SEDIMENTOLOGY AND PETROLOGY OF THE CEDAR DISTRICT FORMATION, LATE CRETACEOUS, SOUTHWESTERN BRITISH COLUMBIA

by

RIYADH ABDUL-RAHIM RAHMANI

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Department of Geology

The University of British Columbia
Vancouver 8, Canada

Date July, 1968

ABSTRACT

The Upper Cretaceous (Campanian) Cedar District Formation of the Gulf Islands and adjacent areas is composed of shale and sandstone, which are present as thick sequences of shale, which may or may not be fossiliferous, and as alternating rhythmic sandstone-shale sequences of the flysch-type. Presence of graded bedding, ripple and convolute laminations, and sole marks in the latter suggest a turbidity current origin. The internal structures of the individual turbidite units correspond largely to the C-E divisions of Bouma (1962) and other authors, and indicate that their deposition took place largely within the lower flow regime.

Convolute lamination in the sandstones was formed by oversteepening and deformation of pre-existing ripple lamination and by the deformation of pre-existing plane-parallel lamination by the drag of the overpassing currents. Flute and groove casts and frondescent marks were only found in beds thicker than a foot and a half.

Calcareous concretions, most abundant in the shales and occasionally phosphatic, are crossed by organic borings and burrows which are filled with sediments of the surrounding beds. Host rocks of the calcareous concretions tend to thicken around them. The concretions show

deformation when present in beds involved in soft-sediment deformation. All these observations suggest their formation in the early stage of diagenesis, probably shortly after burial.

Sandstones of the Cedar District Formation show a gradation from arenites that lack matrix and have a calcite cement, to wackes rich in fine-grained matrix. The majority of the wackes and the arenites are feldspathic and arkosic, using the classification of Gilbert (1954). Their composition indicates that the major source was acidic to intermediate igneous and/or low to medium grade metamorphic rock , sedimentary and volcanic rocks were a secondary source. The major source area was possibly a region of high relief that had undergone rapid uplift and erosion, and experienced mainly mechanical weathering. Paleocurrents and lithologic lateral variation indicate that the major source area for the coarse clastics was situated to the east and southeast of the study area. The pre-Jurassic low grade metamorphic rocks of the Cascade Mountains to the east, and the pre-Carboniferous crystalline rocks of the San Juan Islands to the southeast served as possible source areas for the coarse clastics.

Deposition of shaley, fossiliferous parts of the formation in the southeastern part of the study area,

took place in littoral to upper neritic depths. Turbidite (flysch-type) sequences were deposited in deeper water, below the wave base. The unfossiliferous shale of the central and northern parts of the study area was deposited either at about the same depths as the turbidites, or in deeper water, since thin, delicate, horizontal and cross laminations are preserved in these rocks. Paleontologic evidence suggests that deposition took place in a somewhat restricted basin having a narrow connection with the open ocean to the west. Paleontologic and mineralogic data suggest that the bottom conditions of the central and northern parts of the basin of deposition were stagnant and reducing.

Facies relationships suggest that the basin of deposition had its longest dimension trending SE-NW. Its eastern, southeastern, and southern boundaries were situated between the mainland of British Columbia-Washington and the Gulf-San Juan Islands. Its northern and northwestern boundaries were possibly near the city of Nanaimo and Gabriola Island. To the west, it was connected at least partially to the open ocean. In the southeastern part of the study area, alternation of thick, fossiliferous shale sequences, and sequences which are predominantly turbidites suggests fluctuations in the depth of the basin floor, either due to changes in sea level or to tectonic movements.

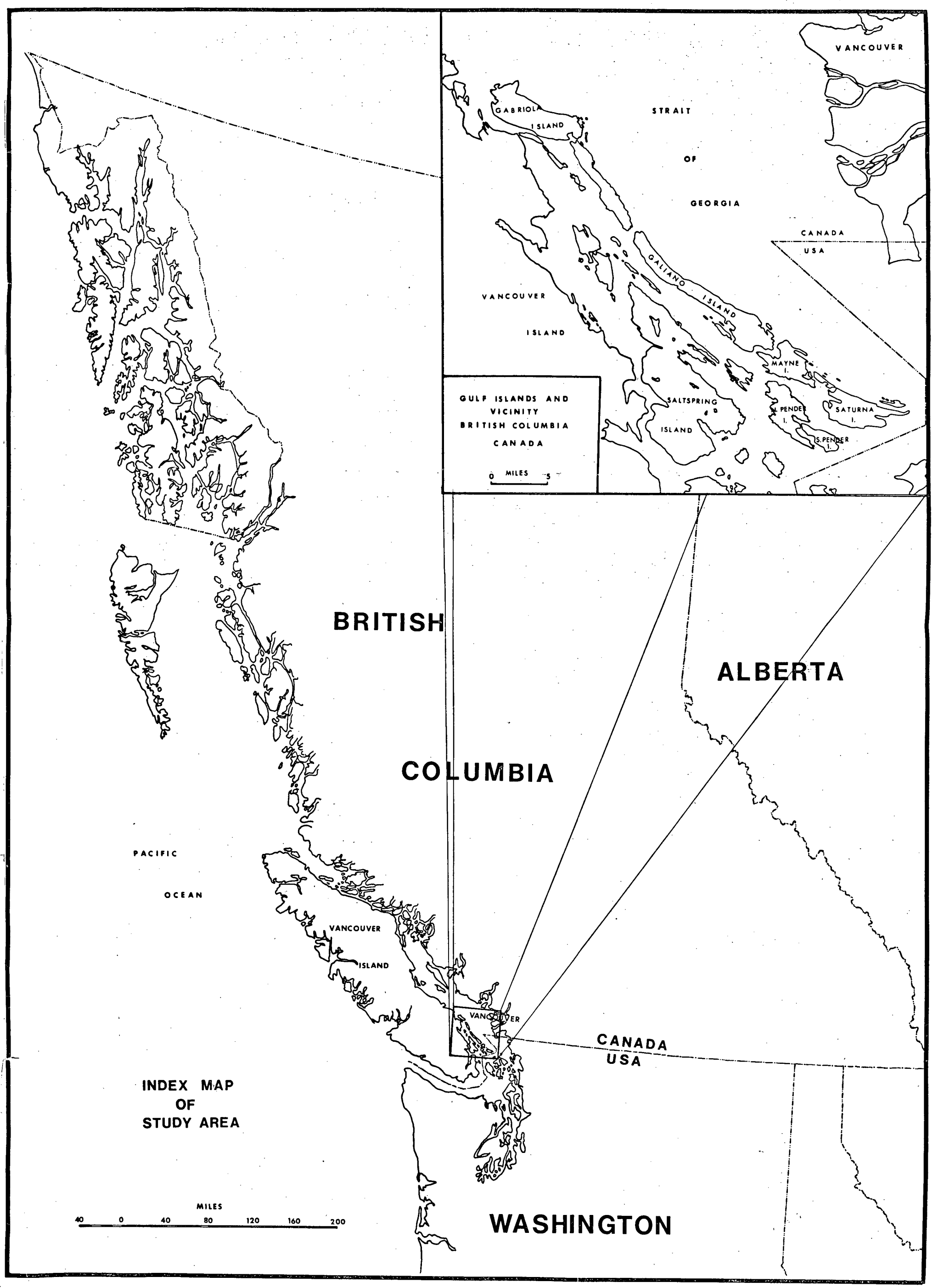
ILLUSTRATIONS

1. INTRODUCTION

A. Purpose and Scope of the Present Investigation.

The area of study is situated on the Gulf Islands and part of the southeastern coast of Vancouver Island in the southwestern part of the Province of British Columbia in Canada (fig. 1). In a NW-SE direction this area extends from just south of the city of Nanaimo on Vancouver Island to the southern part of Saturna Island, a distance of about 43 miles. In a NE-SW direction, it extends from Mayne Island to the western part of Salt Spring Island, a distance of about 15 miles (fig. 2).

Currently a study of the Upper Cretaceous Nanaimo Group is being carried out by the Department of Geology in the University of British Columbia, supported by The British American Oil Company Ltd. The author's part of this project concerns one unit in the Nanaimo Group, the Cedar District Formation, and the objective of the present investigation was to study the detailed petrological, sedimentological, and paleogeographical aspects of that particular formation. Because turbidites form an important part of the Cedar District Formation, a large part of this investigation will be concerned with this type of rock.


VANCOUVER
GABRIOLA
ISLAND
STRAIT
OF
GEORGIA
CANADA
USA
GALIANO
ISLAND
VANCOUVER
ISLAND
MAYNE
I.
GULF ISLANDS AND
VICINITY
BRITISH COLUMBIA
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0 MILES 5
SALTSPRING
ISLAND
PENDER
I.
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S.PENDER
I.
BRITISH
ALBERTA
COLUMBIA
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OCEAN
VANCOUVER
ISLAND
VANCOUVER
CANADA
USA
INDEX MAP
OF
STUDY AREA
MILES
40 0 40 80 120 160 200
WASHINGTON

Fig.1

B. Acknowledgements

To Dr. Robert E. Garrison the author wishes to express his deepest thanks for consistently excellent advice, constructive criticism, stimulation, support, and consolation. Dr. Garrison's position as a thesis advisor could not have been filled more adequately. Thanks are due to Mr. Michael Pullen for his help in trips among the islands by boat and for discussions in the field. To those inhabitants of the field area, and particularly to Mr. and Mrs. Hindmarch, goes the author's express gratitude for generous help and accomodation while carrying out the field work on Saturna Island. This work was supported by a grant from The British American Oil Company Ltd.

C. General Geology of the Nanaimo Group

This discussion will be a brief account of the geology of the Nanaimo Group, drawn mainly from previous studies of these rocks.

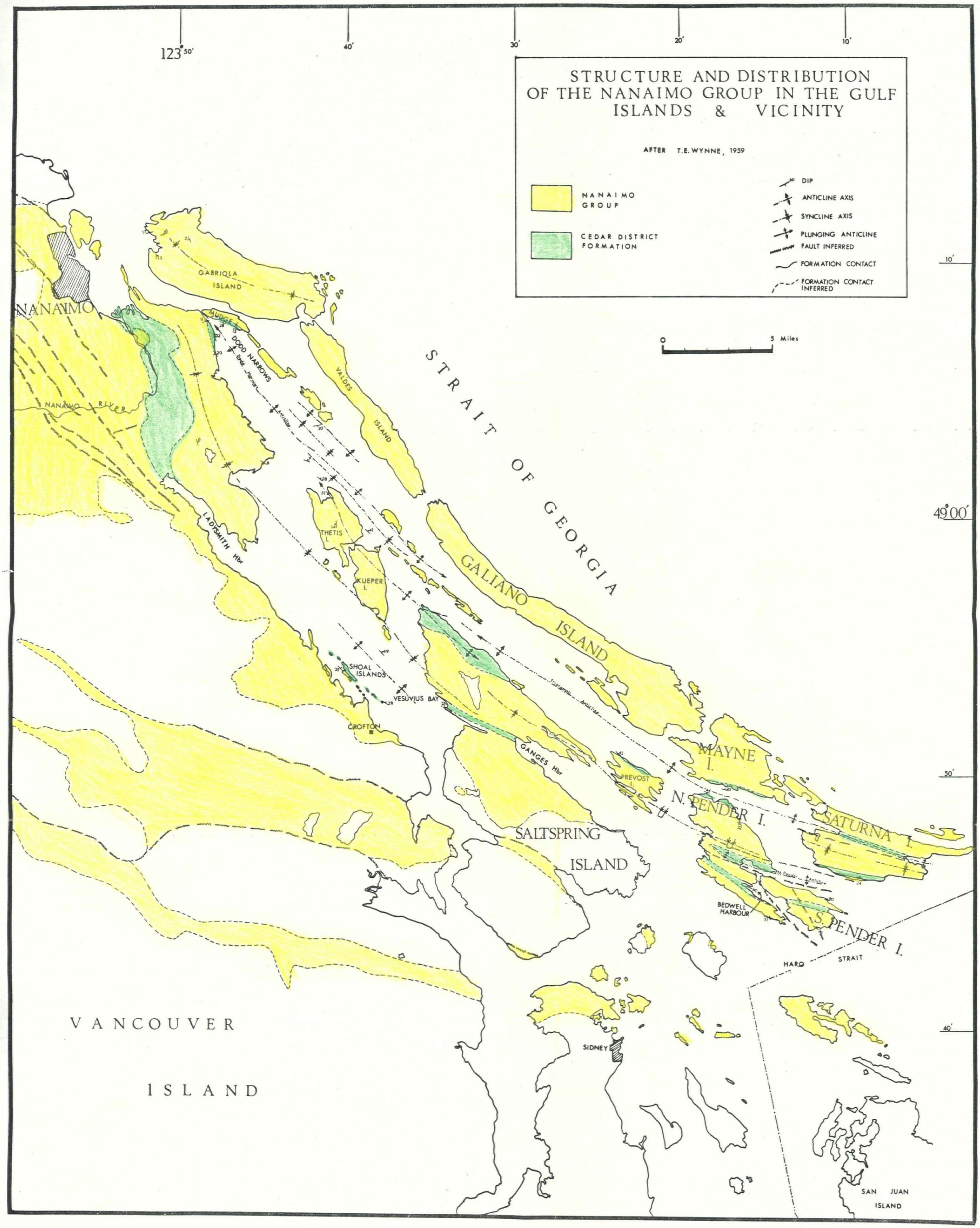
a. Stratigraphy

The Nanaimo Group ranges in age from the Santonian to Maestrichtian (Muller and Jeletzky, 1967). It outcrops on the east coast of Vancouver Island and the associated islands that fringe the coast. It occurs in two main areas

of outcrop, a smaller area around the town of Suquash in the northeastern part of the island, and a large area extending from Campbell River on the east coast of Vancouver Island in the north to the San Juan Islands in Washington State to the south. On the east, the outcrop areas are bounded by the waters of the Queen Charlotte and the Georgia Straits, on the west by the mountain ranges of mid-Vancouver Island.

The Nanaimo - Comox and the Suquash basins, in which the Nanaimo Group has been deposited, were part of the Insular Belt of British Columbia (A. Sutherland Brown, 1966, figs. 6-2 to 6-10). This area has been a site of tectonism and deposition from Late Paleozoic to the present time. During Late Paleozoic to Jurassic time, several successive eugeosynclinal basins developed. During Late Cretaceous time, a downwarped or downfaulted trough, the Georgia Seaway developed in the southeastern part of the Insular Belt and was the site of the Nanaimo Group deposition (Sutherland Brown, 1966, p. 84).

The Nanaimo Group comprises a thick sequence of clastic rocks consisting of conglomerates, shales, and some coal of mixed continental and marine origin (Usher, 1952). In general, the group is thickest in the southeastern part of the Nanaimo basin, where it reaches 10,000 feet and thins toward northwest edge of the basin to about 7,500 feet.


STRUCTURE AND DISTRIBUTION OF THE NANAIMO GROUP IN THE GULF ISLANDS & VICINITY
AFTER T.E. WYNNE, 1959
NANAIMO GROUP
CEDAR DISTRICT FORMATION
DIP
ANTICLINE AXIS
SYNCLINE AXIS
PLUNGING ANTICLINE
FAULT INFERRED
FORMATION CONTACT
FORMATION CONTACT INFERRED
0
5 Miles
123°50'
40'
30'
20'
10'
10'
49°00'
50'
40'
NANAIMO
NANAIMO RIVER
GABRIOLA ISLAND
MUDGE I.
DODD NARROWS
VALDES ISLAND
STRAIT OF GEORGIA
LADYSMITH Hbr
THETIS I.
KUEPER I.
GALIANO ISLAND
SHOAL ISLANDS
VESUVIUS BAY
CROFTON
GANGES Hbr
PREVOST I.
MAYNE I.
N. PENDER I.
SATURNA I.
SALTSPRING ISLAND
BEDWELL HARBOUR
S. PENDER I.
HARO STRAIT
VANCOUVER ISLAND
SIDNEY
SAN JUAN ISLAND

In the Comox basin to the northwest of the Nanaimo basin, the Nanaimo Group measures between 5,000 and 6,000 feet.

J.E. Muller and Jeletzky (1967, fig. 1, p. 38), divided the Nanaimo Group rocks into "four complete transgressive and regressive cycles of sedimentation"; each cycle "starting with non-marine beds and grading up to a marine formation". The non-turbidite (shaley) part of the Cedar District Formation is considered by them as a littoral facies ("Haslam-type facies") of the second cycle of sedimentation; they consider the turbidite part of the formation to represent deeper water deposition.

The lithology is marked by both vertical and lateral variation, and only a few of the formations have a wide lateral extent; among the latter, the marine shales and the rhythmic sandstone-shale sequence are the best examples. The Nanaimo Group rests unconformably above Late Paleozoic (Early Permian) metamorphosed volcanic and sedimentary rocks of the Sicker Group, Triassic-Jurassic volcanics of the Vancouver Group and Late Jurassic and/or Early Cretaceous acidic intrusions. Erosional relief along this unconformable surface is locally very large; Clapp (1914) reported relief of up to 2,000 feet, and Buckham (in W.B. Hoen, 1958) recorded about 440 feet of relief in the northern part of the area.

The Nanaimo Group occurs in five separate areas,

interpreted by Hoen (1958) as representing separate sedimentary basins. These "basins" are the Nanaimo, Comox, Cowichan, Alberni, and Suquash basins, of which the Nanaimo and the Comox basins are the largest in area. A prominent ridge of volcanic rocks of the Vancouver Group separates the southern basins (Nanaimo and the Cowichan) from the northern basins (Comox and Alberni). This ridge lies across Nanoose Bay, about 10 miles northwest of the city of Nanaimo. J.D. Mackenzie 1922 (in Hoen, 1958) believed that the Comox and Alberni basins were originally a single basin. Usher (1952) placed all of the formations included in the Nanaimo Group into two major basins, the Nanaimo basin south of Nanoose Bay, and the Comox basin to the north. Hence, he grouped the Comox and the Alberni basins (he did not consider the Suquash basin) in one basin he called the Comox basin, and the Nanaimo and the Cowichan basins into another basin which he termed the Nanaimo basin. These two major basins have in general similar faunal and lithological successions, and during times of maximum marine flooding must have been connected. However, a separate set of names has been applied to each of the two basins by Usher (1952). The following are the reasons presented by Usher for the separate terminology in the two basins: -(1) Lack, in the Comox basin, of formations equivalent to some of the lowest in the Nanaimo basin; (2) differences

AGE	NANAIMO BASIN		
	FORMATION	THICKNESS IN FEET	LITHOLOGY
Maestrichtian	Gabriola	2,000-3,000	Sandstone
	Northumberland	2,000-2,700	Shale Sandstone Shale
Campanian	De Courcy	800-1,000	Sandstone
	Cedar District	333(?)-1584	Shale & Sandstone
	Protection	650	Sandstone
	Ganges: Newcastle	215-400	Sandstone, Shale; Newcastle & Douglas coal seams
	Ganges: Cranberry	200-600	Sandstone, Conglomerate
Lower Campanian or (?) Santonian	Extension	600-800	Conglomerate, Sandstone
	East Wellington member	35	Sandstone; Wellington coal seam
	Haslam	600-1,500	Shale
	Benson	100	Conglomerate

Table 1:
List of the Nanaimo Group formations in the Nanaimo basin. Modified from Usher (1952) & Wynne (1959).

in the coal horizons in the two areas; (3) distinctions between the respective faunas; and (4) difficulties encountered in trying to apply formational names over a considerable distance to stratigraphic units that show a pronounced lateral variation in lithology. The first reason proved to be incorrect as will be seen later. Table 1 lists the formations in the Nanaimo basin (adopted from Usher, 1952 with minor modifications). More recent work based on detailed microfaunal and macrofaunal investigations has shown that the lowest formations in the Comox basin are as old as those of the lowest in the Nanaimo basin (McGugan, 1962, and 1964, fig. 2, and Muller and Jeletzky, 1967, table 2).

J.E. Muller (personal communications) is inclined to think of two major basins of deposition: (1) the Nanaimo-Comox basin which includes the Nanaimo, Cowichan, Comox, and the Alberni basins; (2) the Suquash basin.

b. Structure

Discussion of the structure of the Nanaimo Group will be confined to the Nanaimo basin since this research was carried out in the Nanaimo basin only.

The general structure of the Nanaimo Group in the Gulf Islands and vicinity is a northeast dipping monocline

Fig. 3:
Two sets of intersecting joints in sandstone. Bedwell Harbour, North Pender Island.

Fig. 4:
Two sets of intersecting joints in shale. Bedwell Harbour, North Pender Island.

Fig. 5:
Variation in spacing of joints with variation in bed thickness. Joints in thick sandstone beds are wider spaced than joints in the thinner beds. Bedwell Harbour, North Pender Island.

Fig.3

Fig. 4

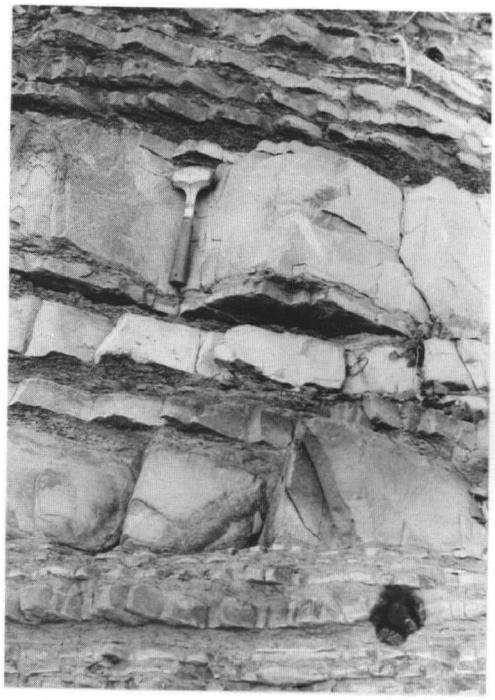


Fig.5

with numerous NW-SE trending folds and associated faults. Toward the north, folds are broader with few faults but become more tightly folded with numerous faults southward (Wynne 1959), figure 2.

Limbs of folds in the northern part of the basin have average dips ranging from 12° to 20°, and average trends ranging from N30°W to N55°W. To the south, on Salt Spring and North Pender Islands, dips as high as 60° and 78° were recorded.

Jointing has not been mentioned by the previous workers except for Clapp (1914) who indicated their irregularity, and, in a few places, the presence of parallel sheet jointing. From the present author's experience with the rocks of the Cedar District Formation, it was observed that there are at least two sets of joints intersecting at an angle which varies from approximately 90° to about 50°. These joints are present in the sandstones and the shales of the formation (figs. 3 and 4). It was also observed that these joints tend to be more widely spaced in the thick beds and closely spaced in the thinner ones (fig. 5).

c. Previous Work on the Nanaimo Group

Nothing has been published prior to this thesis on the detailed sedimentological and paleogeographical aspects of

the Nanaimo Group rocks. Most previous work has focused on the stratigraphy and paleontology of these rocks. For detailed review of this previous work, the reader is referred to Usher (1952, p.2-6), and this section will deal only with the major contributions to the understanding of the geology of the Nanaimo Group, drawn mainly from Usher (1952) and from more recent publications.

The earliest work on the rocks of Late Cretaceous age along the southeastern coast of Vancouver Island began nearly a century ago. Interest in these rocks began with the discovery of extensive coal deposits in them in 1835. Their age remained unknown until 1857 when Newberry (in Usher, 1952) stated that they belonged to the Cretaceous System.

James Richardson made the first systematic stratigraphical,structural, and paleontological studies of the Nanaimo Group coalfields (J. Richardson, 1871-72, 1872-73, and 1876-77). He divided the succession into many rock-stratigraphic units that he called "Divisions", which later came to be known as formations.

G.M. Dawson, in the course of geological exploration of British Columbia between 1875 and 1890, did extensive work on the coalfields of Vancouver Island. He named all Cretaceous rocks on eastern Vancouver Island the "Nanaimo Group" (Dawson, 1890). The first comprehensive work on

the invertebrate fossils of the group was carried out by Whiteaves in 1879 (in Usher, 1952). Clapp made further investigations of the Upper Cretaceous, as well as of the older, and younger rocks of the east coast of Vancouver Island in the years between 1908 and 1917. He has been credited for naming the formations of the Nanaimo Group in the Nanaimo map-area (Clapp 1911, and 1914).

In the years 1945 and 1948, Usher made a detailed paleontological investigation in the Comox and the Nanaimo basins (Usher, 1952). He introduced a formational subdivision of the Nanaimo Group which was slightly modified from Clapp's (1914). Usher's publication (1952) has an excellent description of the formations, including a systematic description of the enclosed macrofauna. Richfield Oil Corporation carried out mapping of the Gulf Islands in 1958, and assembled a geological map with a scale of 2 miles to the inch (Wynne, 1959).

McGugan, in the years 1958 and 1959 made extensive sampling of the shaley formations in the Nanaimo and Comox basins, and studied their foraminiferal assemblages. He subdivided the Nanaimo Group into three zones based on foraminifera (McGugan, 1962 and 1964). J.E. Muller in the course of his regional mapping on Vancouver Island for the Geological Survey of Canada, which started in 1963 and is still in

progress, remapped the Nanaimo Group. Muller's and J.A. Jeletzky's work has resulted in introducing a biochronological-lithological relationship between the formations in the Nanaimo, Comox, and the Suquash basins (Muller and Jeletzky, 1967). D.L. Scott (1967) has presented the first description of the sedimentary structures exhibited by some formations in the Nanaimo Group, especially graded bedding and the presence of turbidites. He also suggested, that some more detailed work should be done on the petrological, sedimentological, and paleoenvironmental aspects of these formations.

D. Terminology Applied to Turbidite Sequences

The following general discussion will serve to introduce the reader to certain aspects of turbidite terminology, and to describe the procedures followed by the author in studying the rocks which are the subject of this investigation.

By definition turbidites are the rocks or sediments deposited by turbidity currents. Since the postulation, by Kuenen and Migliorini (1950), that turbidity currents are a likely mechanism for transporting sandy materials to deep water, and for the formation of graded bedding, many rocks of this nature have been studied in different

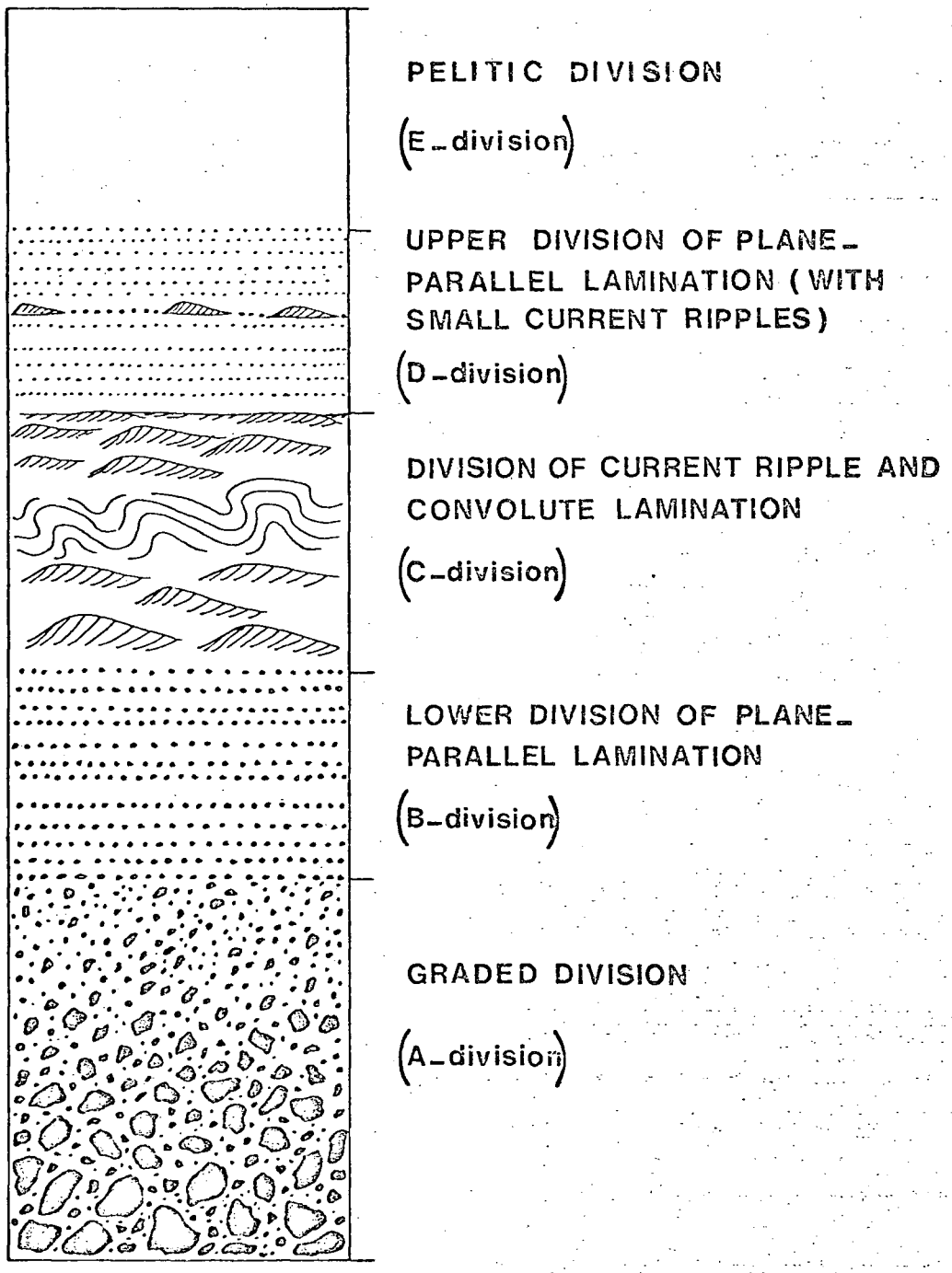


Fig. 6:
A complete turbidite unit and its divisions in an ideal turbidite. Modified from Bouma (1962), Walker (1967), & Hubert (1967). Thicknesses of the individual units may range from a few inches to a few feet.

parts of the world and in different parts of the geologic column.

