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THE UNIVERSITY OF ALBERTA

DIAGENESIS OF TERTIARY CLASTIC ROCKS
OF THE
CARMANAH GROUP, VANCOUVER ISLAND, CANADA

by

ELIZABETH J. BURWASH

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH
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OF MASTER OF SCIENCE

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THE UNIVERSITY OF ALBERTA

FACULTY OF GRADUATE STUDIES AND RESEARCH

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled Diagenesis of Tertiary Clastic Rocks of the Carmanah Group, Vancouver Island, Canada, submitted by Elizabeth J. Burwash in partial fulfilment for the requirements for the degree of Master of Science in Geology.

F.J. Longstaffe

Supervisor

Date October 8, 1986

DEDICATION

With love to Doug

and my parents.

ABSTRACT

The Tertiary rocks of the Carmanah Group, Vancouver Island, are composed of marine clastics derived from andesitic volcanic and dioritic intrusive source rocks. The Escalante, Hesquiat and Sooke Bay formations are upward successive formations of the Carmanah Group.

Sandstones from all three formations are lithic arkoses and feldspathic litharenites. A different paragenetic sequence of authigenic minerals was observed in each formation. The Escalante Formation at the type locality contains pyrite, regularly interstratified chlorite/smectite rims, plagioclase and K-feldspar overgrowths and laumontite cement. The overlying beds of the Hesquiat Formation contain randomly interstratified chlorite/smectite, smectite, calcite cement and, locally, chlorite, kaolinite and quartz. The Sooke Bay Formation contains smectite rims and calcite cement.

Since detrital modes in sandstones from each formation are similar, the differences in diagenetic products likely result from different depths of burial, fluid flow and (or) tectonic history. A progressive decrease in the ordering of chlorite/smectite at stratigraphically higher levels suggests that depth of burial may have influenced its formation. Lateral variations in the degree of ordering may have been caused

by localized areas of higher temperatures created by intrusion of Tertiary stocks.

The distribution of authigenic minerals in the Hesquiat Formation corresponds to the location of faults. Authigenic minerals formed after the development of secondary porosity in rocks from highly fractured parts of the section.

The authigenic mineral assemblage in the Sooke Bay Formation reflects early diagenetic processes in the depositional environment, without subsequent changes due to burial and uplift.

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Table of Contents

Chapter Page

List of Tables

List of Figures

List of Plates

List of Abbreviations

The following abbreviations are used in this study:

Lithologies:

Slst = siltstone
Arg sst = argillaceous sandstone
C sst = coarse-grained sandstone
M sst = medium-grained sandstone
Congl = conglomerate

Mineralogy from thin section:

Qm = monocrystalline quartz grains
Qp = polycrystalline quartzose grains
Pl = plagioclase
KF = potassium feldspar grains
L_v = volcanic rock fragments
L_s = sedimentary rock fragments
Acc = accessory minerals
Det = detrital component
Cmt = cement
Por = porosity
Q = total quartz component
F = total feldspar component
L = total lithic component

Abbreviations (Continued)

Mineralogy from X-ray diffraction and scanning electron microscopy:

Q = quartz
Pl = plagioclase
KF = potassium feldspar
Ca = calcite
Sm = smectite
Bi = biotite
I = illite
Chl = chlorite
K = kaolinite
C/S = mixed-layer chlorite/smectite
Py = pyrite
AQ = authigenic quartz
L = laumontite
Z = zeolite
1 μm = micrometre (1 X 10^{-6} m)
1 Å = Angstrom (1 X 10^{-10} m)

Mineral abundances:

nd = not detected
tr = trace

I. INTRODUCTION

A. Purpose

The purpose of this study is to describe and interpret the diagenetic changes in Tertiary clastic rocks of the Carmanah Group, Vancouver Island. Interpretation will focus on the relationships between diagenesis and rock type, depositional environment and tectonism.

The Carmanah Group comprises the Escalante, Hesquiat and Sooke Bay formations. It is composed of marine conglomerates, sandstones and shales, derived primarily from andesitic volcanic and dioritic intrusive source rocks. The large proportion of volcanic rock fragments and plagioclase grains in the detrital fraction result in clastic rocks which are compositionally unstable. Although the three formations which comprise the Carmanah Group have similar source terranes, they were deposited in different environments. The Escalante Formation consists of a shallow marine basal conglomerate which grades upwards into progressively deeper water deposits of the Hesquiat Formation. The Sooke Bay Formation consists of fluvial and deltaic sandstones and conglomerates (Muller et al., 1981).

Widespread faulting in the Nootka Sound area (Figure 1.1) has affected both Tertiary sedimentary rocks and the underlying strata. Most of the faults visible in the sedimentary strata are steep and show minor amounts of

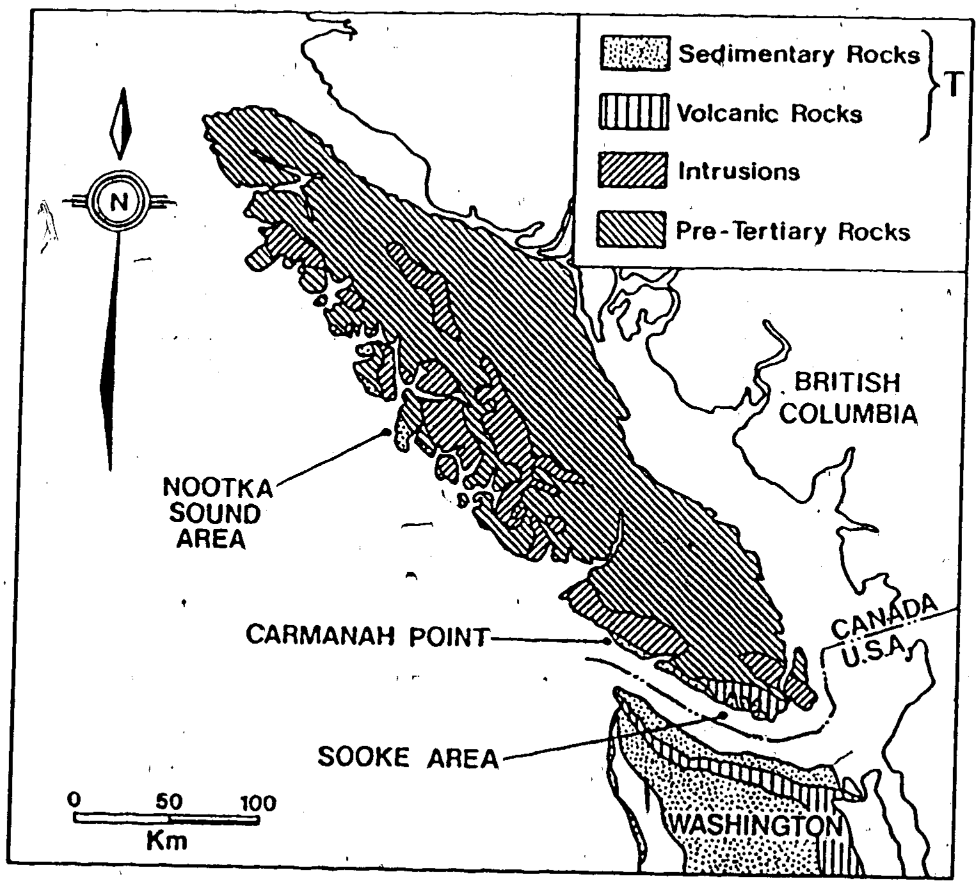


Figure 1.1. Distribution of sedimentary rocks of the Carmanah Group and the location of study areas in relation to regional geology of Vancouver Island and northern Washington.

lateral displacement, with the exception of a steep westward-dipping thrust fault on Hesquiat Peninsula which has displaced Carmanah Group rocks (Cameron, 1980). This widespread faulting is likely to have influenced groundwater flow and to have created conduits for fluid movement through sedimentary and volcanic rocks which, otherwise, have low permeabilities.

The three principal objectives of this study are: (1) to determine how the composition, grain size and texture of detrital phases influence physical and chemical diagenesis; (2) to interpret the conditions which prevailed during and after deposition; (3) to determine whether rocks in fault zones show different diagenetic patterns than those which are undisturbed.

B. Geological Background

Vancouver Island is part of a continental margin that has been tectonically active since at least Late Cretaceous time. Most of the island is composed of Middle Paleozoic and Jurassic volcanic-plutonic complexes resting on gneiss-migmatite terranes, and overlain by Permo-Pennsylvanian and Cretaceous clastic rocks, respectively. All of these comprise the Insular Belt, the most westerly tectonic subdivision of the Canadian Cordillera. Fragments of the Pacific Belt, consisting of Late Jurassic to Cretaceous slope and trench deposits, schist, Eocene basalts and basic crystalline rocks fringe the west and south coasts (Muller, 1977a,b).

Upper Eocene to Pliocene rocks of the Carmanah Group (Muller et al., 1981) were deposited in the Tofino Basin, which is considered to be a fore-arc basin formed at the juncture of the North American and Juan de Fuca Plates (Brandon, 1985; Yorath et al., 1985). At present the easternmost extent of this basin consists of isolated outcrops along the west coast of Vancouver Island; the western limit is not known. Late Eocene to Pliocene age sedimentary rocks were also encountered in six Shell Canada wildcat wells drilled on the continental shelf (Shouldice, 1971).

In the Nootka Sound and Carmanah Point areas the Carmanah Group rests unconformably on Paleozoic and Mesozoic amphibolite, metasedimentary rocks and quartz diorite of the Westcoast Complex and on early Jurassic volcanic rocks of the Bonanza Group (Figure 1.2). The best exposures of the Escalante and Hesquiat formations are on Hesquiat Peninsula and Nootka Island. At these localities the Escalante Formation is about 150 m thick, and the Hesquiat Formation is 1100-1200 m thick. On Nootka Island, sandstones, tentatively assigned to the Sooke Bay Formation (Cameron, 1980), are in fault contact with the top of the Hesquiat Formation.

In the Sooke area only the Pliocene Sooke Bay Formation is subaerially exposed. An offshore well in

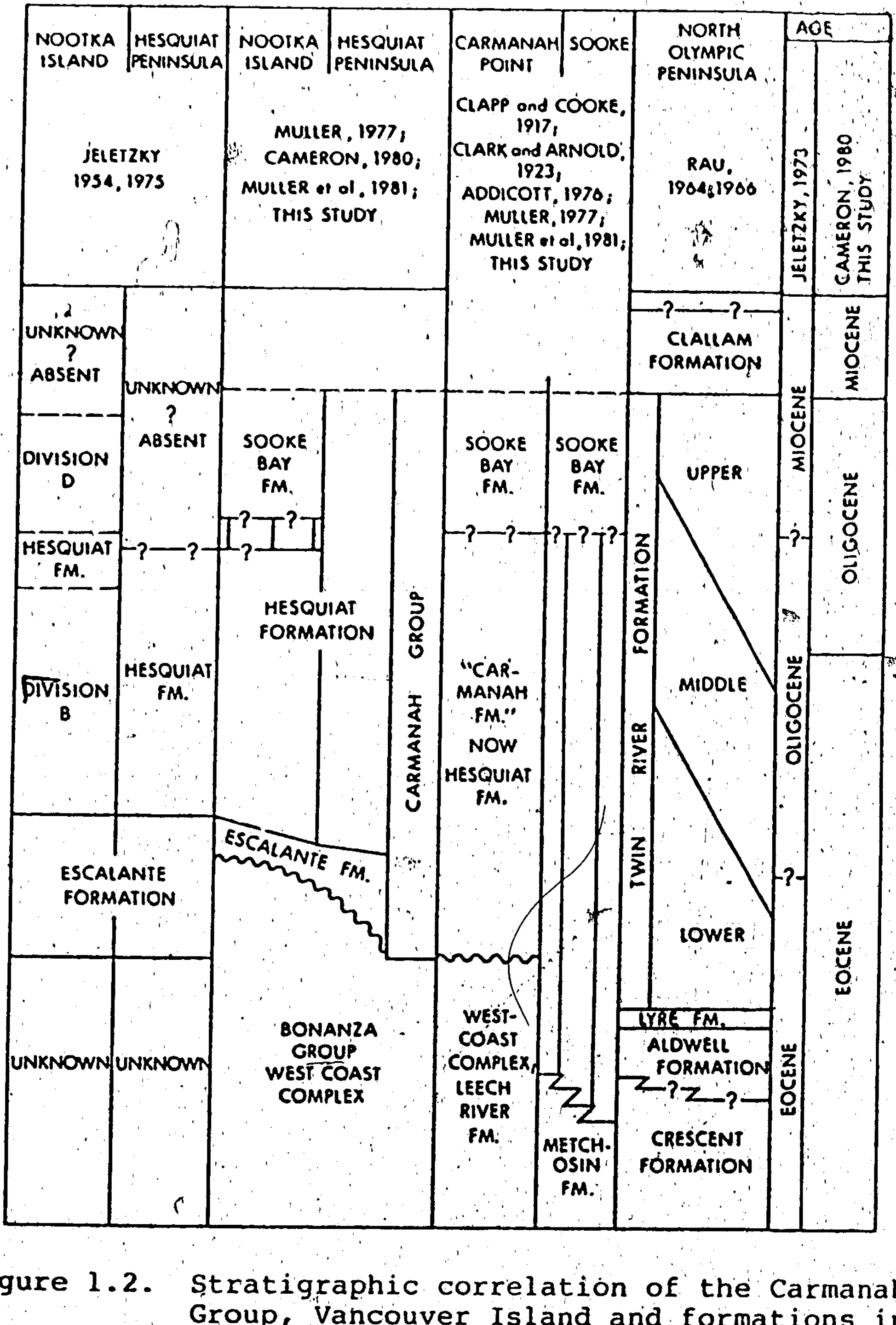


Figure 1.2. Stratigraphic correlation of the Carmanah Group, Vancouver Island and formations in northern Washington (modified after Muller et al., 1981).

this area encountered over 2000 m of Pliocene sedimentary rocks (Shouldice, 1971). The Sooke Bay Formation overlies metamorphic rocks of the Leech River Formation, tholeiitic basalt of the Metchosin Formation and Sooke Intrusion gabbro. Tertiary strata, equivalent in age and depositional environment to Carmanah rocks, are exposed along the north coast of the Olympic Peninsula, Washington (Figure 1.1).

C. Previous Work

The Carmanah Group consists of three formations: the basal Escalante Formation (Bancroft, 1937), the Hesquiat Formation (Jeletzky, 1975b), and the Sooke Bay Formation (Muller, 1977). "Sooke Formation", as first described by Clapp (1910), was renamed Sooke Bay Formation (Muller, 1977) to avoid confusion between it and "Sooke Gabbro" or "Sooke Intrusions" (Clapp and Cooke, 1917), names which are also in general use.

Sedimentary rocks exposed in the Carmanah Point and Sooke areas were first recognized as Tertiary in ~~age~~ by Merriam (1896). Rocks on Hesquiat Peninsula were recognized as "the oldest Tertiary sediments thus far found on Vancouver Island" (Bancroft, 1937). Until 1954, when Jeletzky described them as Tertiary, most of the other clastic rocks in the Nootka Sound area were considered to be Cretaceous in age (Brewer, 1921; Dolmage, 1921). Studies by Shouldice (1971) and Tiffin et al. (1972) described the offshore geology and the regional tectonic patterns. Muller et al. (1981) presented the only comprehensive description, to date, of the Carmanah Group. There are no known detailed mineralogical studies of sedimentary rocks of the Carmanah Group.

Sooke Area and Carmanah Point

The sedimentary rocks of the Sooke area were studied by Clapp (1912), and Clapp and Cooke (1917). They described a section, considered to be "Sooke Formation", along Kirby Creek and the coastline east of the creek mouth. Clarke and Arnold (1923) studied the fauna in this formation and named Clapp and Cooke's section as the type section (Muller, 1981). Cox (1962) and Russell (1968) worked on palynology and vertebrate fossils, respectively.

Merriam (1896) and Clarke and Arnold (1923) concluded that the Sooke strata exposed at Carmanah Point were older than those in the Sooke area. Their conclusions were based on palaeontological studies. In 1973, Snavely, McLeod and Muller confirmed this age difference, after studying fossil material from the same localities (Muller, 1981).

Nootka Sound Area

One of the early works in the Nootka Sound area defined the Escalante Formation type section, located at Escalante Point (Bancroft, 1937). The most recent and detailed studies of Tertiary clastic rocks in the area are those of Jeletzky (1954, 1975) and Cameron (1980).

Jeletzky defined and described the type Hesquiat section and studied macro-fossils contained in both the Hesquiat and Escalante formations. His lithological descriptions were based on megascopic examination only. Cameron (1980) concentrated on the microfaunal assemblages of these same formations and examined the rocks to determine the depositional and tectonic history of the area.

D. Sampling and Analytical Methods

Outcrop samples were used for this study. Most of the samples from the Nootka Sound area were collected by B.E.B. Cameron (Geological Survey of Canada, Pacific Geoscience Centre, Sidney, B.C.). His principal interest was the microfauna contained in shales. However, he also sampled some sandstone and conglomerate beds within the major resistant members. To complete the missing lithologic units and to obtain more detailed coverage, a sampling program was carried out during the summer of 1984. Samples collected from the Hesquiat Type section and Carmanah Point were from tidal flats exposed only at low tide. The outcrops sampled in the Sooke area were inland or formed coastal bluffs above tide level; all had heavy tree cover.

In most areas, the low permeability of the sandstones and conglomerates has inhibited weathering except for the outer 1 to 2 centimetres. This weathering rind was discarded prior to mineralogical analyses. Weathering is more intense in the Sooke area, so separation of the weathered material may have been less complete.

Petrographic Analyses

Thin sections were made from seventy-six sandstone and conglomerate samples. Thin section blanks were cut perpendicular to bedding. All sections were impregnated with blue epoxy. Several of the sections containing carbonate cement were stained with alizaran red to identify the presence of calcite. Point counts were done for representative samples from Hesquiat Peninsula and the Sooke area; 500 points were used for sandstones and conglomerates. Partially altered or replaced detrital grains were classified according to their original composition. The criteria proposed by Dickinson (1970) were used to interpret the composition of detrital grains.

X-ray Diffraction Analyses

Rock samples were crushed by hand and the detrital grains larger than 2 mm were removed by passing the crushed samples through a No. 10 sieve. The <2 mm material was mixed with 125 ml of 4 per cent sodium hexametaphosphate solution and left to soak for 8 hours to further disperse the particles. These slurries were then dispersed in distilled water. Clay size particles of <2 μm and 2-20 μm were separated by repeated settling and decantation using settling times calculated according to

Stoke's Law. After separation, NaOCl was added to each size fraction and the samples were heated to 60° C for two days to destroy any organic material present. Samples were repeatedly washed with distilled water using a high speed centrifuge. The <2 μm size fraction was then split into three portions: one was saturated with 2 molar Ca^{2+} solution, another saturated with 2 molar K^+ and one left "as is". The saturated samples were washed and freeze-dried.

Approximately 50 mg of the saturated material was mixed with distilled water and suctioned onto ceramic discs, resulting in oriented samples. The discs were analysed using a Phillips X-ray diffractometer with graphite filtered Co K-alpha radiation and scanning speed of 1 degree two-theta per minute. X-ray diffractograms were obtained for each sample, following the treatments and conditions used by Ignasiuk et al. (1983):

Ca-saturated disc; 54% humidity,

Ca-saturated disc, glycolated; humidity not controlled,

K-saturated disc; zero humidity and 54% humidity,

K-saturated disc after heating at 300° C for 3 hours, and

K-saturated disc after heating at 550° C for 2 hours.

The <2 μm size fraction was used for analyses of clay minerals because relatively few non-clay minerals are present in this size fraction. The 2-20 μm size-fraction of most samples was also analysed using unsaturated, oriented samples. Prior to analyses, the 2-20 μm size fractions (and all other samples analyzed at 54 per cent humidity) were equilibrated for 24 hours over a magnesium nitrate solution. The humidity conditions established for all samples were maintained throughout the X-ray diffraction analyses.

The relative proportions of clay minerals in the <2μm size fractions were estimated using peak areas (Biscaye, 1965). The areas of the kaolinite (001), illite (001), smectite (001) and chlorite/smectite ($001_{14}/001_{17}$) were measured on charts of Ca-saturated ethylene-glycolated samples. The chlorite (001) peaks were measured on X-ray diffraction charts of samples which were K-saturated and heated to 550° C. The following factors were used (Biscaye, 1965):

1) smectite x 1
2) chlorite x 1
3) kaolinite x 2
4) illite x 4
5) chlorite/smectite x 1.

To account for the overlap of the chlorite (002) and kaolinite (001) peaks at 7Å the weighted kaolinite area was subtracted from the chlorite area. All weighted areas were summed and recalculated to 100 per cent. The calculated percentages were rounded to the nearest 5 or 10 per cent, which is the greatest accuracy to be expected using this method (Brown and Brindley, 1980).

Scanning Electron Microscopy (SEM)

Analyses were made of rock chips from the unweathered portions of several samples. The chips were mounted on stubs using silver paint and sputter-coated with 20 nm of gold. The prepared stubs were analysed using a Cambridge Stereoscan S250 with accelerating voltage fixed at 25 KEV and a Kevex system 7000 for energy dispersive X-ray analysis (EDA). The chemical composition of mineral phases observed in SEM were obtained using spot analysis in areas where count rates of at least 700 counts per second could be reached. The qualitative chemical analyses and the observed crystal or grain morphology were used in conjunction to identify specific minerals.

II. MINERALOGY OF THE CARMANAH GROUP

A. ESCALANTE FORMATION

The Escalante Formation is the basal unit of the Carmanah Group (Muller et al., 1981). The type section is located at Escalante Point and consists of conglomerate and sandstone unconformably overlying metavolcanic rocks of the Westcoast Complex. Escalante Formation strata are also exposed at Tatchu Point, east Hesquiat Peninsula, Nootka Island and Flores Island (Figure 2.1). In the type area this formation consists of a basal conglomerate bed grading upward into pebbly grit and then into calcareous sandstone. The conglomerate and grit units are about 10 metres thick and contain several lenticular beds with a concentration of broken shell fragments. The conglomerate contains subrounded to rounded diorite and metavolcanic pebbles and boulders which are poorly sorted and measure up to 40 cm in diameter (Plate 2.1a). Sandstones comprise the remaining 130 m of the section. Minor beds of shelly conglomerate and numerous calcareous concretions are found in the sandstone. Carbonaceous remains or crab exoskeletons form the central core of most of the concretions, which range up to 60 cm across but average about 10 cm in size (Plate 2.1b).

