NANAIMO GROUP STRATIGRAPHY AND PALEOECOLOGY

STRATIGRAPHY, PALEOECOLOGY AND FUNCTIONAL MORPHOLOGY OF HETEROMORPH AMMONITES OF THE UPPER CRETACEOUS NANAIMO GROUP, BRITISH COLUMBIA AND WASHINGTON

By

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ABSTRACT

The litho- and biostratigraphy of the Upper Cretaceous Nanaimo Group of the Vancouver Island region is revised on the bases of new fossil and field data. The Extension, Ganges and Protection Formations, recently subordinated into the Extension-Protection Formation by Muller and Jeletzky (1970) are readily mappable units, and are redefined as separate formations. The Haslam Formation contains previously unrecognized turbiditic facies. A new range zone, based on the range of *Baculites chicoense* Trask and *Submortoniceras chicoense* (Trask) is superjacent to the Schmidti Zone and subjacent to the Vancouverense Zone. The Pacificum subzone of the Vancouverense Zone (Muller and Jeletzky, 1970) is given full zonal status because of the non-overlap of *Metaplacenticeras* cf. *pacificum* (Smith) and *Pachydiscus suciaensis* (Meek).

The paleoecology of the Elongatum Zone is examined using multivariate techniques. Four faunal assemblages are differentiated with cluster analysis: an inocerami-ammonite assemblage, a deposit-feeding bivalve dominant assemblage, an infaunal suspension feeding bivalve assemblage, and an anomiid bivalve-ammonite assemblage. The majority of the heteromorph ammonites of the Nanaimo Group were facies independent, suggesting either a wide enviromental tolerance, or extensive post - mortal transportation.

A detailed morphological examination of a number of Nanaimo Group heteromorph ammonites indicates near or neutral buoyancy for the complete living animal and shell.

Volume and density estimates for the heteromorphic species *Didymoceras (Bostrychoceras) elongatum* (Whiteaves), *Glyptoxoceras subcompressum* (Forbes), *Ryugassella ryugasensis* Wright and Matsumoto, *Baculites inornatus* (Meek), *B. anceps pacificus* Matsumoto and *Pseudoxybeloceras (Cyphoceras) nanaimoense* Ward and Mallory all show positive buoyancy for complete animal without cameral fluid. A new technique to simulate living positions using exact and scale models made of microcrystalline sculpting wax of varying densities is employed. Baculitids show a near-vertical orientation in all growth stages. *D. elongatum* has a vertical orientation (apex upwards) until formation of the U-shaped body chamber, when a slight tilting of the entire shell takes place. *G. subcompressum*, with a complex sequence of orthoconic, torticonic and finally gyroconic stages, shows a variety of attitudes. The hamitid *P. nanaimoense* shows a progressive "tumbling" in orientation during growth.

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CHAPTER 1

INTRODUCTION

One of the most remarkable aspects of the history of the Ammonoidea is the development of the irregular, non-planispiral forms--the heteromorphs. Diverse in both number and form, these species radiated during short intervals of the Triassic and Jurassic and throughout the Cretaceous to become important and, in some cases, numerically dominant constituents of many ammonitiferous facies.

Unfortunately, little is known about either habit or habitat of these species, or possible adaptive advantages conferred by their shell shapes. Many past workers considered them to be prime examples of "racial senility"; since they appeared near the end of the history of the ammonites, it was felt that they were short-lived, non-adaptive mutations (see Wiedmann, 1969, for a review). A second pervasive concept found in ammonoid literature is that most (or all) heteromorphs were benthonic. The striking parallelism of the trochoid turrilitid heteromorphs and the many similar, vagile gastropods has fostered this view, as has their probable poor swimming ability. Writers advocating a benthonic existence include Diener (1912), Berry (1928), Beurlen (1928), Trueman (1941), Kauffman (1967) and Wiedmann (1973).