Bouma (1962), in his study of the flysch deposits of the Alp Maritimes in Europe, observed that in a complete turbidite unit (fig. 6) (a unit here might represent one or more beds, of thickness varying from an inch to a few feet) there are five divisions, called intervals by Bouma (1962) and divisions by Walker (1965). These divisions are as follows from the bottom to the top of the turbidite unit (reproduced from Bouma 1962, p. 49 with some modification):

a. Graded Division (A-division):- The bottom part of this division consists of sand, showing more or less distinct graded bedding. This grading may be indistinct or even absent if the material is well sorted. The texture of this division is sandy and sometimes granules and pebbles may be found. Occasionally sole markings are present at the lower contact of this division, and they range from load casts to scour marks.

b. Lower Division of Plane-Parallel Lamination (B-division):- In this division parallel lamination due to an alternation of more and less clayey sand laminae predominates. Grading may be present, but lamination predominates. The contact between the A- and B- divisions is generally gradational.

c. Division of Current Ripple and Convolute Lamination (C-division):- This division consists of current ripples, which are in most cases less than 5 cm thick. A distinct fore-set lamination is often visible. Sometimes the ripples are more or less oversteepened or convoluted; convolute lamination, if present in the turbidite unit, is restricted to this division. The contact between the B- and C- divisions is either sharp or gradational.

d. Upper Division of Plane-Parallel Lamination (D-division):- An indistinct lamination is characteristic of this division, but if the layer is weathered or deformed the lamination becomes invisible. The material consists of a very sandy to silty clay. Sometimes an upward decrease in sand content is visible. The contact between the C-division and this division is usually very distinct.

e. Pelitic Division (E-division):- The upper division of the turbidite unit shows no visible sedimentary structures. A small upward decrease in grain size and sand content may be found. Often, a rapid upward increase in the lime content is found. Foraminifera may be found in this pelitic division. Their number generally increases with increase of lime content and decrease of grain size. The contact between the upper two divisions generally is completely gradational.

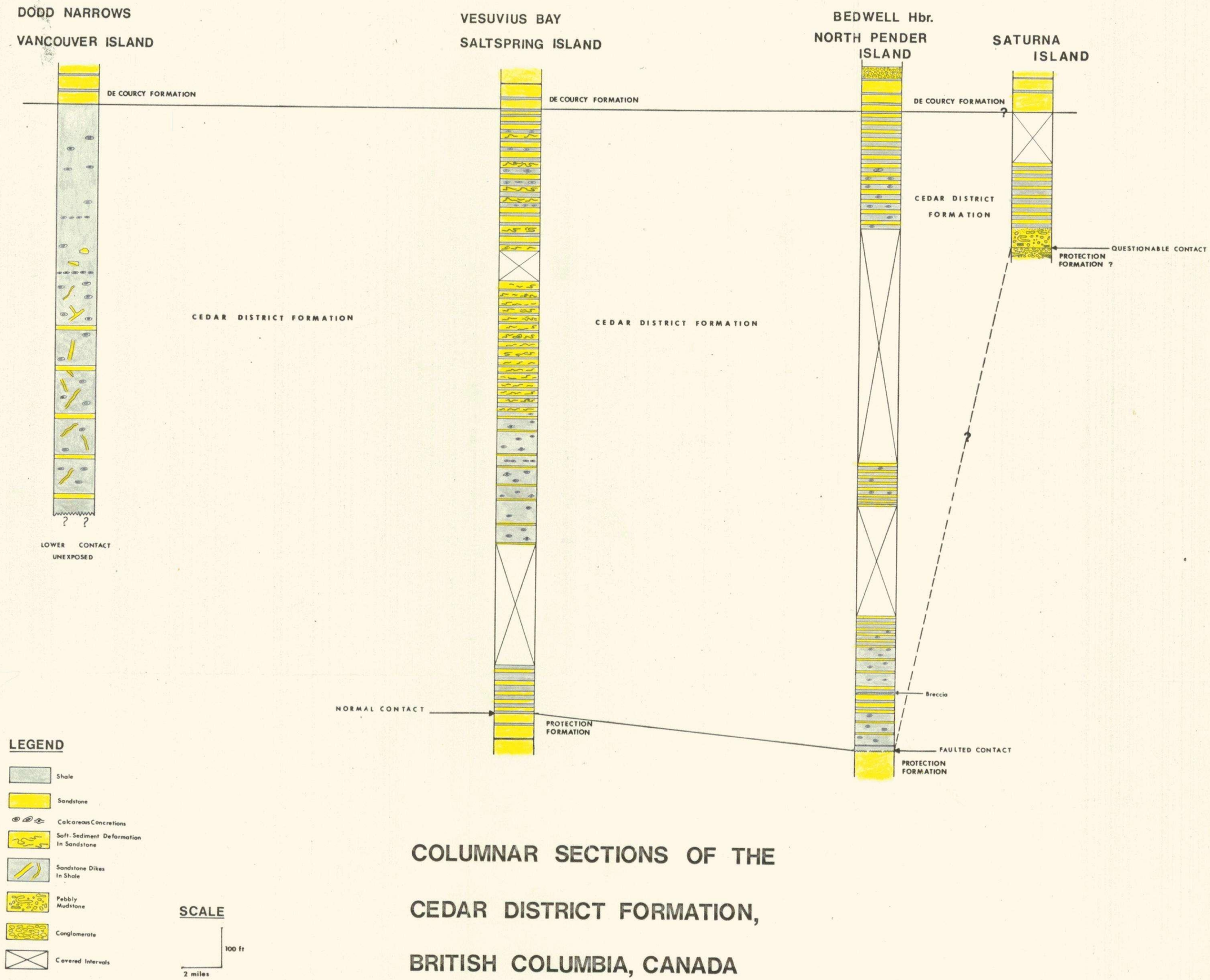
Because the author has not been able to distinguish

between the upper two divisions in the field, in the present study the upper two divisions have been grouped under one division which is called interturbidite division (DE-division) (Walker, 1967). The term interturbidite is suitable for the upper two divisions because they represent deposition of sediments by normal gravity settling between two periods of turbidity current deposition. In discussing the field techniques and the use of the logging chart, the author will refer to the divisions by their respective letters (e.g. graded division is the A-division, lower division of parallel lamination is the B-division .... etc.).

The reader should be aware that the above description of the different divisions might not be representive of turbidites in general all over the world, but they describe the turbidites of the Alpe Maritimes in Europe (Bouma, 1962), and they show agreement to a large extent with the turbidites of the present study. A number of workers have related the various divisions to flow conditions within a turbidite current, as will be discussed subsequently.

E. Methods of Study

The field phase of this investigation focused on ..



COLUMNAR SECTIONS OF THE CEDAR DISTRICT FORMATION, BRITISH COLUMBIA, CANADA

detailed measurements of sections of the Cedar District Formation in different parts of the area. Because of the scarcity of outcrops favorable for this kind of study, two complete sections, one questionably complete section, and one partial section, (representing only the upper part of the formation) were measured (fig. 7). Field work was conducted mainly on the wave cut cliffs, since these exhibit the best outcrops. Inland, the rocks tend to be covered either by soil and vegetation or by glacial deposits, and at best, only partial sections are exposed; The best sections are found along shorelines approximately perpendicular to the strike of the formation.

a. Field Techniques

Systematic logging of the measured sections has been carried in two ways depending on the percentage and distribution of the sandstone beds, as follows:

(1) In parts of sections where sandstone beds are few and shale dominates, 5-foot intervals were measured by Jacob's staff, and the persentage of the sandstone was calculated within each 5-foot interval.

(2) In other parts of sections where sandstone beds are abundant, detailed inch-by-inch logging was conducted. This logging included measurements of the thickness, color, grain size, and sedimentary structures for each division

within each separate turbidite unit. Paleocurrent directions were measured from directional sedimentary structures within the turbidite units and along bedding planes, along with sampling, sketching and photography.

All of these data were recorded in a tabulated form in the field on a graph paper roll. The appendix at the end of this thesis shows a sample of a logging chart and its explanation, the properties measured and their symbols.

b. Laboratory Techniques

Microscopic:

Petrographic examination of the different rocks was conducted, with special emphasis on the sandstones. Quantitative compositional analysis of 26 sandstone samples was done by point counting which included counting from 400 to 700 counts per thin section depending on the grain size, the least counts being made on fine-grained sandstones.

The size of 100 grains was measured in 15 sandstone thinsections to determine the size distribution; no attempt was made to convert the thin-section size distribution (number) into the sieve-size distribution (weight) as was done previously by Friedman (1958, and 1962), since he delt with well sorted sandstones. Qualitative

microscopic examination of 8 shale samples and 11 calcareous concretion samples was done for the purpose of determining their composition.

Feldspar Staining:

Thin sections of 12 sandstone samples, chosen from different levels within the section in five localities, were stained for feldspar. The method consists of etching the thin sections for approximately 40 seconds with hydrofluoric acid fumes and then dipping them into sodium cobaltinitrite solution for 40 seconds. The K-feldspars are stained yellow, plagioclase feldspars white, and quartz is unaffected. Next, the percentage of K-feldspar was determined by point counting under the microscope.

X-Ray Analysis:

Five shale samples were analysed by x-ray diffraction for semi-quantitative clay mineralogy and determination of Kadinite/Illite ratio. Four sandstone samples were analysed selectively for the mineralogic composition of the clay-size matrix. This was done by crushing each rock sample, sieving them through a 230 mesh screen (U.S. Standard), and collecting the portion of the sample which passed through this screen. All the samples were treated to get rid of the calcium carbonate,

organic matter, and iron oxides in order to minimize any possible effects of flourescence from these materials during the process of x-raying. The samples were next centrifuged in order to recover that portion of the sample less than or equal to two microns, which was then x-rayed.

Electron Microscopy:

Three calcareous concretion samples were examined under the electron microscope after making replicas of part of the samples' surfaces by the two-stage replica method (Honjo and Fischer, 1965). Purpose of this part of the investigation was to study micro-textures and recognize any fossil nannoplankton.

2. DISTRIBUTION, THICKNESS, AND STRUCTURE OF THE CEDAR DISTRICT FORMATION

The outcrop area of the Cedar District Formation extends from the mouth of the Nanaimo River delta on Vancouver Island on the northwest, to Sucia Island in Washington State on the southeast (fig. 2). Sucia Island is situated 5 miles southeast of Saturna Island, but is not shown on the map of figure 2.

On Vancouver Island, the formation underlies a wide valley with a nearly north-south trend extending from the

mouth of the Nanaimo River to Ladysmith Harbour and passing through the Cedar District area (where the formation was first defined by C.H. Clapp, 1914). Within this valley the formation is covered largely by drift, but there are several small scattered outcrops, and portions of the formation are fairly well exposed at a few places along the Nanaimo River (Clapp, 1914). It is also exposed 2 to 3 miles to the east, on the shores of Vancouver and Mudge Islands surrounding the Dodd Narrows, occurring on the limbs of a plunging anticline (only the upper part of the formation is exposed here). In the latter area the beds dip at an angle which varies from 11° to 32°, and the strike changes rapidly within a short distance due to the fact that the beds are located near the nose of a plunging anticline, and because of soft sediment deformation. The author did not attemp to measure the section in this area because of the complexities mentioned above. But a thickness of 1010 feet has been measured by J.E. Muller in 1967 of the Geological Survey of Canada (personal communication), this thickness representing the upper part of the formation. The base is not exposed here (fig. 2).

On Salt Spring Island, the formation outcrops in two belts, one on the northern and northeastern part of the

island where it forms several minor folds with dips from 11° to 62°; in this area only the upper part of the formation is exposed. The second belt extends from Vesuvius Bay on the northwest coast of the island to Ganges Harbour on the southeast coast. Along this belt, the formation is well exposed only on the beaches and the adjacent low cliffs of Ganges Harbour and Vesuvius Bay. In Vesuvius Bay, the beds dip very steeply to the northeast, the dip angle varying from 71° to 80°. A thickness of 1503 feet has been measured in Ves vius Bay, where only 19% of the sequence was covered by beach gravel and sand. In the Ganges Harbour-region the beds dip steeply, assuming a vertical attitude and occasionally being overturned, (fig. 2).

The upper 150-200 feet of the formation also outcrops on the north and northeast coast of Prevost Island, forming a narrow strip along the beach and the nearby cliffs. It is exposed here on the southwestern limb of the Trincomali Anticline, the axis of which lies in the waters of the Trincomali Channel. Beds on Prevost Island dip from 28° to 47° to the southwest, (fig. 2).

It also occures as a narrow belt on the southern coast of Mayne Island, forming the beach and the nearby cliffs which range from 40 to about 100 feet high.

About the upper 200 feet of the formation are exposed here, lying on the northeastern limb of the Trincomali Anticline and dipping with angles from 33° to 45° northeast (fig.2).

The formation forms the core of the Trincomali Anticline in the Lyall Valley of Saturna Island, thus the base of the formation is not exposed. On the same island, the formation is exposed along the beaches and the nearby cliffs on the southern coast, where it lies on the northeastern limb of the faulted North Pender Anticline, and dips northeast with angles varying from 24° to 31°. In the latter area, if the conglomerate (fig. 7) at the base of the exposed section does not belong to the Cedar District Formation, the thickness then is 333 feet, with about 37% covered by vegetation, soil, and blocks of sandstone from the overlying DeCourey Formation (fig. 2). But if this conglomerate belongs to the Cedar District Formation (as Breitsprecher, 1962, concluded in his study of the formation in Sucia Island), the thickness of the Cedar District Formation will be more than 333 feet. The present author feels that this conglomerate (which is thicker than 20 feet, and has characteristics of a beach conglomerate) does not belong to the Cedar District Formation exposed here, which is almost entirely a turbidite sequence.

On North Pender Island the formation outcrops in three belts. The first lies on the southwestern limb of the Trincomali Anticline at the northern coast of the island, and the second forms the core of the North Pender Anticline around Port Browning. The third belt extends from the Bedwell Harbour southeast to the west coast of the island. In this latter locality a thickness of 1584 feet has been measured; but a faulted lower contact might obscure a greater thickness. On Bedwell Harbour, the formation dips at angles from 51° to 60° northeast. On South Pender Island it forms one belt along the northeastern limb of an anticline (fig. 2). The author has visited all the above outlined localities, except for the area along the Nanaimo River and the exposures on South Pender Island.

3. FOSSILS, AGE, AND CORRELATION

Most of the fossils that have been recovered from the Cedar District Formation came out from the shaley part of the formation; and almost all of these fossils were found on Saturna and Sucia Islands, but there are some sparse occurrences on the other islands, (Usher 1952, McGugan 1962 and 1964, Breitsprecher 1962, and Muller and Jeletzky 1967).

The Cedar District Formation macrofauna is composed

almost entirely of mollusks, of which the cephalopods, pelycepods, and gastropods are the most important. Scaphopods and shark teeth have been reported by Breitsprecher (1962) on Sucia Island. Regarding the microfauna, benthonic foraminifers are the dominant type, (McGugan, 1962 and 1964, and Breitsprecher,1962), with a few to rare occurrences of ostracods.

The author had hoped to find coccoliths in the shales and the calcareous concretions. Five samples of shale were sent to the United States Geological Survey marine laboratory in La Jolla, California to recover coccoliths, but all the samples "proved to be conspicuously barren", (David Burky, 1968, written communication). Three samples of calcareous concretions were examined under the electron microscope, but they also contain no visible coccoliths.

The Cedar District Formation has been considered to be of Late Campanian age by all the previous workers who investigated the paleontology of the formation. This age was indicated by some ammonites and benthonic foraminifers, (Usher, 1952, Breitsprecher, 1962, McGugan, 1962 and 1964, and Muller and Jeletzky, 1967), see table 1.

The stratigraphic sections measured on Saturna, North Pender, Salt Spring, and Vancouver Islands are shown in fig. 7. On Saturna Island, considering the conglomerate

and the underlying rocks (the latter are covered by water) as part of the Cedar District Formation, as Breitsprecher (1962) did on Sucia Island, and assuming that the minimum true thickness of the Cedar District Formation measured by Breitsprecher on Sucia Island is 800 feet instead of 1200 feet (the latter thickness is questionable because of structural complications), then the thickness of the Cedar District Formation on Saturna Island may reach as much as 800 feet. Accordingly, the thickness of the Cedar District Formation appears to increase from Sucia and Saturna Islands toward North Pender and Salt Spring Islands, in other words from southeast to northwest. It is unknown whether the formation becomes thicker or thinner towards Dodd Narrows in the northwestern margin of the study area, since only the upper 1010 feet are exposed.

There is no way to divide the formation into members that could be correlated laterally throughout the study area, with the possible exception of the upper 250 to 300 feet in the North Pender and Salt Spring Islands sections which are composed of similar appearing turbidite sequences. But towards the northwest in the Dodd Narrows, this sequence is not present, and the entire section there is composed of shale. Similar turbidite sequences are also present in other stratigraphic levels

of the Salt Spring, North Pender, and Saturna Islands sections, but they are usually thinner than the turbidite interval at the top of the formation on Salt Spring and North Pender Islands.

On the stratigraphic sections (fig. 7), the contact between the Cedar District and the DeCourcy Formations is used as a reference line. This is not meant to be a time line, since there is no paleontological control available, but is used because this contact was exposed in all sections, whereas the lower contact with the Protection Formation is faulted on North Pender Island and unexposed in the Dodd Narrows section, and possibly also in the Saturna Island section.

4. LOWER AND UPPER CONTACTS

The Cedar District Formation lies between two sandstone formations, the DeCourcy Formation at its top, and the Protection Formation at its bottom. Contacts with these underlying and overlying units appear to be gradational, and the sandstone beds in the Cedar District Formation increase in thickness and number both upwards and downwards toward the adjacent units.

Fig. 8:

Pebbly mudstone of Saturna Island. Dark objects (arrows) are slate clasts and pebbles of basic igneous rocks. Milky quartz pebbles can be seen at the center of the left half of the picture. Note concentric concretionary weathering of the shale matrix (upper right corner). The scale is 3 inches long.

Fig. 9:

Portion of a conglomerate layer that underlies the pebbly mudstone in fig. 8. Note the abundance of milky quartz pebbles. Other portions of this layer have coarser pebbles and cobbles. Saturna Island.

Fig. 10:

Contact of the Cedar District Formation (to the left of the hammer), and the Protection Formation (to the right of the hammer). Beds dip at 78° to the left. Vesuvius Bay, Salt Spring Island.

Fig. 8

Fig. 9

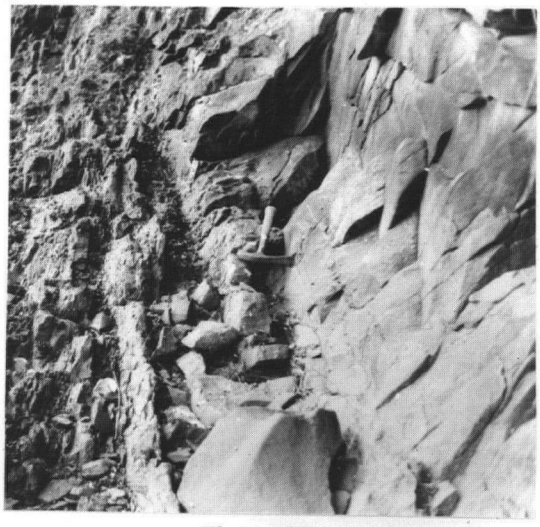


Fig. 10

A. Lower Contact

The lower contact of the Cedar District Formation is exposed at the following localities:

(1) Along the southern coast of Saturna Island, assuming the conglomerate at the base of the section does not belong to the Cedar District Formation, the lower contact is well exposed for a distance of a mile and a half, and lies between a pebbly mudstone sequence (fig.8) of 48 feet thickness, which belongs to the Cedar District Formation, and a pebble-cobble conglomerate (fig. 9), which the author assigns to the underlying formation.

(2) In Bedwell Harbour of North Pender Island, the lower contact is faulted, and dark grey, silty shale beds of the lower part of the Cedar District Formation lie with structural discontinuity against a very thick-bedded sandstone of the Protection Formation.

(3) In Vesuvius Bay on Salt Spring Island, the lower part of the formation consists of interbedded sandstone (bed thickness ranges from 0.3 to 5.7 inches, with an average of 1.7 inches) and shale (bed thickness ranges from a fraction of an inch to 33 inches and averages 5 inches). The contact with the underlying Protection Formation is drawn at the point where the thickness of the sandstone beds increases abruptly to more than 3 feet (fig. 10).

Fig. 11:
Sandstone beds at the base of the DeCourcy Formation near the contact with the underlying Cedar District Formation. Vesuvius Bay. Salt Spring Island.

Fig. 12:
Contact (just above the hammer) between the DeCourcy Formation and the underlying Cedar District Formation. Dodd Narrows, Vancouver Island.

Fig. 13:
Concentric concretionary weathering in the shale of the Cedar District Formation. Bedwell Harbour, North Pender Island.

Fig. 14:
Shale sequence cut by irregular sandstone dike. Note the light colored calcareous concretions indicated by the arrows. Dodd Narrows, Vancouver Island.

Fig. 15:
Typical turbidite sequence of interbedded shale and sandstone beds, with high sandstone percentage. Scale on the right is 3 feet long. Bedwell Harbour, North Pender Island.

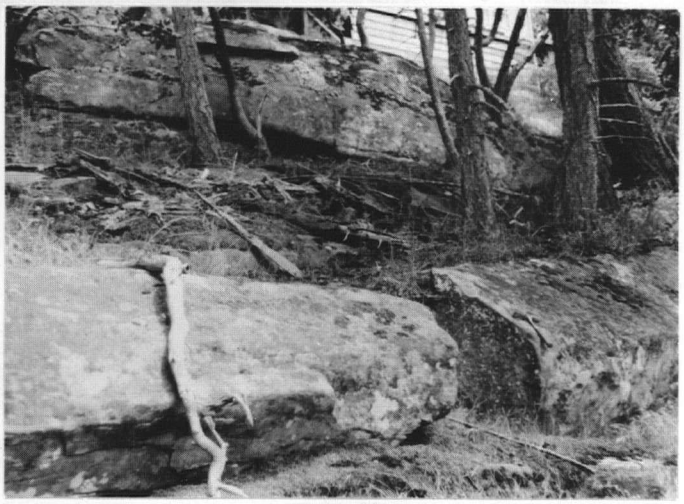


Fig. 11

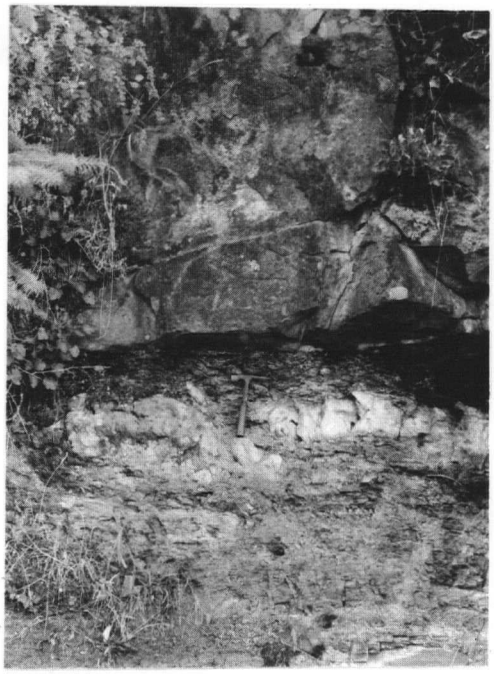


Fig. 12

Fig. 13

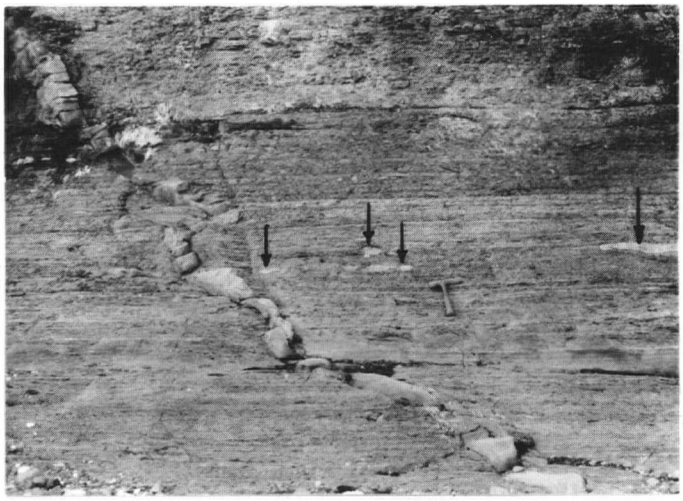


Fig. 14

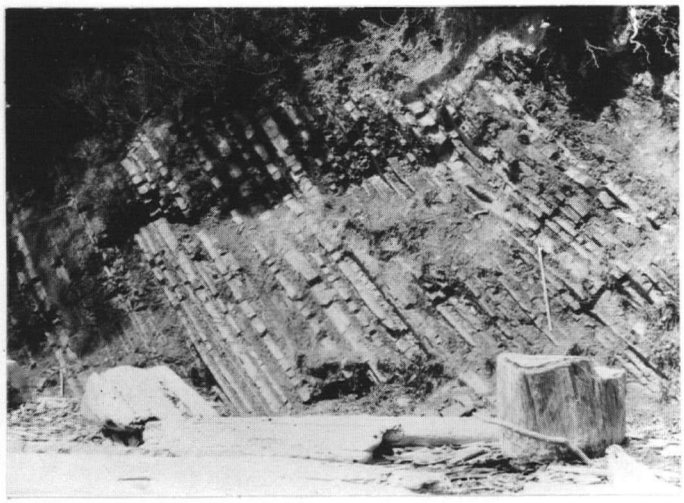


Fig. 15

B. Upper Contact

In the three localities mentioned above, this contact is typically more gradational than the lower contact. Sandstone beds usually increase in thickness upward. Where these sandstone beds reach a thickness of more than 3 feet, and where typical turbidite structures are no longer found, the upper contact of the formation with the overlying De Courcy Formation is drawn (fig. 11).

On Mayne Island, in contrast, this contact is sharp. Sandstone beds change abruptly from thin-bedded (about 6 inches thick) in the topmost Cedar District Formation to very thick-bedded (over 3 feet thick) in the lowermost De Courcy Formation.

Along the east coast of Vancouver Island around the Dodd Narrows, the upper contact is extremely sharp. Here, dark grey silty shale, which composes almost the entire exposed part of the Cedar District Formation, lies directly below massive, very thick-bedded sandstone of the De Courcy Formation (fig. 12).

5. GROSS LITHOLOGY

The Cedar District Formation is a relatively thick sequence of alternating marine shales and sandstones. Shale comprises approximately 73% by thickness of the

measured portions. Sandstone is second in abundance. Calcareous concretions occur throughout most of the section, commonly associated with shale but also found associated with sandstones. A bed of pebble-breccia, averaging five inches thick, is found only in North Pender Island section. The basal 48 feet of the Saturna Island section is composed of pebbly mudstone that contains a range of very angular to well rounded pebbles and cobbles of varying composition along with sandstone clasts of varying shape and size.

A. Shale

The Cedar District shales are grey, bluish grey to brownish grey when fresh and dry. Generally they are silty to sandy, and thin sections contain black spots of pyrite and carbonaceous matter. They are highly indurated, possibly due to the very fine-grained siliceous cement. They show fine lamination, and commonly posses concentric concretionary weathering (fig. 13).

Intervals of shale range in thickness from continuous sections hundreds feet in thickness, with no clear bedding except for the lamination (fig. 14), to well defined layers interbedded with sandstones (fig. 15), to mere partings separating succesive sandstone beds.