Westcoast Complex rocks crop out on the northwestern edge of Escalante Island (Figure 2.2) and are overlain by conglomerates of the Escalante Formation. Based on these

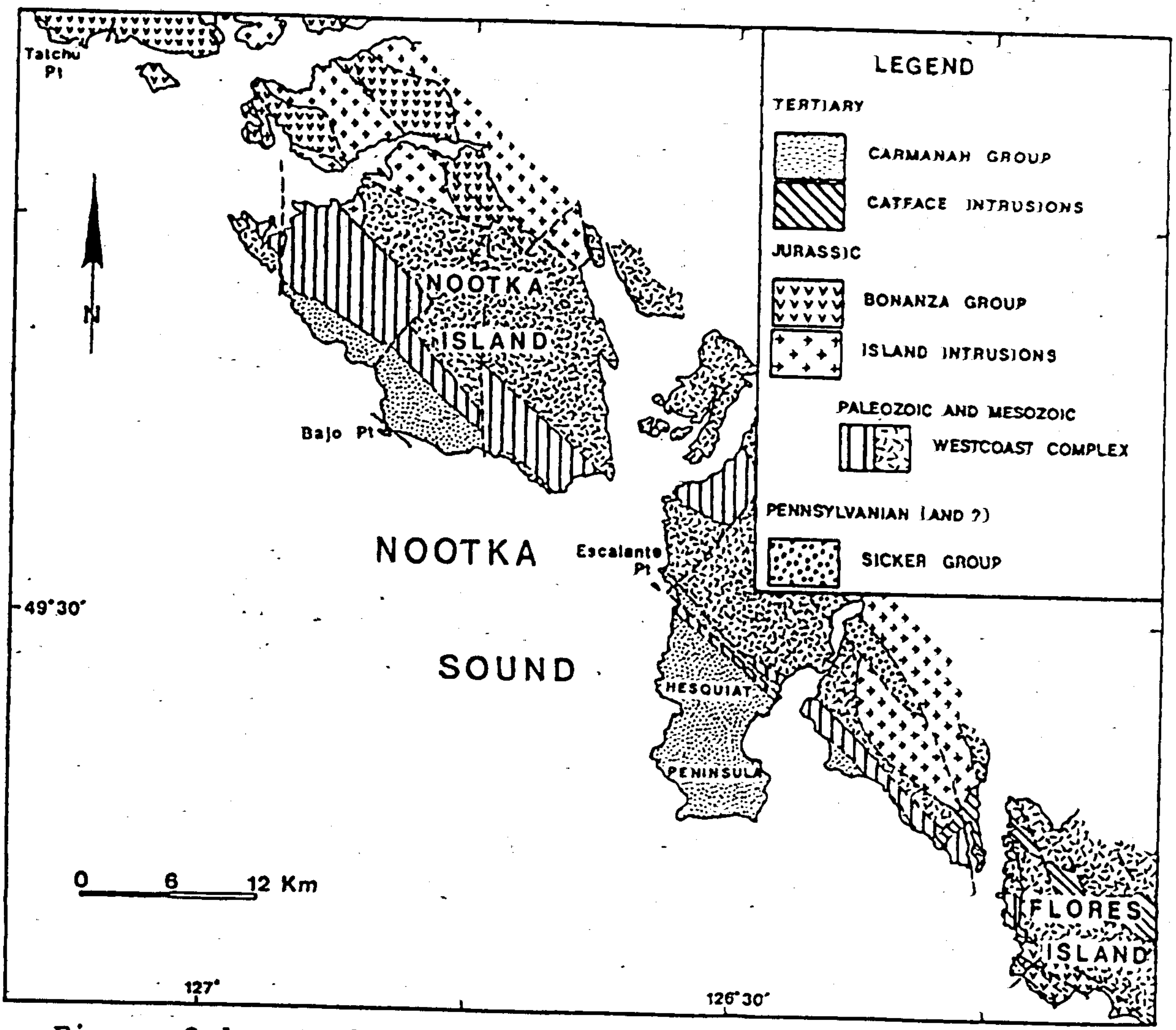


Figure 2.1. Geology of the Nootka Sound area (modified after Muller et al., 1981).

field relationships Cameron (1980) concluded that a west-dipping thrust fault is present between the island and the mainland. This fault repetition is also seen on the east side of Hesquiat Peninsula (Figure 2.2). At this locality, the Escalante Formation is approximately 90 m thick. It thins to the southeast and is represented on Flores Island by about 50 m of sandstone resting unconformably on Bonanza volcanics (Cameron, 1980). On Nootka Island, northwest of the type area, approximately 150 m of sandstone and grit, interbedded with argillaceous sandstone, overlie amphibolite of the Westcoast Complex (Figure 2.1). Based on microfaunal analyses, Cameron (1973, 1980) suggested that the Escalante Formation at the type section may be older than at the other localities. Throughout the Nootka Sound area the contact with the overlying Hesquiat Formation is gradational.

Interpretations of the depositional environment of the Escalante Formation are based on foraminiferal assemblages (Cameron, 1980) and macroinvertebrates (Jeletzky 1954, 1973, 1975b; Cameron, 1980). The coarse grained basal strata of the type section contain few foraminifers. A small number of in-situ specimens, found 70 m above the base of the section, suggest deposition in lower neritic to upper bathyal water depths (Cameron, 1980). Foraminiferal assemblages from the uppermost strata of the type section and those from Nootka Island

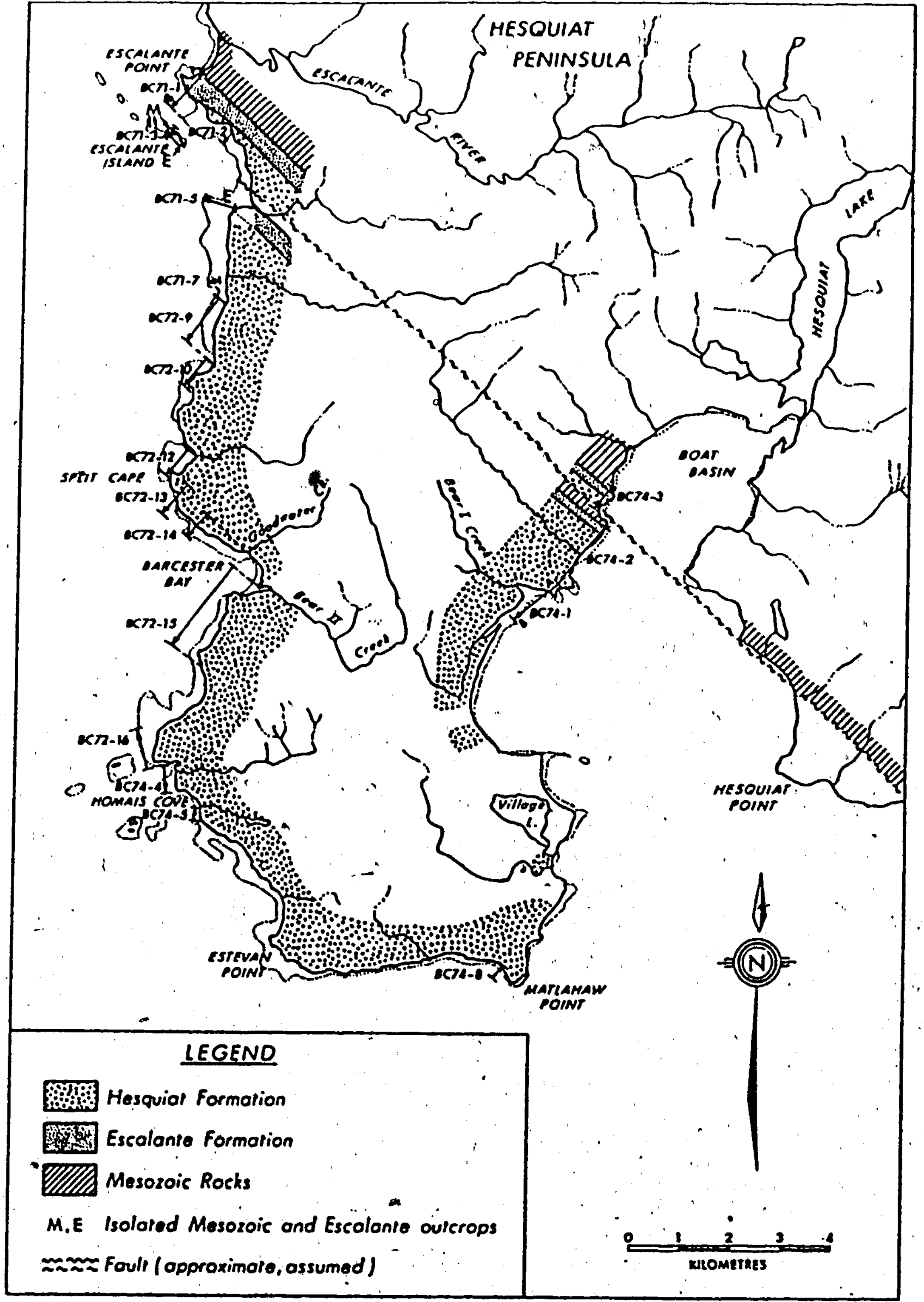


Figure 2.2. Geology of the Carmanah Group at Hesquiat Peninsula, and locations of sections measured by Cameron (1980) (modified after Cameron, 1980).

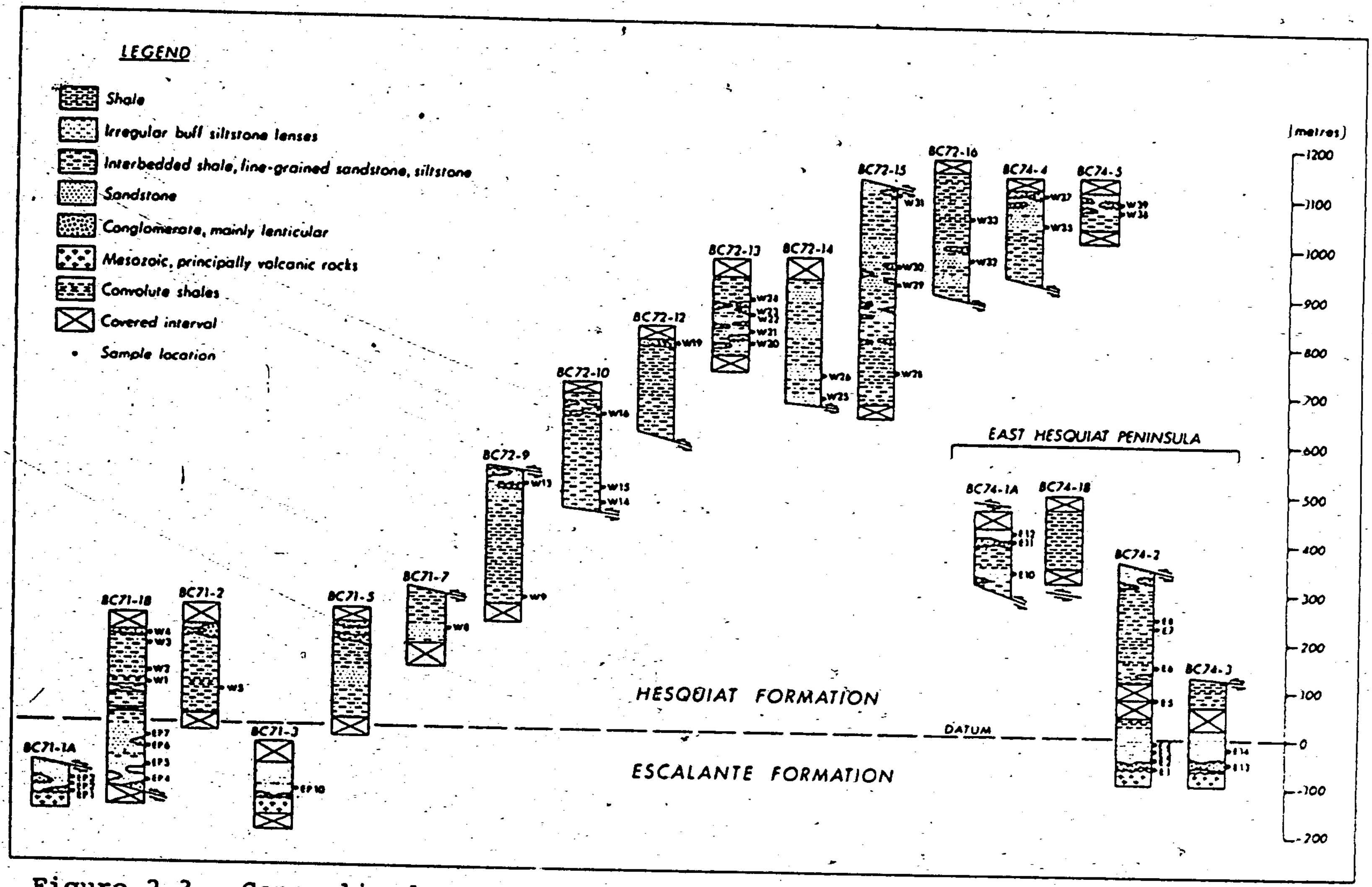


Figure 2.3. Generalized Tertiary succession, Hesquiat Peninsula (modified after Cameron, 1980).

and Flores Island indicate deposition in bathyal water depths (Cameron, 1980). Jeletzky (1973, 1975b) examined molluscan faunas from the Escalante Formation on Flores Island and East Hesquiat Peninsula (Figure 2.1). He interpreted the faunal assemblage from the base of the formation to be indicative of littoral to supratidal and inner neritic water depths, and the assemblage from the upper parts of the formation to be indicative of inner neritic or outer littoral water depths. This interpretation has been questioned because the concentration of shallow water pelecypods within lenticular conglomerate beds at the type section and at other localities suggests some transport occurred prior to deposition (Cameron, 1980; Muller et al., 1981).

DETRITAL MINERALOGY OF SANDSTONES AND CONGLOMERATES

The detrital mineralogy of sandstone and conglomerate from outcrops on Hesquiat Peninsula, Flores Island and Nootka Island was determined by thin-section and bulk X-ray diffraction analyses. All samples contain abundant volcanic rock fragments, diorite and quartz diorite fragments, plagioclase, K-feldspar and biotite. Minor components include sedimentary and metamorphic rock fragments, hornblende, chlorite, sphene and opaques (Table 2.1).

The pebbles in the conglomerates are subrounded to rounded (Plate 2.1a); the detrital grains in the

Table 2.1. Petrology of sandstones and conglomerates from the Carmanah Group.

SAMPLE	DETRITAL MINERALS (%)								CMT (%)	POR (%)	QFL (%)		
	Q_m	Q_p	Pl	KF	L_s	L_v	Mtx	Acc			Q	F	L
Hesquiat Formation													
W 8	14	6	27	2	tr	39	2	tr	9	-	23	33	44
W14	10	7	22	2	tr	46	6	3	4	1	19	28	53
W22	16	4	26	2	2	14	8	13	-	11*	31	44	25
W24	14	9	25	2	tr	34	4	5	6	1	27	32	41
W25	11	12	21	1	1	35	11	1	6	1	28	27	45
E11	12	9	22	2	-	33	6	9	6	1	27	31	42
Escalante Formation													
EP1	4	5	19	11	9	32	4	4	12	0	11	38	51
E 1	14	13	21	7	7	19	3	3	13	0	33	35	32
Sooke Bay Formation													
S 9	3	8	30	9	2	40	-	3	5	-	12	42	46
S10	4	3	28	11	-	34	-	12	2	6	9	49	42

* secondary porosity

sandy matrix are subangular to subrounded. In the sandstones, detrital grains are subangular to subrounded.

Estimations of detrital modes by point counting were possible only in samples in which detrital grains were coated with clay. Samples in which this coating was not present were too highly altered to make positive identifications. The average detrital mode for Escalante Formation sandstones from Hesquiat Peninsula is $Q_{11}F_{38}L_{51}$ (Table 2.1). Based on the proportions of detrital components these rocks are classified as feldspathic litharenites according to the scheme of Folk (1968; Figure 2.4).

Authigenic clay rims and laumontite cement have occluded all porosity in sandstones and conglomerates from the base of the Escalante Formation at the type section (Plate 2.2a,b). Only slight alteration of detrital grains has occurred; volcanic rock fragments have been partially replaced by laumontite (Plate 2.2a). These rocks show no visible evidence of deformation on outcrop or hand specimen scale.

In contrast, the localities sampled at east Hesquiat Peninsula are adjacent to the fault mapped by Cameron (1980; Figure 2.2). Prior to faulting, the rocks at this

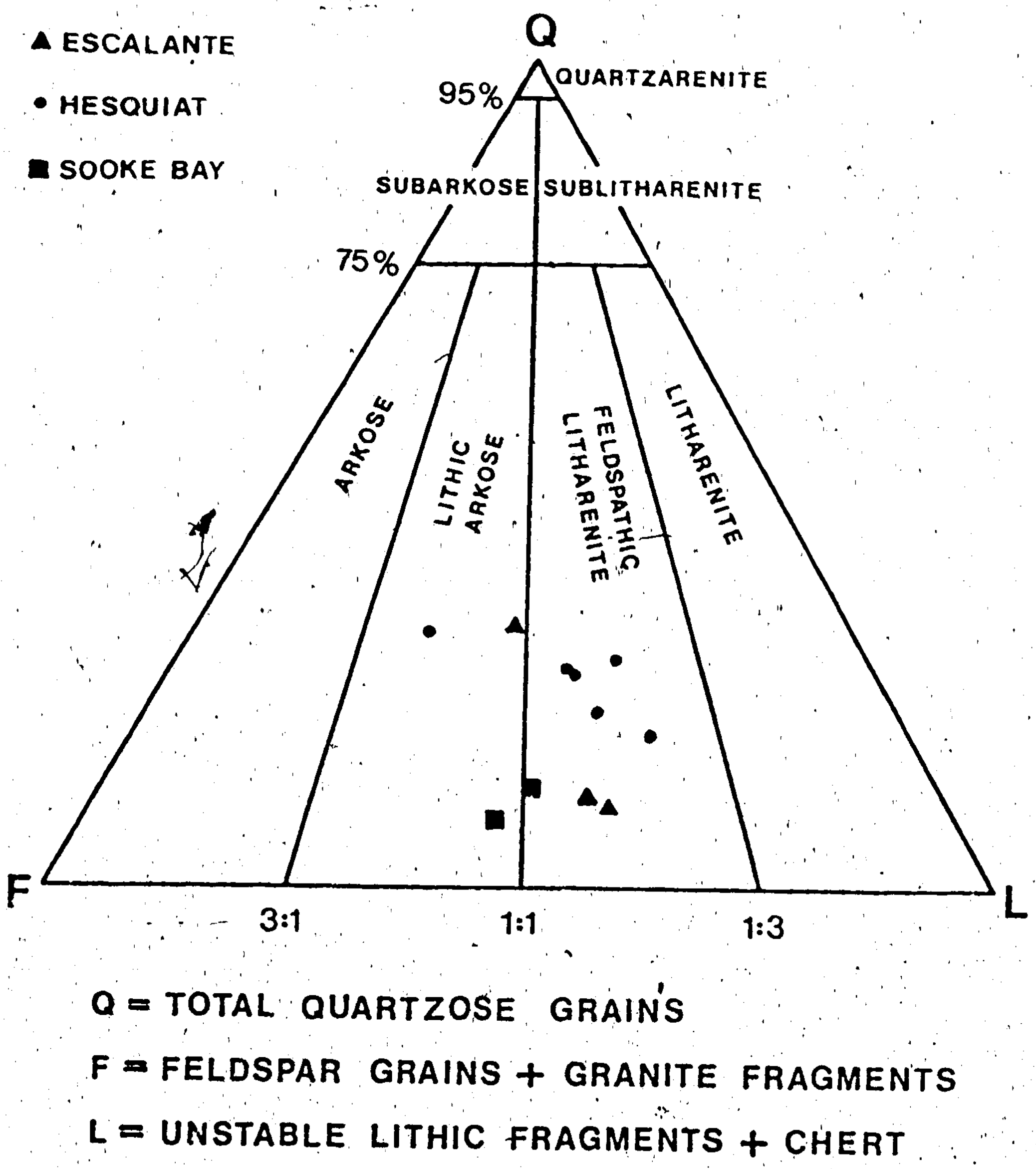


Figure 2.4. Triangular diagram showing composition of detrital framework grains, Escalante, Sooke Bay and Hesquiat formations.

location were firmly indurated, as indicated by the clean breakage of pebbles and granules. Relict patches of laumontite cement occur in a sandstone from locality E1 (Figure 2.3). This sample contains highly altered detrital grains, and point counts indicate unusually high porosity (26%). Dissolution of detrital grains also occurred in other sandstones from the base of the Escalante Formation at east Hesquiat Peninsula (Plate 2.4a,c). Removal of authigenic cement may have exposed the detrital grains to fluids which caused their alteration.

AUTHIGENIC MINERALS IN THE ESCALANTE FORMATION

Siltstones, sandstones and conglomerates from the Escalante Formation were analysed using optical microscopy and SEM to determine the distribution and morphology of authigenic clay minerals. Authigenic phases identified in thin section include: rims and pore fillings of clay minerals; laumontite and calcite cement; and euhedral pyrite, albite and quartz crystals. X-ray diffraction analyses of the <2 μm and 2-20μm size fractions were used to identify the clay minerals.

