1.00	0.93	1.00	1.00	0.91

Point Count Modal Percentages - West Half of Field Area Continued

Whole Rock Count

Sample:	MYS-147	CHI-36	SOM-49	MYS-303	SOM-208	SOM-88	COR-96
Qm	7.2	12.5	19.2	22.0	11.0	31.2	20.0
Qp	.7	3.0	12.7	5.2	14.0	6.7	8.0
K	.2	2.7	-	1.5	.2	2.5	.7
P	23.7	14.5	2.0	11.7	1.5	11.0	11.7
Lith	15.7	19.5	30.2	17.5	19.2	11.5	16.0
Mi	-	1.5	1.7	.5	7.2	.2	-
Pyx	-	-	-	-	-	-	-
Op	1.7	1.0	1.0	.7	1.7	-	.5
Am	32.7	2.5	.2	8.5	-	.7	4.0
Acc	3.0	.5	2.5	2.5	1.5	.5	2.0
Cem	13.2	39.7	27.7	26.5	37.2	33.5	31.7
Misc	1.5	2.2	2.0	2.5	1.2	2.0	2.5
Fos	-	-	.2	-	3.7	-	-
Mtx	-	.2	.2	.7	1.2	-	2.7

Lithic Count

Qp	2.5	14.1	8.0	19.5	28.0	37.0	25.0
Qpf	.5	3.3	26.0	.5	22.5	2.5	3.0
Lvl	8.0	55.5	35.0	54.5	2.5	27.5	40.0
Lmi	.5	2.3	.5	1.5	-	2.5	1.5
Lvm	85.5	1.9	9.0	7.5	.5	5.5	4.5
Lvmisc	1.5	7.5	3.0	9.5	4.0	14.0	13.0
Lpm	-	2.8	-	1.5	-	.5	-
Lmmisc	-	9.0	3.0	1.5	12.5	1.0	2.5
Qma	-	.5	.5	1.5	1.0	3.5	.5
Qmt	.5	.9	14.5	1.0	25.5	.5	2.0
Ls	-	.9	.5	1.0	2.0	3.0	4.0
Lmisc	1.0	2.8	-	.5	1.5	2.5	4.0

Modal Percentages for Ternary Diagrams

Q-F-L	17-50-33	30-33-37	50-3-47	47-23-30	54-4-42	61-21-18	49-22-29
Qm-F-Lt	15-50-35	24-33-43	30-3-67	38-23-39	24-4-72	50-21-29	35-22-43
Qp-Lv-Lsm	3-96-1	18-70-12	34-48-18	20-75-5	52-5-43	41-51-8	29-61-10
P/F	0.99	0.84	1.00	0.89	0.86	0.81	0.94

Point Count Modal Percentages - West Half of Field Area Continued

Whole Rock Count

Sample:	SOM-91	MYS-700	SOM-93	SOM-320
Qm	34.2	-	26.0	20.5
Qp	10.0	-	9.7	7.0
K	2.2	-	2.2	2.7
P	8.7	28.7	6.0	15.2
Lith	9.2	19.0	16.2	14.2
Mi	.2	-	.5	.7
Pyx	-	-	-	-
Op	-	4.5	.2	-
Am	-	13.0	.2	.5
Acc	-	10.0	1.2	.7
Cem	32.2	15.5	35.7	36.0
Misc	3.0	3.5	1.2	2.0
Fos	-	5.7	-	-
Mtx	-	-	.5	1.2

Lithic Count

Qp	46.0	-	35.0	25.0
Qpf	1.5	-	1.0	4.0
Lvl	34.5	-	19.0	28.0
Lvmi	-	-	-	2.0
Lvm	.5	-	3.5	-
Lvmisc	9.0	-	16.5	24.5
Lpm	-	-	.5	-
Lmmisc	.5	-	3.5	9.0
Qma	.5	-	.5	1.5
Qmt	2.0	-	3.0	-
Ls	5.5	-	6.0	2.0
Lmisc	-	-	7.0	4.0

Modal Percentages for Ternary Diagrams

Q-F-L	69-17-14	0-60-40	59-14-27	47-29-24
Qm-F-Lt	53-17-30	0-60-40	43-14-43	35-29-36
Qp-Lv-Lsm	47-44-9	------	40-45-15	30-57-13
P/F	0.80	1.00	0.69	0.90