The cumulative frequency of the thickness of 727

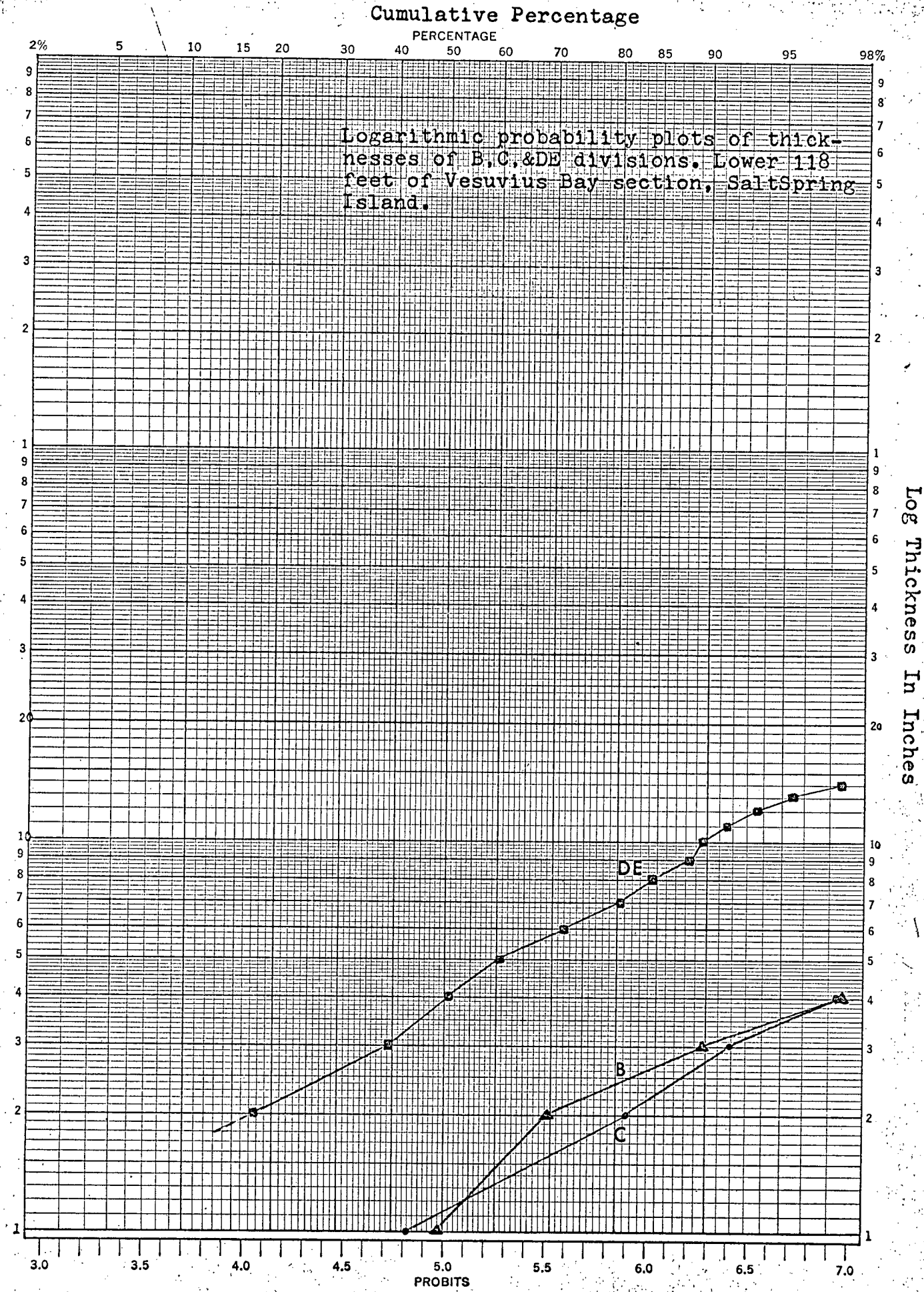

Cumulative Percentage
PERCENTAGE
2% 5 10 15 20 30 40 50 60 70 80 85 90 95 98%
Logarithmic probability plots of thicknesses of B.C.&DE divisions. Lower 118 feet of Vesuvius Bay section, SaltSpring Island.
DE
B
C
Log Thickness In Inches
3.0 3.5 4.0 4.5 5.0 5.5 6.0 6.5 7.0
PROBITS

Fig. 16

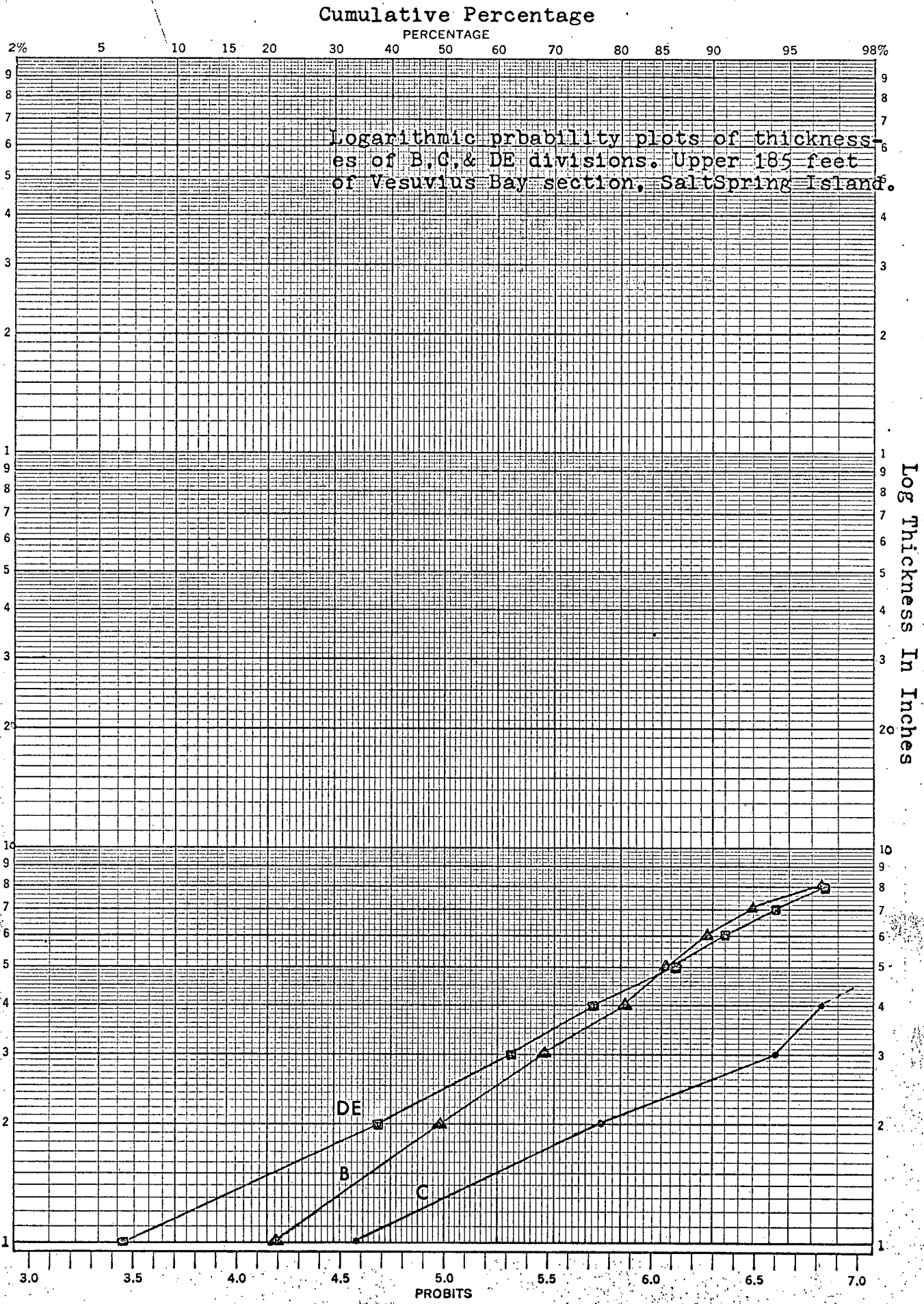

Cumulative Percentage
PERCENTAGE
2% 5 10 15 20 30 40 50 60 70 80 85 90 95 98%
Logarithmic prbability plots of thicknesses of B,C,& DE divisions. Upper 185 feet of Vesuvius Bay section, SaltSpring Island.
Log Thickness In Inches
DE
B
C
3.0 3.5 4.0 4.5 5.0 5.5 6.0 6.5 7.0
PROBITS

Fig. 17

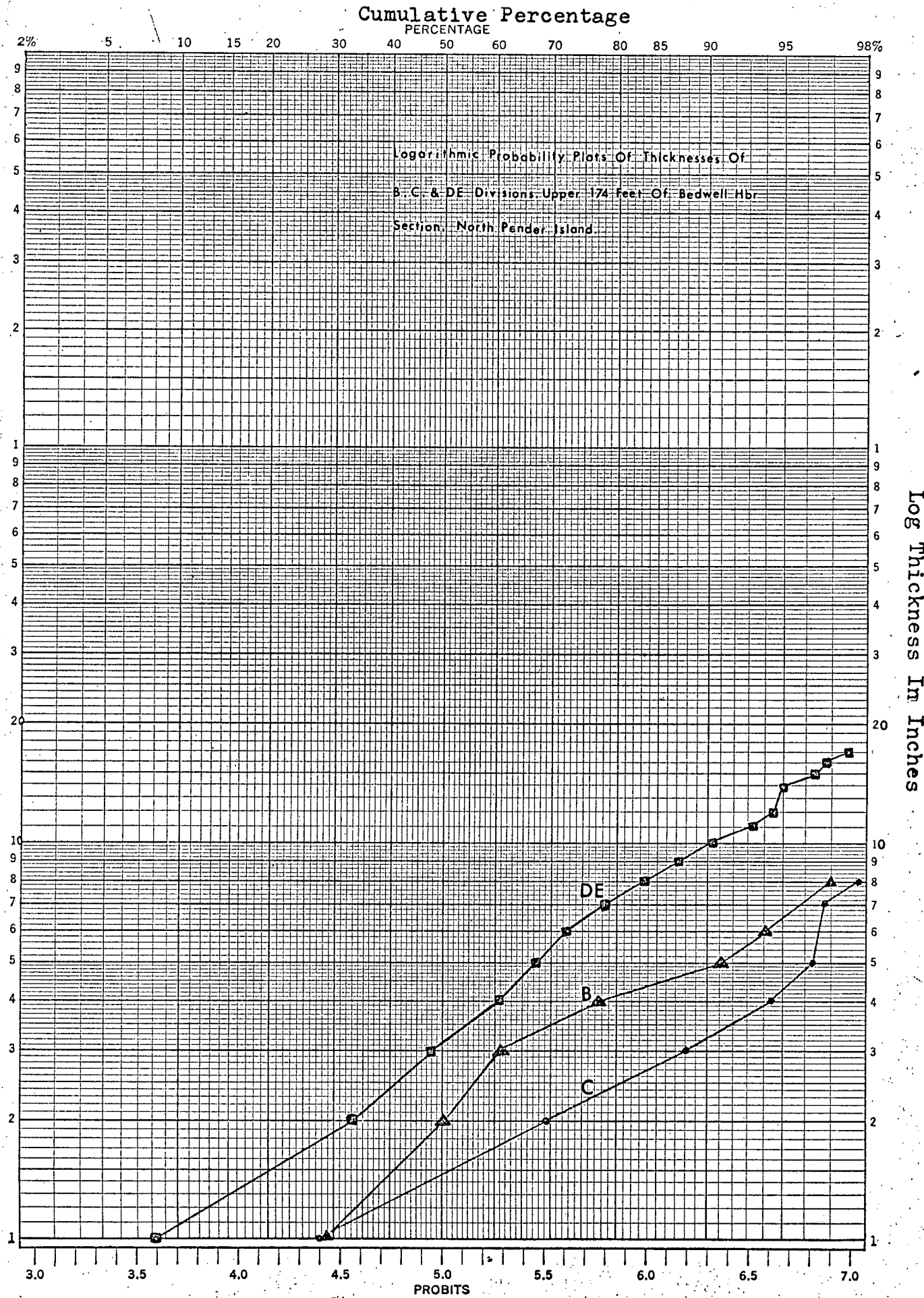

Cumulative Percentage
PERCENTAGE
2%
5
10
15
20
30
40
50
60
70
80
85
90
95
98%
Logarithmic Probability Plots Of Thicknesses Of
B. C. & DE Divisions Upper 174 Feet Of Bedwell Hbr
Section, North Pender Island.
DE
B
C
Log Thickness In Inches
3.0
3.5
4.0
4.5
5.0
5.5
6.0
6.5
7.0
PROBITS

Fig. 18

shale beds (i.e. DE-division) from Salt Spring and North Pender Islands, grouped into one inch class intervals, is plotted on logarithmic probability paper (figs. 16, 17, and 18). There are also a few shale beds reaching a thickness of about three feet; but they are not abundant enough to be plotted on a cumulative frequency curve. The three plots of the shales show that the distribution is approximiately log normal. A log normal relationship has also been reported for shales interbedded with graded beds by Bokman (1953), Nederlof (1959, in Hubert, 1967), McBride (1962), Scott (1966), and Hubert (1967). Pettijohn (1957, p. 161), after a comprehensive survey of the thickness variations shown by sedimentation units of different origins (e.g. turbidites, varves, loess etc.), stated: "It is apparent, therefore, that many sedimentation units of unlike origins tend to show thickness fluctuations that are log normal."

The mineralogy of the course fractions (sand to silt size) of the shales has been determined semiquantitatively under the petrographic microscope. Micas are the most abundant constituents, quartz and feldspars are second in abundance, and, in some samples, chlorite is as abundant as quartz and feldspars. Pyrite and carbonaceous matter are present in almost all samples and give the dark grey

color to the shale.

Fractions of the shales finer than 2 microns have been x-rayed, and the results show that illite ranges from 23 to 59 percent, kaolinite from 9 to 35 percent, montmorillonite from 4 to 32 and chlorite from 7 to 24. The method used for determining these percentages was adopted from notes given in a clay mineralogy course at Duke University, North Carolina in 1965-1966, (summarized from Freas 1962, Kunze 1959, Warshaw, Rosenberg, and Roy 1960, and Warshaw and Roy 1961). These percentages were obtained by measuring the intensities of the 001 peaks of the illite, montmorillonite, kaolinite, and chlorite in each sample. The intensities of the peaks were obtained by measuring the peak height above a base line and the peak width at half height. These measurements were multiplied as follows:

(1) For montmorillonite, multiply peak height by peak width at half height by 0.71.

(2) For chlorite and illite, follow step one but multiply by 2.7.

(3) For kaolinite, follow step one but multiply by 1.0.

These results were added for each sample, and the percentage of each mineral out of the above four minerals was determined.

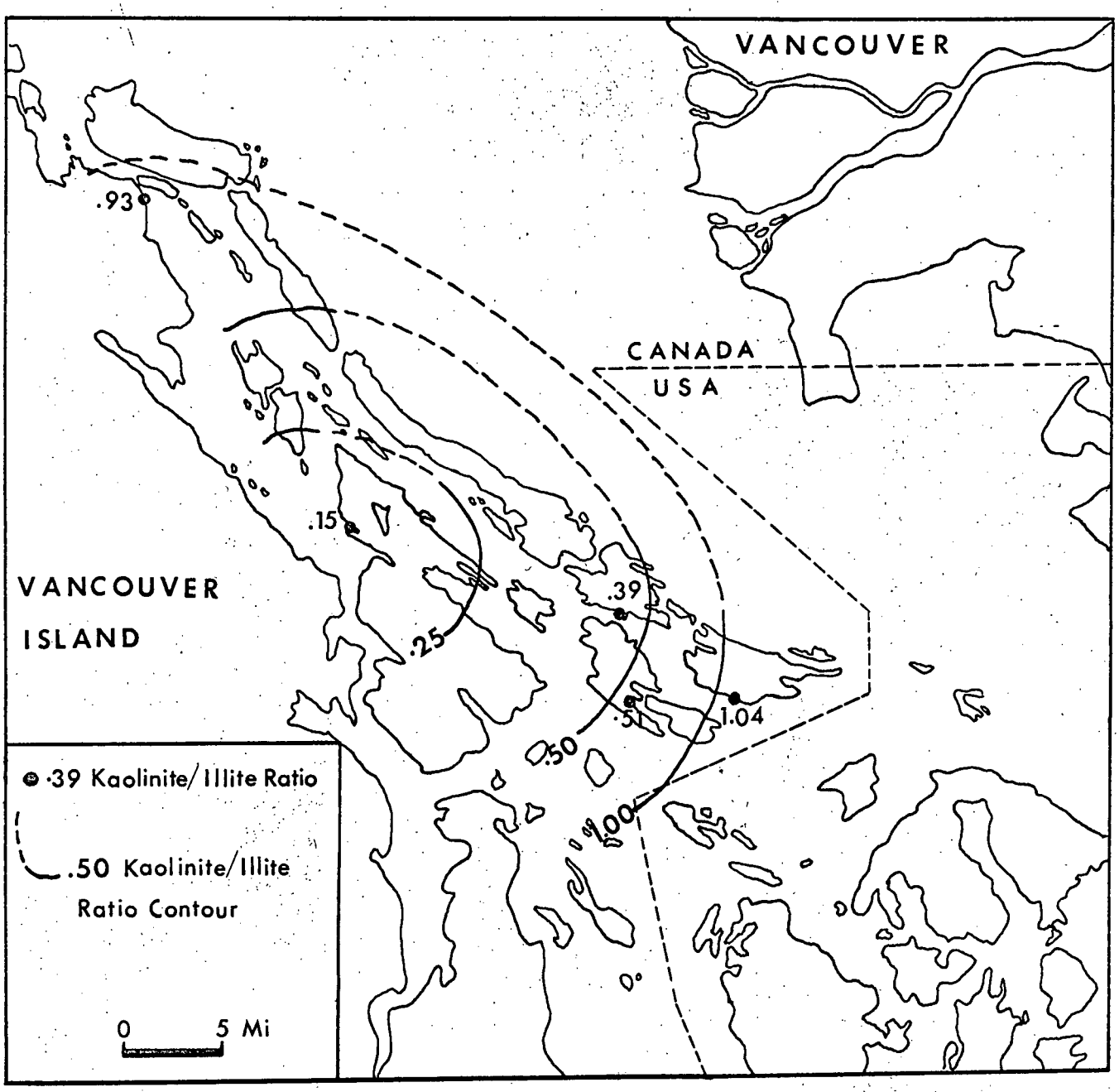


Fig.19:
Kaolinite/Illite ratio contour map of the shale of the Cedar District Formation.

The x-ray diffraction data also indicate that the kaolinite/illite ratio decreases from the Dodd Narrows, Saturna Island, North Pender Island, and Mayne Island toward Vesuvius Bay on Salt Spring Island (fig. 19). This ratio has been used by Parham and Austin (1967) in their study of the shales of the Glenwood Formation, South-eastern Minnesota to determine the direction of the source area which supplied the clays in this unit. Their work was based on previous work by Parham (1966) on the clay mineral assemblages in modern and ancient sediments, where he showed that "in basins of sediment accumulation kaolinite is concentrated closer to shore with respect to illite, and illite reaches maximum abundance seaward of kaolinite". If the above is true, fig. 19 suggests that Vesuvius Bay area on Salt Spring Island was the most distant area from the paleo-shoreline relative to the other localities where kaolinite/illite ratio is higher.

B. Sandstone

Sandstone comprises the bulk of the non-shale portion of the Cedar District Formation. It has a grey to greenish color, and varies from coarse grained to very fine grained sandstone, occasionally becoming silty, especially in the C-division of the turbidite units. This section of the thesis deals largely with field occurence

Fig. 20:
Shaley part of the Vesuvius Bay section just below the middle of the section. Sandstone percentage is about 5%. Vesuvius Bay, Salt Spring Island.

Fig. 21:
Turbidite sequence of alternating sandstone beds with thinner shale beds. High sandstone percentage. Vesuvius Bay, Salt Spring Island.

Fig. 22:
Alternating sandstone beds with thicker shale beds. Low sandstone percentage. Bedwell Harbour, North Pender Island.

Fig. 23:
Thick massive sandstone bed. Note a sandstone dike injected from below the sandstone bed and cutting through the underlying shale. Dodd Narrows, Vancouver Island.

Fig. 24:
Turbidite sequence of alternating shale and sandstone. Note the lateral uniformity in bed thickness. Bedwell Harbour, North Pender Island.

Fig. 25:
Turbidite bed showing repetition of its divisions. B-division (B) at the lower half of the bed is followed by thin C-division (C), then a second B-division (B), and the rest of the bed is composed of C-division (C). Bedwell Harbour, North Pender Island.

Fig. 20

Fig. 21

Fig. 22

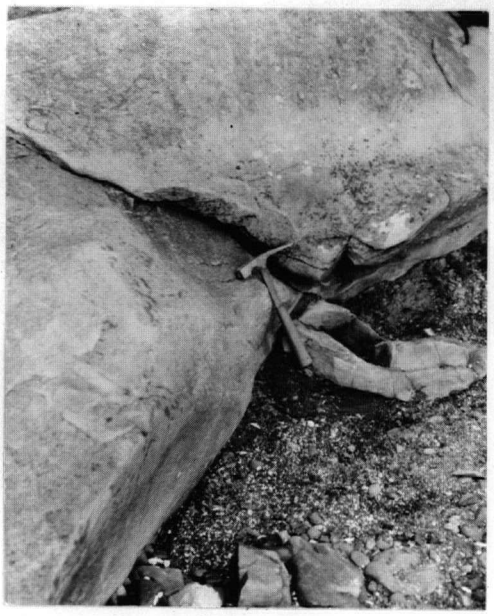


Fig. 23

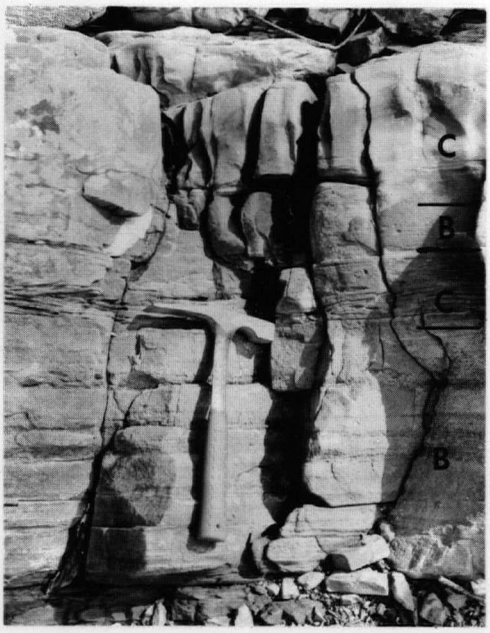


Fig. 25

Fig. 24

and distribution of sandstones; discussion of sedimentary structures and detailed petrographic data are presented in following sections.

The percentage of sandstone varies both vertically throughout the formation and horizontally throughout the outcrop area. In the Vesuvius Bay section, sandstone comprises about 44% by thickness of the measured part. Within one 350 foot interval just below the middle of this section, sandstone averages 5% (fig. 20); in other intervals, especially the top 800 feet, sandstone averages about 70% by thickness, with thick sandstone beds alternating with thinner shale beds (figs. 21 and 26). In the Bedwell Harbour section of North Pender Island, the sandstone averages 25% by thickness of the measured part, and, as in Vesuvius Bay section, the percentages varies vertically (figs. 15 and 22). On the southern part of Saturna Island, sandstone comprises 20% by thickness of the measured part, with the basal 48 feet lacking sandstone beds (except for exotic sandstone clasts).

Along Dodd Narrows on Vancouver Island, with only the top 1010 feet of the formation exposed, sandstone forms only 5% by thickness (sandstone dikes are not considered in this figure). There are only a few thick beds (3 to 6 feet thick) of sandstone present in this section,

thus the typical alternation of sandstone and shale beds present in other sections is not present here (figs. 14 and 23). On Mayne Island, the percentage of sandstone has not been measured, but the outcrop appearance is similar to that of the upper part of the Bedwell Harbour section on North Pender Island (fig. 15).

Individual sandstone beds have a remarkably even thickness laterally and are continuous within the area of the outcrop which is usually of no more than 300 to 500 feet in width (fig. 24). No lateral pinching out of these beds have been observed, even when they have a thickness of a fraction of an inch, although many of them have irregular lower bedding planes due to loading and other sole marks.

The thicknesses of successive beds show a large variation, from thin sandstone laminae within a thick sequence of shale, to beds having thickness of about 7 feet, to beds about 9 feet thick, the latter due to the amalgamation of two thick beds. Bed thickness can be classified into 3 types:

(1) In flysch-like sequences of rhythmically alternating shale and sandstone beds, sandstone beds generally have an average thickness of about 4 to 5 inches, with a range from a fraction of an inch to about 2 feet (figs. 5, 15, 21, 24, and 25).

(2) In some intervals of the section where sandstone percentage is very low and shale is the dominating lithology, sandstone bed thickness averages about an inch, and varies from thin laminae to 5 inches (figs. 20 and 22).

(3) Beds that have a range in thickness from 2 to 7 feet are also present. They are found at the middle and top of the formation, especially at Vesuvius Bay. In the Vesuvius Bay section of Salt Spring Island, there is also a 330 feet interval of very thick bedded sandstone (up to 7 feet thick), which commonly shows soft sediment deformation (figs. 26 and 27). Very thick beds of sandstone (average of 5 feet in thickness) are also found in the Dodd Narrows section of Vancouver Island, and are usually associated with sandstone dikes (fig. 23).

Regarding thicknesses of the A through E divisions within turbidite units, the cumulative frequency of the thicknesses of 163 B-divisions and 704 C-divisions from 728 turbidite units from Salt Spring and North Pender Islands sections, grouped into one inch class interval, is plotted on logarithmic probability paper (fig. 16, 17, and 18). There are also a few B-divisions reaching a thickness of a foot and a half, but they are not abundant enough to be plotted on a cumulative frequency curve.

Distribution of the C-division is closer to log normal than that of the B-division. A log normal relationship of the B- and C-divisions is reported by Hubert (1967).

These sandstone beds exhibit a variety of primary sedimentary structures which are discussed in detail in a following section.

C. Pebbly Mudstone on Saturna Island.

The lowermost 48 feet of the Cedar District Formation on southern Saturna Island is a chaos of clastic materials of all sizes and compositions embedded in a shale matrix (fig. 8).

The lower 25 feet of this interval consist of shale which contains isolated pebbles and cobbles of different shapes, varying from very angular to very well rounded. Milky quartz and basic igneous pebbles and cobbles tend to be well rounded, the angular fragments are metamorphic rocks which are commonly dark blueish-grey slates. Also scattered throughout this interval are sand and granule size fragments of the same composition as the larger fragments. Sandstone clasts of varying size and shape (size varying from a sandstone lump a fraction of an inch in diameter to blocks a few feet across) are present, showing no localization to a certain horizon; they are commonly intricately folded, the result of soft sediment deformation,

and resemble the "the slump overfolds" of Crowell (1957). Also present are calcareous concretions of the same type found in the other parts of the formation. There is no size sorting (figs. 28 and 29), and no imbricate structures, which are typical of conglomeratic, deltaic, foreset beds, were observed. The shale matrix shows lamination and concretionary weathering.

At the same locality, the top 23 feet of this interval is more sandy and fossiliferous. Fossils are broken fragments of pelecypods, gastropods, and possibly cephalopods shells. In the top 6 to 8 inches, these broken shell fragments become concentrated to form a coquina bed.

A mile and a half to the northwest and along the strike, this interval of pebbly mudstone becomes 25 feet thick. Accompanying this thickness decrease is the disappearance of the angular and rounded pebbles and fossil fragments. The criteria used to correlate it with the 48 feet interval to the southeast are its stratigraphic position and the presence of chaotic and folded clasts of sandstone embedded in the shale matrix.

The composition of the rounded pebbles and cobbles present in this interval is closely identical to the composition of the pebbles and cobbles of the directly underlying conglomerate, especially the abundance of milky

quartz pebbles and cobbles (fig. 9).

Crowell (1957) has described several sequences with characteristics very similar to those of the Saturna Island pebbly mudstone. He ascribed their emplacement to "a downslope movement under gravity". The present author concurs with Crowell's hypothesis for the mechanism of emplacement, that is slumping due to gravity, which resulted in the absence of sorting and the great contrast in size and shape of the pebbly mudstone constituents. The following is a model for the emplacement of the pebbly mudstone of Saturna Island, modified from Crowell (1957).

Pebbles and cobbles of contrasting shape and composition were carried by a high density turbidity current and deposited on a sloping, muddy bottom. Some of the pebbles and cobbles sank into the underlying mud. This loading of the mud by the coarse clastics and the occurrence of a slope initiated a gravity movement of the mud and overlying coarse clastics. The flow was viscous enough to prevent any size sorting, but not viscous enough to prevent complete mixing of the different size fractions. During the course of this gravity mass movement, clasts of sandstone from the underlying sediments were peeled off, rolled up, and incorporated with the flow, and formed the folded sandstone clasts.

Fig. 26:

Thick bed of sandstone encloses a deformed thinly bedded sandstone clast (derived from the underlying beds?). The sandstone clast grades in grain size from coarser at the bottom of the hammer to finer toward the head of the hammer. Vesuvius Bay, Salt Spring Island.

Fig. 27:

Thick bed of sandstone encloses a thinly laminated clast of sandstone. The scale is one foot long. Vesuvius Bay, Salt Spring Island.

Fig. 28:

Pebbles of different shape, size, and composition, from the pebbly mudstone of Saturna Island.

Fig. 29:

Specimen from the upper part of the pebbly mudstone where sand percentage increases. It contains fragments of all sizes of organic shells (arrows). Saturna Island.

Fig. 30:

Turbidite bed with its basal A-division composed of breccia. Note the sharp contact between A and B-divisions to the left of the hammer head. Bedwell Harbour, North Pender Island.

Fig. 31:

Polished specimen of the turbidite breccia of fig. 30. Two graded cycles are present; their approximate contact is indicated by the dashed line. Bedwell Harbour, North Pender Island.