Although the hypothesis of racial senescence is no longer seriously considered in light of modern genetic and evolutionary knowledge, the hypothesis of the heteromorph shell as an exclusively benthonic adaptation remains in the literature and in textbooks (see Moore, Lalicker and Fischer, 1952; Tasch, 1974), even though virtually untested. This thesis was initiated with the premise that a detailed examination of facies and faunal relationships, and an examination of form of heteromorph species from a restricted geographic and temporal setting would allow better insight into the problem of heteromorph habitat and function. Therefore, the major questions posed within this study are as follows:

1) Are correlations between heteromorph ammonite occurrence and lithologic faunal parameters observable, and if so, can inferences about either habit or habitat be inferred?

2) Can detailed morphologic study of heteromorphs provide information on such paleoecologic aspects as buoyancy capabilities and life orientation?

The Upper Cretaceous Nanaimo Group of the Vancouver Island area was chosen as the study area, since it is accessible, shows excellent fossil preservation, contains a diverse suite of ammonites, including numerous heteromorphic species, and has a long history of previous investigation. During my course of study, however, it became apparent that extensive revisions to the stratigraphy and taxonomy were warranted in light of my taxonomic and stratigraphic interpretations. example, previous to this study, only three species of Baculites were recorded from the Nanaimo Group (Usher, 1952; Muller and Jeletzky, 1970); I found one of these, B. chicoense Trask, to be comprised of six distinct species well known in Japan and California. This differentiation, in association with the collection of a number of other ammonites previously unknown from the Nanaimo Group, suggested a more refined biostratigraphy. As a second example, field work in areas of the Nanaimo Group only briefly discussed by previous workers revealed the presence of a previously unknown paleogeographic and sedimentological feature, a large-scale turbidite basin running across a portion of southern Vancouver Island. The presence of turbidites in an area previously considered to be comprised of "shelf" sediments necessitated revised interpretation of the habitat of faunal constituents.

In light of these discoveries, therefore, the first four chapters of this work concern revisions of the lithostratigraphy, ammonite biostratigraphy, systematic paleontology and paleogeography of the Nanaimo Group. Although these topics increased the scope of the work beyond the bounds of its original problems, I consider these topics necessary prerequisites to the reconstructions of paleoecology and functional morphology treated in later chapters.

CHAPTER 2

STRATIGRAPHY

2.1 Introduction

The Nanaimo Group of Western British Columbia and Northwestern Washington State is comprised of marine and non-marine clastic sediments deposited during the late Santonian to Maestrichtian of the Cretaceous Period. Nanaimo strata are exposed along the southeast coast of Vancouver Island from the Saanich Peninsula to Cambell River, at inliers along Lake Cowichan and in the Alberni area, and on the Gulf Islands and San Juan Islands in the Strait of Georgia. Location of Nanaimo Group strata is shown in Figure 2.1.1.

Geologic investigations of the Nanaimo Group were initiated over a century ago, and were spurred by the discovery of productive coal deposits near the eastern coast of Vancouver Island. Newberry (1857) first established a Cretaceous age for the Nanaimo Group. Richardson (1872, 1873, 1897) published the first detailed stratigraphic and structural interpretations, delineating, from north to south, three separate depositional basins: the Comox, Nanaimo and Cowichan. Clapp (1912, 1917) first established formational subdivision and nomenclature, giving separate names to formations in the Comox, and combined Nanaimo-Cowichan areas.