All rocks from the type area contain abundant mixed-layer chlorite/smectite and lesser amounts of chlorite, calcite, pyrite and zeolites (Table 2.2). Smectite, kaolinite and illite are minor phases or are not present in these samples. Samples from east Hesquiat Peninsula

Table 2.2. X-ray diffraction results for < 2 um size fraction, Escalante Formation.

SAMPLE I.D.	ROCK TYPE	METRES ABOVE DATUM*	CLAY MINERALOGY <2 um SIZE FRACTION RELATIVE PERCENT						OTHER PHASES PRESENT			
			SM	CHL	I	K	Ord C/S	Rdm C/S	Q	Pl	Ca	OTHER
Type Area, Escalante Point												
EP2	C SST	2	nd	60	5	nd	35	nd	x	x	nd	laumontite
EP4	CONGL	8	nd	45	5	nd	50	nd	x	x	x	laumontite
EP3	CONGL	13	10	40	15	5	30	nd	x	x	x	laumontite
EP5	F SST	50	nd	40	15	nd	45	nd	x	x	nd	laumontite
EP6	SLST	50	nd	50	5	nd	45	nd	x	x	x	
East Hesquiat Peninsula												
E 2	CONGL	20	nd	60	20	nd	20	nd	x	x	nd	
E 3	SLST	50	15	45	20	20	nd	nd	x	x	x	
E13	C SST	50	nd	75	10	nd	15	nd	x	x	nd	
E14	C SST	55	nd	50	15	nd	35	nd	x	x	x	
Flores Island												
FI6	M SST	9	35	55	tr	10	nd	nd	x	x	x	
FI7A	C SST	47	45	20	25	15	nd	nd	x	x	x	
FI7B	CONGL	47	60	20	20	nd	nd	nd	x	x	x	
FI8A	C SST	133	50	15	25	10	nd	nd	x	x	x	

* Datum is the basal contact of the Escalante Formation.

tr = est. abundance < 5%
x = est. abundance > 5%

contain less chlorite/smectite and more chlorite than rocks from the type area. Samples of Escalante Formation from Flores Island do not contain chlorite/smectite and contain a greater amount of smectite (Table 2.2).

Laumontite cement is common in sandstones and conglomerates from the base of the type section (Plate 2.2; Table 2.2). It also occurs in the basal sandstone on Nootka Island (Figure 2.1). These basal rocks also contain minor amounts of calcite cement (Plate 2.5a). Calcite cement is common in all rock types from the upper part of the type section and is the only cement in sandstones from the Escalante Formation on Flores Island (Figure 2.1).

Pyrite

Authigenic pyrite occurs in all rock types in the Escalante Formation. Most of the pyrite in sandstones and conglomerates formed in or adjacent to volcanic rock fragments (Plate 2.2a). In the finer-grained rocks from the type section, authigenic pyrite developed adjacent to shell fragments and carbonaceous debris and in concretions (Plate 2.1b). Authigenic pyrite occurs as framboids or as individual crystals (Plate 2.3g,h).

Chlorite/Smectite

Chlorite/smectite is abundant in siltstone, sandstone and conglomerate samples from the Escalante

Formation type area (Table 2.2). It is present in equivalent rocks from east Hesquiat Peninsula and is not present in the sandstones from Flores Island (Table 2.2).

Chlorite/smectite occurs as a grain coating and developed perpendicular to grain surfaces (Plates 2.2b and 2.3a). It also coats authigenic pyrite (Plate 2.3h). Chlorite/smectite was identified by X-ray diffraction analyses. X-ray diffraction patterns of Ca-saturated, glycolated samples show a superlattice diffraction at 31Å. This indicates a regular alternation of 14 Å chlorite and 17 Å smectite layers (Blatter et al., 1973; Hower, 1981). After heating K-saturated samples to 550° C the diffraction patterns show diagnostic diffractions at 23Å and 12 Å (Figure 2.5).

Ordered chlorite/smectite occurs in samples from the lowermost 50 m of the Escalante Formation at the type section (Figure 2.6). A comparison of the $(002)_{31}$ and $(004)_{31}$ diffraction values for chlorite/smectite in these samples with diffraction values calculated by Hower (1981) indicate chlorite layers comprise 45-60 per cent of the chlorite/smectite (Table 2.3).

Randomly interstratified chlorite/smectite occurs in samples from the uppermost beds exposed southwest of the fault at east Hesquiat Peninsula (Figure 2.7). The $(001)_{14}/(001)_{17}$ and $(002)_{14}/(002)_{17}$ diffraction values for the randomly interstratified chlorite/smectite indicate

Figure 2.5. X-ray diffraction patterns of regularly interstratified chlorite/smectite, <2 μm size fraction, Escalante Formation conglomerate, sample location EP2.

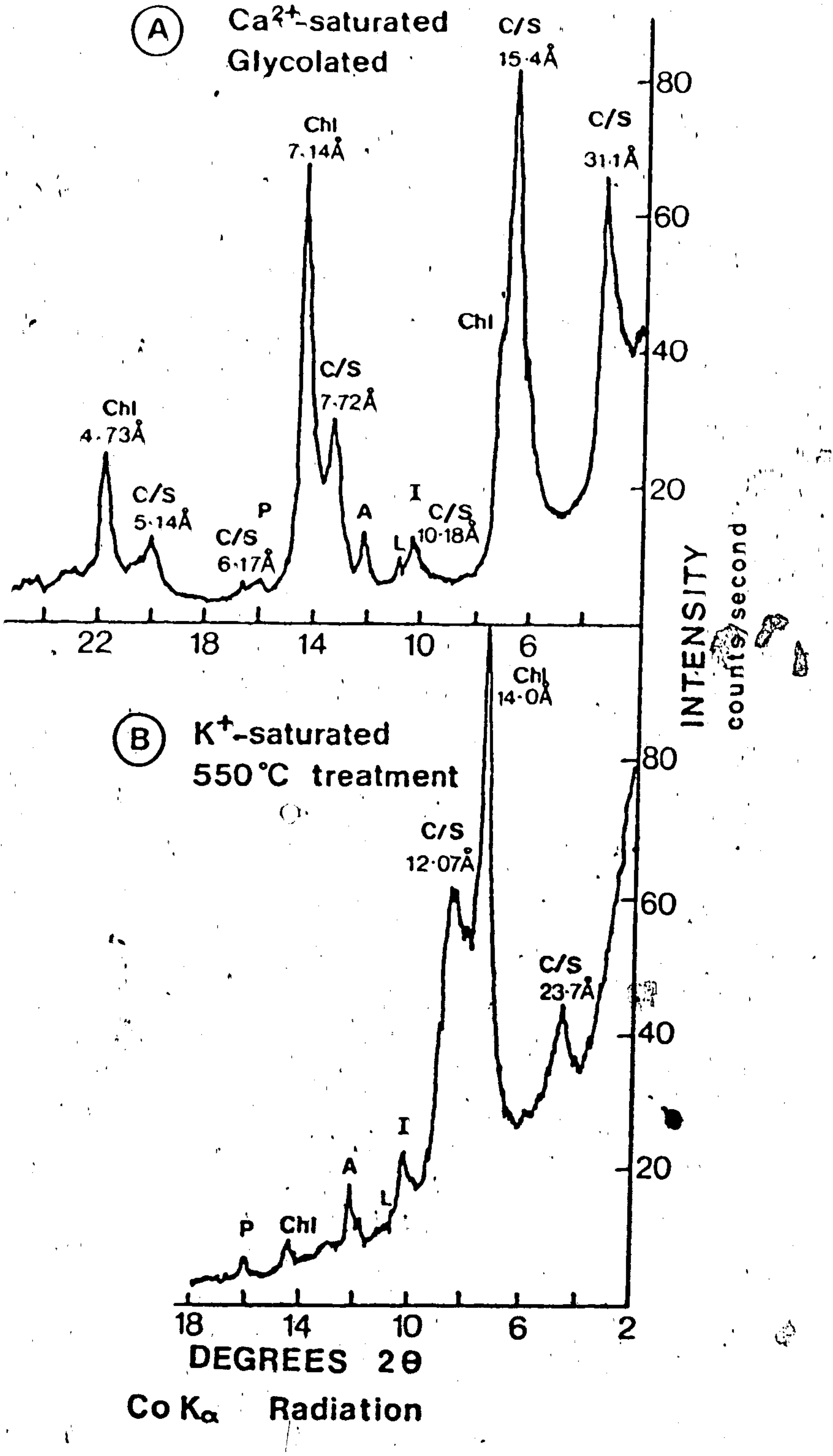


Figure 2.6. X-ray diffraction patterns of <2 µm size fraction, oriented discs, calcium saturated and glycolated samples.

All four samples are from within 50 m of the basal contact at Escalante Point and contain authigenic, regularly interstratified chlorite/smectite, chlorite and laumontite. Chlorite/smectite is abundant in fine-grained sandstone (A), pebble conglomerate (C) and coarse-grained sandstone (D). The siltstone (B) is cemented with calcite, and contains greater amounts of chlorite relative to chlorite/smectite. Calcite in the pebble conglomerate is from shell fragments crushed during sample preparation.

Diffractogram (A) is at a scale of 2 x 10 counts/second; diffractograms (B), (C) and (D) are at a scale of 1 x 10 counts/second.

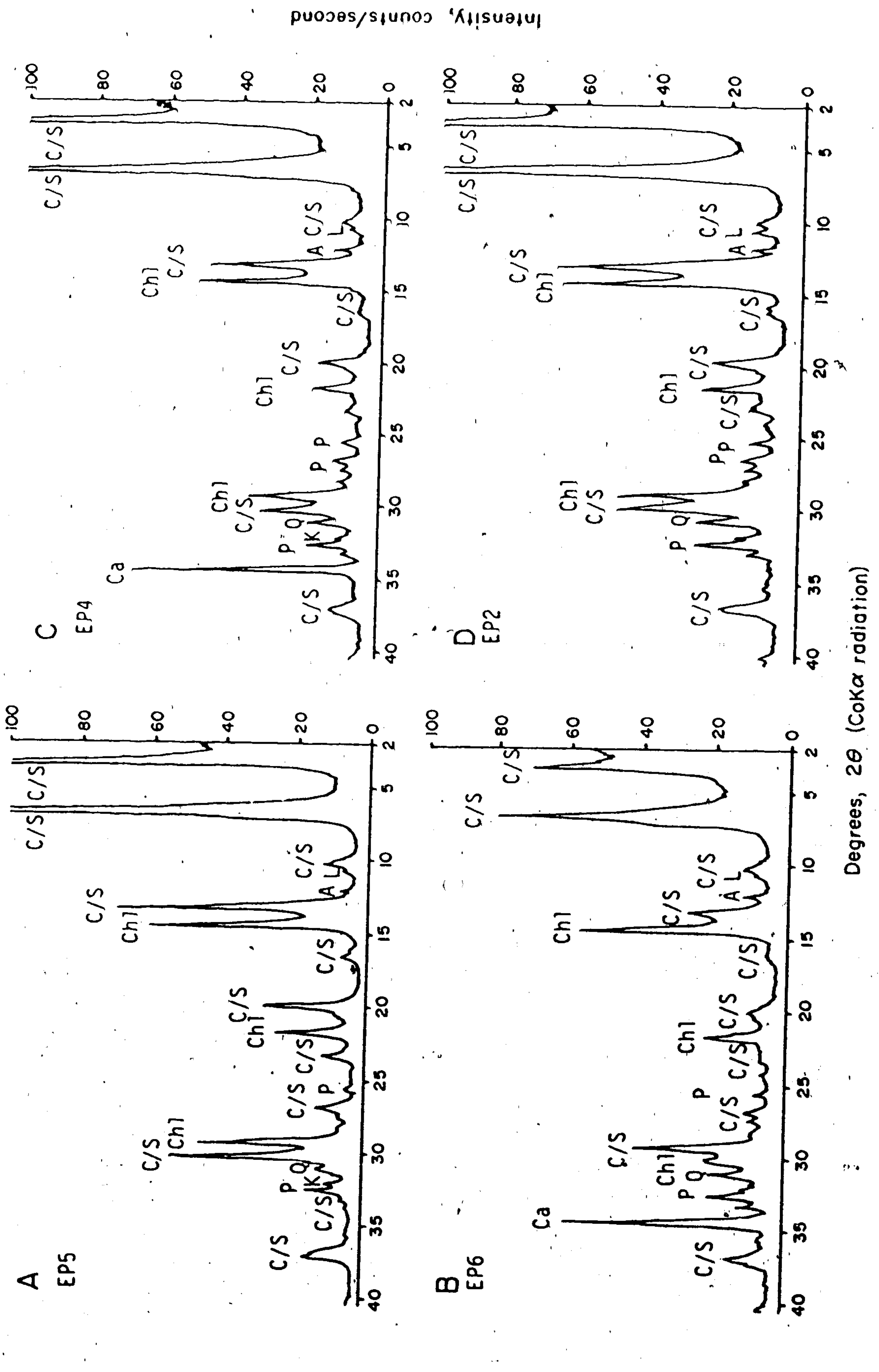

Intensity, counts/second
A
EP5
B
EP6
C
EP4
D
EP2
C/S
Ch1
A
L
P
Q
K
Ca
0
20
40
60
80
100
2
5
10
15
20
25
30
35
40
Degrees, 2θ (CoKα radiation)

Table 2.3. Positions of diffractions for chlorite/smectite and determinations of per cent chlorite layers.

SAMPLE I.D.	ROCK TYPE	METRES ABOVE BASAL CONTACT	$(002)_{31}$ or $(001)_{14}/(001)_{17}$ *	% CHLORITE LAYERS	INTERSTRATIFICATION
Type Area, Escalante Point					
EP 2	C sst	2	15.6	50	well-ordered
EP 4	Congl	8	15.5	50	well-ordered
EP 3	Congl	13	15.4	60	well-ordered
EP 6	Slst	50	15.6	50	well-ordered
EP 5	F sst	50	15.7	45	well-ordered
W 1	F sst	290	16.8	5	random
W 2	F sst	330	15.4	60	poorly-ordered
W 3	Slst	380	15.4	60	poorly-ordered
East Hesquiat Peninsula					
E 2	Congl	20	14.9	75	poorly-ordered
E 3	Slst	50	16.9	0	random
E13	C sst	50	15.1	70	poorly-ordered
E14	C sst	55	15.2	65	poorly-ordered

* Diffractions measured on X-ray diffractograms of <2 μm size fraction.

Figure 2.7. X-ray diffraction patterns of the <2 μm fraction of Escalante Formation samples. All patterns are calcium saturated and glycolated samples.

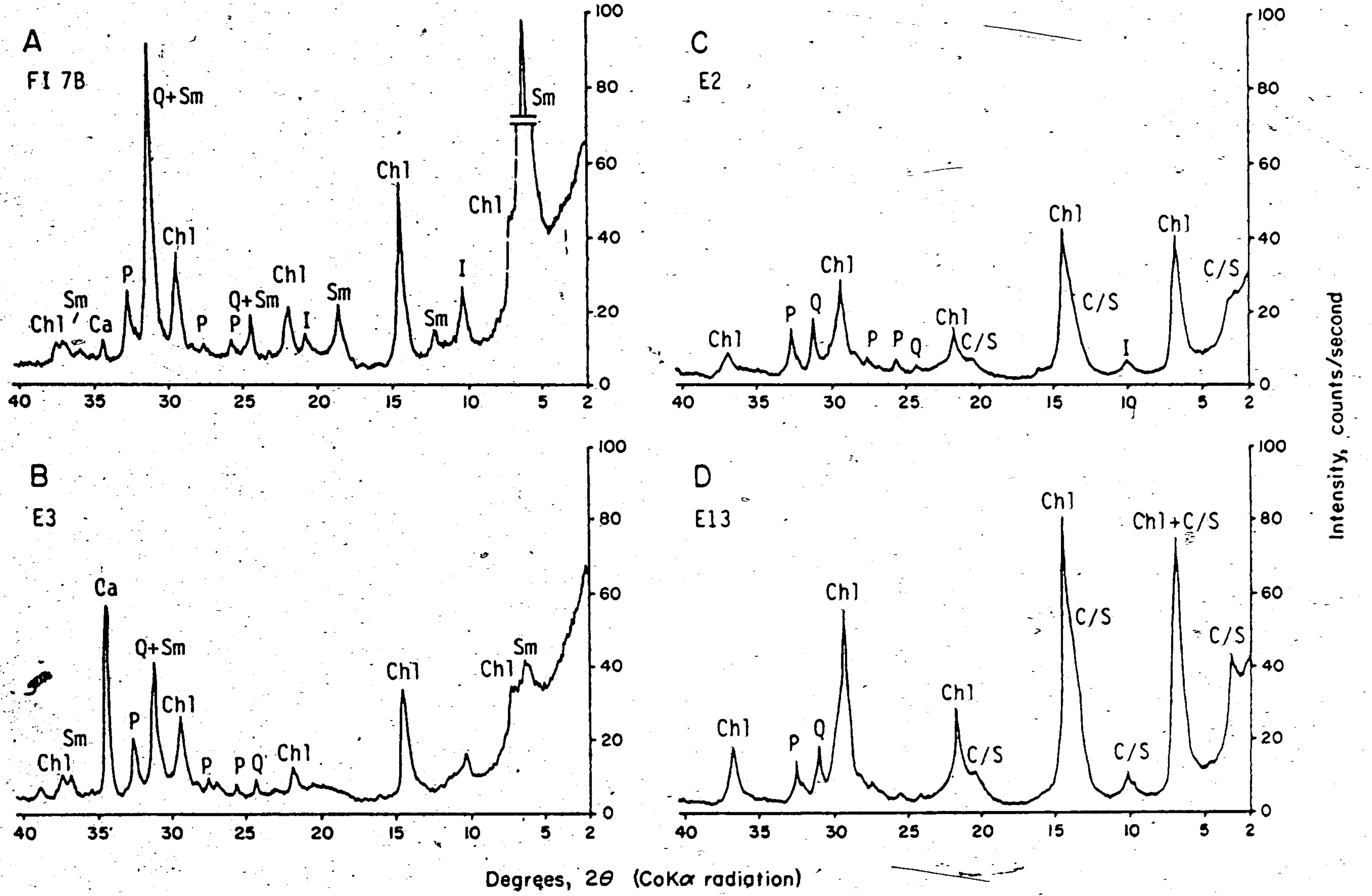
Conglomerate (A) from Flores Island contains abundant smectite and lesser amounts of chlorite and illite.

Siltstone (B) and conglomerate (C) were collected 50 m above the basal contact at east Hesquiat Peninsula, above the fault; chlorite occurs in both samples.

(C) contains minor amounts of ordered chlorite/smectite, indicated by a weak diffraction at 31Å and a shoulder on the chlorite (002) diffraction. Ordered chlorite/smectite is also present in coarse grained sandstone (D) from 50 m above the base of the formation, but collected below the fault.

Comparison of the relative intensities of the 31Å diffraction in these samples and samples from Escalante Point (Figure 2.6) indicates that poorly-ordered chlorite/smectite occurs at east Hesquiat Peninsula.

Diffractograms (A) and (B) are at a scale of 1 x 10 counts per second; diffractograms (C) and (D) are at a scale of 2 x 10 counts per second.


A
FI 7B
Q+Sm
Sm
Chl
Chl
Chl
P
Chl
I
Sm
Q+Sm
Sm
Chl ' Ca
P
P
I
Sm
B
E3
Ca
Q+Sm
Chl
Sm
Chl
P
Chl
Sm
P
P Q
Chl
Chl
C
E2
Chl
Chl
Chl
C/S
C/S
P Q
Chl
P P Q
C/S
I
Chl
D
E13
Chl
Chl+C/S
Chl
C/S
C/S
Chl
Chl
P Q
C/S
C/S
100
80
60
40
20
0
40 35 30 25 20 15 10 5 2
Intensity, counts/second
Degrees, 2θ (CoKα radiation)

0-5 per cent chlorite layers (Table 2.3).

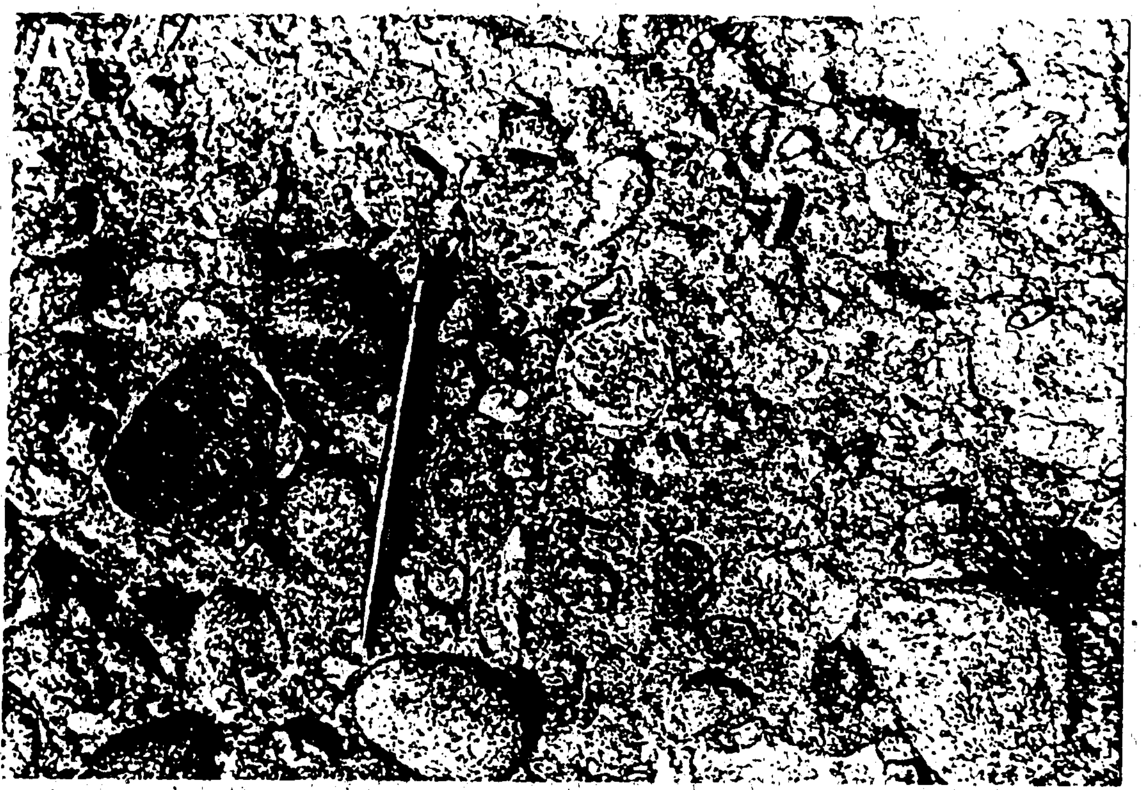
Zeolites

Laumontite cement is common in sandstones and conglomerates from the type area (Plates 2.2, 2.4 and 2.5). Another calcic zeolite, tentatively identified as heulandite, occurs in a fine-grained sandstone from the type area. Examination by SEM reveals blocky, tabular crystals within pore spaces (Plates 2.3c and 2.5b) and elongate pyramidal crystals developing on grain surfaces (Plate 2.3e). Analyses with EDA shows both forms contain Ca, Si and Al as major components, and minor Fe. The blocky crystals contain less calcium relative to the elongate crystals (Plates 2.3d and 2.3f). Laumontite cement and heulandite crystals cover and partially envelop authigenic chlorite/smectite, which indicates that the zeolites formed after the clay rims (Plates 2.2b and 2.3c).