Fig. 26

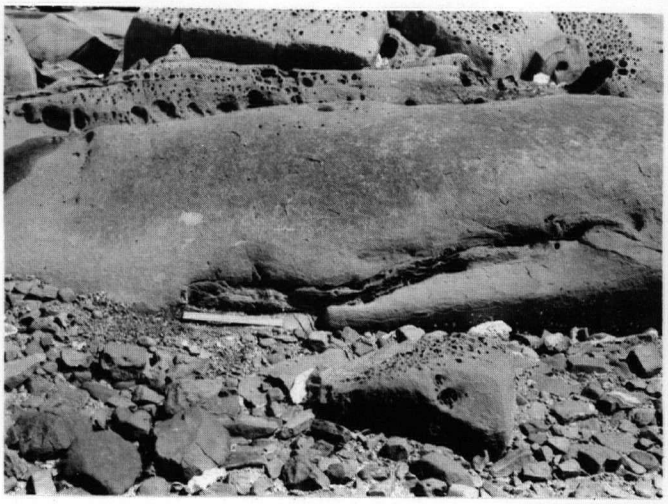


Fig. 27

Fig. 28

Fig. 29

Fig. 30

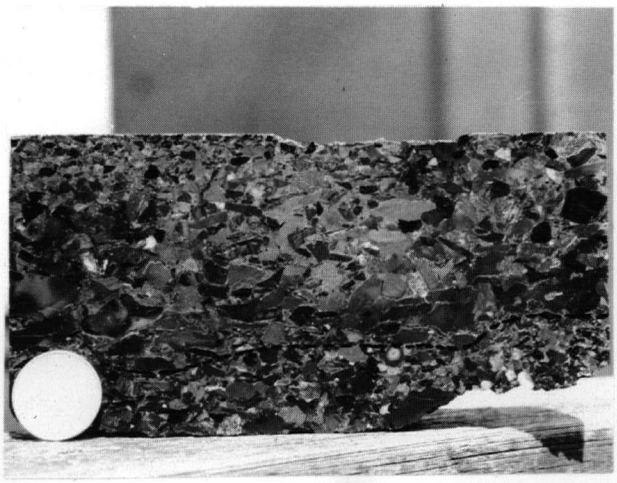


Fig. 31

D. Turbidite Breccia

A breccia bed with granule and pebble size clasts was found at the base of a turbidite unit (i.e. A-division) in the Bedwell Harbour section of North Pender Island. It was found to be continuous along strike within the outcrop area for a distance of about 300 to 400 feet. It is covered with the B-division of parallel lamination, but the contact between these two divisions is irregular (fig. 30). Breccia thickness averages about 5 inches.

The constituent fragments are very angular ranging in shape from equidimensional to rodlike (fig. 31). Color is mainly buff grey and brownish grey. The breccia clasts are composed of a great variety of rock fragments and minerals. Rock fragments, which are the dominant constituent, are shale, limestone, chert, and volcanic, granitic, and metamorphic rocks. Mineral identified is quartz. Also present are fragments of organic shells.

The breccia shows an overall grading in grain size from its bottom to its top, with a sudden decrease in size as the B-division of parallel lamination is reached (fig. 30), however, size grading also continues through the B-division. Within the overall grading of the breccia, at least two cycles of grading are observed (fig. 31). Fragments show no preferred imbrication.

A possible mode of emplacement of this breccia, is its transportation as a traction carpet (traction carpet defined by Dzulynski and Sanders, 1962 as: "The dense saltation zone ... which is not invaded by turbulent eddies of any size from the overlying turbulent flow") below a mature turbidity current; the latter is defined by Walker (1965) as a turbidity current with vertical and horizontal grading in grain size. In this type of flow, the traction carpet carries the coarser materials of the load and flows slower than the overlying sediments which move as a turbidity current. Consequently, the finer material in the tail of the overlying turbidity current will eventually overtake the traction carpet and deposit its load on top of the coarse sediment of the traction carpet, producing the sharp, non-gradational contact between A- and B-divisions illustrated in fig. 30.

E. Calcareous Concretions

Calcareous concretions were found to be very common throughout the formation in all the localities studied, except for the basal 118 feet exposed at Vesuvius Bay.

They are not restricted to a special type of rock, and are found associated with both sandstone and shale (figs. 32 and 33). Their longest dimension ranges from a few inches to several feet, and occasionally theyform a

Fig. 32:
Calcareous concretions (outlined by dashed lines) enclosed in a sandstone bed. Note thickening of the sandstone bed around the concretions. Vesuvius Bay, Salt Spring Island.

Fig. 33:
Calcareous concretion embedded in shale. One foot scale. Vesuvius Bay, Salt Spring Island.

Fig. 34:
Calcareous concretion with a thin very fine-grained sandstone bed crossing it (sandstone bed indicated by arrows). Scale is one foot long. Vesuvius Bay, Salt Spring Island.

Fig. 35:
Calcareous concretions joined to form a discontinuous bed. Bedwell Harbour, North Pender Island.

Fig. 36:
Calcareous concretion with its long dimension cutting shale lamination. Note organic borings (indicated by arrows). Vesuvius Bay, Salt Spring Island.

Fig. 37:
Calcareous concretion enclosing a bivalved shell. Pencil points to a broken shell fragment. Vesuvius Bay, Salt Spring Island.

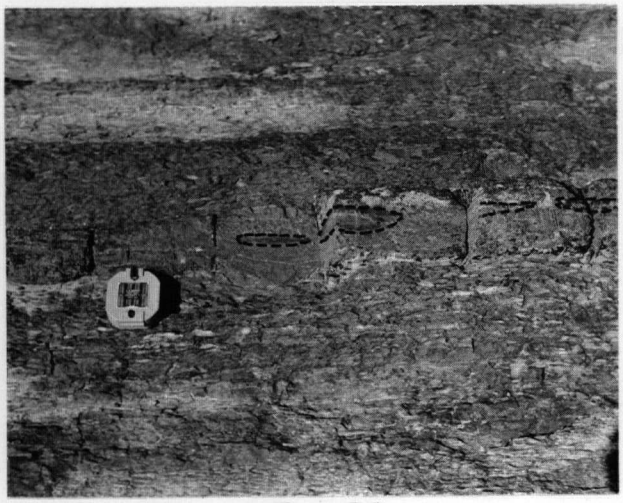


Fig. 32

Fig. 33

Fig. 34

Fig. 35

Fig. 36

Fig. 37

discontinuous bed of joined concretions (figs. 33, 34, and 35). They exhibit a wide range of shapes, from biconvex disc-shaped, to globular, to tube-like; others are lens-shaped as seen in the outcrop in two dimensions (figs. 33, 34, and 36).

They have two modes of occurrence relative to the surrounding beds. The first and most common is the type whose long dimensions are always parallel and concordant to the surrounding bedding or lamination (figs. 32, 33, 34, and 35). The second is the type that has a random orientation of the long dimensions, cutting through and disturbing the surrounding bedding and lamination (fig.36). Both types contain animal burrows or borings that are filled with sand and silt of the enclosing beds, suggesting burrowing took place while the concretions and the surrounding sediments were soft; alternatively, these might be borings into an already lithified concretion lying on or near the sea floor. In either case, this observation and other evidences mentioned below indicate early diagenetic formation of the concretions. Some of the concretions contain shells of bivalved invertebrates (possibly Inoceramus), (fig. 37), others have tabular shells (possibly ammonites), and some others contain fragments of broken shells. They frequently contain laminae

Photomicrographs of Calcareous Concretions

(Sample numbers at end of captions)

Fig. 38:
Fossil foraminifers(?) in calcareous concretion, filled with pyrite (black) and sparry calcite (white). Crossed nicols. Vesuvius Bay, Salt Spring Island. (V12).

Fig. 39:
Detrital grains of quartz, feldspar, mica, and clay minerals, in a calcareous concretion. Crossed nicals. Vesuvius Bay, Salt Spring Island. (V21).

Fig. 40:
Planktonic foraminifer (?) (in the center) surrounded by other fossil foraminifers(?). The matrix (or cement) is composed of fine-grained (micritic) calcite. Crossed nicols. Vesuvius Bay, Salt Spring Island. (V16).

Fig. 41:
Phosphatic pellets (indicated by arrows) in calcareous concretion. The matrix is composed mainly of micritic calcite and detrital quartz and feldspar. Note how the pellets are bent around a foraminifer (?) test. Plane polarized light. Vesuvius Bay, Salt Spring Island. (V21).

Fig. 42:
Photomicrograph to show, in detail, part of one of the phosphatic pellets in fig. 41. White grain in the center is quartz. Dark grains are phosphatic materials, the light grains are clay minerals. Crossed nicols. Vesuvius Bay, Salt Spring Island (V21).

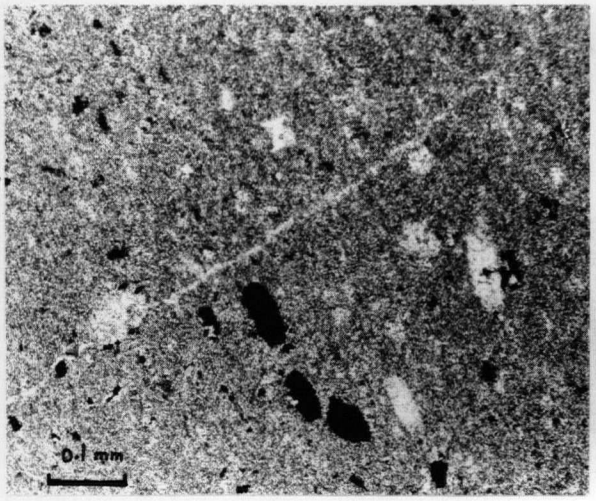


Fig. 38

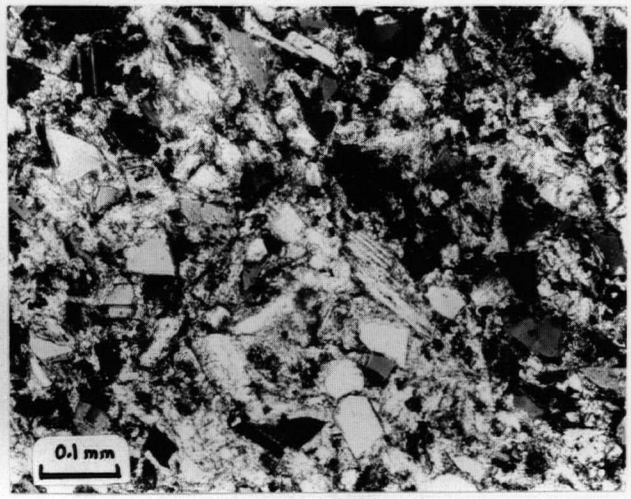


Fig. 39

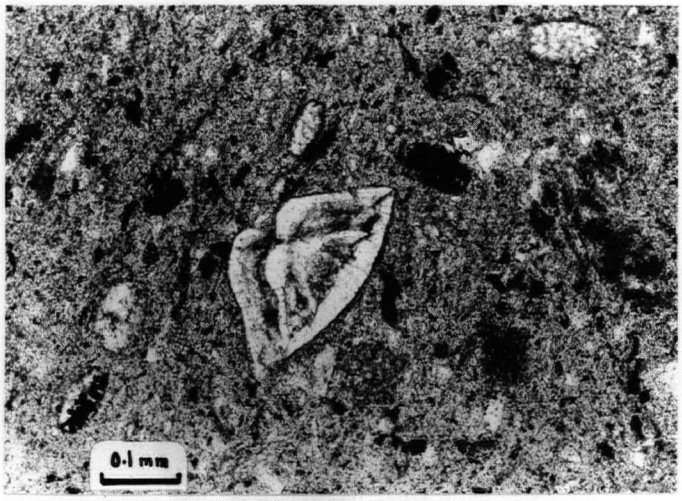


Fig. 40

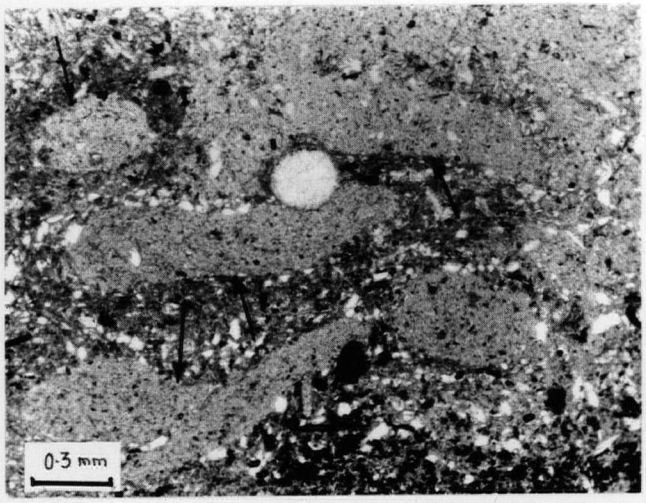


Fig. 41

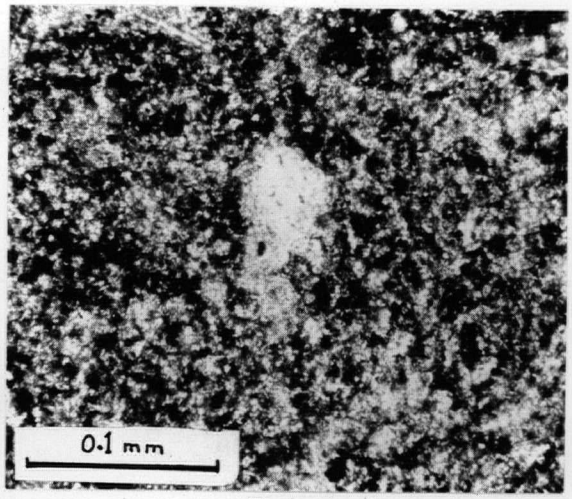


Fig. 42

which continue into the surrounding shale or sandstone; these laminae exhibiting the same sedimentary structures as in the surrounding rocks (fig. 34).

The concretions are grey in color and are composed mostly of calcite with some clay minerals and pyrite (fig. 38). When crossed or surrounded by silty shale or sandstone beds, they usually have a high percentage of the same detrital quartz, feldspar, and other minerals that constitute the surrounding rocks (fig. 39). They commonly contain circular and elliptical tests of microfossils (possibly foraminifers) which are usually filled with sparry calcite, and occasionally by pyrite (figs. 38 and 40).

Phosphatic pellets were observed in two concretions. They are globular to elongate and have a size range from ½ to 2 mm (fig. 41). Their colour is light brown under polarized light, and greenish brown under crossed nicols. Phosphatic material is also found disseminated throughout the concretions around the pellets. Detrital quartz, feldspars, and clay minerals within the concretions are also found enclosed in the pellets mixed with the phosphatic material (fig. 42). In concretions that have been intersected by silty or sandy laminae, the pellets are confined to the very fine grained calcite-rich parts of

Fig. 43:

Electron micrograph of a calcareous concretion. Minerals with high relief are detritial quartz, silicate minerals, or rock fragments. Rodlike grains are probably micaceous minerals. The low-relief grains are calcite matrix (or cement). Black grains are possibly illite. Note replacement of the detrital grains by the calcite cement along their irregular boundaries. Bedwell Harbour, North Pender Island. (P31).

Fig. 44:

Electron micrograph showing detrital grains embedded in calcite cement of variable grain size and shape. Vesuvius Bay, Salt Spring Island. (VSE7).

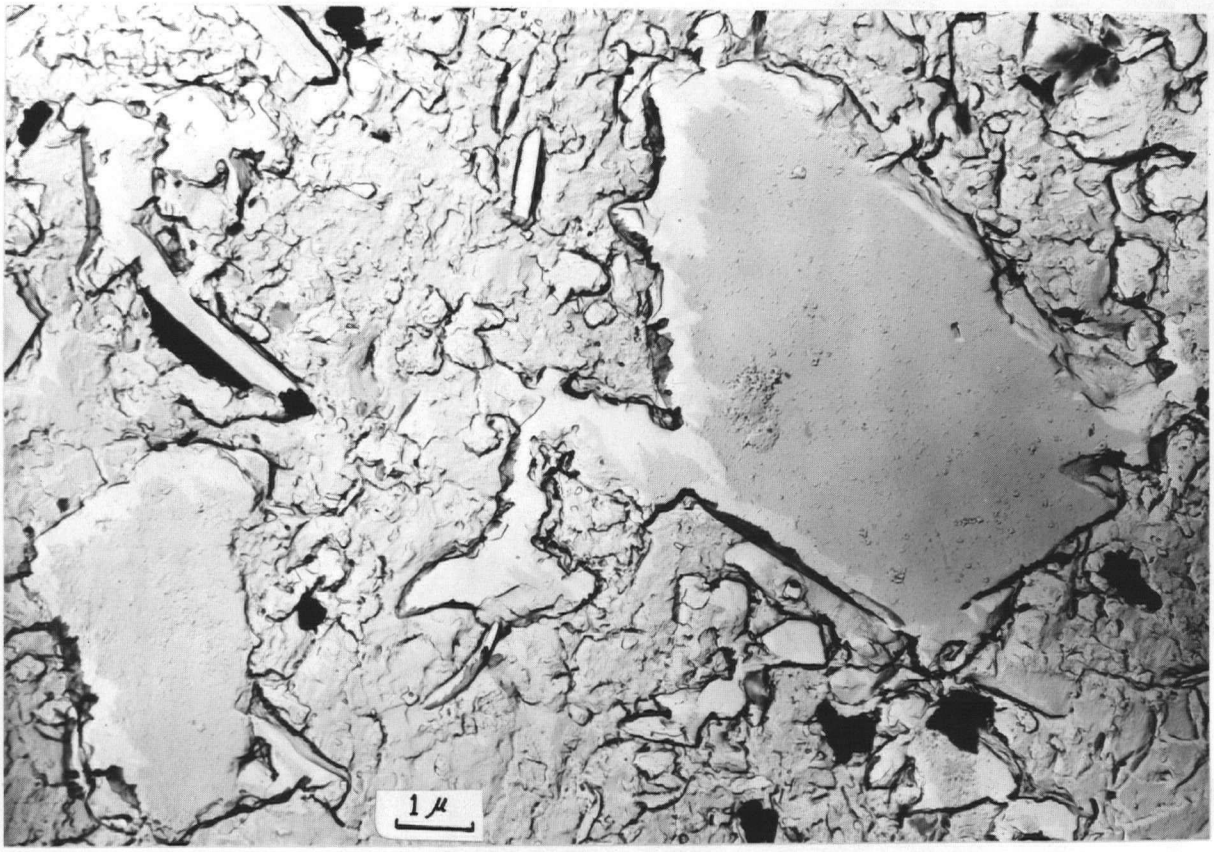


Fig. 43

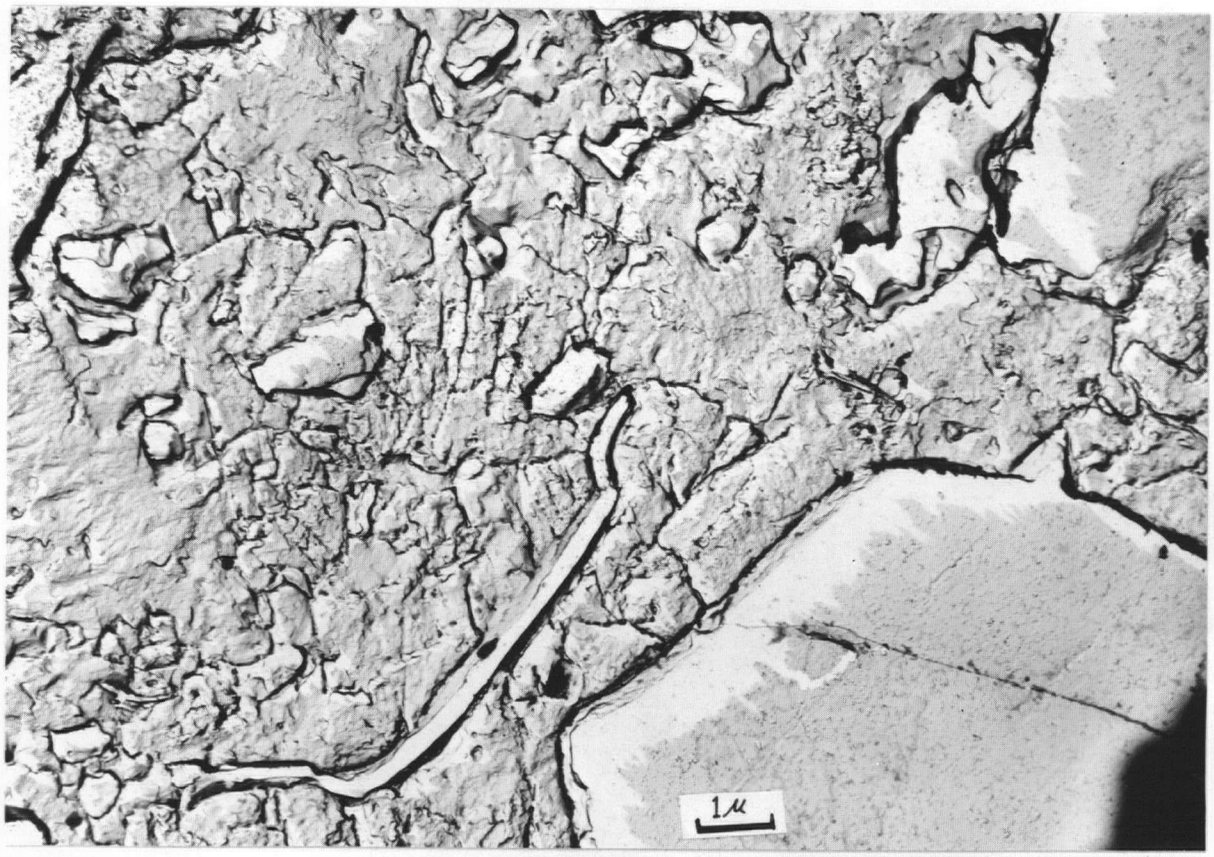


Fig. 44

the concretion. In one thin section, a pellet was observed to be bent around a foraminifer test (fig. 41), suggesting that this pellet settled on the test while the former was soft.

Study of electron micrographs of the calcareous concretions reveals some information regarding the detailed textures of the calcite cement and the enclosed detrital grains. The detrital grains (quartz, silicate minerals, or rock fragments) stand up with higher relief than the surrounding calcite cement (figs. 43 and 44), because they are less affected by the acid etching during preparation of the replica. The detrital grains commonly are partially replaced along their boundaries by the calcite cement (figs. 43 and 44). In some grains the replacement is confined to only a part of the grain boundary (fig. 43). Grain boundaries showing replacement are generally highly irregular and show interlocking of the calcite cement with the detrital grains.

The cement is composed of calcite grains of irregular and variable shapes with their boundaries highly embayed. The size is variable and ranges from about 0.1 micron to about 9.0 microns (figs. 43, 44 and 45). The surface of the calcite grains appear quite hummocky and irregular with numerous small inclusions.

Fig. 45:

Electron micrograph showing branching rod-like grains with calcite grains (low relief grains) between them. Vesuvius Bay, Salt Spring Island. (VSE7).

Fig. 46:

Deformed calcareous concretion (indicated by arrows) enclosed in a sandstone bed that underwent soft-sediment deformation. Vesuvius Bay, Salt Spring Island.

Fig. 47:

A-division (A) grades gradually upward into B-division (B). The dark rind is caused by seepage of sea water into the sandstone along fractures. Vesuvius Bay, Salt Spring Island.

Fig. 45

Fig. 46

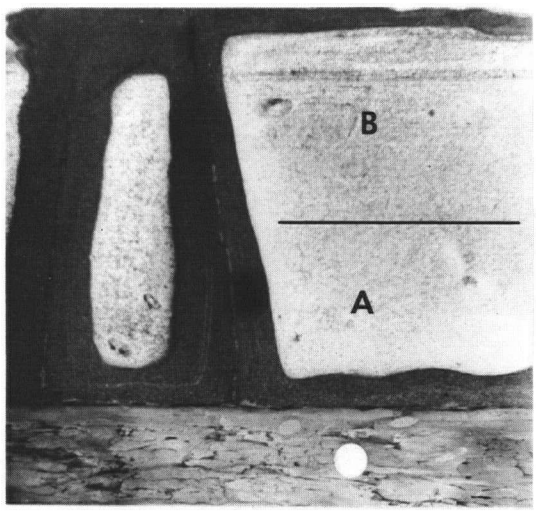


Fig. 47

The black grains (figs. 43, 44, and 45) are probably extracted clay minerals and have shapes somewhat similar to what Grim (1953, p.120 and 121) has identified as illite. The rod-like grains that stand up with high relief relative to the surrounding calcite cement (figs. 43, 44, and especially 45) are perhaps sections of micaceous minerals cut perpendicular to the 001 plane. In fig. 45 these grains are connected in a manner which suggests forceful separation along 001 cleavage planes by crystallization of calcite between these planes during diagenesis, (R. E. Garrison, 1968, personal communication).

Regarding the genesis of the calcareous concretions, the author suggests an early diagenetic origin (very early burial stage) during which, carbonates precipitated from interstitial solutions, are localized around a nucleus (e.g. organic shells or detrital grains) that may or may not leave a relic (figs. 33 and 37). During this precipitation there was apparently extensive replacement of detrital grains by secondary calcite. Some of these concretions are found within sandstone beds (fig. 32); the bed tends to be thicker around them suggesting that the concretion and the enclosing sandstone hardened earlier than the surrounding sandstone, therefore escaped strong compaction. In summary, the following criteria suggest

an early diagenetic origin for these concretions:

1. Organic borings and burrows filled with sediment of the surrounding beds.

2. Thickening of beds where concretions occur.

3. Their deformation when present in beds showing soft sediment deformation, (fig. 46).

4. Undeformed relics (bivalved shells) enclosed in the concretions (fig. 37).

G. Müller (1967, p. 154), in a discussion of the carbonate contretions enclosed in mudstones and shales poor in carbonates, stated "It seems probable that most of the concretions started to form in the shallow burial (and early) stage of diagenesis, because the enveloped relics of organisms are commonly not deformed."

Lippmann (1955, in G. Müller 1967, p. 154) explained the genesis of calcareous concretions as follows: "Ammonia resulting from the decomposition of organisms or amines gives rise to a strongly alkaline reaction in the vicinity of the animal (or plant) embedded in the sediment, and the pH is increased. As the solubility of the carbonates decreases with increasing pH, they are precipitated on the fossil from the interstitial solutions, which have been saturated with carbonates by dissolving the disseminated calcareous material (also present in

predominantly argillaceous sediments). Thus here the carbonate concentration of the pore solution decreases in comparison to the surrounding environment, and because of the difference in concentration, more carbonate is constantly diffused to the fossil. This process, accompanied by a constant growth of the concretion, continues until the production of ammonia stops, or until there are no more dissolved carbonates available in the vicinity."

The pyrite present in these concretions and the host rocks, is probably the result of the reducing conditions prevalent in the vicinity of the decomposing organisms. The significance of the rare phosphatic material noted above is not known. The author has not observed it to be associated with other types of rocks in the formation. Phosphatic material in sediments is typically a product of slow deposition or non-deposition; its association with the calcareous concretions may indicate the latter formed during intervals of reduced sedimentation rates.

6. SEDIMENTATY STRUCTURES

The sandstones and shales of the Cedar District Formation exhibit a wide range of sedimentary structures. They range from primary structures formed either by the filling

of marks made by an erosive current on a muddy bottom (e.g. different kinds of sole marks), and/or during the settling of the sediments out of the transporting current (e.g. graded beds, parallel lamination, current ripple lamination, etc.); to structures formed after deposition and before burial due either to gravitational movements (e.g. slump structures), or drag by sediment loaded currents flowing over soft sediments (e.g. deformational structures resulting from high density turbidity currents); to structures due to forceful injection of soft sediments through fissures (e.g. clastic dikes).

A. Internal Structures Within Turbidite Units

Within individual turbidite units, a limited number of sedimentary structures have been observed. These structures tend to exist always in a fixed order or succession (except for occasional repetition of a certain structure within the same turbidite unit, fig. 25) within the unit from its bottom to top. Terminology of the different structures has been discussed earlier in this paper. Some of the turbidite units show all the possible structures (divisions), but the majority tend to lack one or more of them.

These structures have been described in different parts of the world, and in sediments ranging in age from

the Precambrian to present (see PH. H. Kuenen and F. L. Humbert bibliography, 1964; the reader may also refer to K.O. Emery, 1964 for discussion of turbidites from Precambrian to present).

Walker (1965) has attributed the variation in the nature of the graded division (e.g. well defined or crude grading in A-division) to the type of turbidity current from which grading has formed. He also relates the variation in the nature of the other divisions (e.g. variation in types of current ripple lamination in C-division) to the hydrodynamic conditions of the current. He has (Walker, 1967) interpreted the hydrodynamics of the different divisions by analogy with the flow regimes of Simons and others (1965). In his view, the A- and B-divisions were formed within the upper flow regime, the C-, D-, and E-divisions within the lower flow regime.

a. Graded Division (A-division)

Out of the individual 746 turbidite units measured in the upper 185 feet and the lower 118 feet of the Vesuvius Bay section of Salt Spring Island, and the upper 174 feet of the Bedwell Harbour section of Pender Island, only 20 graded divisions were recorded. Additional units with A-division occur in other parts of the sections where systematic measurements of the different divisions were not

Fig. 48:
Massive A-division (bottom of the pencil) lies below laminated B-division with a sharp contact. Vesuvius Bay, Salt Spring Island.