PLATE 2.1

A. Escalante Formation conglomerate containing rounded quartz diorite pebbles, andesite pebbles and shells in a sandy matrix. Outcrop photograph. Escalante Point, sample locality EP3. Pen = 14 cm.

B. Rusty-weathering concretion in fine-grained argillaceous sandstone of the Escalante Formation. Crab remains form the core. Outcrop photograph. Escalante Point, sample locality EP8. Hammer = 35 cm.


A

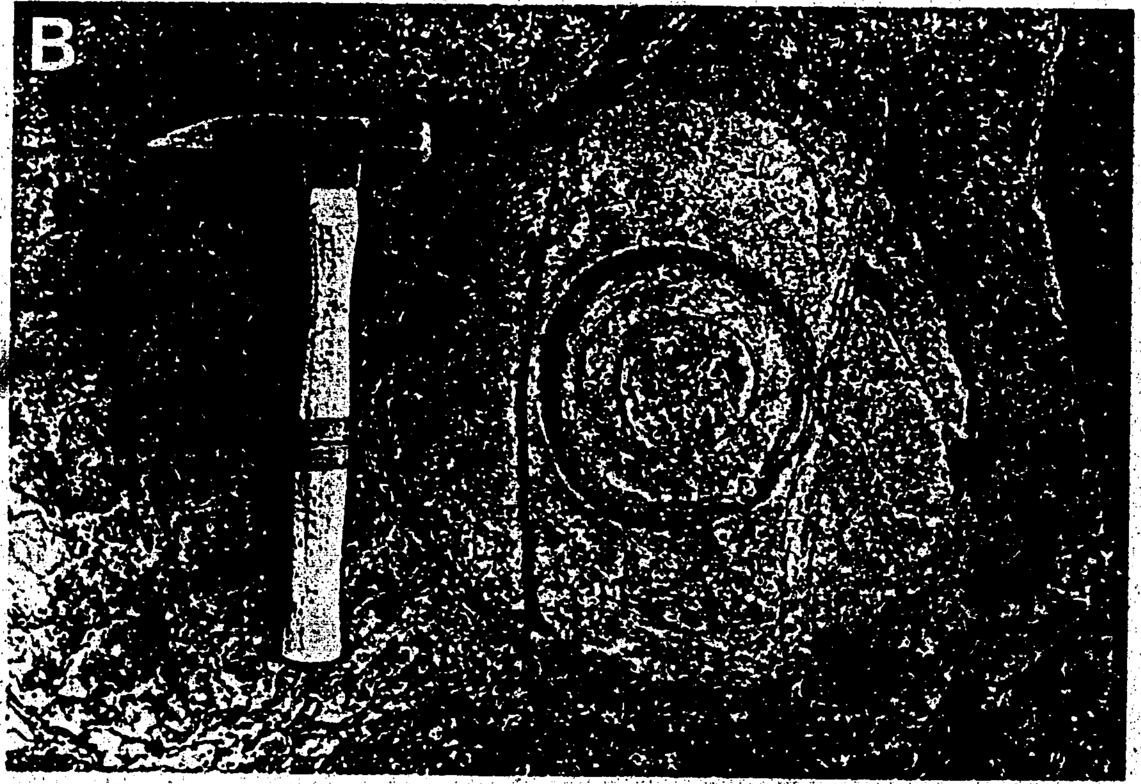

B

PLATE 2.2

A. Authigenic, mixed-layer chlorite/smectite (CS) rims on detrital rock fragments. Authigenic pyrite framboids (Py) formed within volcanic rock fragments. Laumontite cement (L), with characteristic well-developed cleavage, fills pore space. Thin section photomicrograph, plain polarized light, field of view = 2.0mm x 1.3mm, Escalante Formation sandstone, sample locality EP1.

B. Authigenic chlorite/smectite (CS) rim developed perpendicular to grain surface and predating laumontite cement (L). Thin section photomicrograph, crossed nicols, field of view = 0.5 mm x 0.3 mm, Escalante Formation sandstone, sample locality EP1.


A
Py
CS


B
CS

PLATE 2.3

A. Authigenic, regularly interstratified chlorite/smectite (CS) coating detrital grain. EDA (photograph B) indicates the presence of Fe, Ca, Mg, Si, and Al. SEM photomicrograph, Escalante Formation conglomerate, sample locality EP3.

C. Zeolite (Z) crystals forming over chlorite/smectite grain coating. The zeolite is tentatively identified as heulandite, based on the "coffin-shaped" morphology, EDA (photograph D) which indicates Ca, Al, Fe, Al and Si, and X-ray diffraction analysis. SEM photomicrograph. Escalante Formation sandstone, sample locality EP5.

E. Fibrous mineral (arrow) developed on surface of laumontite cement. EDA analysis (photograph F) suggests that it is calcite. SEM photomicrograph, Escalante Formation sandstone, sample EP5.

G. Authigenic pyrite framboid formed on a mat of individual pyrite crystals. SEM photomicrograph, Escalante Formation sandstone, sample locality E4.

H. Enlarged view of authigenic pyrite crystals (Py) which are coated with authigenic chlorite/smectite (CS). SEM photomicrograph, Escalante Formation sandstone, sample locality E4.

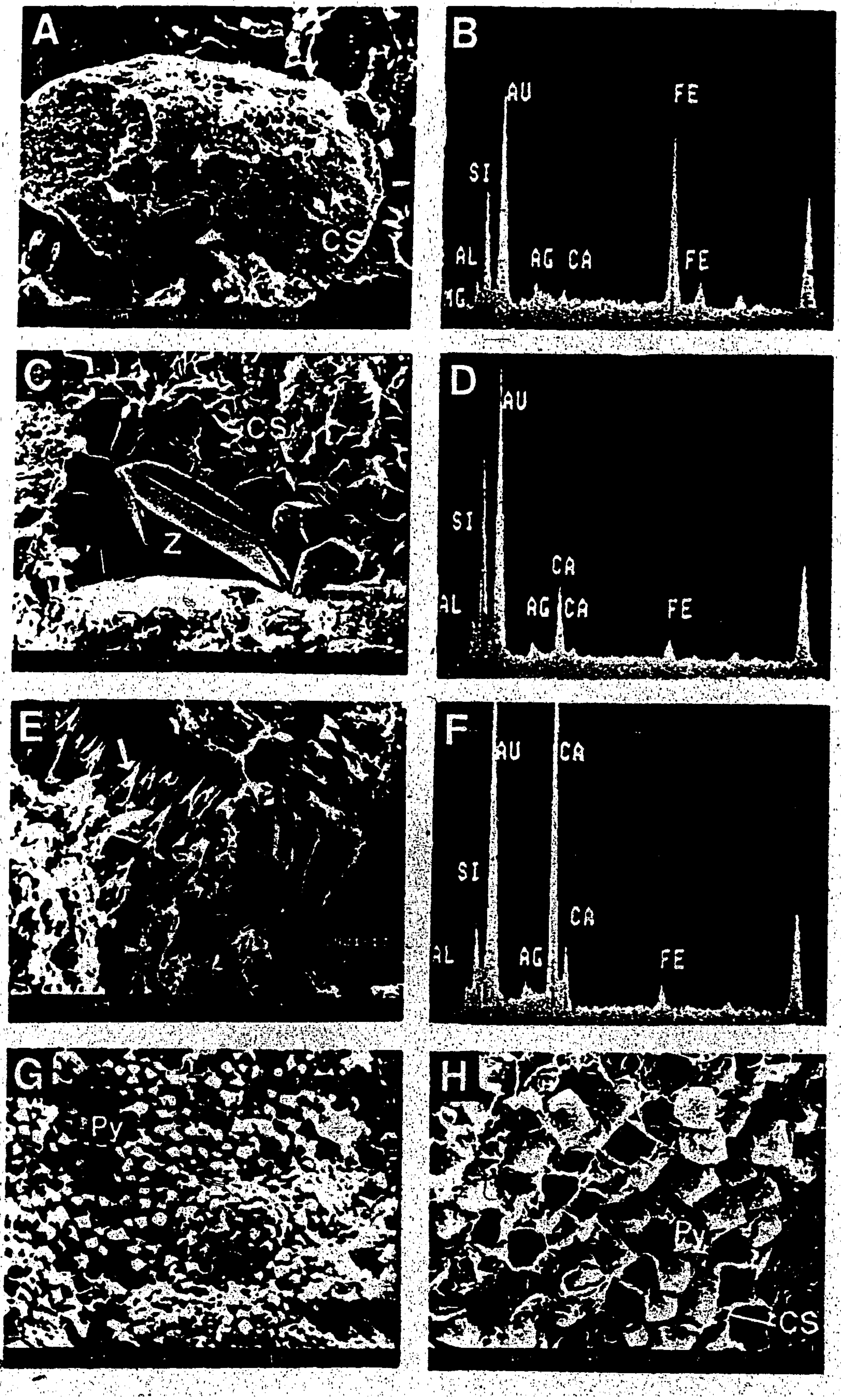

A
CS
B
AU
FE
SI
AL
AG
CA
FE
MG
C
CS
Z
D
AU
SI
CA
AL
AG
CA
FE
E
F
AU
CA
SI
CA
AL
AG
FE
G
Py
H
Py
CS

Plate 2.4

A. Plagioclase feldspar overgrowth (AO) on partially dissolved detrital grain. EDA (photograph B) shows Na, Al and Si, indicating the overgrowth may be albite. SEM photomicrograph, Escalante Formation sandstone, sample locality E1.

C. Detrital plagioclase grain (Pl) showing preferential dissolution along twin planes (arrow). SEM photomicrograph, Escalante Formation sandstone, sample locality E4.

D. Authigenic chlorite (Chl) and quartz (Q) in pore space. SEM photomicrograph, Escalante Formation sandstone, sample locality E1.

E. K-feldspar overgrowth (KF) on detrital K-feldspar host. Composition of overgrowth shown by EDA analysis (photograph F). SEM photomicrograph, Escalante Formation sandstone, sample locality E1.

G. Authigenic chlorite/smectite (CS) which predates the development of authigenic K-feldspar. SEM photomicrograph, Escalante Formation sandstone, sample locality EP5.

H. Photograph of EDA results for authigenic K-feldspar shown in photomicrograph G.

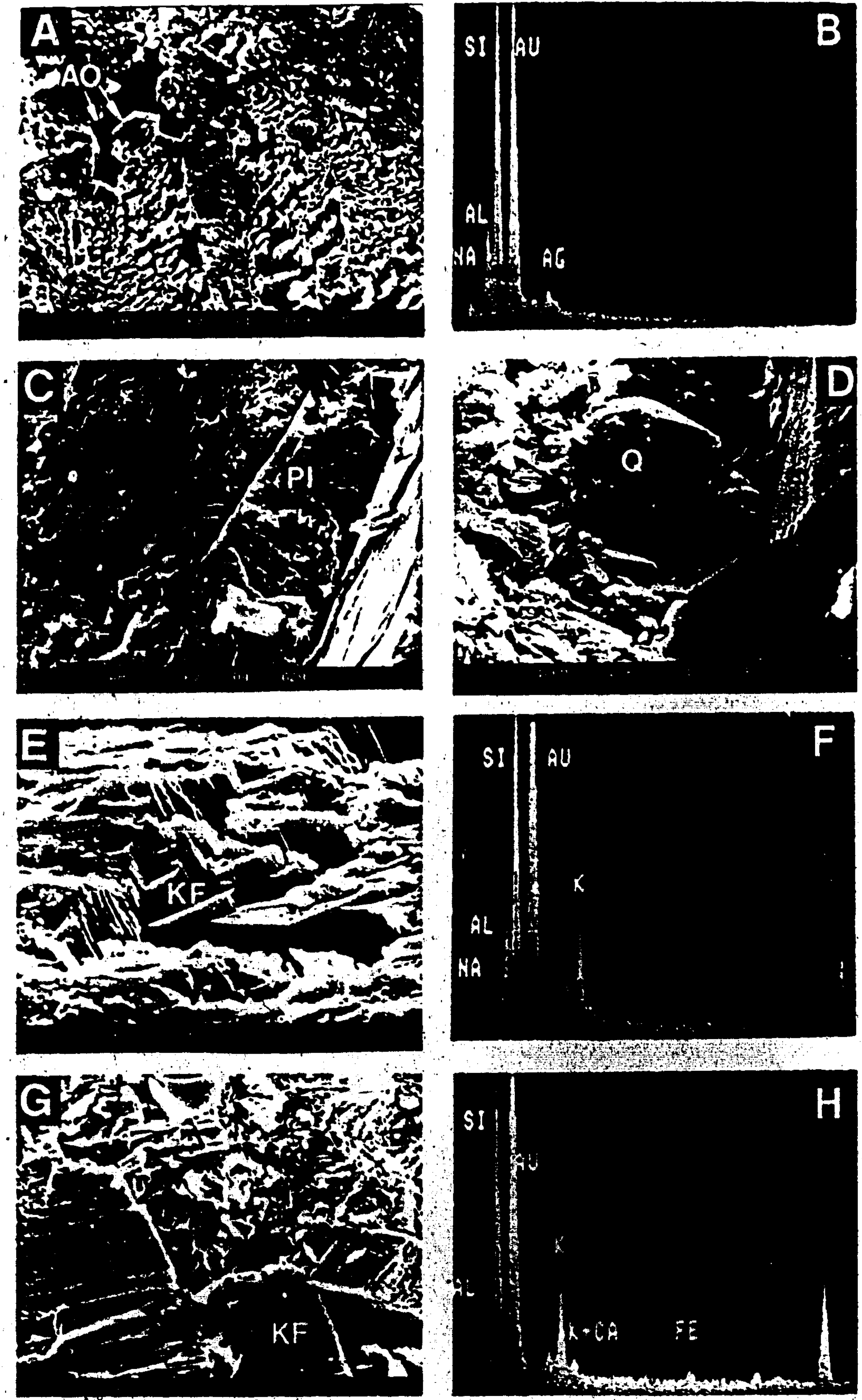

A
AO
B
SI
AU
AL
NA
AG
C
PI
D
Q
E
KF
F
SI
AU
K
AL
NA
G
KF
H
SI
AU
K
AL
K+CA
FE

PLATE 2.5

A. Laumontite (L) and calcite (Ca) cements. Abrupt terminations of laumontite crystals along boundary suggests that calcite postdates laumontite. Authigenic pyrite framboids (Py) adjacent to volcanic rock fragment. Thin section photomicrograph, crossed nicols with 1/4 λ plate inserted, field of view = 2.0 mm x 1.3 mm, Escalante Formation sandstone, sample locality EP1.

B. Zeolite (Z) developed in pore space. Volcanic rock fragment (Lv), plagioclase (Pl). Thin section photomicrograph, crossed nicols, field of view = 2.0 mm x 1.3 mm, Escalante Formation sandstone, sample locality EP1.


A
L
Ca
Py
B
Z
Lv

PLATE 2.6

A. Laumontite cement (L) which exhibits a good biaxial negative (-) figure, is length slow and has 2V = 30. Clay rim (arrow) surrounding igneous rock fragment. Thin section photomicrograph, crossed nicols with 1/4 λ plate inserted, field of view = 1.0 mm x 0.65 mm, Escalante Formation sandstone, sample locality EP 1.

B. Albite overgrowth (Ab) in optical continuity with altered plagioclase grain (Pl). Albite in contact with zeolite pore fill (Z). A concentration of clay minerals (arrow) occurs at the boundary between altered and unaltered plagioclase. Thin section photomicrograph, crossed nicols with 1/4 λ plate inserted, field of view = 1.0 mm x 0.65 mm, sample locality EP1.


A
L
AQ


B
Z
Ab
Pl

B. HESQUIAT FORMATION

The Hesquiat Formation conformably overlies the Escalante Formation. The type section is located along the west coast of Hesquiat Peninsula (Figure 2.2, 2.3). The rocks in the type section consist of sandy shale, graded beds of shale-siltstone-sandstone, slightly argillaceous sandstone, pebbly mudstone and conglomerate. Silty shale and mudstone, interbedded with minor amounts of siltstone and sandstone comprise the Hesquiat Formation on Nootka Island and Flores Island.

The entire sequence is interpreted as a series of upper to mid bathyal turbidite deposits (Cameron, 1980). The proximal facies are exposed on western Hesquiat Peninsula and at a few localities on Flores Island. The distal facies are exposed on Nootka Island and eastern Hesquiat Peninsula.

The thickness of the Hesquiat Formation type section has been the subject of controversy between Jeletzky (1975b) and Cameron (1980). Jeletzky estimated that the formation was between 2135 m (7000 ft.) and 3050 m (10,000 ft.) thick (1954, 1975b). In his initial report on the Tertiary sedimentary rocks of the Nootka Sound area Jeletzky (1954) states:

> The only seemingly complete section of the rocks of Division C on Hesquiat Peninsula was measured on its western side of the northeast limb of the Hesquiat syncline. In view of the fact that all individual beds, lithological zones, and major mappable litho-

logical phases of this division are strongly lenticular, the thickness given may be considered as only roughly approximate. The circumstance that the rocks of Division C are often badly faulted, sheared, and locally strongly contorted in this section has further reduced the precision of the measurements made.

Cameron (1980) suggested a thickness of approximately 1100 m for the type Hesquiat Formation. This estimate was based on correlation of foraminiferal assemblages between continuous sections which were apparently unfaulted (Figures 2.2 and 2.3). Cameron examined outcrops exposed at low tide on Escalante Island (Figure 2.2) and identified a contact between metavolcanic rock and conglomerate. Based on field observations he concluded that the basal conglomerate and the overlying sandstones are part of the Escalante Formation. From these observations it is evident that a thrust fault caused repetition of 600 m of strata near the base of the section. Cameron also recognized repetition of strata higher in the section on the basis of foraminiferal zones. The relative importance assigned to repetition of section explains the discrepency between the estimates of thickness given by Jeletzky and Cameron.

Cameron's estimate of the thickness of the Hesquiat Formation is used in this study for several reasons. Samples collected by Cameron and correlated with his foraminiferal zones formed the initial material available for the study. Also, the locations at which samples were collected by the author were established using Cameron's field logs of outcrop sections. Several major faults indicated on these logs are clearly visible in the exposures of Hesquiat Formation at east Hesquiat Peninsula and between Homais Cove and Split Cape (Figure 2.2).

The Hesquiat Formation consists of two distinct members which alternate throughout the section (Figure 2.3). The resistant member is composed of normally graded beds of shale and sandstone cut by beds of chaotic pebble conglomerate (Plate 2.7a,b). The graded beds have sharp lower contacts and sole marks are common in the sandstone (Plate 2.8). The conglomerate beds have very abrupt lower contacts and incorporate rare rip-up clasts of shale. It is not possible to correlate individual conglomerate beds laterally between the sections described by Cameron (1980). However, the thickest of these beds can be followed for up to 500 m along strike. The second member is composed of shale and thinly bedded shale-fine-grained sandstone (Plate 2.9a). It separates the more resistant members and predominates in the lower parts of the section.

Jeletzky (1954) described the Hesquiat Formation bed by bed. Based on this field study he divided the formation into seven successive resistant and recessive members. These members were also recognized by Cameron (1980), although on the basis of foraminiferal assemblages, he concluded that several of them were fault repetitions of the same members. The chaotic structure of the sandstone and conglomerate deposits comprising the resistant members suggests that they were deposited as a result of mass-flow processes (Cameron, 1980).

The first recessive member crops out south of Escalante Point (Figure 2.2) and comprises the uppermost 185 m of section BC 71-1 and all of section BC 71-2 (Figure 2.3). It is the transitional unit between the Escalante and Hesquiat Formations and consists of interbedded shale, siltstone and fine grained sandstone. Rusty-weathering calcareous concretions are common in this member.

The first resistant member is exposed at the top of sections BC 71-1, BC 71-2, BC 71-5 and at the base of BC 71-7 (Figure 2.3). It is located about 200 m stratigraphically above the base of the Hesquiat Formation and has an average thickness of 25 m, but it varies laterally, some lenses being about 50 m thick. There is an erosional disconformity between this member and the underlying shales and sandstones of the first recessive member. The upper contact is covered by the channel between Escalante Point and Escalante Island (Figure 2.2). This member consists of pebbly mudstone grading upward into highly argillaceous sandstone and conglomerates. The conglomerate is matrix-supported and contains subangular to subrounded quartz diorite and metavolcanic pebbles and sandstone and shale fragments from the beds below. The conglomerate is similar in overall appearance to the basal conglomerate of the Escalante Formation, but contains calcareous cement.

The second resistant member is located at the top of section BC 72-9 (Figure 2.3). It is separated from the first resistant member by 250 m of thinly-bedded shale, siltstone and sandstone. It consists of approximately 80 m of coarse-grained sandstone, and coarse to medium pebble conglomerate, both similar in composition to those of the first resistant unit, but the conglomerate has a sandier matrix. The entire member is cut by a series of minor lateral faults trending southwest and west. The upper contact is covered, but is believed to be the location of a fault (Cameron, 1980).

The third resistant member crops out near the top of section BC 72-10 and consists almost entirely of conglomerate. It is 40 m thick, has an erosional lower contact with the underlying argillaceous sandstone and grades upward into thinly-bedded gritty sandstone. Subrounded volcanic boulders, up to 1 m across, are incorporated in the pebbly conglomerate. Few faults affect this member.

In this study the fourth, fifth and sixth resistant members originally described by Jeletzky (1954) are considered to be fault repetitions of a single member, designated as unit four. This member is at least 100 m thick in the Split Cape area and forms the promontory on the southwest shore of Barchester Bay (Figure 2.2). In both localities, pebble conglomerate predominates over coarse-grained sandstone and pebbly mudstone. Incorporated in the conglomerate are subangular sandstone pebbles, probably derived from underlying units, irregular blocks of volcanic rock measuring up to 15 m across, quartz diorite pebbles and boulders, and blocks of sandstone possibly derived from older formations (Cameron, 1980). This unit is highly fractured and is cut by a major left-lateral transform fault.

The fifth and uppermost resistant unit is located at the top of sections BC 72-15, BC 74-4 and BC 74-5 (Figure 2.3) It consists mainly of medium to coarse-grained sandstones, although lenses of medium to coarse pebble conglomerate are also present. The sandstone exhibits both parallel bedding and cross-bedding and contains abundant carbonaceous remains and mica.

DETRITAL MINERALOGY

Sandstone samples were classified on the basis of petrographic analyses. In many samples recognition of the original composition of detrital grains is complicated by alteration and replacement by calcite, chlorite and (or) clay minerals. Only those samples in which these replacements were not complete were useful for modal point counts. The average detrital composition of seven sandstones from the Hesquiat Formation is $Q_{27}F_{35}L_{38}$ (Table 2.1). The lithic component is mainly volcanic rock fragments; the feldspar component is almost entirely plagioclase (An 30-35). Based on the relative percentages of detrital components, these rocks are classified as lithic arkoses or feldspathic litharenites (Figure 2.4). Accessory minerals, comprising 1 to 10 per cent of the detrital fraction, include biotite, muscovite, chlorite, hornblende, opaque minerals and carbonaceous material (Table 2.1). Mica and carbonaceous debris are most abundant in thinly-laminated sandstones and are concentrated within individual laminae (Plate 2.11a).

Sandstones and conglomerates from the fourth and fifth resistant members contain highly altered feldspar grains and volcanic rock fragments. Alteration appears to be due to partial replacement by calcite (Plate 2.12a), followed by a later stage of calcite dissolution (Plate 2.12b). Point counts of these samples show higher quartz values and more authigenic kaolinite than in rocks from the lower resistant members in which calcite cement was still intact (Table 2.1). The apparent elevation in quartz values may reflect the complete alteration of some plagioclase and volcanic rock fragments.

AUTHIGENIC MINERALS IN SANDSTONES AND CONGLOMERATES

Authigenic minerals in the Hesquiat Formation were identified using optical microscopy, SEM and X-ray diffraction analyses. Calcite cement and kaolinite were the only authigenic phases clearly visible in thin sections of sandstones and conglomerates. SEM and X-ray diffraction were used to identify other fine-grained phases and their relative abundance. Chlorite, smectite, mixed-layer chlorite/smectite, kaolinite, quartz and calcite were identified (Table 2.4).

Chlorite

Chlorite occurs as a replacement of volcanic rock fragments in sandstones from the highly fractured parts of the section. X-ray diffraction results indicate that the chlorite is iron-rich. The (001) diffraction is less intense than the (002) and (004) diffractions, indicative of chamosite (Brown and Brindley, 1980). EDA analyses also indicate an iron-rich composition (Plate 2.10e).

Chlorite also occurs as a pore-filling phase. It developed as rosettes or bladed crystals and is usually associated with authigenic quartz and kaolinite. Textural relationships indicate that chlorite predates quartz (Plate 2.10c and 2.10d). The relative timing of chlorite and kaolinite development is not as clear. Chlorite is most common adjacent to grain surfaces and kaolinite most common within pore spaces suggesting that chlorite predates kaolinite.

Smectite

Smectite occurs as a grain coating in a fine grained

Table 2.4. X-ray diffraction results for < 2 μm size fraction, Hesquiat and Sooke Bay Formations.

SAMPLE I.D.	ROCK TYPE	METRES ABOVE DATUM	CLAY MINERALOGY < 2 um SIZE FRACTION RELATIVE PERCENT						OTHER PHASES PRESENT			
			SM	CHL	I	K	Ord C/S	Rdm C/S	Q	Pl	Ca	OTHER
West Hesquiat Peninsula *												
W 1	ARG F SST	90	60	40	tr	tr	nd	nd	x	x	nd	amphibole
W 2	F SST	100	nd	55	15	nd	30	nd	x	x	tr	
W 3	SANDY SLST	160	tr	55	15	nd	30	nd	x	x	nd	amphibole
W 8	F SST	200	tr	35	10	30	nd	25	x	x	x	
W 9	SHALE	270	45	20	30	5	nd	nd	x	x	nd	
W14	M SST	460	35	60	5	tr	nd	nd	x	x	x	
W13	SHALE	500	25	30	30	15	nd	nd	x	x	nd	
W25	M SST	690	40	30	5	25	nd	nd	x	x	tr	
W28	M SST	740	15	25	30	30	nd	nd	x	x	x	
W22	M SST	860	tr	55	30	15	nd	nd	x	x	x	
W23	CONGL	861	tr	40	20	25	nd	nd	x	x	nd	
W24	M SST	890	tr	40	15	30	nd	nd	x	x	nd	
W30	M SST	960	20	20	30	30	nd	nd	x	x	x	
W31	CONGL	1100	50	25	5	20	nd	nd	x	x	nd	
East Hesquiat Peninsula *												
E 8	F SST	250	tr	50	20	nd	nd	20	x	x	nd	
E10	M SST	330	5	30	35	30	nd	nd	x	x	x	
E11	M SST	400	5	30	25	40	nd	tr	x	x	nd	
E12	M SST	415	5	50	20	25	nd	tr	x	x	nd	
Sooke Area **												
S 9	CONGL	2	85	5	10	tr	nd	nd	x	x	x	amphibole
S10	M SST	3	95	tr	5	tr	nd	nd	x	x	x	amphibole

* Datum is the contact between Escalante and Hesquiat Fms.

** Datum is the contact with the Metochin Volcanics.

tr = est. abundance < 5%

x = est. abundance > 5%

sandstone from the first recessive member (Plate 2.9a). The value of the smectite (001) diffraction for a glycolated sample is 16.8Å (Table 2.3), and the (002) diffraction overlaps the low angle side of the chlorite (002) diffraction. This suggests that the smectite contains about 5 per cent chlorite layers.

Smectite is also present in shales, sandstones and conglomerates from the remainder of the type section (Table 2.4; Figure 2.8). Authigenic clay rims are absent in sandstones and conglomerates from the resistant members of the Hesquiat Formation, and crystalline smectite was not observed in samples analysed using SEM. This suggests that smectite is a detrital phase in these rocks.

Chlorite/Smectite

Chlorite/smectite occurs as a minor phase in calcareous siltstone and fine grained sandstone from the first recessive member (Tables 2.3, 2.4). The superlattice diffraction at 31Å is characteristic of an ordered interstratified chlorite/smectite. Sharp peaks on the X-ray diffraction charts suggest that it is a well-crystallized authigenic phase although no obviously authigenic crystals were seen with SEM.

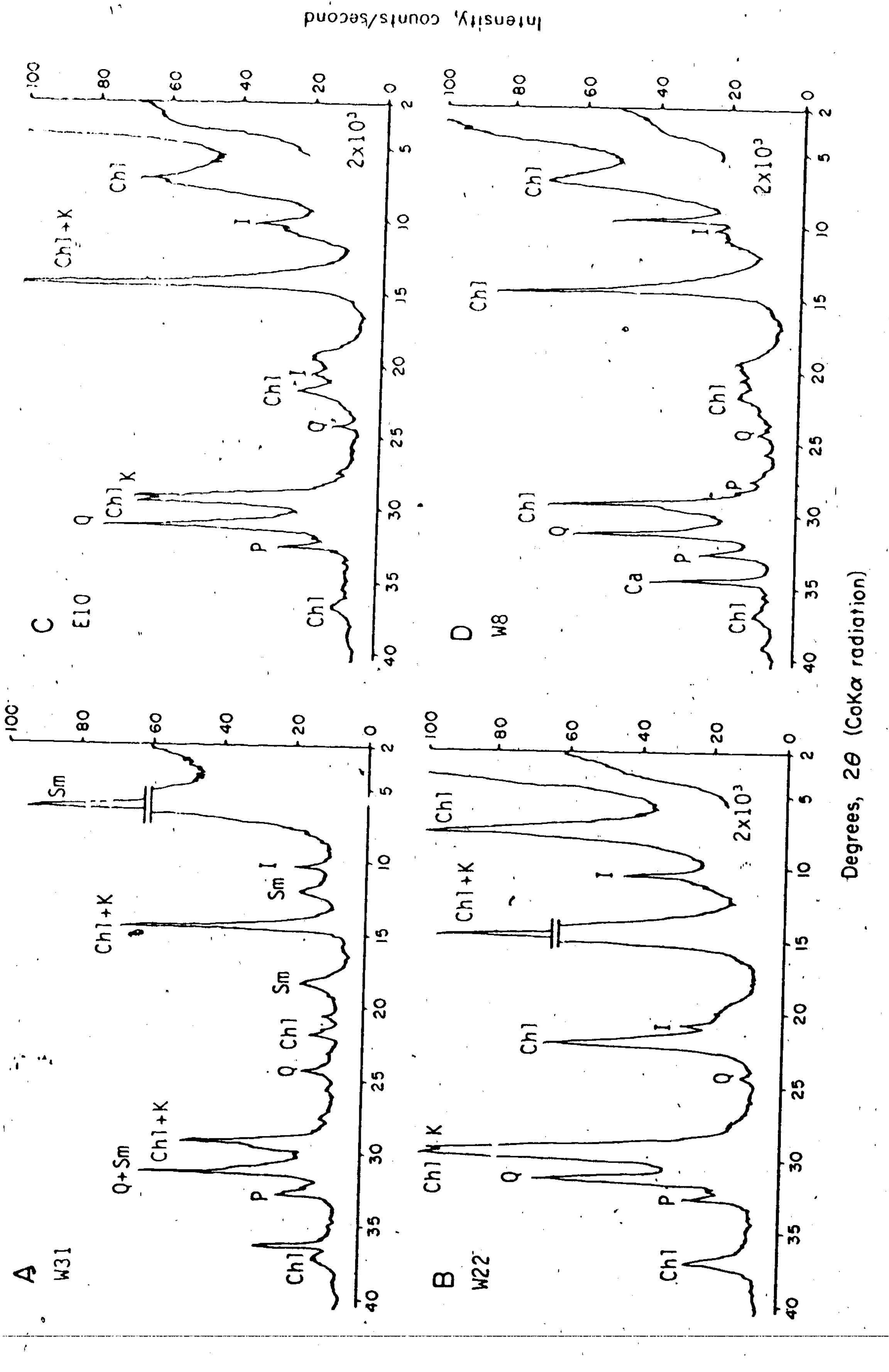
Randomly interstratified chlorite/smectite occurs in fine grained sandstone from the base of section BC 71-7 (Figure 2.3; Table 2.4). The value of the $(001)_{14}/(001)_{17}$ diffraction is 15.3Å, suggesting that

Figure 2.8. Representative X-ray diffraction patterns of the <2 μm fraction of samples from the resistant units of the Hesquiat Formation.

Medium grained sandstones from highly fractured parts of the formation at east Hesquiat Peninsula (C) and Split Cape (B) contain abundant chlorite, illite and kaolinite. The chlorite (002) diffraction overlaps kaolinite (001) diffraction at 7Å , but the (004) and (002) diffractions are separated on the peak at 3.5Å .

Conglomerate (A) from the top of the section contains abundant smectite and lesser amounts of chlorite and kaolinite.

All diffractograms are at a scale of 1 x 10 counts/second.


A
W31
B
W22
C
E10
D
W8
Sm
Chl+K
Sm I
Sm
Q Chl
Q+Sm
Chl+K
P
Chl
Chl
I
Chl+K
Chl
I
Q
Chl K
Q
P
Chl
Chl
I
Chl+K
Chl
I
Q
Chl K
Q
P
Chl
Chl
I
Chl
Chl
Q
P
Chl
Q
P
Ca
Chl
2x10³
Intensity, counts/second
Degrees, 2θ (CoKα radiation)
0
20
40
60
80
100
2
5
10
15
20
25
30
35
40

chlorite/smectite in this sample contains about 70 per cent chlorite layers (Figure 2.8).

Kaolinite

Kaolinite occurs in sandstone and conglomerate samples from all resistant units in the Hesquiat Formation. It also occurs in rocks from the recessive units, except those comprising the first recessive member (Table 2.4). On X-ray diffraction charts of the <2 μm size fraction, the presence of kaolinite and chlorite is indicated by resolution of the large peak at 3.5 Å into 3.58 Å and 3.55 Å components, the kaolinite (002) and chlorite (004) diffractions, respectively (Figure 2.8). After heating to 550 °C, the kaolinite (001) peak at 7 Å is diminished, indicating partial destruction of the kaolinite structure.

Kaolinite is most abundant in the highly fractured sandstones and conglomerates of the fourth resistant unit, which crops out at Split Cape (Figure 2.2). Large patches of authigenic kaolinite occurs in these samples and may have replaced detrital grains (Plate 2.12a,b).

Kaolinite occurs as well-developed stacks of tabular crystals which range in width from 2 μm to 8 μm and average about 6 μm across (Figure 2.10f). Several large patches of authigenic kaolinite cover the surfaces of plagioclase grains. It could not be determined whether the kaolinite was directly replacing plagioclase or whether the detrital grains were a substrate upon which kaolinite was precipitated.

Other Fine-grained Phases

Feldspar and quartz are the most common non-clay minerals in the <2 μm and 2-20 μm size fractions. The feldspar is plagioclase, as identified on X-ray diffraction charts by a major peak at 3.18Å and by several smaller diagnostic peaks, including one at 6.39Å. Quartz was identified by peaks at 3.34Å and 4.26Å (Figure 2.8).

Authigenic quartz occurs with chlorite and kaolinite in sandstones and conglomerates (Plate 2.10c,d and f). Textural relationships suggest that quartz formed after chlorite (Plate 2.10d), and may have formed at the same time as authigenic kaolinite (Plate 2.10f).

Calcite

Calcite cement is common in sandstones and conglomerates in the Hesquiat Formation. Authigenic calcite in sandstone from the first resistant member completely fills intergranular pore space (Plate 2.11b). The detrital grains in this sample have not been altered or replaced by calcite. Samples from higher in the type section also contain calcite cement, but most of the calcite in these rocks has been partially or totally dissolved (Plate 2.12a,b). Calcite also replaces plagioclase grains (Plate 2.12a). It appears that the dissolution voids in plagioclase grains may have resulted from the removal of this replacement calcite (Plate 2.12b).

PLATE 2.7

A. Chaotic pebble conglomerate comprising the resistant member of Hesquiat Formation. Outcrop photograph. Southwest side of Barchester Bay, west Hesquiat Peninsula.

B. Flame structure in resistant member, Hesquiat Formation. Outcrop photograph. Mouth of Goodwater Creek, west Hesquiat Peninsula.

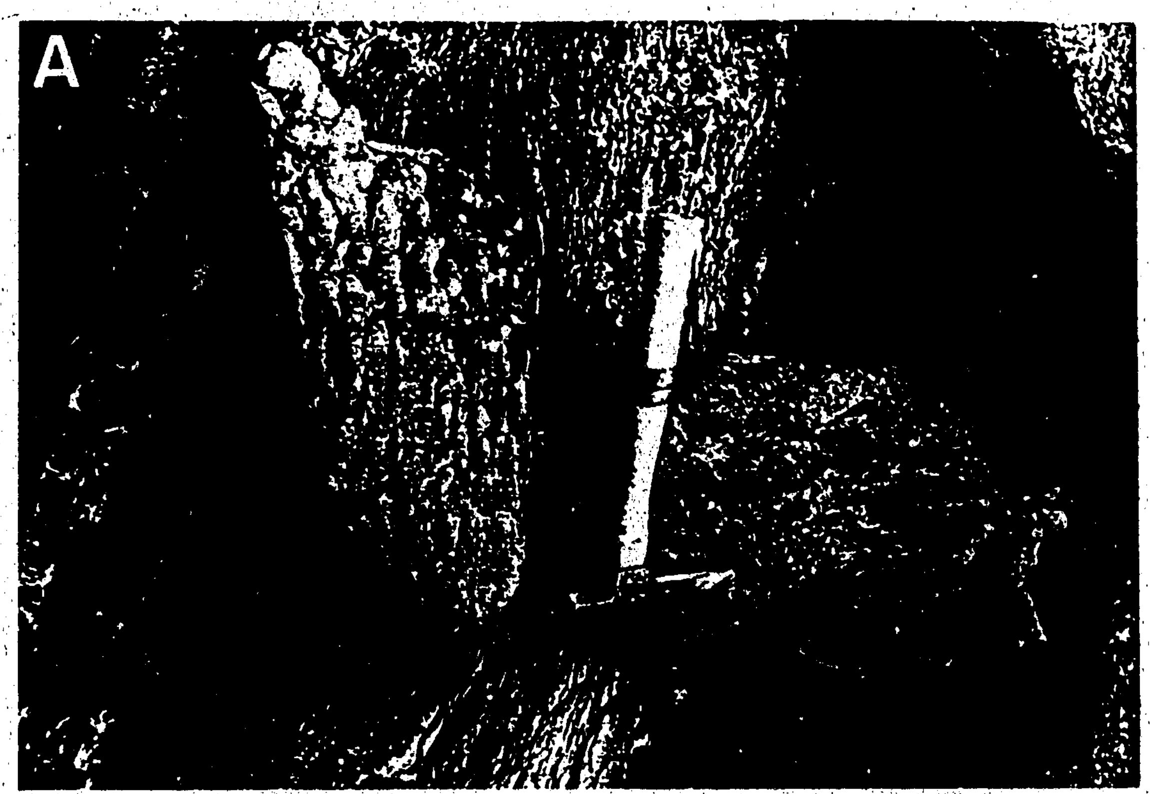

A


B

PLATE 2.8

A. Soles of sandstone beds (inverted slabs) with flute casts and grooves. Sandstone beds of the resistant unit of the Hesquiat Formation cropping out at Leclair Point, east Hesquiat Peninsula.

B. Outcrop photograph of sandstone bed of previous photograph, Leclair Point, east Hesquiat Peninsula.


A

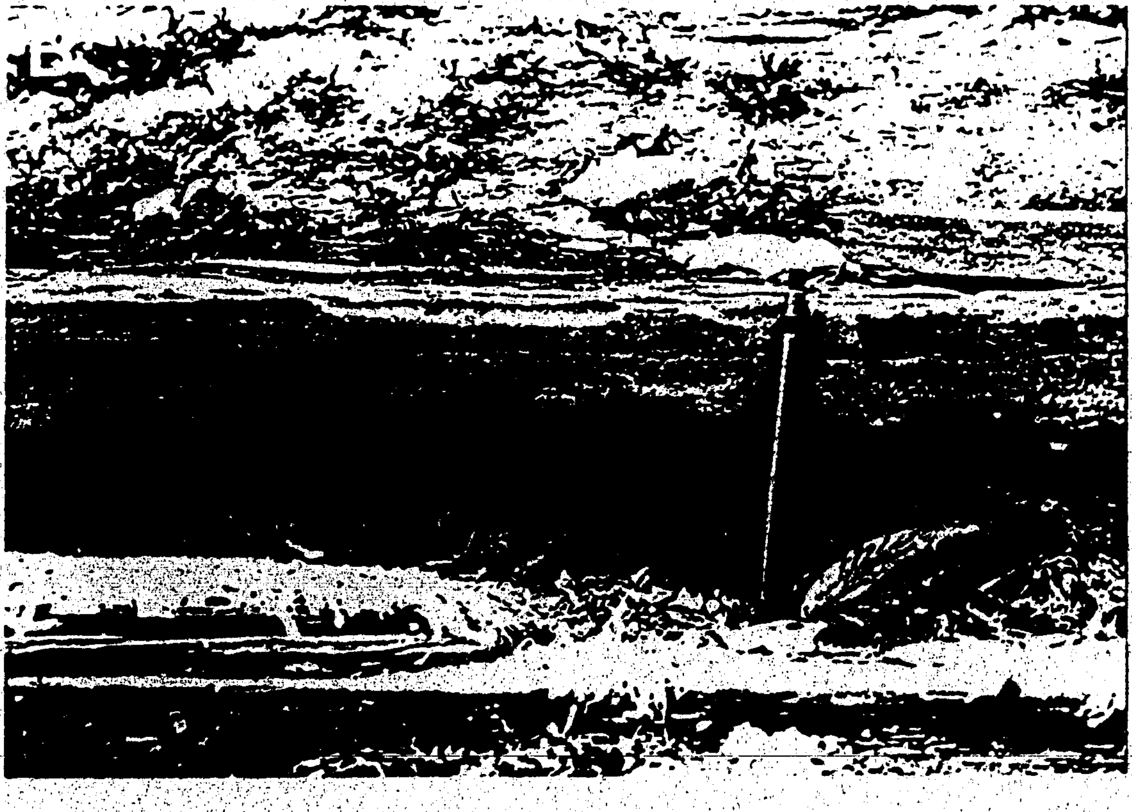
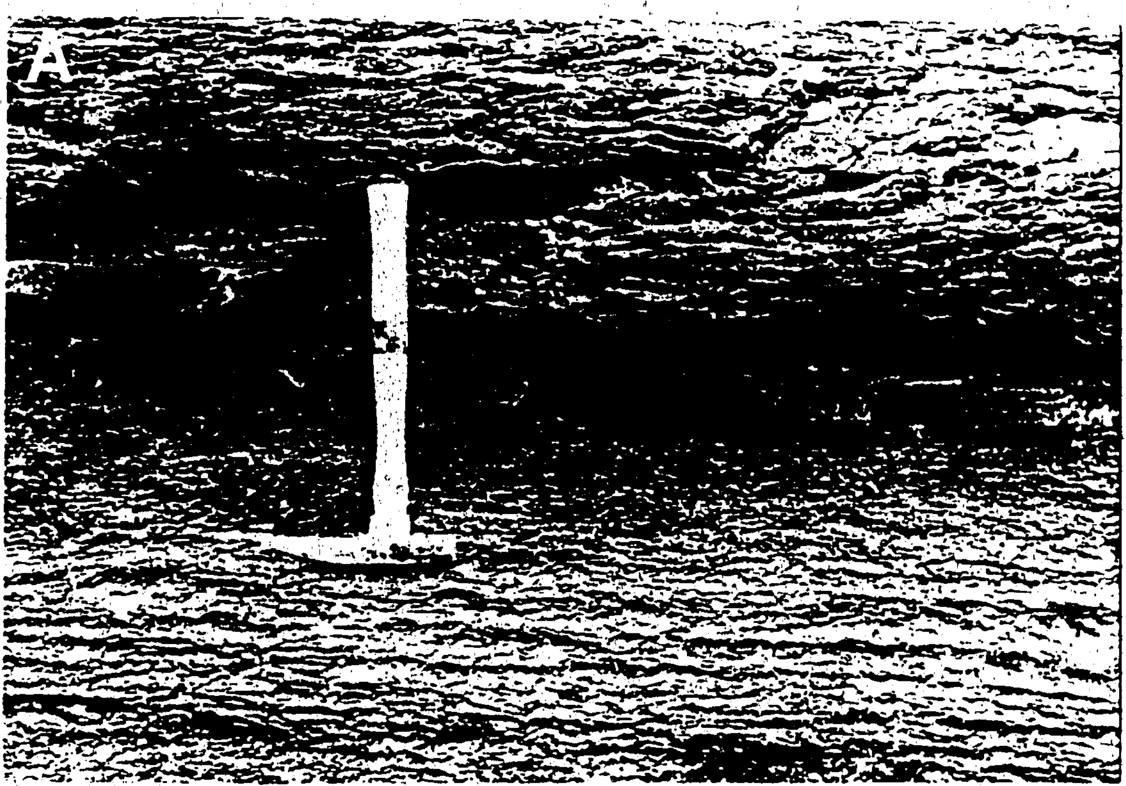


PLATE 2.9

A. Interbedded sandstone, siltstone and shale typical of the recessive member of the Hesquiat Formation. Outcrop photograph, west Hesquiat Peninsula.