Fig. 49:
Thick, faintly laminated, graded sandstone bed with its sole showing flute casts (a), bounce casts (b), and fine, closely spaced groove casts (c). Current from left to right. Bedwell Harbour, North Pender Island.

Fig. 50:
Plane-parallel lamination (B-division) caused by alternating dark, thin, fine-grained and light, thick, coarse-grained sand laminae. The top ½ inch shows cross lamination (C-division). Note organic reworking. Bedwell Harbour, North Pender Island.

Fig. 51:
Climbing ripple laminae of McKee (1965), (C-division). Vesuvius Bay, Salt Spring Island.

Fig. 52:
Upper bedding plane of sandstone bed showing slightly asymetrical branching ripple marks. Mayne Island.

Fig. 53:
Two superimposed C-division. Note the difference in thickness and types of structures between the lower thin, and the upper thicker C-divisions. Vesuvius Bay, Salt Spring Island.

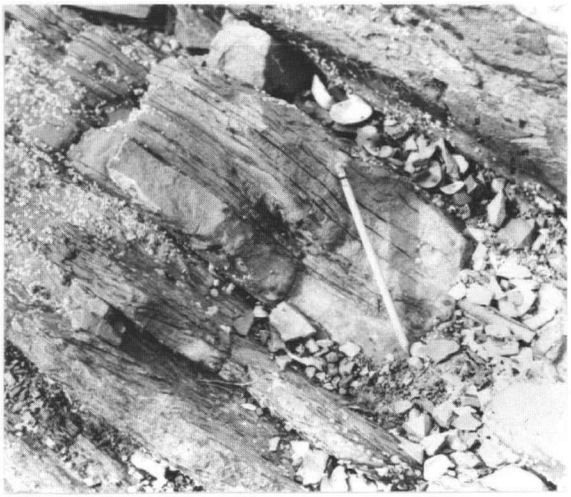


Fig. 48

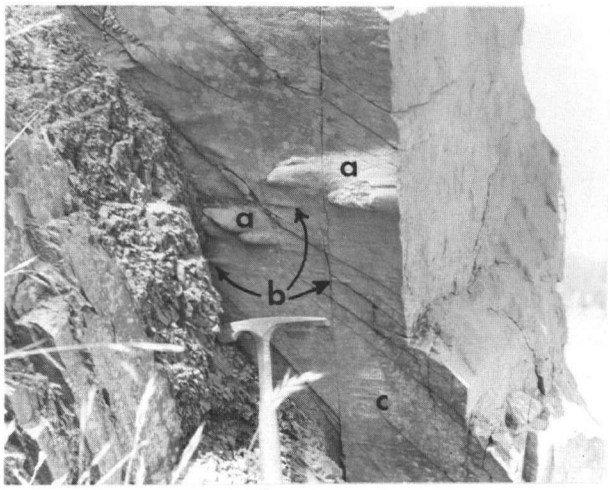


Fig. 49

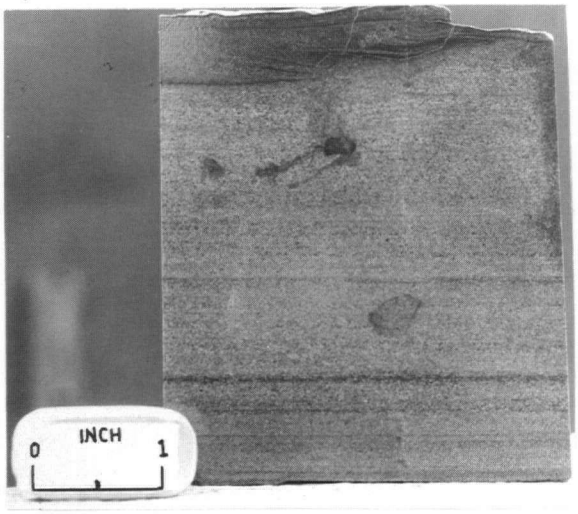


Fig. 50

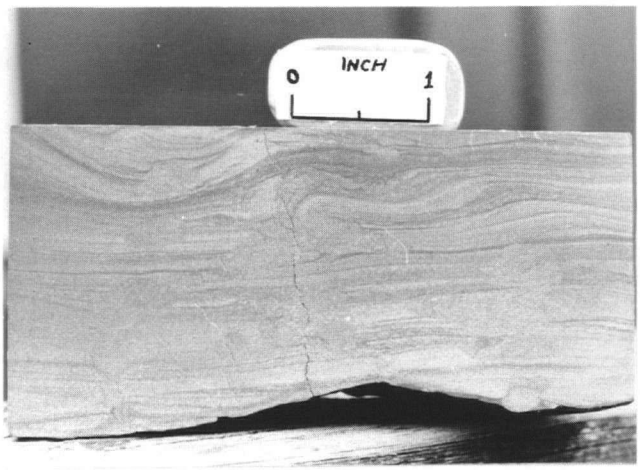


Fig. 51

Fig. 52

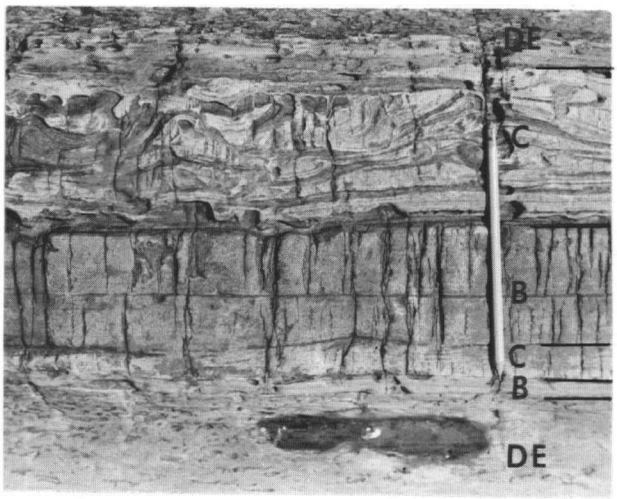


Fig. 53

made; these are mainly very thick beds (average thickness about 3 to 4 feet) with crude grading, and usually contain large clasts of deformed shale and sandstone (fig. 26 and 27). Other than these very thick, graded beds, two types of grading have been observed:

(1) A-division grades upward gradually without a sharp contact into the overlying B-division (fig. 47).

(2) A-division lies below B-division with a sharp well defined contact (fig. 48).

In both cases, the A-division has a sharp lower contact with the underlying DE-division.

Walker (1965, p. 13) suggested possible mechanisms to explain these two types of grading. The first type, he suggests, has been formed by the reworking of the upper part of a pre-existing A-division. This reworking, resulted in the formation of a plane-parallel division (B-division) at the top of A-division, The second type of grading in his view has been formed by primary deposition of A- and B-divisions from the turbidity current, with no reworking. In both cases, the turbidity current responsible for their formation has no traction carpet.

For thick graded beds (fig. 49), where there is faint lamination within the A-division, Walker (1965, p.11) has postulated deposition from turbidity current with a traction carpet. In his opinion the shear applied by the

current is too low to maintain continuous motion within the coarse sediments at the bottom of the current.

b. Lower Division of Plane-Parallel Lamination (B-division)

This division always overlies the A-division when the latter is present. Lamination is caused by the alternation of coarse-grained, thick, light colored laminae and fine-grained, thin, dark colored laminae containing biotite (fig. 50). This kind of lamination was also reported by Bouma (1962, p. 63), and Sanders (1965, p. 199). Occasionally the size of the coarse fraction at the base of this division is larger than the size of the coarse fraction at its top, indicating some degree of size grading. Some units show parting lineation along lamination planes within this division upon spliting.

166 B-divisions were recorded in the 746 turbidite units measured on Salt Spring Island and North Pender Island. Only a few (20) of the 166 B-divisions are underlain by A-division. The rest (146) form the base of 146 turbidite units (i.e. about 20% of the 746 turbidite units have B-divisions at their base). They lie with a sharp, almost planar lower contact over the underlying DE-division (when A-division is absent; fig. 25).

Kuenen (1953, p. 1049) and Sanders (1965, p. 199)

suggested that parallel lamination was formed by the fluctuation or pulsation of the current velocity. Walker (1965, p. 13) thought they were formed in the "plane bed with movement" part of the current regime of Simons et al. (1961), either by primary deposition from the current (fig. 48), or by reworking of previously deposited sediments (fig. 47).

c. Division of Current Ripple and Parallel Lamination (C-division)

This division is very abundant in the turbidite units of the Cedar District Formation. It was recorded in 707 out of the 746 turbidite units measured, and forms the basal part of 77% of the measured turbidite units (i.e. 77% of the units start with the C-division at their base).

Thickness of this division varies from a fraction of an inch to 10 inches, averaging about an inch and a half. Figures 16, 17, and 18 show the cumulative frequency of the thicknesses of 707 C-divisions measured in the Vesuvius Bay section of Salt Spring Island, and the Bedwell Harbour section of North Pender Island. The three lines approach log normal distribution, with a marked deviation at the 5-7 inch interval in the North Pender section (fig. 18), indicating thet C-divisions with this thickness range are rare.

Grains comprising the sediments of this division are mostly in the coarse silt to the very fine sand classes, and show a crude grading from coarse at the base of the division to fine at its top.

Structures observed in this division include:

(1) Current ripples and their associated cross lamination.

(2) Convolute lamination.

Most of the C-divisions exhibit either one of the above structures, but some of them have both structures associated together.

Almost all the cross lamination found in this division is of the type called by McKee (1965, p.76, figs. 4c and d) "pseudobeds", of both high and low angle. This kind of cross lamination has resulted from the migration of the ripples accompanied by deposition of sediments from above, resulting in what is called by McKee (1965) "climbing ripple laminae", (fig. 51). Only one thin bed, which consists entirely of C-division, shows rippling in three dimensions (fig. 52).

These current ripples range in wavelength from two inches to about a foot, their amplitude ranges from a fraction of an inch to about two inches. They occur either in a single set forming a thin C-division (fig. 53, lower C-division) and usually form single sets of cross

lamination "suggesting no fall-out of sediments during rippling", (Walker, 1965, p.15). They may also occur in several sets on top of each other (Fig. 53, upper C-division), or in the form of climbing sets of ripple drift cross lamination; the latter "suggests a fall out of sediments during or immediately after the initial formation of ripples", (Walker, 1965, p.15), (fig. 51). The last two forms tend to make a relatively thick C-division. Convolute lamination may also occur in one or more sets.

In cases where ripple and convolute lamination both occur in the same division, there is a consistent vertical arrangement of these structures. The C-division starts with very broad rippling at the bottom which grades upward into narrower ripples with greater amplitude, and, at the top of the division, the ripples tend to show convolution, (fig. 53, upper C-division; and fig. 54).

In addition to this vertical sequence, it was also observed that one structure could grade horizontally along the strike of the bed into another structure (e.g. current ripple lamination may grade laterally to convoluted lamination). Walker,(1965, p.12) suggested that convoluted lamination forms in cohesive bottom sediments; when the sediments lack such cohesiveness, current ripple lamination will be formed. If this is the case, the

Fig.54:

Grading of structures from plane-parallel lamination with small amplitude, to ripple lamination with larger amplitude showing slight convolution that has been reworked by organisms. Bedwell Harbour, North Pender Island.

Fig. 55:

The upper half of the specimen contains convolute lamination. Laminae involved in the lower ½ inch of the convolution are parallel to each other, but above this the laminae show cross lamination. Vesuvius Bay, Salt Spring Island.

Fig. 56:

Convolute lamination on a bedding plane. The pencil lies on the upper bedding plane surface of a sandstone bed that dips steeply toward the bottom of the photograph. Note similarity of convolute lamination to linguoid ripples. Vesuvius Bay, Salt Spring Island.

Fig. 57:

Organic borings in shale at high angle to the lamination. Vesuvius Bay, Salt Spring Island.

Fig. 58:

Organic borings on the sole of a sandstone bed obliterate questionable loaded flute casts (a). Note a narrow groove cast (indicated by arrows). Current direction from lower right to upper left as indicated by the flute and groove casts. Vesuvius Bay, Salt Spring Island.

Fig. 59:

Loaded flute cast (a) and a wide groove cast (b). Current direction is from lower right to upper left. Vesuvius Bay, Salt Spring Island.

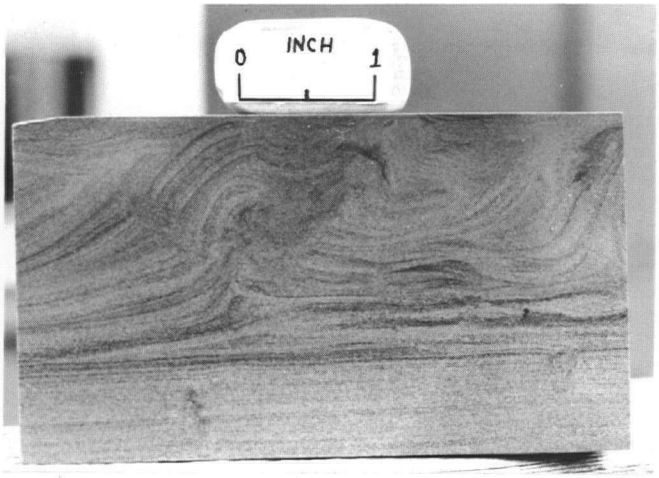


Fig. 54

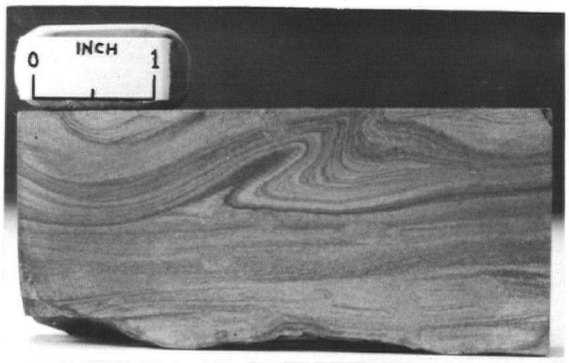


Fig. 55

Fig. 56

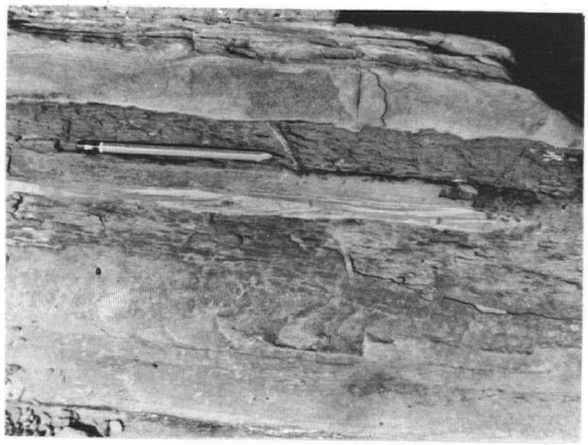


Fig. 57

Fig. 58

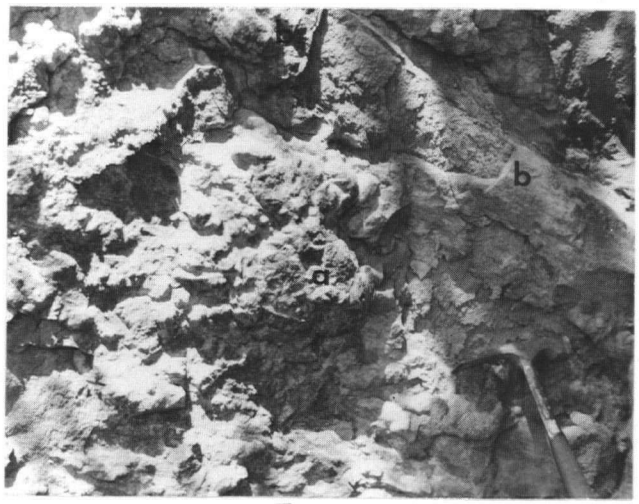


Fig. 59

presence of convoluted and current ripple lamination in the same bed suggests either:

(1) the cohesiveness of the grains of the bottom sediments was not uniform during their deposition, resulting in the formation of both current ripple and convoluted lamination; or

(2) that current ripple lamination formed first in cohesionless sediments, then locally the cohesion increased, and the overlying current deformed the ripple lamination into convolute lamination (this phenomenon of increase in cohesion was called the "Hjulström effect" by Sanders (1963, p.178). Both assumptious seem valid, since it was observed that there are two types of convolute lamination present. The first type, in which the convoluted laminae are parallel to each other (fig. 55, the laminae of the basal ½ inch of convolute lamination are parallel to each other), indicates that these laminae were originally plane parallel and not current ripple laminae, and were deformed due to the shear applied by the overpassing current on cohesive sediments. In the second type, convolution was developed after rippling since ripple cross lamination is still preserved in the convolute lamination (fig. 54).

Convolute lamination could not be observed in three dimensions, except for one bed where the upper bedding

plane is exposed (fig. 56). From this picture it seems that the original structure before convolution was a bed of linguoid ripples.

Regarding the origin of convolute lamination, Kuenen (1953, p. 1057) attributed their formation to "intensification of ripple mark by hydrodynamic pressure combined with loading in the troughs": Ten Haaf (1956, in McBride 1962, p. 52) modified this mechanism slightly and proposed "that the action of accelerated deposition in troughs of probable incipient ripple marks combined with the expulsion of water through the crests was the cause". Sanders (1963 and 1965) and Walker (1965), pointed out the importance of cohesiveness of the bottom sediments in their formation. Other workers feel they may be post-depositional, deformational structures, formed by "Lateral intrastratal flow of liquified beds" (Williams, 1960), or by "creep when sedimentation took place on a slope." (Holland, 1959).

d. Interturbidite Division (DE-division)

Because it was difficult to differentiate between the upper division of plane-parallel lamination (D-division), and the pelitic division (E-division) in the field, the author has called the laminated shale overlying the sandy part of the turbidite unit the "interturbidite

division" (Walker, 1967), (figs. 5, 15, and 36). But the reader should not think of them as entirely non-turbidite in origin, since they show some grading from silt to clay size, suggesting deposition from a current suspended load (Sanders 1965, and Walker, 1965).

The main structure in this division is plane-parallel domination. This lamination was believed by Walker (1965, p. 19) to be formed by the alternation of coarse-grained and finer-grained laminae. Occasional laminae of light colored, very fine-grained sandstone were found to contain foreset lamination.

This division varies in thickness from a fraction of an inch to 33 inches and averages about 2.5 inches. Figures 16, 17, and 18 show the cumulative frequency of the thicknesses of 727 interturbidite divisions measured in Vesuvius Bay section of Salt Spring Island, and the Bedwell Harbour section of North Pender Island. These also show log normal distribution.

The shale of this division contains accasional animal burrows, oriented in various directions. Some are parallel to the bedding, others are inclined at different angles to the bedding plane, (figs. 36 and 57).

B. Sole Marks.

These are marks present on the bottom side of sandstone and siltstone beds. Many of them have been used for determining directions of paleocurrents since they have been formed as fillings of depressions caused by the drag and scouring of currents and their loads along a muddy bottom.

Dzulynski and Sanders (1962, p. 61) have classified sole marks into the following groups:

a. Marks made prior to the arrival of the current which deposited the covering bed:
   1. Organic tracks and burrows.
   2. Structures made by creep or slump of the mud before the current carrying the material for the covering bed arrived.

b. Current marks made in the mud by the passage of the current which carried the sediment forming the covering bed:
   1. Scour marks (flutecasts, channels, and frondescent marks).
   2. Toolmarks: marks which are made by the contact of some object (the tool) and the bottom (e.g. groove casts and bounce marks).

c. Marks made at the interface between the mud and covering bed after deposition of covering bed.

1. Organic tracks and burrows.
2. Structures made by deformation due to flowage, creep, or slumping of the sediment mass. Load casts fall in this category.

Relatively few soles of sandstone beds are well exposed in the study area, but almost all the different marks that belong to the second and third major groups of the above classification have been observed in the Cedar District Formation.

It was observed that current marks (scour and tool marks, especially flute casts and groove casts with occasional channels) are present only on the soles of sandstone beds thicker than a foot and a half. Organic burrows of the type made after the deposition of the covering bed, are present in beds of variable thickness and are not restricted only to thick beds. Burrows which cross loaded flute casts (fig. 58) clearly indicate their post-depositional origin.

a. Flute Casts

These are fillings of scour marks, made by a turbidity current in the underlying mud. The flute casts protrude from the sole; they are oblong with the long dimension parallel to the current direction. At the up-current end the flute cast is narrower and protrudes further from the sole than in the down-current direction; (Bouma, 1962, p. 138).

Well developed flute casts are found only in the section of Bedwell Harbour of North Pender Island. Here, only two beds were observed with flute casts on their soles, and these beds were thicker than a foot and a half. These flute casts are less than five inches in length, and have a width averaging an inch and a half, (fig. 49). On the sole of the same bed containing the flute casts, fine, closely spaced groove casts and bounce marks are also found. A slightly bigger flute cast which shows some loading, was observed on the sole of a three feet thick bed in Vesuvius Bay section, (fig. 59). Questionable flute casts, were observed in the Vesuvius Bay section, extensively modified by loading and organic burrowing; they show parallelism to a groove cast present on the same sole, (fig. 58).

b. Frondescent Marks ?

Scour marks that are filled with coarse grained sandstone containing scattered granules, have been observed on the sole of a thick sandstone bed in the uppermost part of the Vesuvius Bay section of Salt Spring Island; they are associated with and partially obliterate gigantic groove casts, indicating their formation subsequent to the formation of the groove casts (fig. 60). They have a dendritic lobate form; the average length of the individual lobe is four inches and average width is about two inches. The down-current end of each lobe protrudes from the sole more than the up-current end (fig. 61).

Scour marks of a similar nature have been produced experimentally, and called frondescent marks by Dzulynski and Walton (1962, p. 291, plate XXb and XXIa), and Dzulynski (1965, p. 198, fig. 7). Similar marks have been called "cabbage leaf cast" by Ten Haaf (1959), and "fondescent furrow flute casting" by McIver (1961), in Potter and Pettijohn (1962, p. 126-127, fig. 5-10).

Scour marks that cut the underlying lamination in shale have been observed in one locality in Vesuvius Bay in Salt Spring Island. They are filled with coarse-grained sandstone and scattered granules, and a few of them show some loading, (figs. 62 and 63). Due to

Fig. 60:

Frondescent marks (a) partially obliterate groove casts (b) on the sole of a thick sandstone bed that dips steeply away f om the observer. Current direction from lower right to upper left. The scale is 3 feet long. Vesuvius Bay, Salt Spring Island.

Fig. 61:

A close-up of the frondescent marks of the same bed in fig. 60. Current direction from right to left. Scale is about 8 inches long. Vesuvius Bay, Salt Spring Island.

Fig. 62:

Scour marks on the base of a thick sandstone bed underlain by a thin bed of shale. Vesuvius Bay, Salt Spring Island.

Fig. 63:

Loaded scour marks on the base of the same sandstone bed as in Fig. 62. Vesuvius Bay, Salt Spring Island.

Fig. 64:

A sole of a thick sandstone bed (same as in figs. 60 and 61), showing at least 3 generations of groove casts; some show change in direction. Current from lower right to upper left (measured from the frondescent marks to the left of these groove casts). Vesuvius Bay, Salt Spring Island.

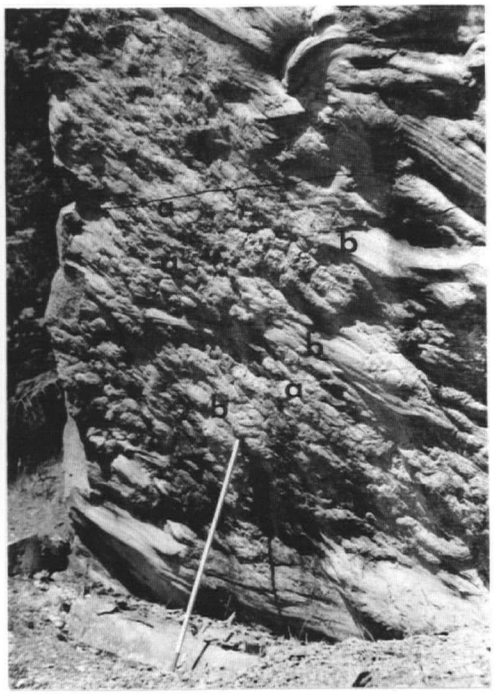


Fig. 60

Fig. 61

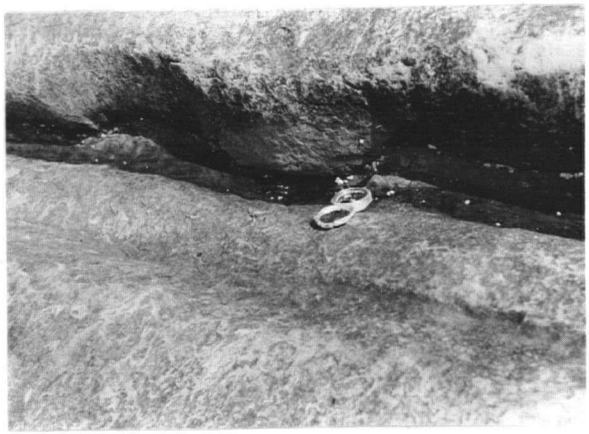


Fig. 62

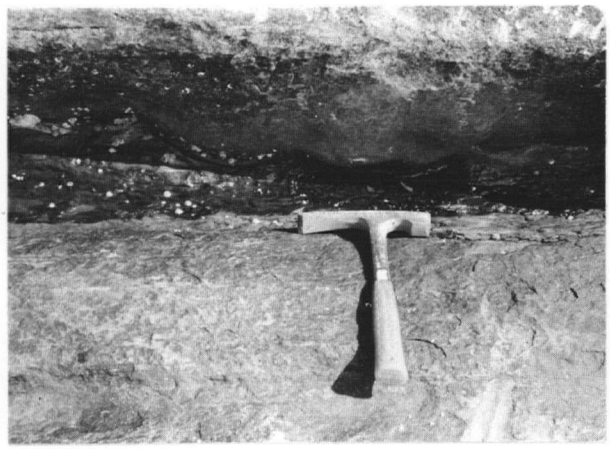


Fig. 63

Fig. 64

incomplete exposures, it was not possible to tell whether they are flute casts or channels.

c.Groove Casts

These structures are formed by the filling up of long grooves scoured in the underlying mud by some object carried in a turbidity current. The grooves are parallel to the current direction. The groove casts themselves reveal only the line of current, but presence of other marks such as flute casts provide information on the current direction.

Groove casts are also observed in beds thicker than a foot and a half. In one locality (fig. 49), they are very narrow, a matter of a fraction of an inch in width, extend along the whole exposed sole, are strikingly closely spaced, and appear to have been formed by coarse grained sand or granules dragged or pushed along the muddy bottom at the base of a traction carpet.

In the uppermost sandstone beds of the Cedar District Formation, just below the DeCourcy Formation at Vesuvius Bay, a thick bed of sandstone has at least three generations of groove casts on its sole, all having different sizes and orientations, (fig. 64 and 65). The same bed about 50 feet to the northwest has two generations of groove casts intersecting at an angle varying from 11 to

30 degrees (fig. 66). Some of these grooves are very narrow and straight (fig. 65), others are wider and raised higher above the sole surface and show superimposed ridges (figs. 64, 65, and 66). Some of the latter group of groove casts show a change in direction (fig. 65).

The shape of the wide groove casts with the superimposed ridges suggests they may have been formed by the drag of a water-logged tree, the main branch or trunk of which made the main groove cast, the superimposed ridges being formed from twigs in the trunk. The narrower groove casts were obviously formed by smaller tools, such as pebbles, wood fragments, or shale fragments, but none of these tools have been found with the casts.

The straightness, continuity, and uniformity of height and structure of groove casts in general led Hsu (1959, p.534) to postulate laminar flow within the current carrying the tools. Dzulynski and Sanders, (1962, p.63) considered their formation not as a result of "sediment-loaden turbulent eddies .... but rather the current caused larger objects (tools), which travel in linear paths as a result of inertia, to strike the bottom in various ways", and concluded that they "are the result of transportation of grains in the traction mechanism (in this case the dominant activity is saltation)".

Fig. 65:

Groove casts of different shapes and sizes. Note the change in direction of the wide grooves with the superimposed ridges (a). Same bed as in fig. 64. Hammer indicated by an arrow. Vesuvius Bay, Salt Spring Island.

Fig. 66:

Two generations of intersecting groove casts with superimposed ridges. Vesuvius Bay, Salt Spring Island.

Fig. 67:

Clasts of laminated, fine-grained sandstone (at both ends of pencil) embedded in coarse-grained, thick sandstone bed. Vesuvius Bay, Salt Spring Island.

Fig. 68:

Deformed clast of laminated, fine-grained sandstone embedded in thick bed of coarse-grained sandstone. Vesuvius Bay, Salt Spring Island.

Fig. 69:

Clast of fine-grained, laminated sandstone showing recumbent folding, embedded in a thick bed of coarse-grained sandstone. Vesuvius Bay, Salt Spring Island.