B. Clay coating (Sm) on unaltered detrital grains in fine grained sandstone from the first recessive member, Hesquiat Formation. Clay is identified as smectite by X-ray diffraction analyses. Thin section photomicrograph, plain polarized light, field of view = 2.0mm x 1.3mm, sample locality W1.


A

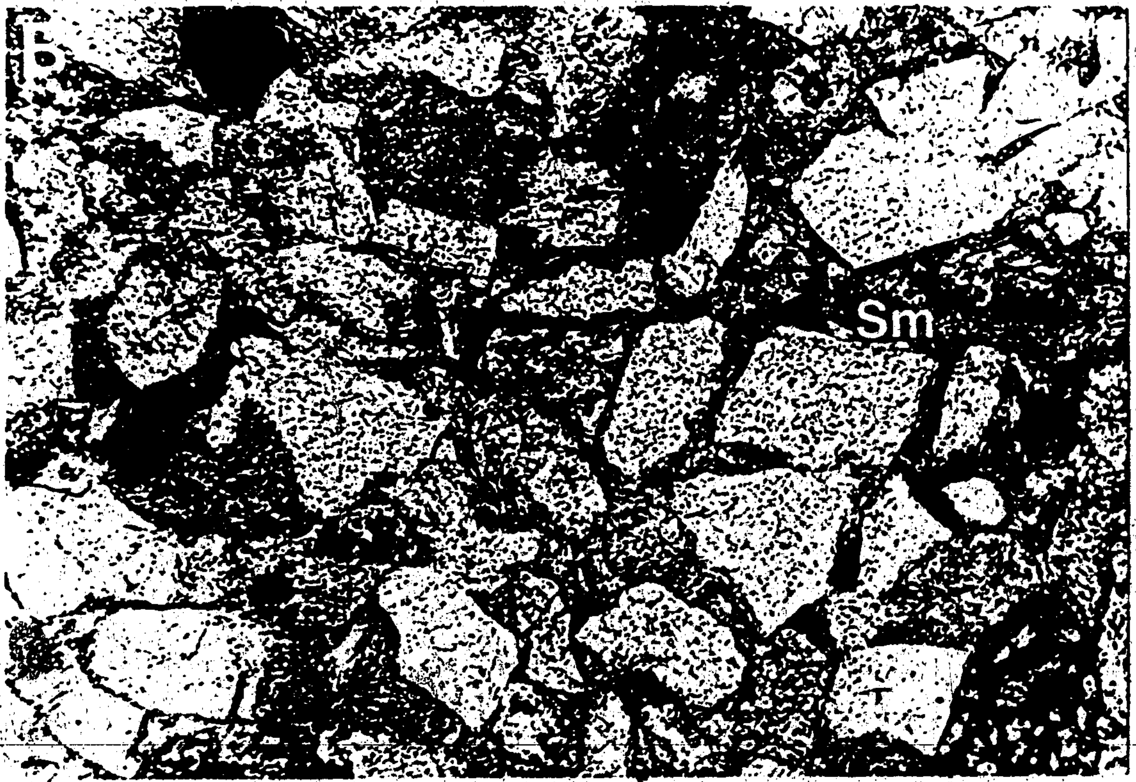

B
Sm

Plate 2.10

A. Authigenic kaolinite (K) which postdates authigenic chlorite. EDA of chlorite (Photograph B) indicates that it is iron-rich. SEM photomicrograph, Escalante Formation, sample locality E3.

C. Authigenic quartz (Q) engulfing authigenic chlorite (Chl). EDA of chlorite (Photograph E) indicates that it is iron-rich. SEM photomicrograph, Hesquiat Formation sandstone, sample locality W22.

D. Enlarged view showing that authigenic chlorite (Chl) predates authigenic quartz (Q). SEM photomicrograph, Hesquiat Formation sandstone, sample locality W22.

F. Poorly-developed termination on authigenic quartz crystal (Q) suggests that it postdates or is coeval with authigenic kaolinite (K). SEM photomicrograph, Hesquiat Formation sandstone, sample locality W22.

G. Authigenic smectite (Sm) coating detrital grain in sandy matrix of a conglomerate. EDA spectrum (Photograph H) shows a high proportion of Ca which may be from calcite cement. SEM photomicrograph, Sooke Bay Formation conglomerate, sample locality S9.

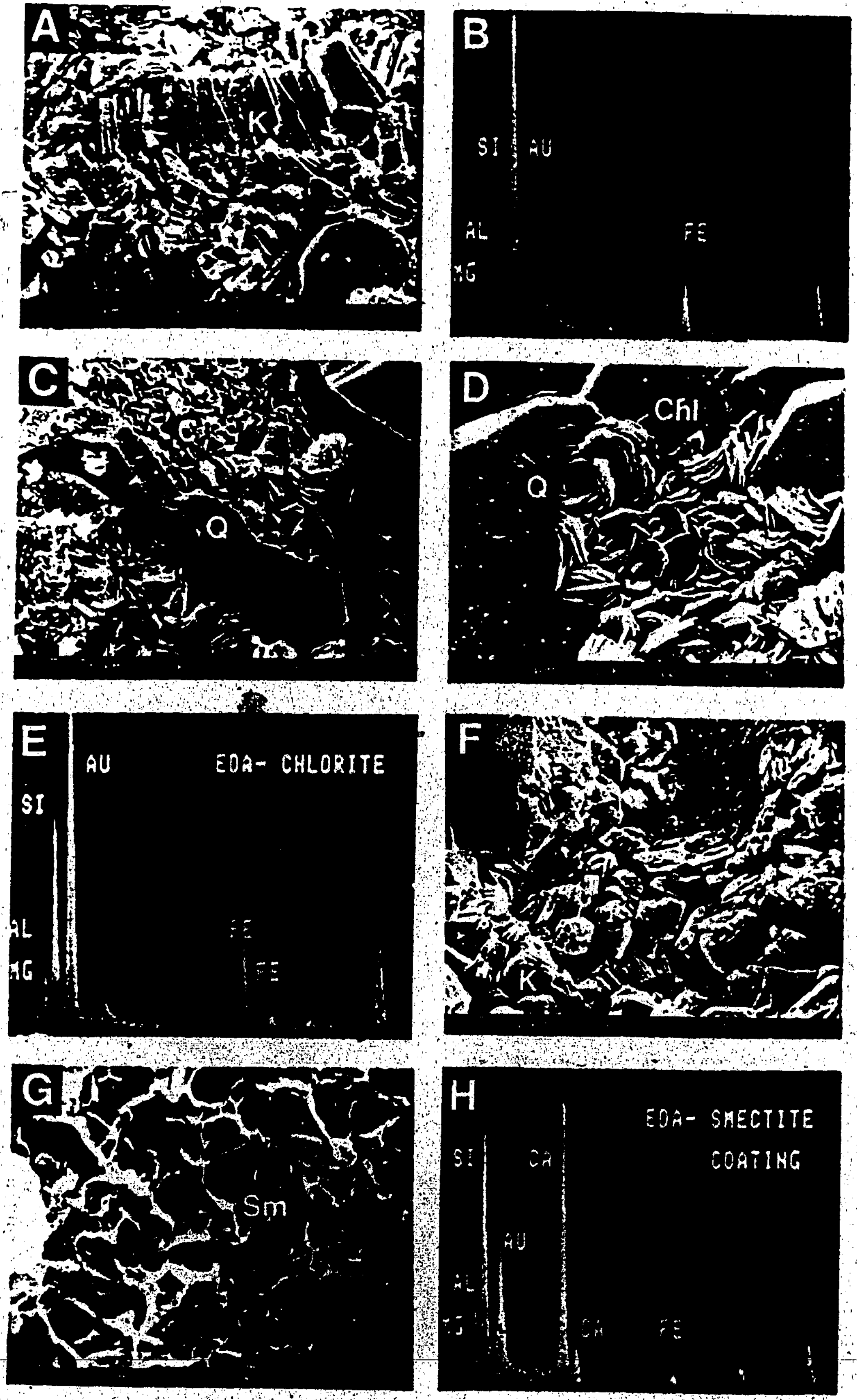

A
K
B
SI
AU
AL
FE
MG
C
Q
D
Chl
Q
E
AU
EDA- CHLORITE
SI
AL
FE
MG
FE
F
K
G
Sm
H
EDA- SMECTITE
COATING
SI
CA
AU
AL
MG
CA
FE

Plate 2.11

A. Authigenic pyrite framboids (Py) associated with biotite (B) and calcite shell fragment (Ca). Biotite, shell fragments and carbonaceous debris are concentrated along lamination surfaces. Thin section photomicrograph, crossed nicols, field of view = 2.0mm x 1.3mm, sample locality W2.

B. Sandstone with calcite cement (Ca) completely occluding intergranular pore space and preserving volcanic rock fragments (Lv) and plagioclase (Pl). Thin section photomicrograph, crossed nicols, field of view = 2.0mm x 1.3mm; Hesquiat Formation sandstone, sample locality W8.

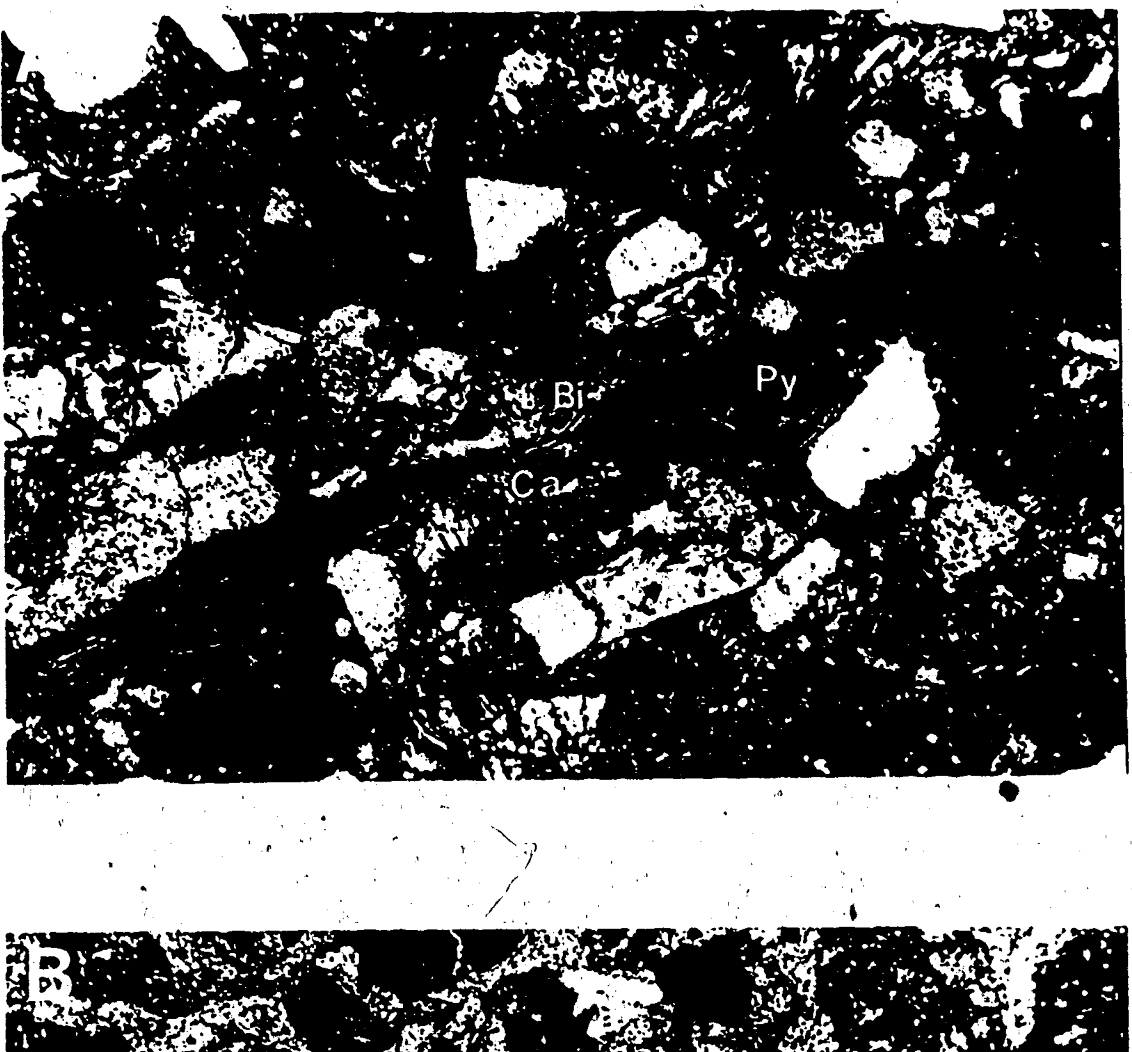

Bi
Py
Ca
B
Ca
Lv
Lv

Plate 2.12

A. Detrital plagioclase grain completely replaced by authigenic kaolinite (K). Calcite (Ca) cement and grain replacement appear to have undergone some dissolution (arrows). Thin section photomicrograph, crossed nicols, field of view = 2.0mm x 1.3mm, Hesquiat Formation sandstone, sample locality W22.

B. Detrital plagioclase grain (Pl) showing preferential dissolution along twin planes (arrow). Halite (na) fills pores. Thin section photomicrograph, crossed nicols, field of view = 2.0mm x 1.3mm, Hesquiat Formation sandstone, sample locality W22.

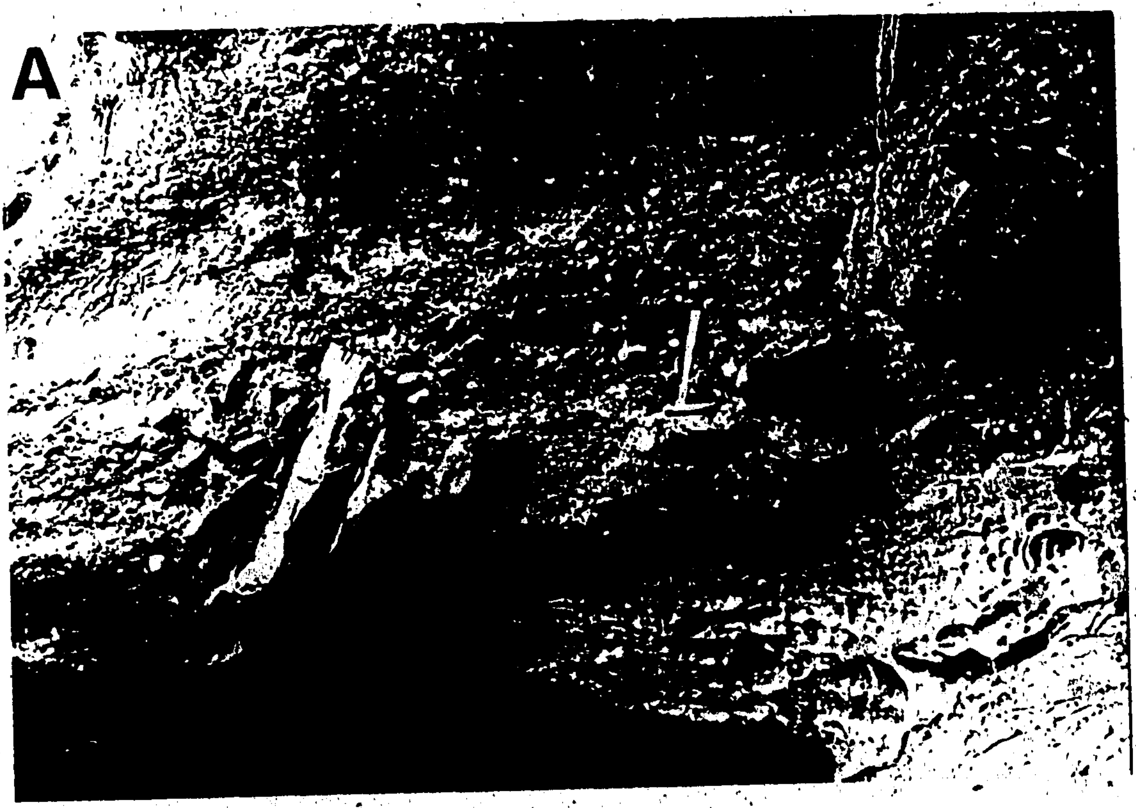

Ca
K


B
na
Pl

Plate 2.13

A. Conglomerate and sandstone of the Sooke Bay Formation directly overlying the polished surface of Metchosin Volcanics (lower right of photo). Outcrop photograph, China Beach, Sooke area.

B. Shell bed in sandstone unit, Sooke Bay Formation, Campers Cove, Carmanah Point area.


A


B

Plate 2.14

A. Authigenic smectite (Sm) has formed rims on detrital grains and predates patches of zeolite (?) cement (arrow). Thin section photomicrograph, plain polarized light, field of view 2.0mm x 1.3mm, Sooke Bay Formation sandstone, sample locality S10.

B. Calcite cement (stained red) in sandy matrix of conglomerate. Thin-section photomicrograph, crossed nicols, field of view = 2.0mm x 1.3mm, Sooke Bay Formation conglomerate, sample locality S9.


A
Sm
Sm


B
Ca

C. SOOKE BAY FORMATION

The Sooke Bay Formation is the uppermost formation in the Carmanah Group. Along the southwest coast of Vancouver Island the Sooke Bay Formation lies unconformably on lower Eocene Metchosin Volcanics (Plate 2.13a). The type section is located along Kirby Creek (Clapp and Cooke, 1917) and consists of about 150 m of sandstone and conglomerate. In the Nootka Sound area the Sooke Bay Formation is exposed on Nootka Island at Bajo Point (Figure 2.1). This outcrop is severely faulted, but the formation is estimated to be approximately 20 m thick. It overlies interbedded sandy shale and sandstone of the Hesquiat Formation; the contact relationship is, however, uncertain (Cameron, 1980). The Hesquiat and Sooke Bay formations also crop out at Carmanah Point, where they appear to be separated by a minor unconformity (Muller et al., 1981).

The sandstone and conglomerate which comprise the Sooke Bay Formation are well sorted; some are cross-beds and other beds contain well preserved shells (Plate 2.13b). These characteristics and palaeontological data support the interpretation of a shallow water or littoral depositional environment (Cameron, 1971; Jeletzky, 1973; Muller et al., 1981).

DETRITAL MINERALOGY

Sandstones from the Sooke area (Figure 1.1) consist of angular grains of plagioclase, quartz, magnetite and volcanic rock fragments, and minor amounts of biotite, muscovite, epidote, pyroxene and chlorite (Table 2.1). The plagioclase and volcanic rock fragments appear to be unaltered. The sandstones and conglomerates contain little or no detrital matrix. Reliable estimates of detrital modes in samples from the Sooke Bay Formation are difficult to obtain. Most of the rocks are poorly consolidated, and thin sections show a high proportion of plucked grains.

The conglomerates consist of subangular to rounded fragments of metabasalt and gabbro, and a sandy matrix similar in texture and composition to the sandstone beds. Shell fragments and calcite cement are common, and the clay coatings on detrital grains are thin or absent (Plate 2.14b).

Detrital grains in sandstones are cemented by thick rims of clay minerals. Zeolite cement is present in trace amounts in all sandstone samples, with the exception of one coarse grained sandstone which contains abundant analcime cement. No samples were available for analyses from the outcrops of Sooke Bay Formation on Nootka Island.

AUTHIGENIC MINERALOGY

X-ray diffraction and SEM determinations indicate that smectite is the most abundant clay mineral in sandstones and conglomerates. Illite, chlorite, quartz, plagioclase, calcite and amphibole are also present in the <2 μm size fraction (Table 2.4). Kaolinite and chlorite/smectite were not detected in any samples.

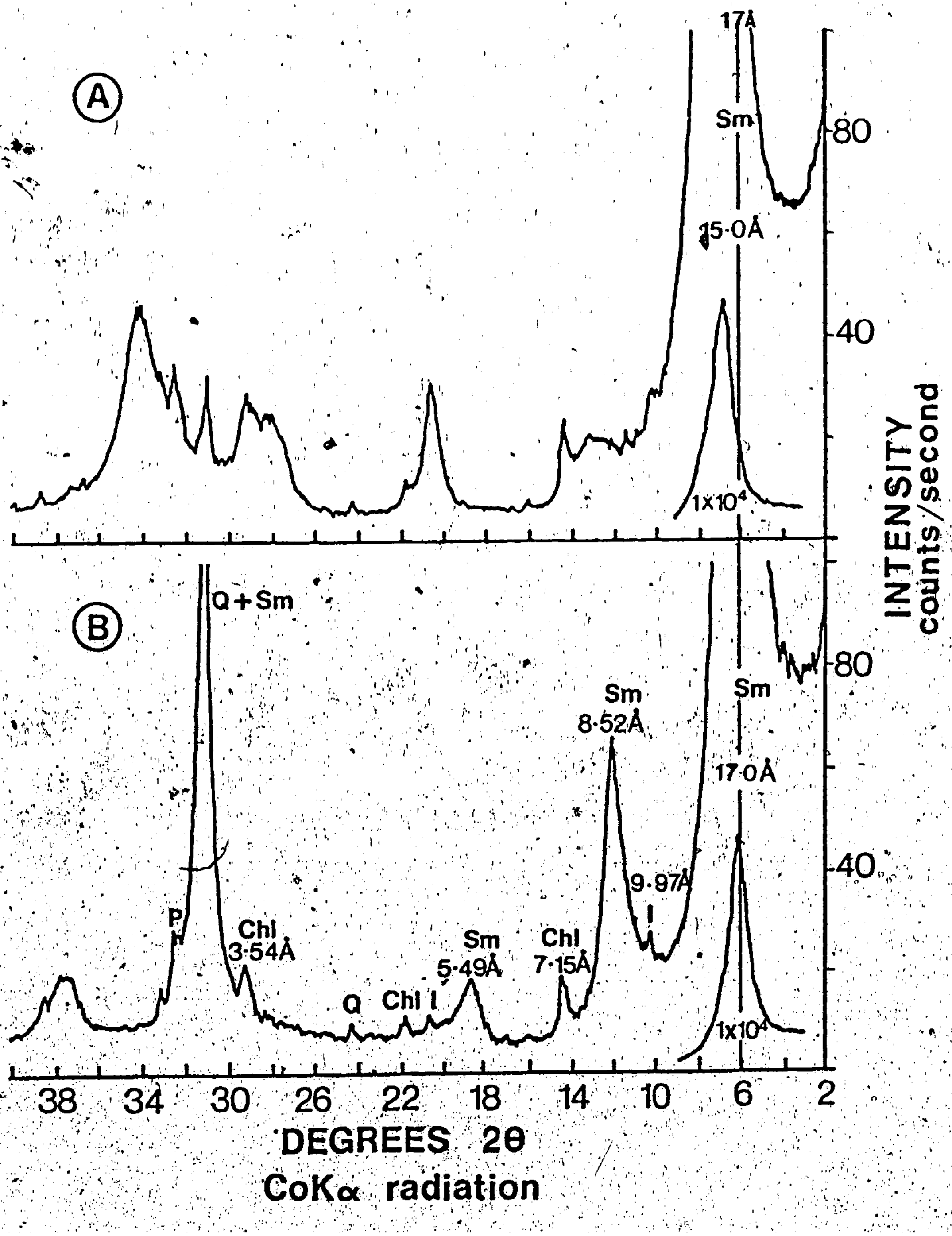
Smectite

Smectite constitutes 85-95 per cent of the clay minerals present in the <2 μm size fraction (Table 2.4). It is identified on X-ray diffractograms by a strong (001) diffraction at 17Å (Figure 2.9). Authigenic smectite developed on the surfaces of detrital grains in sandstone samples (Plate 2.14a). Smectite also occurs as thin coatings on detrital grains in the sandy matrix of the conglomerate (Plate 2.10g,h).

Calcite

Calcite cement is common in conglomerate (Plate 2.14b). Sandstone samples contain only minor amounts of calcite cement associated with shell fragments.

Figure 2-9 X-ray diffraction patterns of smectite in <2 μm size fraction, Sooke Bay Formation sandstone, sample S10, Ca-saturated samples; (A) analysed at 54% humidity, (B) glycolated.



D. PARAGENETIC SEQUENCE

The relative timing of authigenic mineral development and alteration of detrital phases was determined on the basis of textural relationships and their distribution through the stratigraphic sections. Each of the stages in this sequence marks a unique set of conditions within the depositional or post-depositional setting, although in situations where conditions were changing rapidly some minerals may have formed out of equilibrium with the environment. Mineral assemblages in the three formations differ so they will be considered separately.

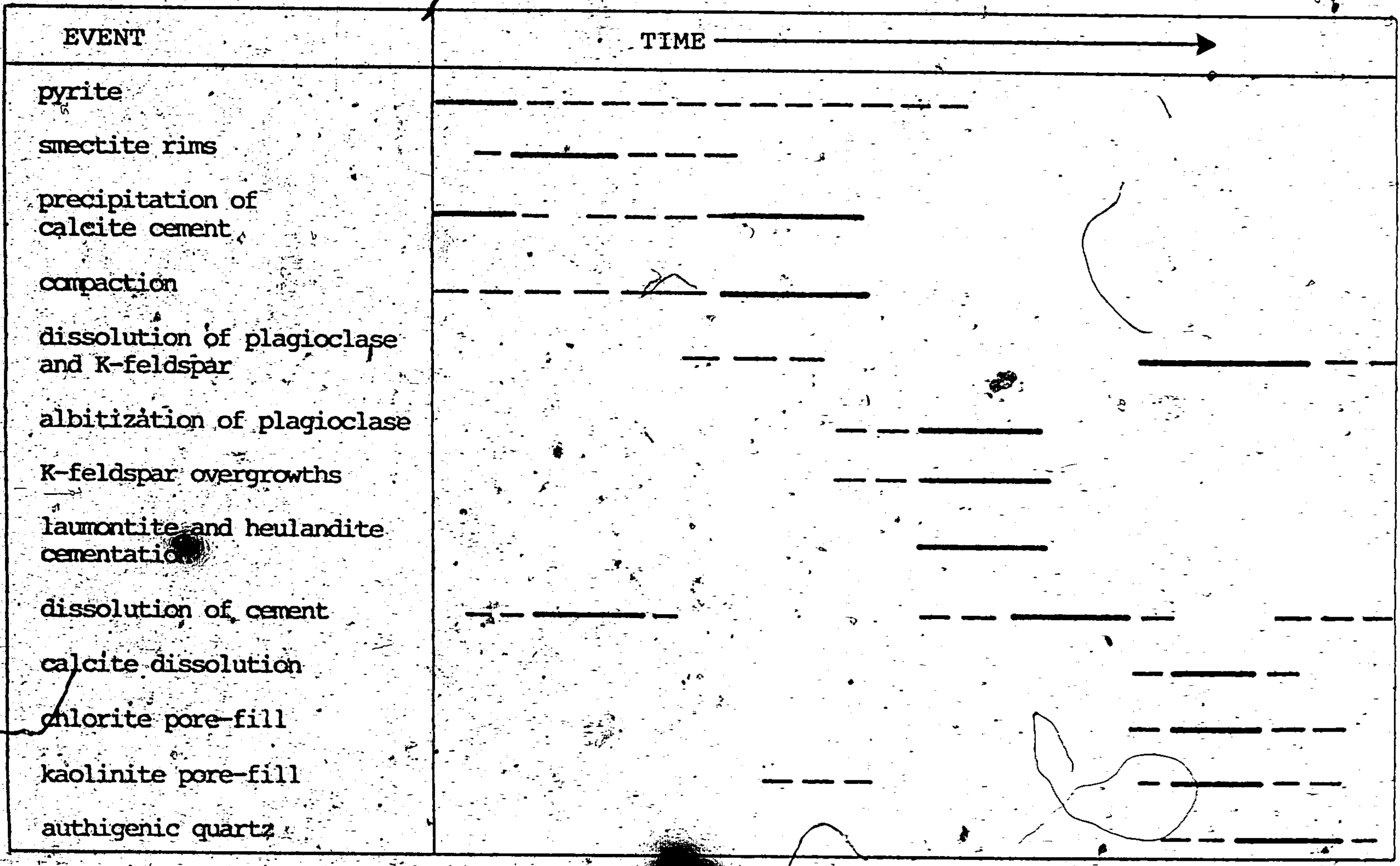
Escalante Formation

Thin sections and SEM reveal the following paragenetic sequence in the Escalante Formation:

1) pyrite + early concretionary calcite,
2) chlorite/smectite rims ± quartz overgrowths,
3) albite and K-feldspar overgrowths ~~and~~
4) laumontite (and heulandite) cementation + calcite cementation (Figure 2.10).

All of the phases occur in rocks from the type area at Escalante Point. In these samples chlorite/smectite completely coats detrital grains (Plate 2.2a; 2.3a; 2.6a). This behavior suggests that chlorite/smectite precipitated prior to compaction. The clay rims were preserved by the subsequent precipitation of laumontite and calcite cements (Plates 2.2b; 2.5a). Fragmented clay rims occur between

Figure 2.10 Paragenetic sequence in the Escalante Formation.



detrital plagioclase grains and albite overgrowths (Plate 2.6b), and between detrital rock fragments and authigenic quartz crystals (Plate 2.6a). Chlorite/smectite also formed prior to authigenic K-feldspar (Plate 2.4g).

Sandstones and conglomerates of the Escalante Formation exposed at east Hesquait Peninsula are fractured and faulted (Figure 2.2) and are more highly altered than rocks at the type area (Figure 2.2; Plate 2.4a,c). Samples from east Hesquiat Peninsula contain a late diagenetic assemblage of chlorite, kaolinite and quartz (Plates 2.4d; 2.10a; Figure 2.10).

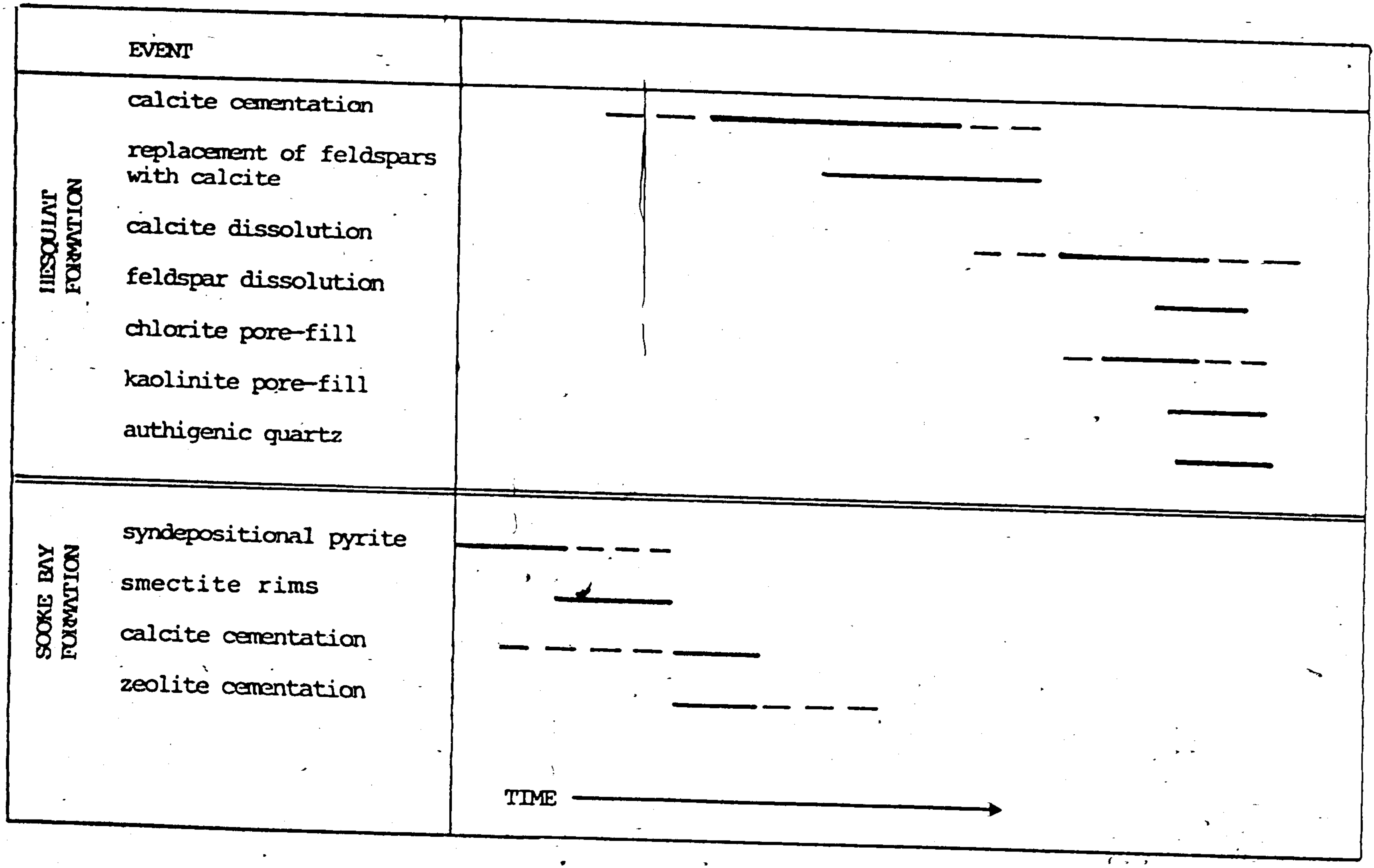
Hesquiat Formation

The first recessive member of the Hesquiat Formation contains chlorite/smectite, laumontite and pyrite (Table 2.4; Plate 2.11a). The sequence of mineral formation in this member is similar to that in the Escalante Formation. Pyrite was the first authigenic phase to form, followed by chlorite/smectite and laumontite.

Authigenic clay rims, pyrite and laumontite are absent in samples from other members in the formation. Calcite cement is the most abundant diagenetic phase in these samples (Plate 2.11b), and apparently precipitated early enough to significantly reduce the porosity and protect detrital grains from alteration (Figure 2.11).

Dissolution of calcite cement created secondary porosity in sandstones and conglomerates from the highly

Figure 2.11. Paragenetic sequences in the Hesquiat and Sooke Bay Formations.



faulted parts of the section (Plate 2.12a,b). The sequence of minerals formed after dissolution of calcite is:

1) chlorite,
2) kaolinite + quartz and
3) secondary calcite (Plate 2.10; Figure 2.11).

Sooke Bay Formation

Three authigenic phases were identified in samples from outcrops in close proximity to the type locality. The sequence of mineral emplacement is:

1) pyrite,
2) smectite and
3) calcite cement + trace amounts of zeolite cement (Table 2.11).

Smectite forms grain coatings which are abundant in the sandstones (Plate 2.14a) and present in lesser quantities in conglomerates (Plate 2.10g,h). Analcime cement was found in a sandstone and a conglomerate from one locality. This occurrence may be of doubtful value for interpretive purposes, because both samples were from highly weathered outcrop.

III. DISCUSSION

The clastic rocks of the Carmanah Group are similar in detrital composition to other arc-derived sedimentary rocks exposed along the northeast Pacific margin (Galloway, 1974, 1979; Burns and Ethridge, 1979; Helmold and van de Kamp, 1984; Chan, 1985). The most abundant detrital phases in these rocks are plagioclase feldspar and andesitic rock fragments. Minor phases include detrital pyroxene, amphibole and mica. This composition results in a number of possible diagenetic reactions, especially hydration and carbonization reactions in the early diagenetic environment and dehydration reactions at greater burial depths (Galloway, 1974; Surdam and Boles, 1979). In a regional study of four arc-related basins, Galloway (1974) concluded that temperature was the dominant control on diagenetic reactions in the mineralogically unstable sandstones which occur in these basins. Other studies of volcanoclastic rocks have suggested that the amount and type of volcanic detritus and the compostitions of fluids interacting with the rock, are equally important influences on diagenetic reactions (Stewart, 1974; Boles, 1974; Surdam and Boles, 1979).

The textural maturity of volcanic sandstones and conglomerates is also significant, primarily because the presence of detrital matrix can limit the contact between reactive detrital grains and fluids. A study of turbidite sandstones from western Oregon concluded that low porosity and permeability, resulting from rapid deposition and burial of poorly sorted sediments, prevented the development of authigenic clay rims and zeolite cement (Chan, 1985). Although fewer diagenetic reactions are likely to occur in volcanoclastic rocks with low porosity and permeability, the local availability of ions from unstable lithic fragments, plagioclase and mafic minerals, allows some reactions to proceed without the movement of large volumes of fluid through the rocks.

Authigenic clay rims on framework grains are a common diagenetic feature in the Escalante and Sooke Bay formations (Figures 2.10 and 2.11). This feature has also been reported in several other formations composed of volcanoclastic rocks, in which solution of volcanic rock fragments, pyroxene and amphibole have provided the necessary components to form authigenic clays (Lerbekmo, 1957; Galloway, 1974; Merino, 1975; Burns and Ethridge, 1979; Davies et al., 1979; Chan, 1985).

In the Hesquiat Formation, authigenic minerals indicative of early diagenetic reactions occur only in the first recessive unit, which comprises the transitional unit between the Hesquiat and Escalante formations (Figure 3.1). In the middle and upper parts of the formation, diagenetic processes were probably inhibited by the low

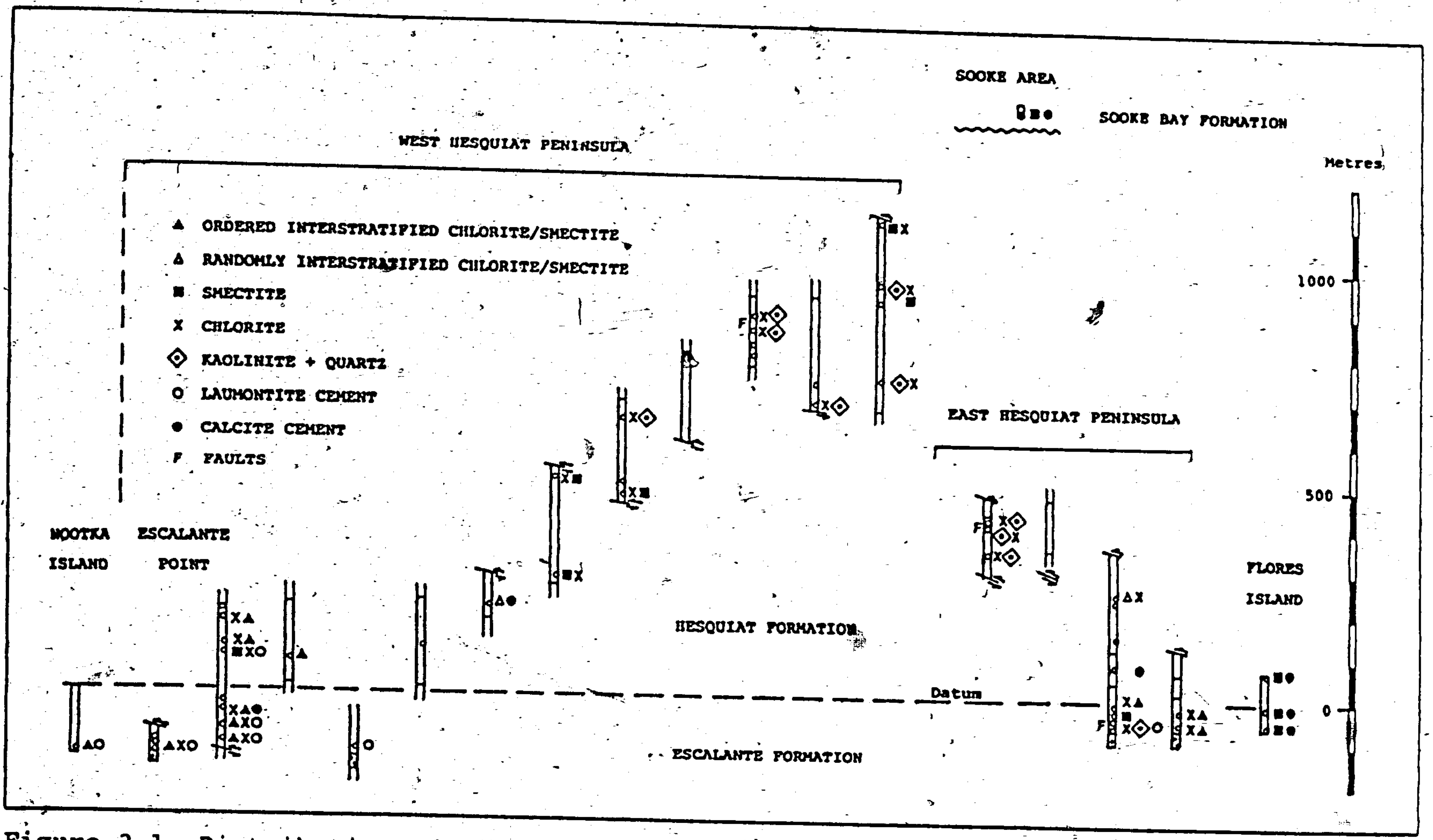


Figure 3.1. Distribution of diagenetic phases in the Carmanah Group.

permeability; the sandstone and conglomerate beds are laterally discontinuous and are separated by shale units. Most of the authigenic minerals occur in sandstone and conglomerate units which have been fractured and faulted, and likely developed as a result of increased fluid flow through these parts of the section.