Fig. 70:

Thinbeds of sandstone and their interlayered shale (at head of the hammer) involved in soft-sediment deformation and engulfed by the overlying thick sandstone bed. Note how these thin beds are still connected with the underlying undisturbed beds. Vesuvius Bay, Salt Spring Island.

Fig. 65

Fig. 66

Fig. 67

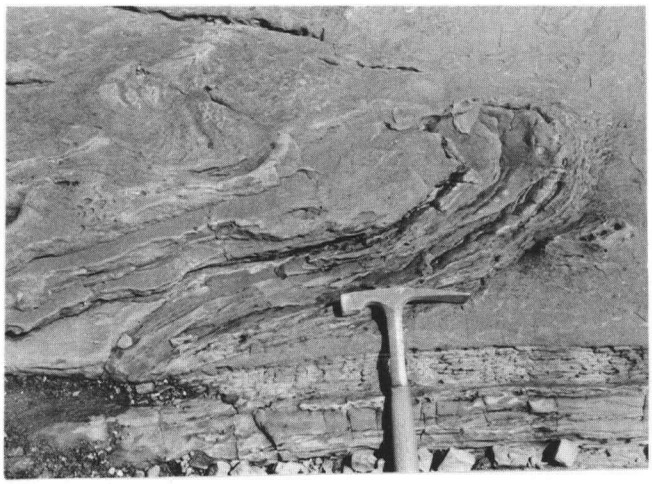


Fig. 68

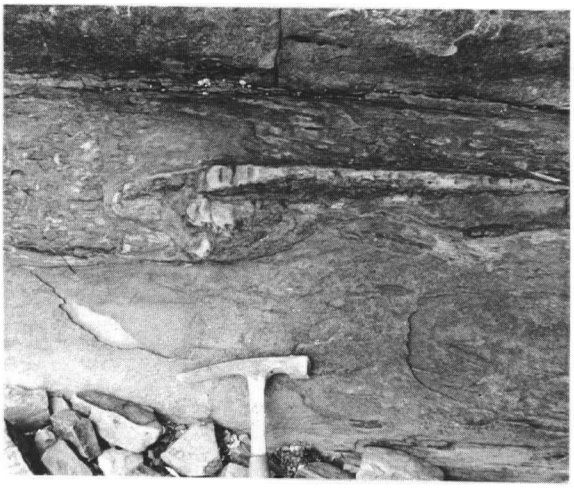


Fig. 69

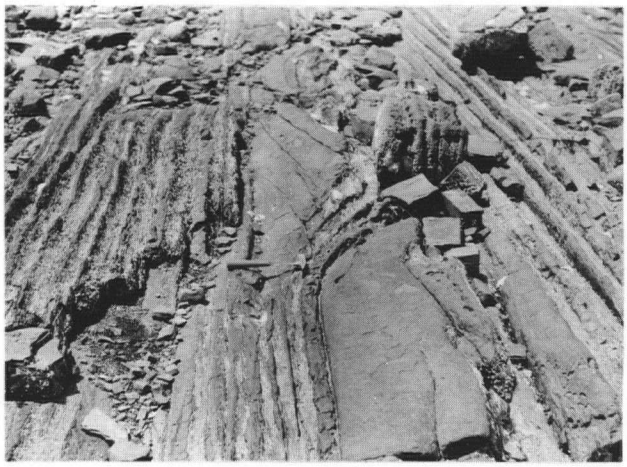


Fig. 70

The variation in direction of groove casts on a single sole (e.g. figs. 64 and 65) has been attributed by Ten Haaf (1959, in Dzulynski and Sanders, 1962, p.86) not to change in the direction of the entire current, but to the criss-crossing of lobate fronts of the current. Dzulynski and Sanders (1962, p.91) suggested that this change in direction of the tool marks is the result of change in direction of movement within the traction carpet.

d. Bounce Casts

These structures are defined by Bouma (1962, p.135) as "sole markings, varying up to 5 cm in length and somewhat less in width, running parallel to the current direction. These short grooves were presumably produced by objects grazing the bottom and rebounding, leaving behind a shallow groove which fades out gradually at both ends." In the Cedar District Formation such casts were only observed on the sole of a sandstone bed in Bedwell Harbour in North Pender Island (fig. 49). They are about one inch long, and a fraction of an inch wide, and tend to be parallel to the associated flute and groove casts. They indicate the track of the current but not its direction, since they fade equally on both ends.

e. Organic Borings and Burrows

Beside the borings and burrows that are found to protrude into shale and the calcareous concretions, there are also some sandstone beds with organic borings and burrows on their soles (fig. 58). That these borings and burrows probably originated after the formation and loading of the scour marks is suggested by the fact that, in some cases, they partially obliterate scour marks on the same sole (fig. 58).

C. Soft-Sediment Disturbed Bedding.

Structures (slump overfolds) that are the result of slumping on Saturna Island, were discussed in a previous section on pebbly mudstone.

An interval of about 330 foot in the middle of the Vesuvius Bay section on Salt Spring Island, is characterized by abundant thick beds of sandstone (up to 7 feet thick). These beds are internally structurless except for rude grain size grading from granules and coarse-grained sand at the bottom to medium and fine-grained sand at the top. Interbedded with these thick beds, are thinner bedded, laminated sandstone (B- and C-division), and shale (DE-division of interturbidite).

These thick beds of sandstone almost always enclose

Fig. 71:
Clasts of fine-grained, laminated sandstone showing slight deformation, enclosed in a thick bed of coarse-grained sandstone. Vesuvius Bay, Salt Spring Island.

Fig. 72:
Clasts of fine-grained sandstone and shale showing asymetrical folding, enclosed in a thick bed of sandstone. White objects are encrusting barnacles. Vesuvius Bay, Salt Spring Island.

Fig. 73:
Recumbent folding in sandstone and shale clasts which are enclosed in a thick bed of sandstone. Vesuvius Bay, Salt Spring Island.

Fig. 74:
Clasts of fine-grained sandstone beds enclosed in coarse-grained thick sandstone bed. These clasts show complex deformation. Beds dip steeply to the left. Vesuvius Bay, Salt Spring Island.

Fig. 75:
Sandstone dike cutting through shale. Mayne Island.

Fig. 76:
Very thin discontinuous sandstone dike cutting through shale. Mayne Island.

Fig. 71

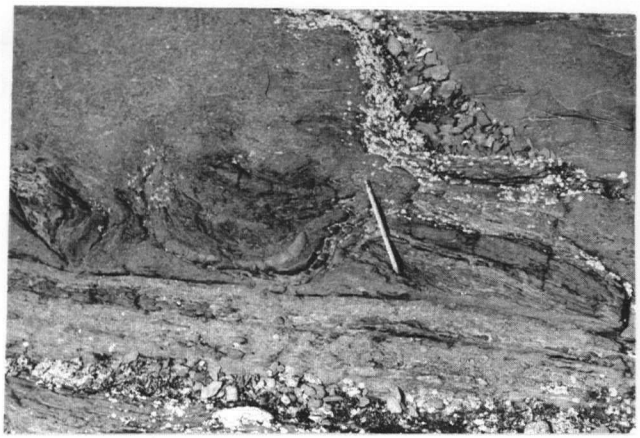


Fig. 72

Fig. 73

Fig. 74

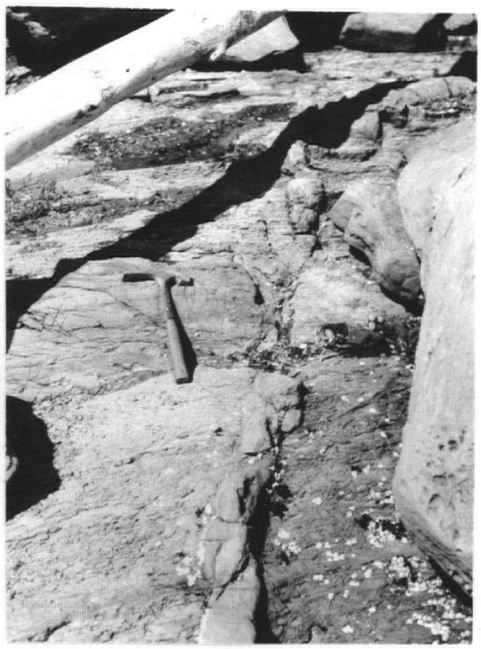


Fig. 75

Fig. 76

clasts and pieces of beds composed of coarse-grained sandstone, laminated fine to medium-grained sandstone, or shale, or a combination of two or three of them. These clasts occur either in the form of small, angular chips a few inches in length (fig. 67), or large, gently or tightly folded clasts ranging in length from a few feet (figs. 27, 68, and 69), to several feet (fig. 26). Some of these deformed layers can be traced laterally and observed to connect with the underlying undisturbed beds (fig. 70). This kind of bedding and the associated enclosed clasts are also present intermittently in the upper part of the Vesuvius Bay section.

These enclosed clasts are fragments of beds that seem to have been stripped from originally coherent layers. They represent fragments of beds belonging to the B, C, and DE divisions. Beds underlying the thick sandstone beds are composed essentially of B, C, and DE divisions.

These clasts exhibit a wide range of structures. Some are gently folded (figs. 27 and 71), others show a symetrical folding (fig. 72), the majority show recumbent folding (figs. 26, 69, and 73), and still others are thrown into a complex pattern of folding (fig. 74). The last type of folding involves clasts that can be traced laterally into the underlying undisturbed beds.

The disturbed layers are always seen in only two dimensions. The strike of their fold axes appears to have a general preferred orientation of northwest-southeast, but precise measurement is not possible, because of lack of three dimensional outcrops. By using graded bedding and the vertical succession of the different turbidite divisions, the author was able to determine top-bottom relationships in the disturbed layers and thus could differentiate between anticlines and synclines in the case of recumbent folds (fig. 26). In the case of thin-bedded, laminated, complexly folded clasts, however, it was not possible to determine top-bottom relationships, hence it was not possible to determine whether the folds are synclines or anticlines.

Certain limitations can be placed on the processes which deformed these beds. Since the beds overlying and underlying the deformed beds are undisturbed, this deformation must have been syndepositional. The thick sandstone host beds were soft enough to engulf the underlying thinner sandstone and shale beds; the latter must have been also soft, but they were cohesive enough to be plastically deformed and not dispersed into a cohesionless mass.

The fact that some deformed clasts, in the thick

sandstone beds, are still connected to the underlying undeformed beds suggests that they were deformed and engulfed without lateral transport during the emplacement of the overlying sand. Other clasts in the thick sandstone beds, which are disconnected from the underlying undeformed beds , may or may have not undergone appreciable lateral transport.

From the above it can be concluded that the enclosed clasts were originally parts of soft, undisturbed, stratified beds on the sea bottom. They subsequently became disturbed and broken up during passage of a current carrying a dense slurry of sand which engulfed them. This slurry was later deposited as a thick sand bed.

Dzulynski and Radomski (1966) experimentally reproduced nearly identical structures by introducing a heavey suspension into a flume tank whose bottom was covered with stratified soft layers. The bottom layers were interlayered clay beds, deposited by normal settling in the flume, and beds of mixed plaster of Paris and coal dust deposited by an artificial turbidity current. The introduced heavey suspension was composed of a mixture of plaster of Paris, cement, sand, and occasionally small pebbles dispersed in water. When this heavey suspension

Fig. 77:
Thick sandstone dike cutting shale sequence. Dodd Narrows, Vancouver Island.

Fig. 78:
Branching sandstone dike (hammer at point of branching). Dodd Narrows, Vancouver Island.

Fig. 79:
Sandstone dike cutting shale. Note contorted lamination within the dike. Dodd Narrows, Vancouver Island.

Fig. 80:
Exotic block of sandstone embedded in shale. Note the bending of shale lamination below the block, and the abrupt termination of laminae against left side of the block. Dodd Narrows, Vancouver Island.

Fig. 81:
Exotic block of sandstone embedded in shale. Also note the bending of shale lamination around the block, and the absence of other exotic materials. Dodd Narrows, Vancouver Island.

Fig. 82:
Deformed, laminated sandstone clasts enclosed in shale. Note fragmented sandstone bed above the clasts. Mayne Island.

Fig. 77

Fig. 78

Fig. 79

Fig. 80

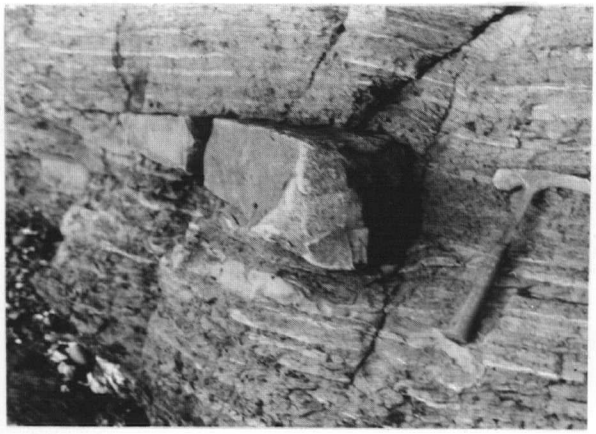


Fig. 81

Fig. 82

was allowed to flow over the soft, stratified bottom sediments in the flume, considerable deformation of the stratified deposits occured. The latter beds were broken up into clasts and engulfed into the heavey suspension. Once the heavey suspension had completely settled as a "thick" sand layer, the enclosed clasts assumed a wide range of deformational patterns (Dzulynski and Radomski, 1966; photos: 1 to 5). The similarity of some of these deformed clasts to what have been called "slump overfolds", "pseudo-nodules", and "ball- and pillow" structures, led the authors to postulate such a mechanism for the formation of these structures.

Likewise, the similarity between these experimentally produced structures and those observed in the Vesuvius Bay section leads the present author to postulate a similar mechanism, i.e. impact of a heavey suspension upon horizontal soft sedimentary layers. This could involve flow of a turbidity current with a traction carpet moving over soft, previously deposited turbidite beds.

D. Sandstone Dikes and Miscellaneous Features

Sandstone dikes were found only in two localities throughout the outcrop area of the Cedar District Formation. In the Dodd Narrows area of Vancouver Island, where the upper 1010 feet of the formation is exposed, sandstone

dikes quite commonly cut a shale sequence containing a few thick sandstone beds (fig. 14). Also on Mayne Island, where the upper 200 feet of the formation are exposed on the south coast, the lower 50 to 70 feet of this section contains occasional sandstone dikes cutting shale beds (fig. 75). Thus in both localities, the sections cut by dikes are mainly shale with a few thick sandstone interbeds.

The sandstone dikes are tabular bodies, ranging in thickness from a fraction of an inch (fig. 76) to about 3 feet (fig. 77). In general they have sharp walls, and they may cut the host beds either at right angles, high angles, or very low angles. Their shapes vary from straight, regular, thick dikes (fig. 77), to irregular thin dikes (fig. 14). Most of the dikes can be traced for only relatively short distances, either because they are discontinuous or because of lack of exposures. In one case (fig. 23), a sandstone dike was observed to extend downward from a thick sandstone bed for a distance of a foot and a half through laminated shale before it disappears into the shale bedding plane. One of the thick dikes is observed to branch into an offshot that runs at a low angle across the bedding planes of the host rocks (fig. 78).

The thick dikes seem to be structureless as observed by the nacked eye in the field. Some of the thin dikes show distinct lamination, which is commonly wavey and occasionally contorted, roughly resembling current ripple and convolute lamination (fig. 79). Whenever the host rocks are faulted, the associated sandstone dikes are also faulted, indicating that the sand injection took place before faulting.

In the same shale intervals where the sandstone dikes are present, are clasts and blocks of rocks, either of lithology foreign to the host rocks (fig. 80 and 81), or of the same lithology as some beds overlying the host rocks (fig. 82). Blocks of the former type are observed only in the Dodd Narrows area on Vancouver Island. Shale lamination overlying and underlying these blocks curves around the blocks (fig. 81), while laterally adjacent lamination ends abruptly against steep sides of the blocks (fig. 80). Because only two or three of these blocks, which are widely spaced in the horizontal direction, have been observed within this shale interval, and because of the fact that they are surrounded by well laminated, undisturbed shale, with no other exotic clasts or pebbles and sand in the vicinity, the possibility of their introduction as a mass slump or slide seems improbable, since

one would expect to find a mixture of clastics of different sizes and shapes, as in a pebbly mudstone. Their origin is problematical, but two possibilities exist: (1) They may represent isolated sand-filled channels. The wedge-like shape of some blocks (fig. 81) and the fact that adjacent shale laminae terminate abruptly against the sandstone (fig. 80) tend to support this interpretation. But the overall shape of other blocks (fig. 80) do not in any way resemble channels. (2) They may represent blocks of sandstone transported individually from elsewhere; the fact that the blocks are not folded would indicate their introduction as highly consolidated or cemented masses, otherwise they would have been deformed. One possibility is that the blocks were detached from shoreline cliffs or sea bottom outcrops by gravity and/or seismic shocks and slid or rolled down into the basin of shale deposition, truncating some laminae during final emplacement. Subsequent burial and compaction around the coherent blocks would produce the curving laminae above and below (fig. 81). Although the exact origin remains unclear, the author is inclined to favor the second possibility, or some variant of it.

Clasts of this latter type occur in one locality as deformed sandstone clasts, which show no preferred

orientation, and are embedded in a shale host rock (fig. 82). Just above this shale and its enclosed clasts is a bed of sandstone with characteristics similar to those of the underlying sandstone clasts. This sandstone bed is fragmented just above the sandstone clasts, as if these clasts were once part of the sandstone bed. This kind of feature seems to have been formed when a sand bed was deposited on a soft muddy bottom; later this bed may have been fragmented into clasts which were then folded and sank into the underlying mud. The disruption of this sand bed into sand clasts could be accounted for by some kind of a shock (e.g. an earthquake).

The formation of sandstone dikes has been accounted for as a result of "earthquake shock, momentary liquification of watersaturated sand, and injection into fissures opened by the shock. The driving force is the pressure of the overlying strata.", (Potter and Pettijohn, 1963, p. 165).

From the above, it could be inferred that during deposition of the shale sequence with occasional sandstone beds, the site of deposition and adjacent areas were tectonically active and suffered a period of intermittent earthquakes. These caused liquification of the soft sand and its injection into fissures opened in the surrounding

Serial No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
Specimen No.	V103C	V11	V26	V30	V34	V39	VSA3	VSC6	VS18	P34	P35	PA25	PB24	PB4	PA7	PB10	PA12	PB13	PC15	S7	Sa	Sb	C1	C6	M4	M2
Quartz	36.5	27.5	45.8	35.5	26.0	33.7	28.0	44.7	39.2	29.7	44.3	52.3	28.4	50.0	48.8	57.4	39.0	51.0	45.2	43.3	49.0	42.2	31.4	34.7	36.3	35.5
K-feldspar	9.2	4.9	4.7	7.1	7.0	12.6	6.5	9.3	20.6	5.3	4.6	3.3	5.1	8.0	8.1	7.7	17.7	10.0	5.2	4.7	9.3	8.3	7.0	4.7	9.0	6.1
Plagioclase	6.5	4.0			20.5		11.5				17.1	12.5			9.5						14.7	5.8	15.6	18.6	12.1	
Mica	9.2	5.3	1.8	4.9	3.8	2.9	8.0	13.6	2.4	2.0	4.3	4.0	4.7	12.4	5.5	3.0	1.4	5.6	8.0	10.0	6.0	7.3	2.9	4.7	2.3	2.1
Chlorite	-	-	0.7	-	-	0.7	-	-	1.2	4.4	0.7	1.0	0.9	0.2	0.8	1.1	1.6	1.3	0.4	0.8	0.7	1.0	-	0.3	0.2	0.7
Volcanic rock fragments	-	0.2	1.7	2.8	5.1	6.1	4.5	-	11.0	0.2	1.6	2.1	-	-	-	-	0.4	1.0	-	-	0.8	-	4.7	6.6	0.2	0.8
Sedimentary rock fragments	0.2	-	0.2	0.2	-	1.5	21.6	-	2.1	4.8	0.7	1.7	1.2	0.4	0.5	1.9	1.6	6.0	-	1.4	0.2	-	-	0.3	-	0.8
Metamorphic rock fragments	-	-	-	1.4	0.4	-	-	0.2	0.3	3.3	-	1.2	-	-	-	-	0.4	0.3	-	-	0.2	-	0.9	0.6	0.3	-
* Polycrystalline quartz	-	0.2	-	3.4	-	0.8	-	-	0.5	7.7	1.8	5.0	-	-	-	0.4	0.4	0.8	1.2	0.6	0.8	-	1.0	0.3	1.3	-
Chert	1.4	0.2	0.3	4.3	4.2	1.3	2.0	0.4	4.4	0.9	0.3	2.7	-	1.8	2.5	1.3	3.6	4.0	2.6	-	1.5	0.5	2.9	0.7	0.3	-
Calcite cement	24.6	49.6	34.5	33.9	-	29.7	-	-	2.7	26.8	4.0	4.6	-	21.0	13.3	12.8	23.3	18.5	26.2	12.3	8.5	29.2	7.4	0.9	14.9	42.1
Siliceous cement	-	-	-	-	-	-	-	-	-	-	4.0	-	-	-	-	-	-	-	6.4	-	-	-	-	-	-	-
Matrix	7.2	2.0	5.3	3.4	27.5	6.3	16.1	27.7	13.9	8.3	14.1	6.2	56.0	1.8	5.0	6.6	7.6	9.6	2.2	24.3	3.7	2.2	23.1	25.4	4.0	6.3
Unknown	1.6	2.0	1.8	1.2	3.8	2.9	0.6	2.7	1.2	2.2	2.1	2.7	0.4	2.4	2.8	1.7	1.2	1.3	-	1.6	2.2	1.7	1.3	0.7	2.1	2.0
Others	3.6	4.2	3.2	2.0	1.7	1.6	1.3	2.4	0.3	4.6	0.6	0.8	2.2	2.2	3.2	6.0	2.0	1.8	2.6	1.2	2.5	1.8	2.0	1.6	1.0	3.6

Table 2:
Composition of the Cedar District sandstones.

* Polycrystalline quartz = Quartzite in classification triangles, figs. 89 & 90 .

coherent mud. These shocks may have also resulted in the disruption of some thin beds of soft but cohesive sand into clasts that sank into the underlying soft mud, forming what are observed now as sandstone clasts embedded in shale host rock with a relic of the "mother" sandstone bed underlying them (fig. 82). At the same time, it is possible that these shocks affected the shore line or sea bottom outcrops, resulting in the detachment of some sandstone blocks which slid or rolled down across the basin slope as individual blocks. Such downslope transportation may have been intermittent, requiring a series of such shocks.

7. PETROGRAPHY OF THE SANDSTONE

The composition of twenty six sandstone samples was determined quantitatively by the method of point-count. Twelve of these samples were stained with sodium cobaltinitrite for potash feldspar determination. Table 2 shows the results of these determinations.

A. Quartz:

This is the most abundant mineral component of the Cedar District sandstone, varying from 26.0 to 57.4 percent and averaging 39.8 percent. No attempt was made to

Fig. 83:

Photomicrograph showing the replacement of a quartz grain by the calcite cement along fractures (indicated by arrows). Crossed nicols. Vesuvius Bay, Salt Spring Island (V39).

Fig. 84:

Photomicrograph showing the replacement of a quartz grain (Q, indicated by arrows) and a feldspar grain (F) by the clay-size matrix. Crossed nicols. Vesuvius Bay, Salt Spring Island. (VS18).

Fig. 85:

Photomicrograph showing the replacement of a feldspar grain (F, indicated by arrows) by the calcite cement along fractures. Crossed nicols. Vesuvius Bay, Salt Spring Island. (V39).

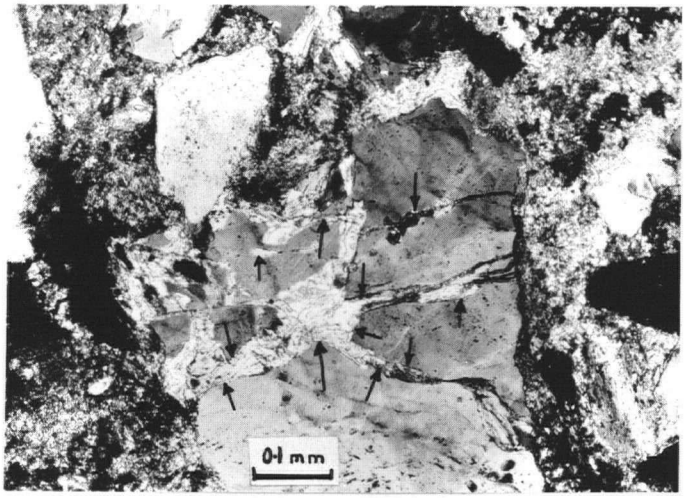


Fig. 83

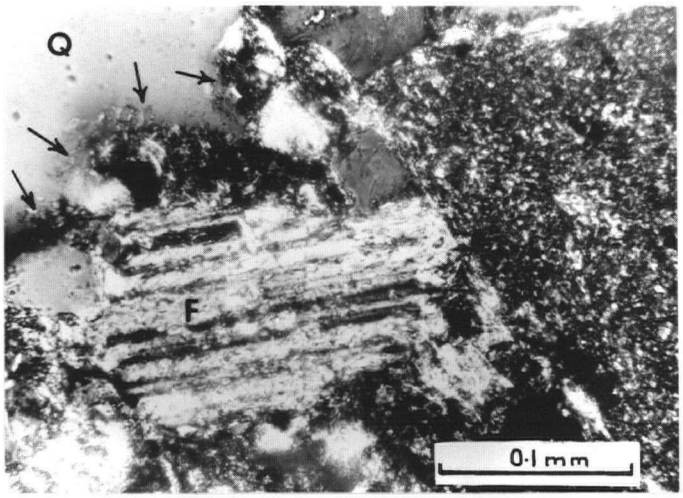


Fig. 84

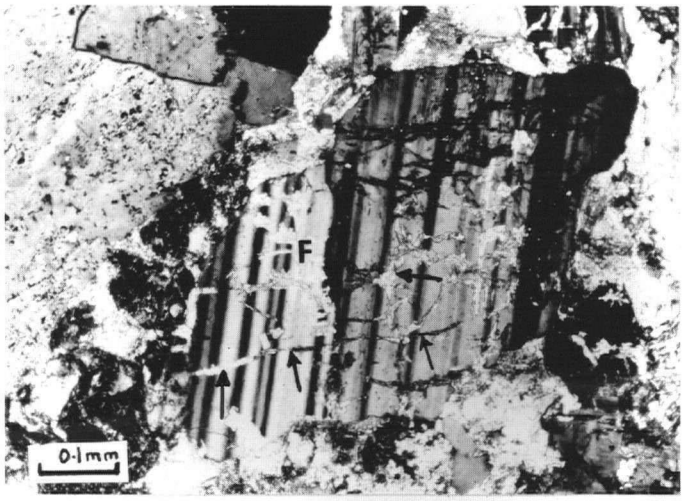


Fig. 85

classify the quartz into the different types based on the external morphology, internal features, and extinction characteristics. The work by Blatt and Christie (1963) has cast doubt on using the above mentioned properties for the purpose of relating the quartz to its parent rocks.

Size of the quartz grains varies from fine silt to very coarse sand, but they most commonly occur as fine to medium grained sand. Roundness shows wide variation, ranging from very angular to rounded, with the majority of the grains being subangular to subrounded. This variation in roundness is believed by the author to be largely due to the replacement of the grains by the calcite cement and by the matrix (figs. 83 and 84).

B. Feldspar:

Several varieties of feldspars are present. In the twelve thin sections that have been stained with sodium cobaltinitrite, potash feldspars (orthoclase and few microcline) show an average of 6.8 percent of the entire assemblages, with a range from 3.3 to 9.3 percent. Plagioclase feldspars have an average of 12.4 percent and range from 4.0 to 20.5 percent. In all twenty six thin sections, feldspars (both potash and plagioclase) show an average of 13.6 percent, with a range of 4.7 to 27.5%.

The plagioclase feldspars, based on their optical properties, are mainly oligoclase and andesine; albite and labradorite are very rare.

The majority of these feldspars are fresh and easily identified, but some show considerable alteration and can be recognized only by twinning. As is the case with the quartz, the feldspars show wide variation in size and roundness, and also show replacement by the calcite cement and the clay matrix (figs. 84 and 85).

C. Rock Fragments

Rock fragments include, volcanic, sedimentary, and metamorphic rock fragments in that order of abundance. They have an average abundance of 4.1 percent, and range from zero to 26.1 percent. They are most abundant in the coarser fractions of the sandstones, and when the coarsest fractions are finer than medium-grained sand, rock fragments become very rare or absent.

Volcanic rock fragments compose an average of 1.9 percent, ranging rom zero (nine thin sections) to 11.1 percent. The majority of the volcanic rock fragments are porphyritic, with a fine grained matrix of plagioclase laths and phenocrysts of plagioclase and/or quartz (fig. 86). Under plane polarized light, these fragments are greyish in appearance due to the scattered iron oxides

dust present as inclusions. Sedimentary rock fragments are almost entirely composed of shale (fig. 87), which is occasionally silty; they average 1.8 percent, and range from zero (seven thin sections) to 21.6 percent. Metamorphic rock fragments (excluding metaquartzite which is included with the polycrystalline quartz) constitute a minor fraction of the rocks composition. They have an average of 0.4 percent, and range from zero (14 thin sections) to 3.3 percent. They consist of slate, phyllite, schist, and some unidentified, chlorite-rich metamorphic rock fragments.