A. INITIAL COMPOSITION OF SANDSTONES AND CONGLOMERATES

Detrital modes in sandstones and conglomerates from the Nootka Sound area indicate that the Escalante and Hesquiat formations had a mixed volcanic-plutonic source terrane. Quartz values are generally less than 40 per cent and are lowest in samples from the base of the Escalante Formation. The detrital composition of these rocks closely reflects the mineralogy of the underlying andesite unit. Slightly higher quartz values in the Hesquiat Formation may be the result of sediment reworking prior to deposition, or a source area farther inland which would include granite and granodiorite of the Island Intrusions (Figure 2.1).

Sandstones from the exposures of the Escalante Formation on east Hesquiat Peninsula and Flores Island contain slightly more detrital quartz than sandstones at the type section. The higher quartz values in these rocks probably reflect the contribution of sediment derived from the metagraywacke and tuff, argillite and breccia which underlie these two areas.

The detrital composition of the sandstones and conglomerates from the Sooke Bay Formation also reflects the composition of the underlying bedrock. Weathering of the Metchosin Volcanics and Sooke Intrusion resulted in sediments containing abundant hornblende, pyroxene, plagioclase and volcanic rock fragments.

Rocks from all three formations in the Carmanah Group have similar detrital compositions. Accordingly, the variations in authigenic mineralogy among these units must relate to differences in depositional environment, fluid chemistry, temperature and (or) tectonic history.

B. DIAGENESIS OF THE ESCALANTE FORMATION

Pyrite and calcite were the first authigenic minerals to form in the Escalante Formation, and probably indicate reducing conditions in the depositional environment. Pyrite occurs within organic remains and volcanic rock fragments. The formation of authigenic pyrite as a replacement of plant remains and within shell fragments is well documented as an early diagenetic reaction in marine environments where bacterial reduction of sulphate to H_2S and HS^- has occurred (Merino, 1975; Berner, 1981). Reducing conditions in the depositional environment of the Escalante Formation would also cause the alteration of magnetite and ilmenite to pyrite. Both oxides are common constituents of the andesite and quartz diorite which underlie the type area and which comprise the majority of rock fragments in the basal conglomerate and overlying sandstone.

The concretions in the upper part of the type area contain iron-poor calcite cement. The composition of the calcite and the presence of authigenic pyrite in the concretions and the surrounding sandstones and siltstones suggests that the calcite cement formed in the sulphate-reduction zone. Nonferroan carbonate concretions probably occur in this zone because the precipitation of pyrite has reduced the concentration of iron in solution to very low levels (Gautier and Claypool, 1984).

Origin of Chlorite/smectite

Authigenic chlorite/smectite occurs in sedimentary, hydrothermal and low-grade metamorphic environments. Occurrences which have been documented and ascribed to these environments include: (1) chlorite/smectite, with associated dolomite, calcite, illite and chlorite, formed in hyposaline restricted marine environments (Almon et al., 1976) and (2) evaporitic lake environments (April, 1981); (3) chlorite/dioctahedral smectite as a product of hydrothermal alteration of dike rock and dike-intruded shales (Blatter et al., 1973); and (4) chlorite/smectite as a decomposition product of ferromagnesian minerals subjected to low-grade metamorphic conditions (Iijima and Utada, 1971; Kimbara, 1973; Hoffman and Hower, 1979).

The authigenic mineral assemblage in the Escalante Formation contains chlorite/smectite and zeolites and does not contain dolomite or evaporitic minerals (Figure 3.1). This mineral association suggests that the chlorite/smectite may have developed in response to hydrothermal or low-grade metamorphic alteration, rather than in the sedimentary environment.

The climate at the time of deposition of the Escalante Formation may have prevented the formation of chlorite/smectite in the depositional environment. The plant remains in the fine-grained sandstone and siltstone comprising the upper part of the section at Escalante Point indicate a humid climate at the time of deposition. Macroflora in the recessive unit which conformably overlies the Escalante Formation were identified as a mixture of temperate and tropical forms (Jeletzky, 1975a, p. 17). Humid conditions preclude the formation of chlorite/smectite in the sedimentary environment, because evaporitic concentration of magnesium does not occur (April, 1981).

The formation of chlorite/smectite is not fully understood, but one generally accepted model proposes that 2:1 layer silicates, exposed to magnesium-rich fluids, aggrade by fixation of brucite sheets in interlayer space.

Blatter et al (1973), Suchecki et al. (1977) and April (1980, 1981) have proposed that smectite and degraded illite were the precursor minerals. Chlorite/smectite has been synthesized experimentally from Mg-saturated dioctahedral smectite in the presence of a $MgCl_2$ solution at 400° C (Eberl, 1978).

In hydrothermal and low-grade metamorphic environments, hydrothermal fluids or the alteration of volcanic rock fragments and ferromagnesian minerals have been proposed as possible sources of magnesium. Scheidegger and Stakes (1977) concluded that the formation of nontronite followed by saponite in recent sediments from the Peru Trench resulted from alteration of tholeitic basalts at temperatures of 300-400°C. This sequence of mineral formation indicated that fluids within the sediment were initially iron-rich, but became enriched with Mg^{2+} and K^+ as alteration of basalts continued. Iijima and Utada (1971) studied a burial metamorphic sequence of volcanoclastic rocks from the Uetsu geosyncline, Japan. From drill hole data they concluded that chlorite/smectite resulted from alteration of ferromagnesian minerals at temperatures of approximately 95°C. They also noted that smectite was present only in samples from the upper part of the drill hole at temperatures less than 95°C.

It is possible that the chlorite/smectite in the Escalante Formation had a smectite precursor. Smectite is absent in the basal beds of the type section which contain highly ordered chlorite/smectite, and in the middle or upper parts of the formation where poorly ordered and randomly interstratified chlorite/smectite occur (Figure 3.1). The clay coatings and pore-filling material in a sandstone collected 290 m above the basal contact consist primarily of smectite (Figure 3.1). This distribution suggests that smectite may originally have been present throughout the section. The most intense alteration took place directly above the basal contact. Alteration became progressively less intense farther from the basal contact.

Platter et al. (1973) reported a similar alteration pattern in shales initially composed of smectite. They concluded that the smectites had been altered to chlorite/smectite by fluids accompanying the intrusion of dikes. Well-ordered chlorite/smectite developed adjacent to the dike; it graded into poorly-ordered chlorite/smectite within 1 m of the dyke contact, and an expansible mixed-layer phase and chlorite at distances farther from the contact.

Diagenesis of the Escalante Formation may have been influenced by late Eocene intrusions. The Catface Intrusions crop out south and northeast of Hesquiat Peninsula (Figure 2.1). An intrusive contact with the sedimentary rocks of the Carmanah Group has not been found, but K-Ar age determinations of the Flores Island

Intrusions and the Hot Springs Stock (Figure 2.1) place the intrusive activity during the upper Eocene to lower Oligocene (Muller, et al., 1981).

The complete alteration of smectite to chlorite/smectite in the basal conglomerates and sandstones of the Escalante Formation on Nootka Island and Escalante Point (Figure 3.1) may have taken place as hydrothermal fluids moved through this porous and permeable unit along the contact with the underlying volcanic rock. The presence of poorly-ordered chlorite/smectite and smectite in the uppermost beds at the type section suggests that smectite was not completely altered (Figure 3.1). Fine-grained sandstones and siltstones predominate in this part of the section: the low permeability in this zone may have restricted the contact between reactive detrital components and hydrothermal fluids. Lower permeability is apparently not the major control however, because ordered chlorite/smectite is abundant in siltstone and fine-grained sandstone from the lower part of the section. On the assumption that a high volume of flow through the basal conglomerate was accompanied by the highest temperatures, the less permeable rocks in the overlying beds would have been affected by lower temperatures.

If the hydrothermal event took place simultaneously with deposition of the sedimentary rocks of the Carmanah

Group, as suggested by Muller et al. (1981), the decrease in ordering of chlorite/smectite at stratigraphically higher levels may reflect decreasing temperatures of the hydrothermal fluids with time. Micropaleontological collections from the type section, east Hesquiat Peninsula, and Flores Island (Figure 3.1) indicate progressively younger ages for the basal beds at each of these localities (Cameron, 1980). The lack of any chlorite/smectite in the basal sandstone on Flores Island may indicate that it was deposited after the main thermal event.

Factors Controlling Zeolite Distribution

The limited distribution of laumontite and heulandite cements in the Nootka Sound area is another indication that an intrusive event may have affected the sedimentary rocks now exposed on Hesquiat Peninsula. Laumontite cement occurs in conglomerate and sandstone from the type section and east Hesquiat Peninsula, and in the first recessive unit of the Hesquiat Formation (Figures 3.1 and 3.2). The basal sandstone from Flores Island contains calcite cement and there is no indication of an earlier stage of zeolite cementation.

Authigenic laumontite is common in medium and coarse grained volcanoclastic rocks of Tertiary age which crop out on the Olympic Peninsula. The widespread distribution of laumontite in these rocks has been related to deep burial and regional metamorphic events at approximately 29 Ma (Tabor, 1972; Stewart, 1974). The distribution was also controlled by local variations in lithology; laumontite developed in sandstones containing volcanic detritus and did not develop in finer-grained, feldspathic, or calcareous rocks (Stewart, 1974).

There is no direct evidence indicating the maximum depth to which the Escalante Formation was buried, or the temperature regime in the Tofino Basin during late Eocene and Oligocene time. A minimum depth of burial can be estimated from the combined thickness of the Escalante and Hesquiat formations (Figure 3.1). Both the top and base of the Hesquiat Formation are exposed on Nootka Island, although the top may be in fault contact with the overlying Sooke Bay Formation. The Hesquiat Formation is 1200 m thick: consequently, the basal beds of the Escalante Formation were buried at least 1350 m deep.

The degree of mechanical compaction visible in sandstones and conglomerates from Escalante Formation at Nootka Island, Escalante Point and east Hesquiat Peninsula suggests these rocks were probably not buried more than 2500 m prior to the development of authigenic chlorite/smectite rims or laumontite cement. Detrital biotite is highly deformed, but volcanic rock fragments and plagioclase grains retain their original shape (Plates 2.2; 2.5). Helmold and van de Kamp (1984) found that strong deformation of biotite occurred in sandstones buried to 2500 m, and deformation of volcanic rock fragments occurred in sandstones buried to 2500-3500 m. If rocks of the Escalante Formation were buried to greater depths after the development of laumontite, the cement would reduce the effects of compaction.

Hoffman and Hower (1979) reported that ordered chlorite/smectite and laumontite coexist at temperatures of about 100-200°C. To attain these temperatures at relatively shallow depths of burial requires an extremely high geothermal gradient or an intrusive heat source. The distribution of chlorite/smectite and laumontite in laterally equivalent sections of the Escalante Formation (Figure 3.1) suggests local temperature variations were present in the Nootka Sound area.

Studies of authigenic laumontite and heulandite indicate that these minerals are stable in alkaline pore fluids of low P_{CO_2}, and that temperature and pressure are important but less critical controls on their stability (Stewart and Page, 1974; Davies et al., 1979; Surdam and Boles, 1979; Crossey et al., 1984). Both chlorite/smectite and laumontite are stable in alkaline fluids. There is no direct evidence available regarding the composition of pore fluids in the Escalante Formation, but it appears likely that slight variations in Pco$_2$ controlled the development of laumontite and calcite cements. A siltstone bed exposed near the base of the type section contains abundant carbonaceous debris, mollusc shells and calcite cement. The adjacent fine-grained sandstone bed does not contain as much organic matter and contains laumontite and calcite cements. Cementation of both beds occurred at approximately the same time (Figure 3.1). Fluids within the siltstone probably contained CO$_2$ produced during decomposition of organic matter, so calcite was stable. The low [illegible]rmeability of this horizon may have limited the movement of CO$_2$ into the adjacent sandstone beds.

The late-stage authigenic mineral assemblage in samples from the highly fractured and faulted strata at east Hesquiat Peninsula consists of calcite, kaolinite and quartz (Figure 3.1). This assemblage can result from the breakdown of laumontite in fluids of low or moderate pH or high Pco$_2$, at temperatures of 75-150°C as indicated by the following reactions (Crossey et al., 1984):

Laumontite+CO$_2$ = calcite + kaolinite + 2 quartz + 3H$_2$0, or

Laumontite+2H$^+$ = kaolinite + 2 quartz + 3H$_2$ 0 + Ca$^+$.

The first reaction involves a 10% decrease in volume, and the second a 28% decrease. Either or both of these reactions may account for the high secondary porosity (26%) in a sandstone from the base of the section.

The destabilization of laumontite in sandstones and conglomerates from east Hesquiat Peninsula probably occurred after faulting provided a pathway for fluid movement (Figure 3.1). The shearing of volcanic and diorite pebbles and granules in the conglomerate indicates that the basal units were highly indurated when fault movement occurred. The fluids moving along the fault may have had high CO_2 levels developed from interaction with the underlying volcanic rocks, or consisted of meteoric water.

C. DIAGENESIS OF THE HESQUIAT FORMATION

The first recessive unit contains an early diagenetic assemblage of pyrite and calcite concretions and a later assemblage of chlorite/smectite and zeolites (Figure 3.1). This suggests that the processes active in the Escalante Formation also affected this unit.

There is an abrupt decrease in the number of authigenic phases at the contact between the first recessive unit and the overlying sandstone and conglomerate (Figure 3.1). In the first resistant unit, late-stage calcite partially replaces detrital grains and occurs as cement. It is the most common diagenetic mineral throughout the remainder of the formation.

The decrease in the number of diagenetic minerals likely reflects the change from normal marine sedimentation in the first recessive member to rapid deposition and burial of the overlying turbidite deposits. Chan (1985) found that sandstones deposited by mass flow processes contained fewer authigenic phases than sandstones deposited in shallow marine or deltaic environments. She concluded that lower initial porosity and permeability in the turbidite sandstones prevented the development of authigenic clay rims and pore-filling cements.

Fluid movement in the Hesquiat Formation seems to have been confined to fault zones. The sandstones and conglomerates affected by faulting contain authigenic chlorite, kaolinite and quartz (Figure 3.1). Calcite grains and plagioclase grains were dissolved, creating secondary porosity.

Dissolution of calcite and plagioclase required the introduction of acidic water into these rocks. The fluids probably originated at depth and moved along fractures in the underlying volcanic rock. Metamorphic decarbonation reactions produce carbon dioxide gas, and so increase Pco in the associated fluids (Schmidt and McDonald, 1979). Thermal maturation of organic matter is frequently cited as a source of CO_2 which combines with water to produce carbonic acid (Schmidt and McDonald, 1979; Hurst and Irwin, 1982). Evolution of CO_2 from organic matter is not likely in the Hesquiat Formation; the shales encountered in offshore wells were reported to have low organic content (Shouldice, 1971) and the shale outcrops on Nootka Island and Hesquiat Peninsula are light coloured and contain only minor amounts of organic matter.

D. DIAGENESIS OF THE SOOKE BAY FORMATION

The authigenic phases in the Sooke Bay Formation probably formed in the depositional environment and at shallow burial depths (Figure 2.11). Clapp (1912) concluded that the sandstones and conglomerates exposed in the Sooke area (Figure 1.1) had not been buried more than 150 m. Textural features support Clapp's conclusion; framework grains in sandstone and conglomerate show no evidence of compaction (Plates 2.14a,b). The most common diagenetic phases in the Sooke Bay Formation are smectite rims in sandstones and calcite cement in conglomerates (Figure 3.1). Smectite rims in the conglomerate are thin or absent, suggesting that the precipitation of calcite decreased porosity and limited the alteration of detrital grains to clay minerals.

IV. CONCLUSIONS

Sandstones from all three formations comprising the Carmanah Group were derived from a mixed volcanic-plutonic source terrane and can be classified as feldspathic litharenites and lithic arkoses. Plagioclase feldspar and andesitic rock fragments are the most abundant detrital constituents. Despite the similarity in detrital composition, different authigenic minerals developed in each formation.

The greatest number of diagenetic phases crystallized in the Escalante Formation and the basal beds of the Hesquiat Formation, which are the oldest and most deeply-buried strata in the Carmanah Group (Figure 3.1). The decomposition of organic matter in the depositional environment resulted in the precipitation of pyrite and calcite cement. The formation of authigenic chlorite/smectite and the precipitation of laumontite cement is estimated to have occurred at burial depths of less than 2500 m, and may have resulted from higher heat flow caused by late Eocene-early Oligocene intrusions (Figure 3.2). The absence of chlorite/smectite and laumontite in the Escalante Formation on Flores Island may be due to shallower depths of burial or lack of proximity to intrusive rock bodies.

A limited number of diagenetic changes occurred

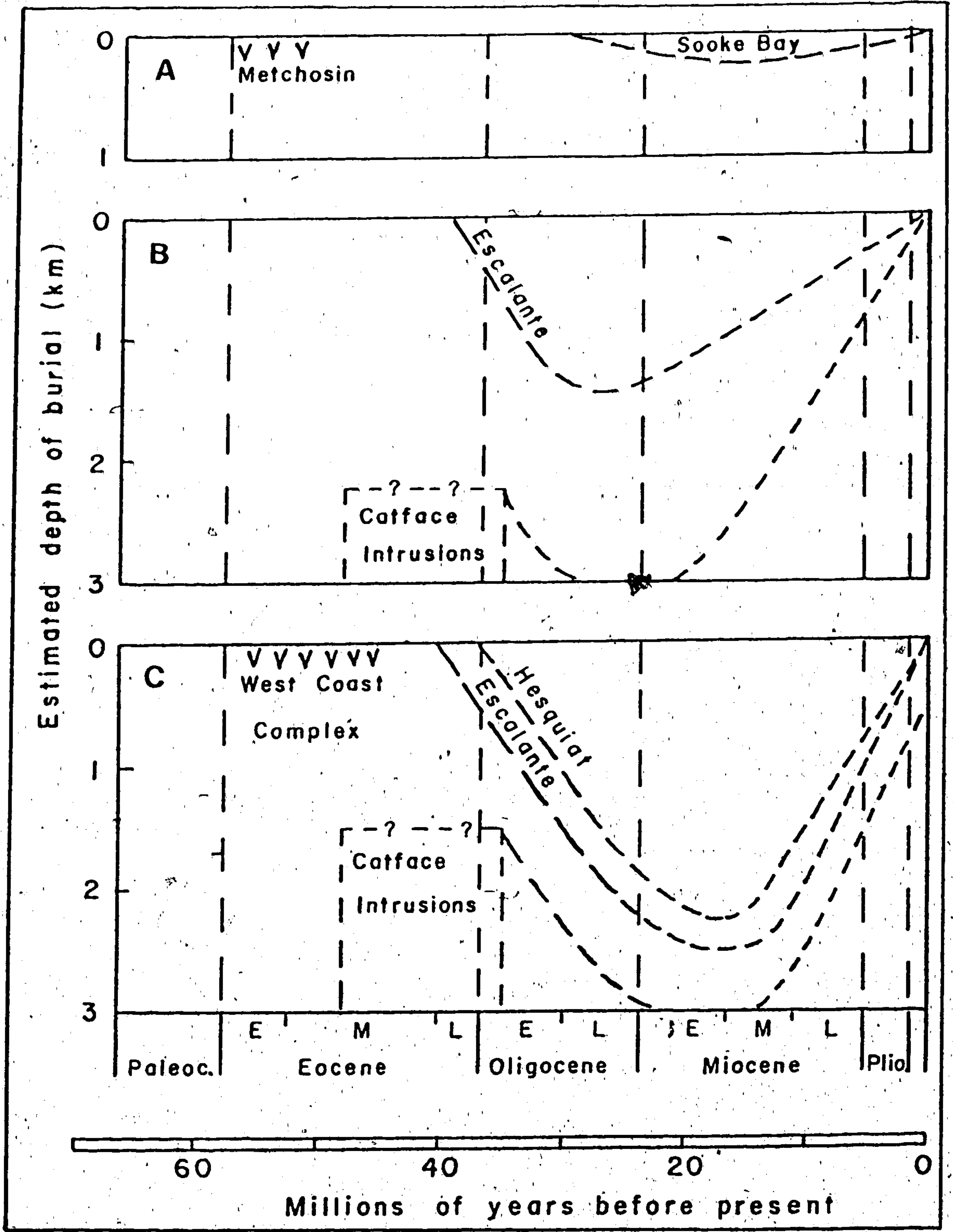


Figure 3.2 Inferred depth of burial of formations in the Carmanah Group, from time of deposition to the present.
A. Sooke Area B. Flores Island C. West Hesquiat Peninsula

during the deposition and burial of the Hesquiat Formation. Reducing conditions did not develop in the sandstones and conglomerates which comprise the resistant members, probably because rapid deposition and burial by mass-flow processes prevented the decay of carbonaceous debris. Calcite was the only authigenic mineral precipitated in the burial environment.

The authigenic smectite and calcite cement in the Sooke Bay Formation precipitated at burial depths less than 150 m. This formation has not been affected by intrusive activity or major fault displacement (Figure 3.2), and the authigenic mineral suite is typical for a permeable volcanoclastic unit. It may be representative of the diagenesis of the Escalante Formation, prior to hydrothermal alteration.

Crystallization of authigenic minerals in the Escalante and Hesquiat formations also occurred during uplift (Figure 3.2). A period of crustal deformation and uplift in the middle Miocene was suggested by Shouldice (1971). This was accompanied by the development of faults in the Nootka Sound area which were probably conduits for fluid migration. The most intense dissolution of cement and framework grains occurred in rocks sheared by northwest trending faults, located near the base of the Hesquiat Peninsula, and by other northeasterly faults exposed on the peninsula. The latest diagenetic phases recognized developed in these faulted and fractured rocks, likely in contact with meteoric water.

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