D. Mica

Micas are ubiquitous. They have an average of 5.3 percent, and range from 1.4 to 12.4 percent. About 90 percent of the micas are biotite, the remainder muscovite. They are observed to be more abundant in the laminated sandstones (plane-parallel, convolute, and ripple lamination) where they constitute the darker laminae (figs. 50, 51, 54, and 55). Most commonly these sandstones have a mean grain size ranging from very fine to fine-grained sand.

E. Chlorite

Chlorite occurs in only minor amounts in these sand-

stones. It has an average of 0.7 percent and ranges from zero (six thin sections) to 4.4 percent. Most of this chlorite seems to be in the process of alteration either from biotite or to biotite; it is usually found grading into the adjacent biotite without a well defined boundary.

F. Polycrystalline Quartz:

All the polycrystalline quartz of different origins have been classified under this category. They include sedimentary quartzite, metaquartzite, and possibly some plutonic polycrystalline quartz. They have an average occurrence of 1.0 percent, and rage from zero (ten thin sections) to 7.7 percent.

G. Chert:

All the microcrystalline and chalcedonic quartz is classified as chert (fig. 94). Their average abundance is 1.7 percent, and rage from zero to 4.4 percent.

H. Other Minerals:

These are the accessory minerals and the carbonaceous matter, with an average abundance of 2.3 percent, and range from 0.3 to 6.0 percent. The accessory minerals are as follows in decreasing order of abundance as

Fig. 86:
Photomicrograph of arkosic wacke showing a volcanic rock fragment (V). Crossed nicols. Vesuvius Bay, Salt Spring Island. (V34).

Fig. 87:
Photomicrograph of lithic wacke showing shale rock fragments (S). Crossed nicols. Vesuvius Bay, Salt Spring Island. (VSA3).

Fig. 88:
Photomicrograph of feldspathic arenite showing siliceous cement (S). Crossed nicols. Bedwell Harbour, North Pender Island (PB13).

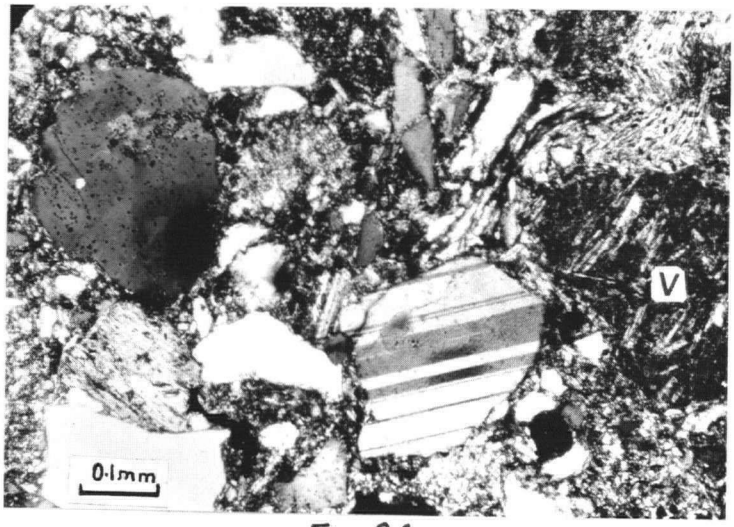


Fig. 86

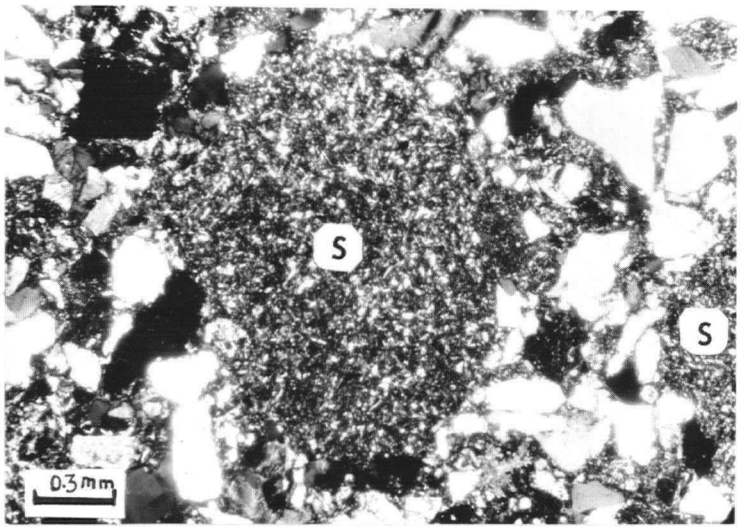


Fig. 87

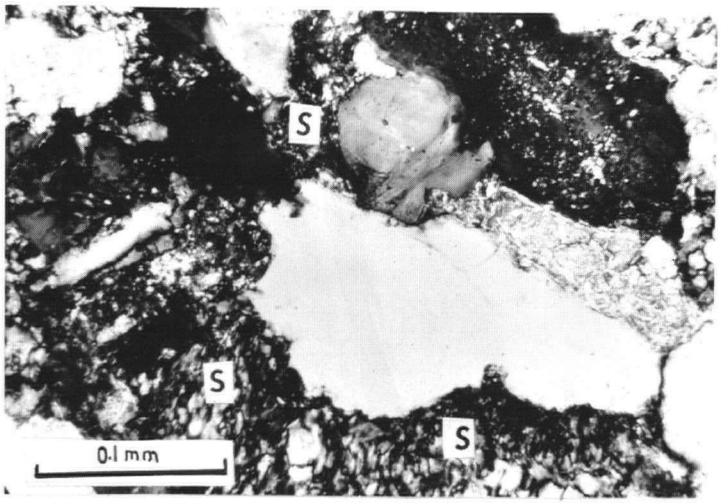


Fig. 88

identified with the petrographic microscope: Pyrite, epidote, apatite, hematite, garnet, and zircon. The carbonaceous matter is as abundant as the pyrite, and is present in almost all the thin sections that have been examined.

I. Unknown Minerals:

These are the minerals that are unidentifyable due to their high degree of alteration. They range from zero to 3.8 percent, and have an average of 1.8 percent.

J. Cement:

Cement is an important constituent in most of the thin sections studied, ranging from zero to 42.1 percent and averaging 17.4 percent; of the latter calcite cement makes up 17.0 percent and siliceous cement 0.4 percent. Calcite cement occurs as micrite and sparite, and it is commonly found to replace the surrounding grains (figs. 83 and 85), changing their size and shape. It is also found to replace the matrix minerals. The siliceous cement, when present, has the texture of chert, but it could be differentiated from chert by its form. Chert occurr always as grains with definite boundaries, while the siliceous cement occurs as filling of pore spaces (fig. 88).

K. Matrix:

The matrix ranges from 1.8 to 56.0 percent, and averages 12.1 percent. Constituents classified as matrix are all grains less than 30 microns in size. Matrix composition is consistent in all samples, consisting mainly of clay minerals, mica, feldspar, and quartz.

The finest constituents of the matrix (e.g. clay minerals and the finely divided mica) commonly replace the surrounding grains (fig. 84) changing their size and shape.

Observations on the matrix-grain relationships in the sandstone of the Cedar District Formation, indicate that at least part of the matrix is of diagenetic origin (R. Rahmani, 1968). Finely divided mica and clay minerals are observed to replace the sand-size grains, thus producing fine-grained material and contributing to the volume of the matrix (figs.84 and 95). Pettijohn (1957, p.305) in a discussion of the origin of matrix of greywacke sandstones, stated: "It seems most probable that all the matrix minerals are, indeed, authigenic and are the result of reorganization of an interstitial mud." Cummins (1962) suggested in his study of the greywacke problem that matrix of greywacke is not of a primary origin, substantiating his suggestion by comparative size analysis of ancient greywackes and of Recent and experimental turbidites. He showed that Recent and experimental turbidites have negligible

Fig.89:
Classification of pure sandstones, or arenites. After Gilbert (1954). Small numbers refer to specimens listed in Table 2

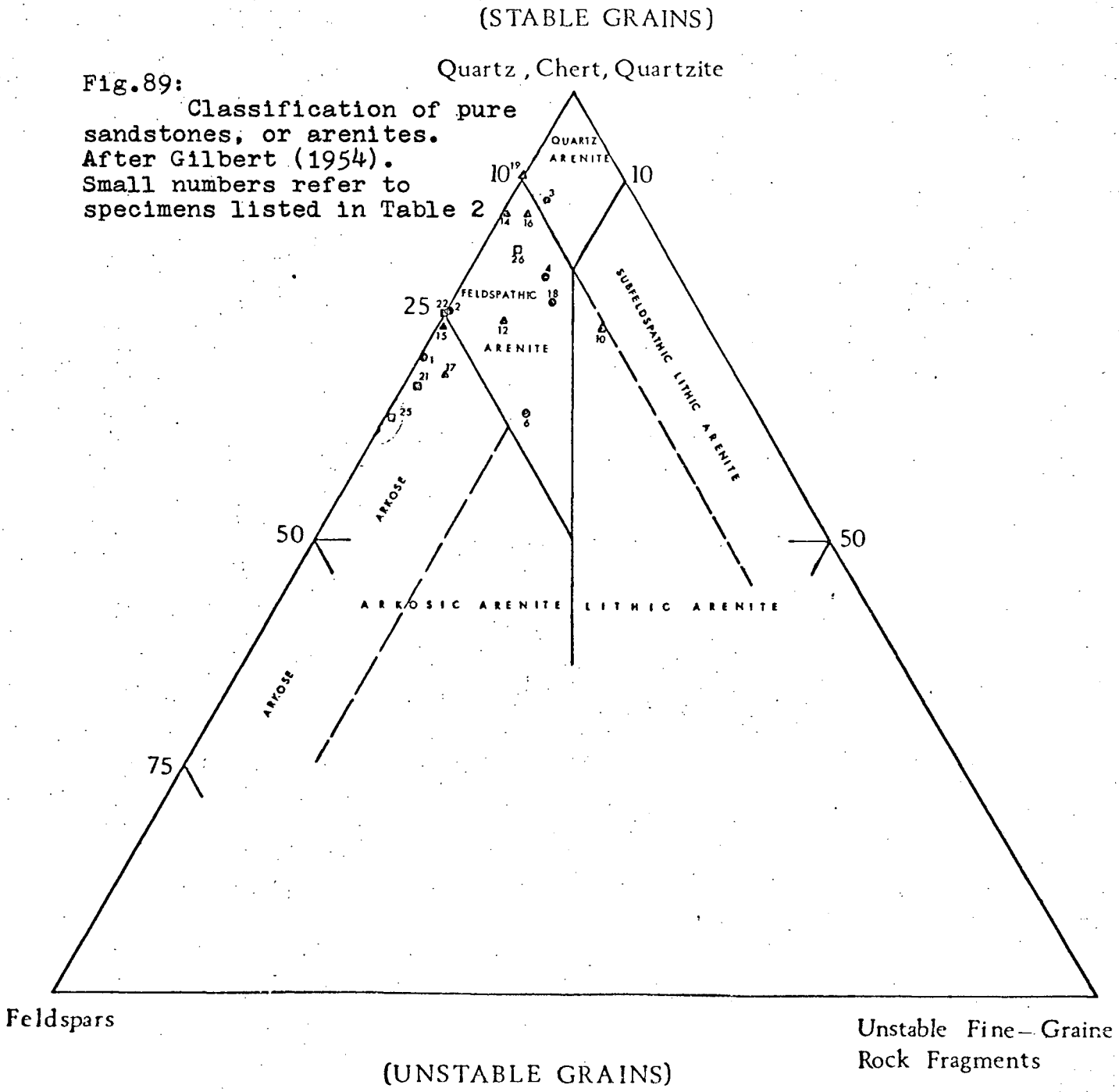
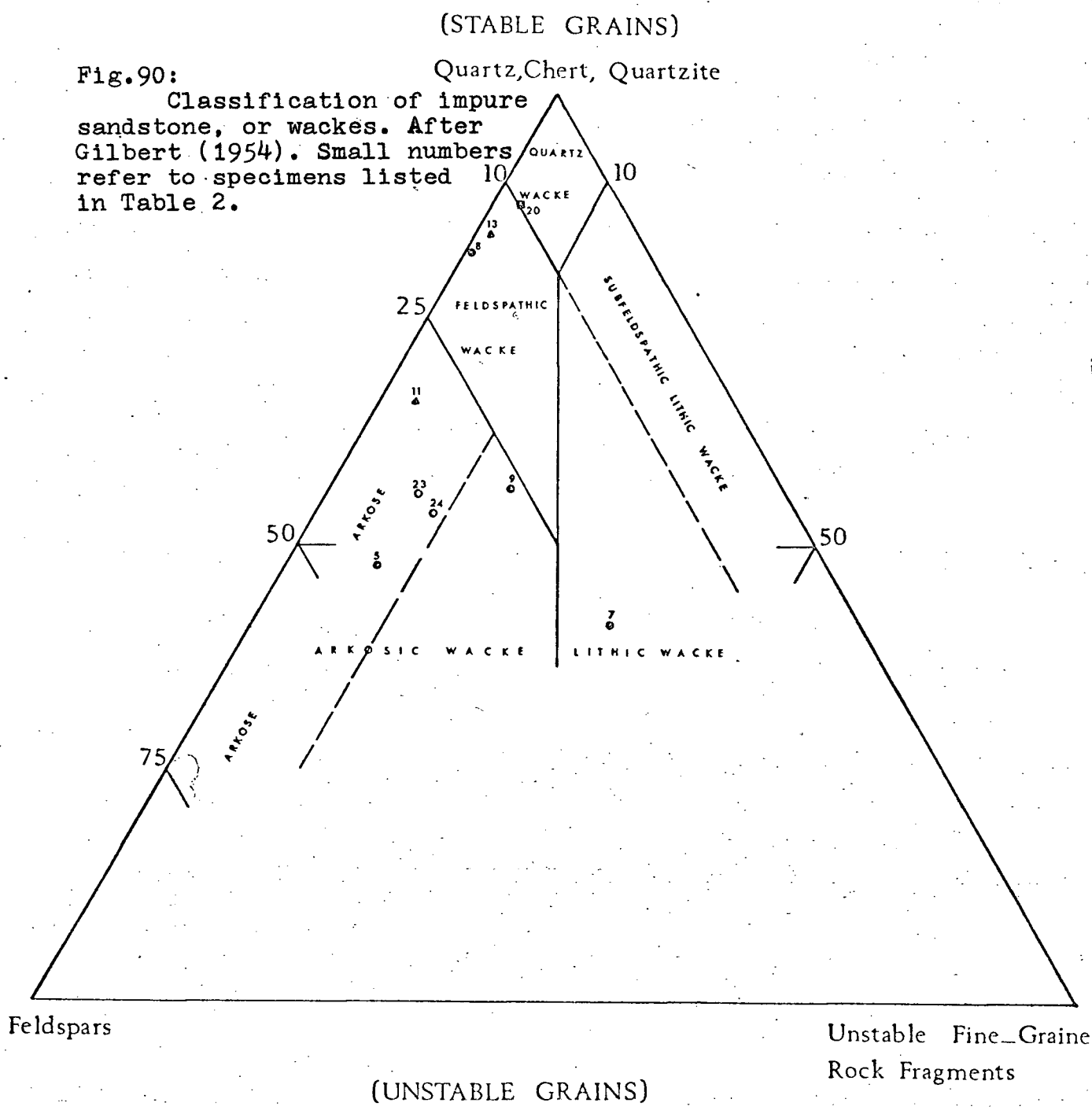


Fig.90: Classification of impure sandstone, or wackes. After Gilbert (1954). Small numbers refer to specimens listed in Table 2.



amounts of matrix, while ancient equivalents (the greywackes) have a high matrix content. For discussion of this problem,the reader should refer to Dott,Jr. (1964).

L. Sandstone Classification:

For the purpose of classification, Gilbert's (1954) scheme was adopted. Briefly, this scheme first classifies sandstones into two major groups accourding to the percentage of matrix present in the rocks. Rocks with less than 10 percent matrix are called arenites, those containing 10 to 50 percent matrix are called wackes (when matrix exceeds 50 percent, the rock is then called a mudstone). Further subdivisions are based on some selected essential components. These components form the corners of the classification triangles (figs. 89 and 90). Quartz, chert, and polycrystalline quartz (the "stable grains") are grouped in one corner, feldspars and unstable fine-grained rock fragments in the other two corners (the "unstable grains"). Therefore, these essential components were recalculated to 100 percent for each sample. According to Gilbert's classification, seventeen samples are arenites and nine are wackes. Out of the seventeen arenite samples, nine samples are feldspathic arenite, five are arkose, two are quartz arenite, and one is lithic arenite (figs. 91, 92, and 93). Out of the nine wacke samples, four samples are arkose, two are feldspathic

Fig. 91:
Photomicrograph of quartz arenite. Crossed nicols. Vesuvius Bay, Salt Spring Island. (V26).

Fig. 92:
Photomicrograph of feldspathic arenite. Crossed nicols. Vesuvius Bay, Salt Spring Island. (5a).

Fig. 93:
Photomicrograph of arkosic arenite. K is stained potash feldspar. Crossed nicols. Mayne Island. (M4).

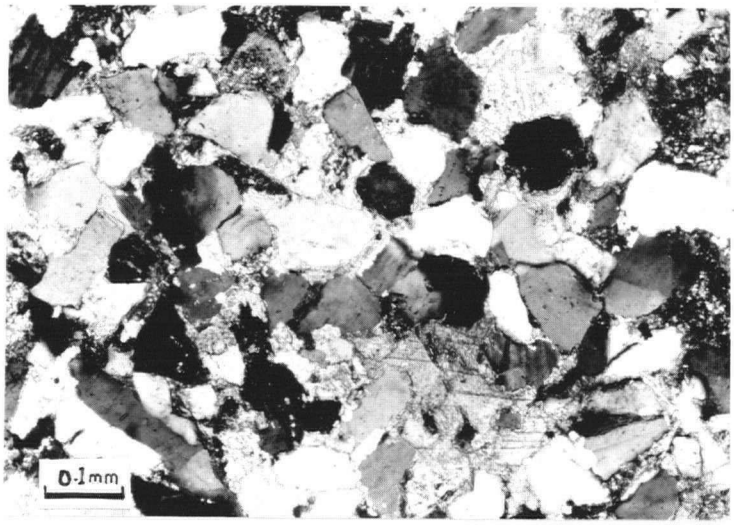


Fig. 91

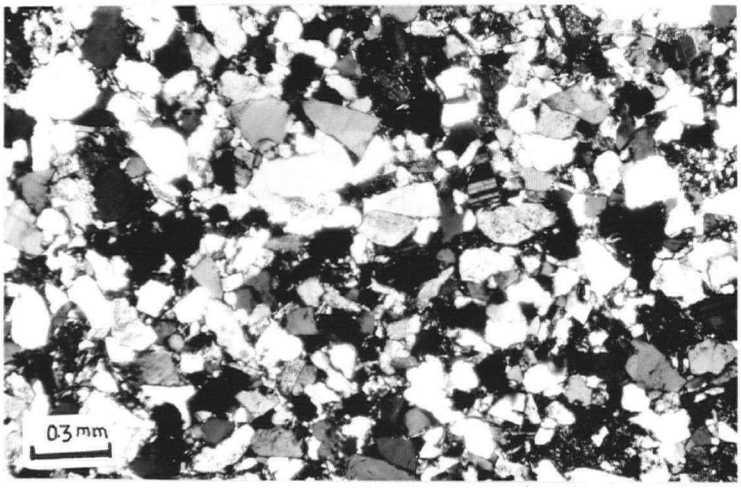


Fig. 92

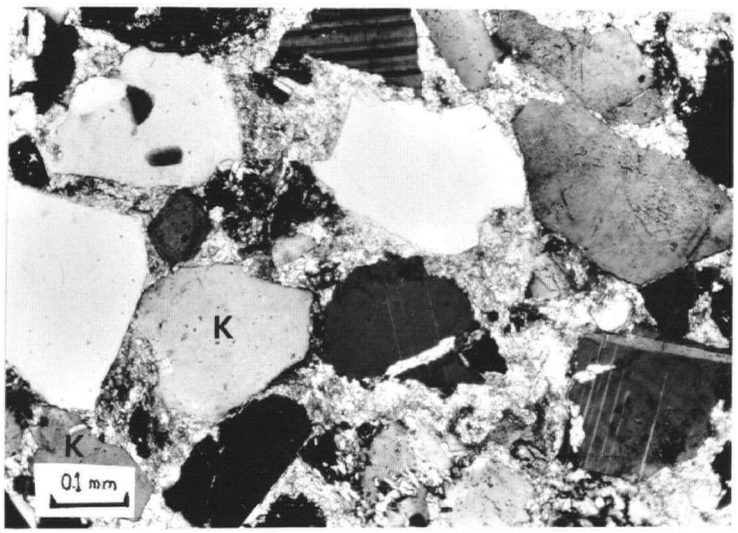


Fig. 93

wacke, one is arkosic wacke, one is lithic wacke, and one is quartz wacke (figs. 86, 87, and 94).

There was no significant variation in composition of the sandstones with stratigraphic position in the formation. Also such variation has not been observed laterally throughout the study area.

9. GRAIN SIZE DISTRIBUTION

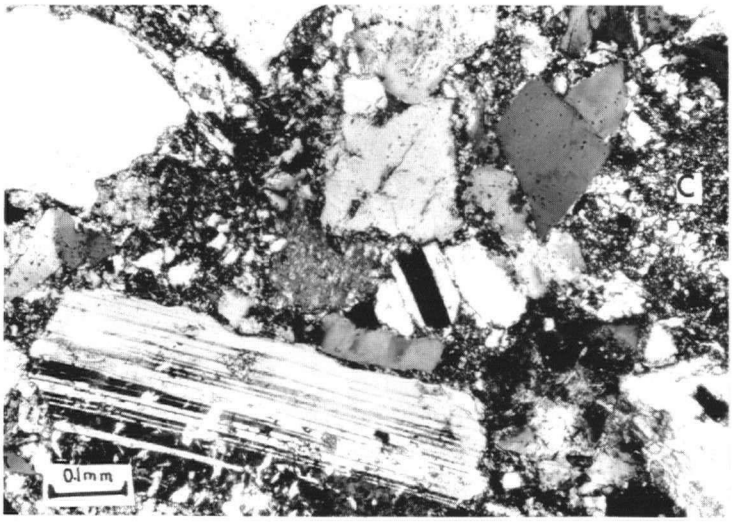
Grain size distribution of fifteen sandstone samples were determined in thin section with the petrographic microscope. The long dimensions of 100 grains were measured in each of the 15 thin sections. Excluded from these measurements are the grains finer than 0.03 mm (i.e. the matrix). Figure 96 shows histograms of the grain size distribution of these samples. No attempt was made to convert the thin-section size distribution (number) into the sieve-size distribution (weight) as was done by Friedman (1958 and 1962), since he dealt with well sorted, quartz-rich sandstones.

Most of the samples have fair sorting, and the majority have the fine admixture dominating. Mean grain size of samples taken from A-division are in the medium-grained sand range, those from B-division samples in the fine-grained sand range, and those from C-division samples in the very fine-grained sand range, (fig. 96).

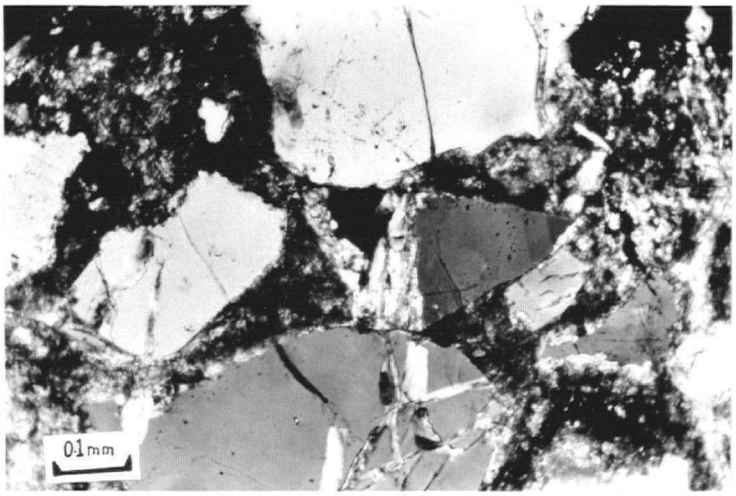
Fig. 94:
Photomicrograph of arkosic wacke showing chert rock fragment (C). Crossed nicols. Vesuvius Bay, Salt Spring Island.

Fig. 95:
Photomicrograph showing the replacement of grains by the surrounding clay-size matrix. Crossed nicols. Vesuvius Bay, Salt Spring Island. (5c).

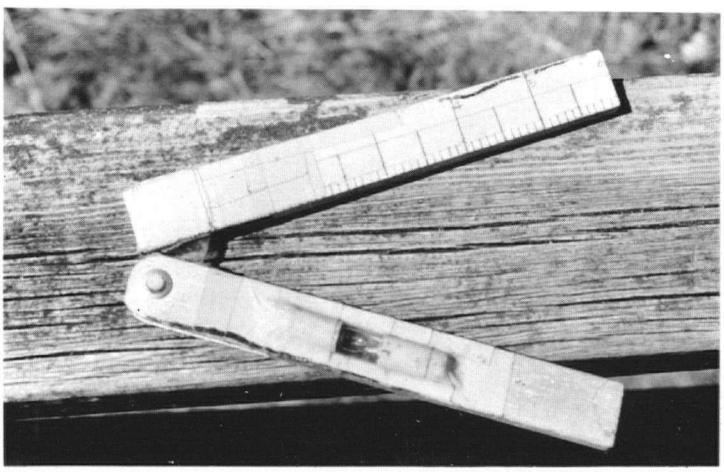
Fig. 97:
Tilt compensator used for measurements of paleocurrent directions. The scale is in inches.



Fig·94



Fig·95



Fig·97

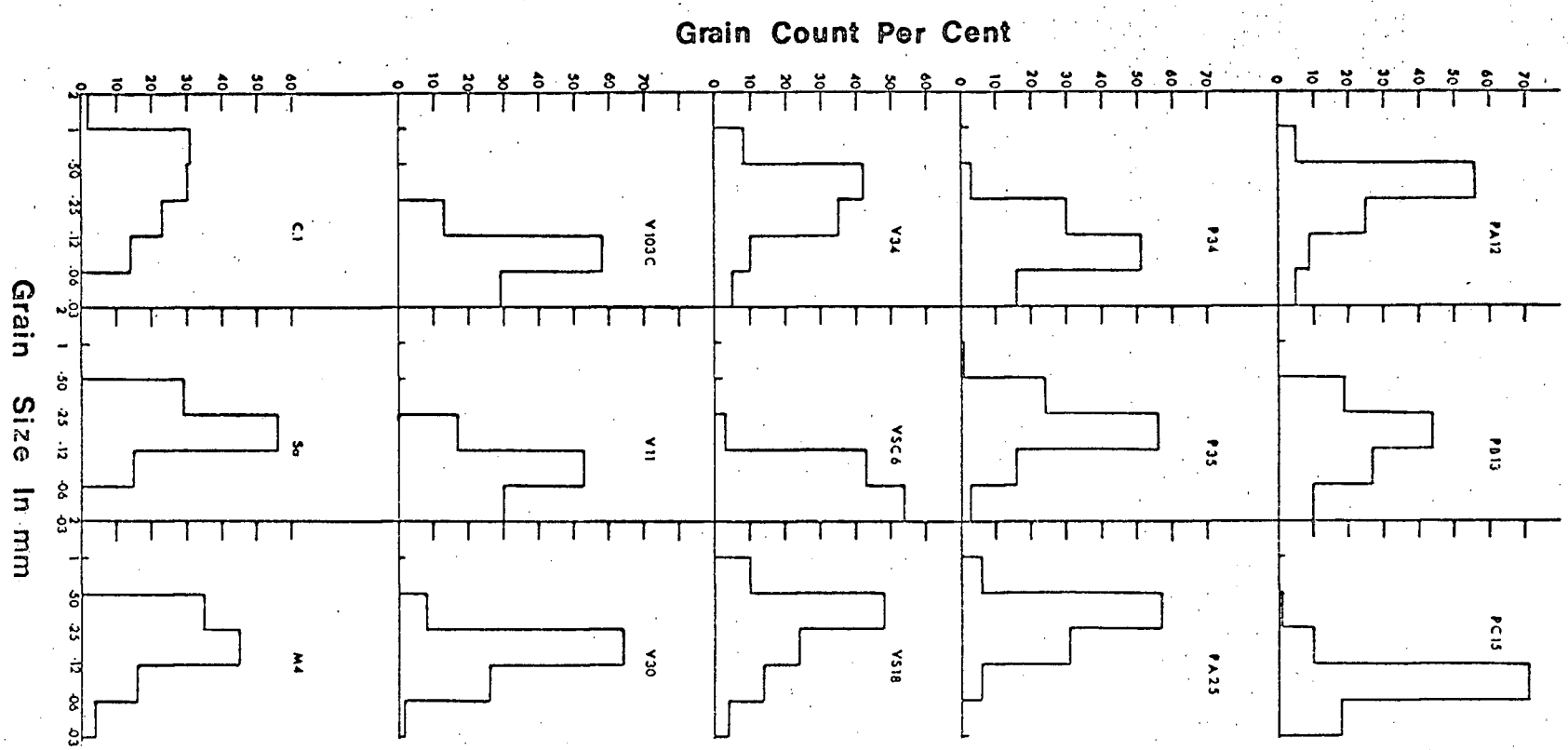


Fig.96: Histograms of the thin-section frequency distribution of sandstone framework grains calculated from grain size counts in thin section. Numerals refer to specimen numbers.

9. DIRECTIONAL STRUCTURES AND PALEOCURRENTS

A. Methods

The orientations of all the available directional sedimentary structures were measured in the field in order to determine the regional paleocurrent pattern.

Because the beds are tilted, correction for dip of the measured orientations was neccessary to obtain the pre-tectonic original current direction. This was done directly in the field during measurement. A tilt compensator (fig. 97) that was developed by Bouma (1962, p.25) was used in the present study for instant reorientation and reading of the original orientation of the directional sedimentary structures. This compensator is composed of two wooden arms (Bouma used a non-magnetic metal) hinged at one end. The dimensions of each arm are 6 X 2/3 X 1/3 inch. A spirit level is mounted to one arm. The compensator is kept horizontal with the arm that has the spirit level held against the lower bedding plane (sole of the bed). The arm with the spirit level now indicates the strike of the bed. Then the compensator is rotated using the spirit level arm as a hinge line until the other arm comes in contact with the bedding plane. Next, the other arm is aligned to coincide with or parallel to the paleocurrent indicator (e.g. groove casts,

flute cast, ... etc.). Then the compensator is swung back to the horizontal position using the spirit level arm as a hinge line. The other arm now indicates the orientation of the current indicator before tilt. Then, using a Brunton compass, this direction is measured.

The structure most commonly measured was the foreset lamination associated with the current ripple lamination of the C-division. In other places, where directional sole marks were available (e.g. flute casts, groove casts, and bounce casts), the current direction was recorded from them and compared with that recorded from the foreset lamination within the bed. Usually one reading per bed was recorded by taking the average direction of the current indicators if there is any variation. However, if the variation exceeds 20°, two readings were taken per bed. Due to the scarcity of well exposed lower bedding surfaces, few measurements of sole markings are available from the study area.

B. Presentation and Interpretation of Data

Rose diagrams of the current directions were made for the Vesuvius Bay area on Salt Spring Island, and in the Bedwell Harbour area on North Pender Island (fig.98). The numbers within the circles of the rose diagrams indicate the number of readings taken in that particular area.

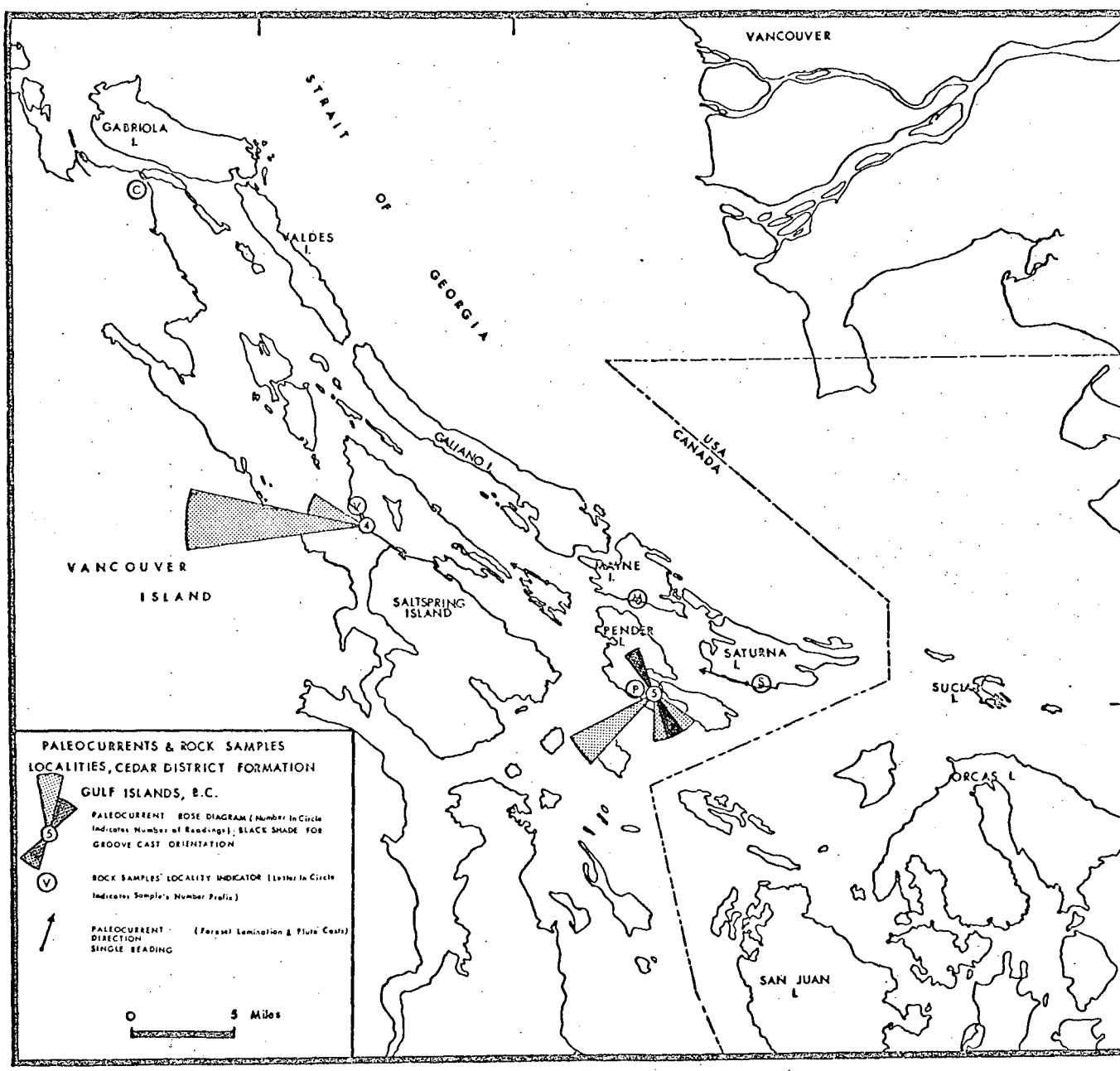

VANCOUVER
STRAIT OF GEORGIA
GABRIOLA I.
VALDES I.
GALIANO I.
USA
CANADA
VANCOUVER ISLAND
SALTSPRING ISLAND
MAYNE I.
PENDER I.
SATURNA I.
SUCIA I.
ORCAS I.
SAN JUAN I.
PALEOCURRENTS & ROCK SAMPLES LOCALITIES, CEDAR DISTRICT FORMATION GULF ISLANDS, B.C.
PALEOCURRENT ROSE DIAGRAM (Number in Circle Indicates Number of Readings); BLACK SHADE FOR GROOVE CAST ORIENTATION
ROCK SAMPLES' LOCALITY INDICATOR (Letter in Circle Indicates Sample's Number Prefix)
PALEOCURRENT DIRECTION SINGLE READING (Foreset Lamination & Flute Casts)
0 5 Miles

Fig. 98

In the other localities shown on the map of figure 98, rose diagrams were not constructed since only one reading was available in each of these localities.

Figure 98 shows that the currents were flowing from the northwest, northeast, ~~south~~ east RARahman!, and southeast. The coincidence in orientation of the turbidite's directional structures and the orientation of the gravity controlled structures (soft-sediment deformation structures) which presumably moved downslope, suggests that the turbidity currents were also flowing down the paleoslope. An example is the coincidence in orientation of the foreset lamination associated with the turbidites, and the orientation of the minor folds of the soft sediment deformation caused by the drag of a traction carpet which is gravity controlled. Another example is found on the southern part of Saturna Island, where the orientation of the turbidite foreset lamination coincides with the direction of the thinning of the pebbly mudstone sequence, the latter probably resulting from downslope slumping.

10. PALEOGEOGRAPHY

A. Basin Geometry:

Since the turbidity currents were apparently flowing down the slope of the basin, as concluded in the previous section, it can be inferred that somewhere within the basin there were slopes with contour lines approximately at right angles to the measured current direction. The currents as measured on Salt Spring, Saturna and North Pender Islands were flowing from the northwest, northeast, east, and southeast, therefore the paleoslopes on the northwestern, northeastern, eastern, and southeastern parts of the study area, were dipping to the southeast, southwest, west, and northwest respectively. If the lines of the current directions were projected eastward to the outer islands, and normals drawn to them, a slope contour line trending southeast-northwest will result. This contour line might indicate the shape of the eastern boundary of the basin but not the eastern limits, (i.e. indicates the trend of the shore-line, Pettijohn, 1957, p. 607). This slope contour coincides approximately in shape with the contours obtained from the Kaolinite/Illite ratios, (fig. 19), and its trend also coincides with the southeast-northwest trend of the outcrops and structures of the formation. The northern and southern

parts of the basin may be delineated by the termination of the outcrops just south of Nanaimo City to the northwest, and on Sucia and the Orcas Islands to the south and southeast. The Late Cretaceous age of the lower part of the non-marine Chuckanut Formation, (W.S. Hopkins, Jr., 1966), which was possibly a continental equivalent to the marine Cedar District Formation, suggests that the shore line of the southeastern part of the basin was somewhere between the mainland of northwestern Washington State and Sucia Island. Paleontological evidence (J.E. Muller and J.A. Jeletzky, 1967, and J.E. Muller 1968, personal communications) suggests that the basin was opened on its western boundaries to the Pacific Ocean. Absence of currents flowing from the west and the south might be due to one or both of the following reasons: (1) there were no turbidity currents flowing from these directions, (2) the regional dip of the basin was to the west, southwest, and south, therefore turbidity currents could not flow up the regional dip.

From the above, some tentative conclusions may be made regarding the shape and dimensions of the Cedar District basin of deposition. But it must be emphasized that the available evidence is sparse and scattered, thus these conclusions are open to further discussion and

modification. The basin had an elongate shape with its longest axis trending southeast-northwest. Its northern and northwestern boundaries may have been located just south of the city of Nanaimo and Gabriola Island, while the southern and southeastern boundaries were probably somewhere on the San Juan Islands between Washington State northwestern coast, and Sucia and the Gulf Islands. To the west it was open to the Pacific Ocean through the paleo-Vancouver Island(s). The location of the eastern boundary of the basin is not known, but indications of the Nanaimo Group have been traced on continuous seismic profiles to about the middle of the Strait of Georgia, (D.L. Tiffin, personal communication); also, non-marine Upper Cretaceous rocks were encountered in two deep wells beneath the Fraser Delta, (W.S. Hopkins, Jr., 1966). Therefore the eastern boundary of the Cedar District basin could be somewhere between the British Columbia mainland and Saturna-Mayne-Galiono Valdes Islands in the present day Strait of Georgia.

W.H. Mathews (1958) has reported at least 20,000 feet of marine sedimentary rocks in the Mount Garibaldi map area of British Columbia. He has dated the lowest and oldest formation (the Cheakamus Formation) of this sequence as "mid-Upper Cretaceous". Therefore, at least

parts of the Mount Garibaldi sequence may be correlative with the Cedar District Formation. It is not known whether these were deposited in a separate basin or in a possible northeastward extension of the Nanaimo Basin.

B. Dispersal

The following facts suggest that the major source area for the sandstone and the coarser clastics was situated to the east and southeast of the study area:

(1) Paleocurrent measurements indicate turbidity currents were flowing mainly from the eastern and southeastern parts of the study area (fig. 98).

(2) The high percentage of sandstone in the central, southern, and southeastern parts of the area relative to its very low percentage in the northern part of the study area.

(3) Restriction of the North Pender Island breccia (figs. 30 and 31) and the Saturna Island pebbly mudstone (figs. 8 and 28) to the south and southeast, and the wedging out of the pebbly mudstone toward the northwest, suggest a source from the east and southeast.

The distance to the source area is difficult to determine, but the occurence of breccia on North Pender Island, and the very poorly sorted pebbly mudstone on Saturna Island might indicate the closeness of the source

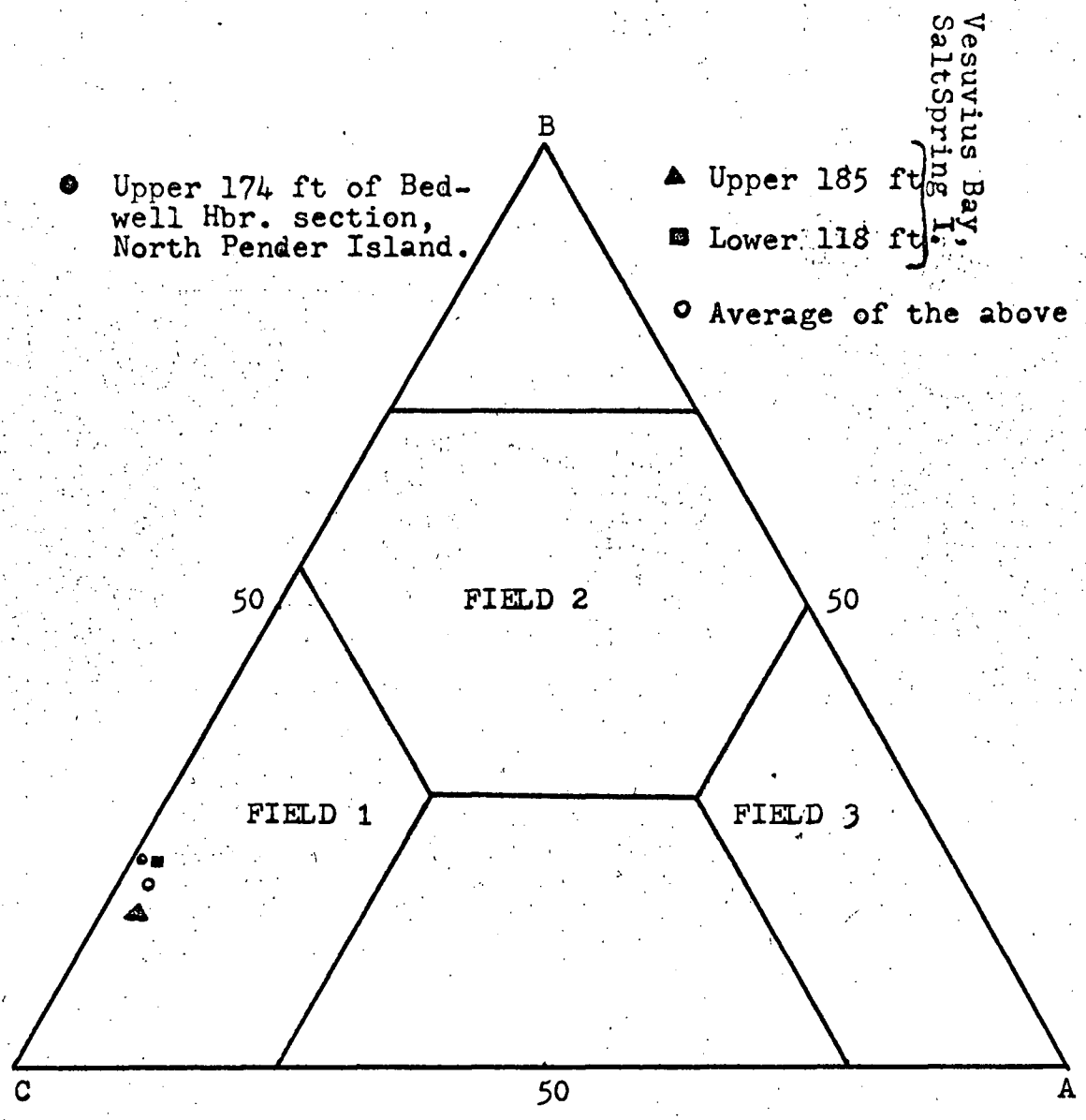


Fig.99:
Each group of turbidites is plotted on the diagram according to the percentage of beds in the group begining with A-division, B-division, & C-division. Field 1 corresponds roughly with the lower flow regime of Simons & others (1965), and fields 2 & 3 correspond with the upper flow regime, 3 representing a higher regime than 2.

area to these parts of the study area.

In parts of the sections which were measured in detail, and in which the frequency of occurrence of the different turbidite divisions was recorded, it was found that 77% of the turbidite units start with C-division at their base (i.e. these are C to E turbidite units). Adopting Walker's scheme (1967, p. 24, fig. 4), the turbidites of the Cedar District Formation apparently have been deposited largely in the lower flow regime of Simons et al (1965), as indicated in fig. 99. Walker, (1967) considers that turbidites formed in the lower flow regime were deposited in distal areas relative to the source area for the turbidity currents, due to the reduction in current velocity away from the source. The author feels, however, that an alternative interpretation is possible; if the velocity of most turbidity currents in a given area were low, then deposition from them would be largely within the lower flow regime, even in proximal areas.

C. Provenance

The composition of the sandstone framework indicates varied rock types in the source area. Abundance of quartz, feldspar (andesine, oligoclase, orthoclase, and microcline), and biotite indicate acidic to intermediate plutonic and/or low to medium grade metamorphic rocks as

major source rocks. The common occurrence of rock fragments, especially sedimentary (shale) and volcanic rock fragments, indicates the presence of sedimentary and volcanic rocks associated with the above mentioned crystalline rocks. It was suggested in the previous section that the source area for the sandstones was to the east and southeast. Looking at the geologic map (Geologic Map of Washington, 1961), the nearest land to the east of the study area is now largely covered with post Cretaceous rocks (the area around the city of Bellingham) which obscure a possible crystalline source area. However, the ultimate source could be still further east, where pre-Jurassic low grade metamorphic rocks are exposed in the Cascade Mountains. To the southeast, in the San Juan Islands, some crystalline rocks are exposed and dated as pre-Carboniferous (Geologic Map of Washington, 1961); these rocks, composed mainly of quartz diorites and gneisses, quite possibly yielded some sediments to the Cedar District sandstones.

The large thickness of the formation, the high percentage of sandstone (i.e. large volumes of the sandstone) in the central, southern, and southeastern parts of the study area, and the angularity of the grains all suggest that the source area was an area of high relief

that had undergone rapid uplift and erosion. Freshness of the feldspars further suggests aridity of the source area, where mechanical weathering was the important factor in breakdown of the source rocks. To the north and northwest, where shale composes about 95% of the exposed section, it was assumed that the source area to the north was a low rolling muddy coastal plain where there were no large rivers or elevated source areas to supply coarse materials; alternatively, these parts of the study area might have been a deeper part of the basin, more distant from the shorelines to the east and southeast.

D. Environment of Deposition

The fauna of the Cedar District Formation indicates deposition in a marine environment. Almost all previous workers have suggested a littoral environment for its deposition. Breitsprecher (1962) concluded, on the basis of the study of the foraminifera and the megafossil fauna in Sucia Island, that the Cedar District Formation was deposited in "littoral to upper neritic depth in tropical to subtropical water temperature". J.E. Muller and J.A. Jeletzky (1967) suggested near-shore shallow depths of deposition for the shaley, fossiliferous parts of the formation, and called them the littoral facies.

The above could be valid for the fossiliferous shaley

parts of the formation, but in other parts of the section, where turbidites are abundant, deposition must have taken place at greater than littoral depths, i.e. at depths below wave base, where lamination and convolution of the sandstone could be preserved, (Muller and Jeletzky, 1967).

The unfossiliferous shale of the central and northern parts of the study area was deposited either at about the same depths as the turbidites, or in deeper water, since thin, delicate, horizontal and cross laminations are preserved in these rocks.

Partial stagnant conditions and reducing environments in the bottom waters of the central and northern parts of the basin are suggested by the almost complete absence of fossils in these parts of the basin, and by the abundance of pyrite and carbonaceous matter in the shales, sandstones, and the calcareous concretions. Complete stagnation and the development of euxenic environments were probably prevented by two factors. One was the periodic introduction into the central part of the basin of turbidity currents which may have transported oxygenated water into this area. The second factor is that there was apparently a connection between the Cedar District basin and the open ocean to the west (Usher, 1952; Breitsprecher, 1962; Muller and Jeletzky, 1967,

and Muller, 1968, personal communication) which might have served to introduce new waters to the basin from the open ocean during tidal fluctuations and storms.

In summary, the nature and abundance of fossils, in the lower shaley intervals of the southern and southeastern parts of the basin suggest littoral to upper neritic depths, where water conditions were favourable to animal life. The scarcity of these fossils in the shaley facies of the central and northern parts of the basin was probably due to unfavorable living conditions resulting from partial stagnation and the formation of reducing environments. The occurence of abundant turbidites in the upper part of the formation in the central and southeastern parts suggests a deepening of the basin.

11. SUMMARY AND CONCLUSIONS

1. Shale composes about 73% by thickness of the Cedar District Formation. Sandstone makes the bulk of the non-shale part. Calcareous concretions are present scattered in the shales and the sandstones.

2. Two types of shale occurrences are present:

   a. Continuous sequences of more than 100 feet in thickness, which may or may not be fossiliferous.

   b. Thin beds interbedded with sandstone beds (i.e. flysch-type shale).

3. Among shales of type (a) above, fossiliferous shales are restricted to the southeastern part of the study area (Sucia and Saturna Islands), where they are vertically associated with turbidite sequences. The unfossiliferous shales occur toward the west and northwest (North Pender, Salt Spring, Mayne, and Vancouver Islands) and are likewise vertically associated with turbidite sequences, except on Vancouver Island at the northwestern end of the study area, where no turbidites are present.

4. In the flysch-like sequences, the rhythmic interbedding of sandstone and shale beds, and the typical turbidite structures exhibited by the sandstones of the Cedar District Formation, all indicate that deposition of

the rhythmic (flysch-like) sequences took place by turbidity currents.

5. Dominance of the C-E turbidite units, indicates that the deposition of these turbidites took place largely within the lower flow regime.

6. Calcareous concretions, most abundant in the shales, have features suggesting they were formed in the early stages of diagenesis, probably shortly after burial.

7. Paleocurrents, and lithologic lateral variation indicate that the major source area for the coarse clastics in the Cedar District Formation was situated to the east and southeast of the study area.

8. Mineral assemblages of the sandstones suggest that the major source rocks were acidic to intermediate plutonic and/or low to medium grade metamorphic rocks.

9. Pre-Jurassic low grade metamorphic rocks of the Cascade Mountains to the east, and the pre-Carboniferous crystalline rocks of the San Juan Islands to the southeast served as possible source areas for the coarse clastics.

10. Composition of the sandstones suggests the major source areas were possibly regions of high relief that had undergone rapid uplift and erosion.

11. Rocks in the source area appear to have experienced mainly mechanical weathering.

12. Deposition of the shaley, fossiliferous parts of the formation took place in littoral to upper neritic depths. Turbidite sequences of the formation were deposited in deeper water, below the wave base. The unfossiliferous shale of the central and northern parts of the study area was deposited either at about the same depths as the turbidites, or in deeper water, since thin, delicate, horizontal and cross laminations are preserved in these rocks.

13. Paleontologic evidence suggests that deposition took place in a somewhat restricted basin having a narrow connection with the open ocean to the west.

14. Paleontologic and mineralogic evidences suggests that the bottom conditions of the central and northern parts of the basin of deposition were stagnant and reducing.

15. Facies relationships suggest the basin of deposition had its longest dimension trending SE-NW. Its eastern, southeastern, and southern boundaries were situated between the mainland of British Columbia-Washington and the Gulf-San Juan Islands. Its northern and northwestern boundaries were possibly near the city of

Nanaimo and Gabriola Island. To the west it was connected at least partially to the open ocean.

16. In the southeastern part of the study area, alternation of thick, fossiliferous shale sequences, and sequences which are predominantly turbidites suggests flunctuations in the depth of the basin floor, either due to changes in sea level or to tectonic movements.

17. The Nanaimo Group includes coal-bearing, non-marine rocks which would be called a typical "molasse" by many geologists. The Cedar District Formation, however, contains turbidite sequences which are thought by some geologists to be typical of "flysch". This juxtaposition of unlike facies results from fluctuations in water depth during deposition of the Nanaimo Group.

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13. APPENDIX

Use of the Turbidite Loggin Chart

Graph paper rolls were used in the field as a logging chart. All properties measured in the field were tabulated on the chart in columns and subcolumns (see the table enclosed with this appendix). The following is a modified version of Bouma's (1962) and Walker's (1967) method of logging.

FIRST COLUMN (Unit thickness)

Thickness of each individual turbidite unit in inches was measured and tabulated under this column. Since the units have surprisingly constant thickness laterally, no attempt was made to measure the thickness along the strike to obtain an average thickness.

SECOND COLUMN (Turbidite unit divisions)

This column has been divided into four subcolumns, each subcolumn recording the properties of a single division.

For A-division, thickness, grain size, carbonate presence, andcolor were recorded. Grain size measurements were made using a hand lens (x10) and recorded as follows:

cS: Coarse-grained sandstone

mS: Medium-grained sandstone

fS: Fine-grained sandstone

cZ: Coarse-grained siltstone

sZ: Sandy silt

Color was recorded by using the following symbols:

G : Grey

mG: Medium grey

lG: Light grey

bG: Brownish grey

gnG: Greenish grey

For B-division, the same properties as for A-division were measured. For C-division, an extra subcolumn was added to record the type of structure exhibited by that division; the following categories were logged:

Foreset lamination

Oversteepened foreset lamination

Current ripple lamination

Convolute lamination

For the interturbidite division (DE-division), thickness, carbonate presence, color, and structures were recorded. No attempt was made to measure grain size in the field, since almost all of the interturbidites have silty to sandy-clay size. Under structures, only one structure was recorded, that is plane-parallel lamination; its symbol is: .

THIRD COLUMN (Sedimentary structures)

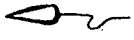
Sedimentary structures have been divided into two types:

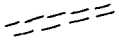
1. Bedding plane structures

They are sedimentary structures present on the bedding plane. These were divided into primary and secondary structures:

a. Primary structures

 Channelling

 Flute Casts (loaded)

 Groove Casts

b. Secondary structures

 Load Casts

 Burrows

2. Bed internal structure

(A bed usually includes one or more turbidite division).

These structures are found within the bed, (e.g. graded bedding, disturbed bedding, etc.). They are classified as primary structures (i.e. depositional structures); and secondary structures (i.e. post-depositional structures). The following symbols were used:

a. Primary Structures


Disturbed bedding (caused by high density turbidity currents)


Detached clasts


As above but bent


Combination of the first and second


Combination of the first, second, and third


Graded bedding

b. Secondary structures


Burrows


Calcareous concretions with random orientation


Widely separated calcareous concretions elongate parallel to bedding


As above but usually in strings more than one


Discontinuous bed of joined calcareous concretions

FOURTH COLUMN (Paleocurrent directions)

Under this column the direction of paleocurrents measured from directional sedimentary structures was recorded.

FIFTH COLUMN (Unit number)

Turbidite units were numbered in the field, starting from the base of the section with number one; the numbers

increase upward in the section.

SIXTH COLUMN (Specimen number)

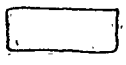
This column was used to record the number of the specimen or specimens taken from each separate unit.

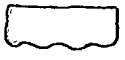
SEVENTH COLUMN (Photograph number)

This is to record the photograph number taken at any particular position in the measured section.

EIGHTH COLUMN (Nature of bedding)

The following symbols were used to describe the nature of bedding:


Beds where upper and lower planes are almost straight.


Beds where the lower bedding plane is undulating (due to rippling, loading or sole marks).


Beds where upper and lower boundaries are undulating.

NINTH COLUMN (Remarks)

This column records observations other than those mentioned above. Such observations include tectonic structures, bed attitude, sketches where photos proved to be inadequate, and the recording of some preliminary field interpretations of the measured properties.

SAMPLE OF TURBIDITE SEQUENCE LOGGING CHART

Modified from Bouma (1962) and Walker (1967).

Unit Thickness in Inches	Turbidite Unit Divisions																	Sedimentry Structures				Paleocurrent Directions	Unit Number	Specimen Number	Photograph Number	Nature of Bedding	Remarks
	A				B				C					Interturbidite DE				Bedding-Plane Structures		Bed Internal Structures							
	Thickness	Grain Size	Carbonates	Color	Thickness	Grain Size	Carbonates	Color	Thickness	Grain Size	Structures	Carbonates	Color	Thickness	Carbonates	Color	Structures	Primary	Secondary	Primary	Secondary						
15.5	6.0	cS	✓	lG	2.0	mS	✓	lG	1.0	fS	Y	✓	lG	6.5	x	mG	≋					235°	1	V1A	A1		photo A1 shows calcareous concretion.
44.0	26.0	cS	x	lG	5.0	mS	x	lG	5.0	fS	∿	x	lG	8.0	x	mG	≋					—	2	—	—		Beds dip at 72° N65°W.
30.0	15.0	cS	x	lG	5.0	mS	x	lG	3.0	fS	Y	x	lG	7.0	x	mG	≋					55°-235°	3	V2C	—		—
7.5	—	—	x	—	1.2	mS	x	mG	2.3	fS	Y	x	mG	4.0	x	mG	≋	—				—	4	—	A2		Photo. A2 shows cross Lamination