Intra- and interregional correlation of Nanaimo strata has been the focus of most stratigraphic investigation since Clapp. Usher (1952)

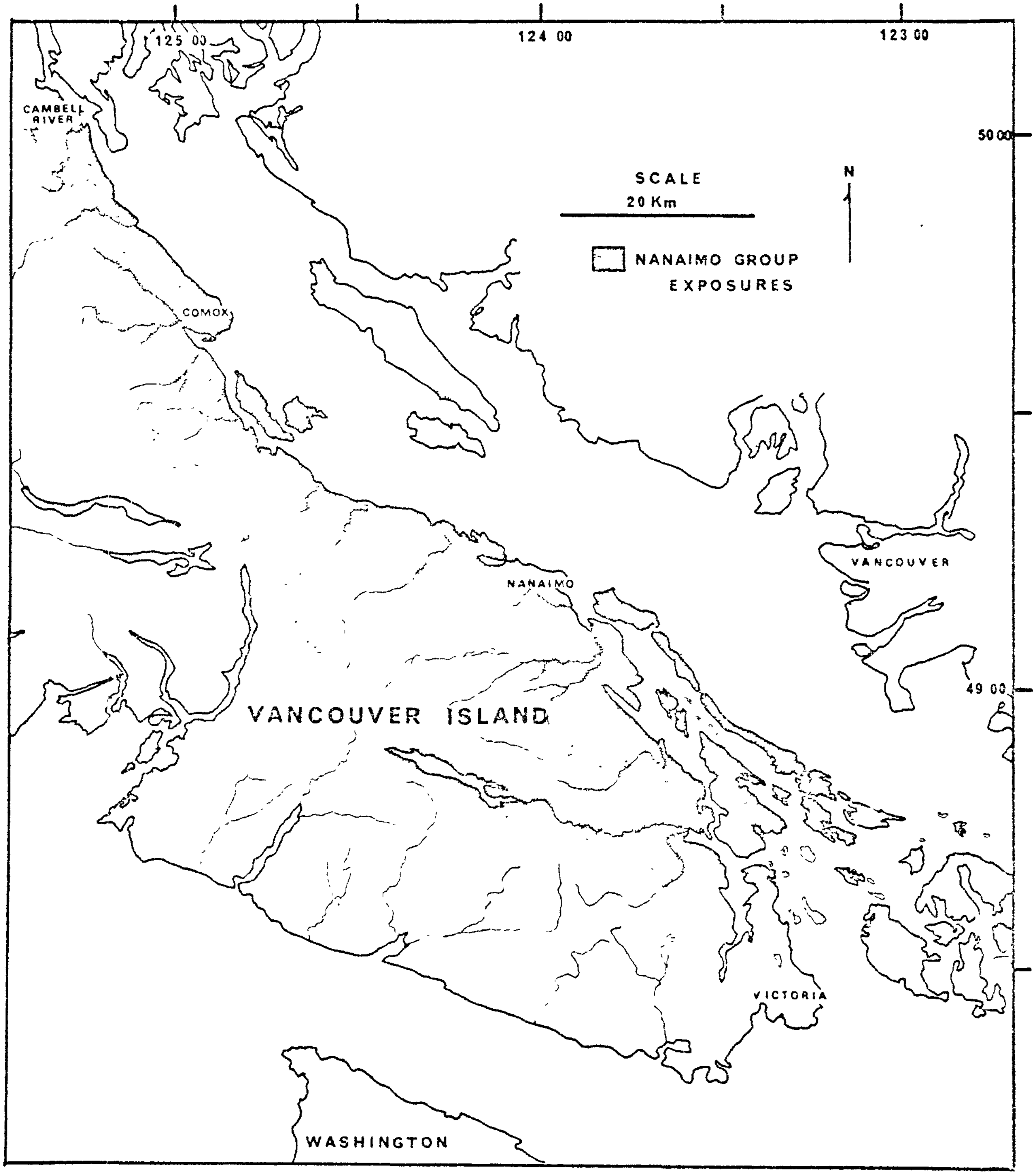


FIGURE 2.1.1 Location of Nanaimo Group outcrops

monographed the ammonites from the Nanaimo Group, established four faunizones based on ammonite occurrences, and correlated these faunizones with Upper Cretaceous European Stages. McGugan (1962, 1964) described the foraminiferans from the Nanaimo Group, and first suggested that several previously correlated formational boundaries in the northern and southern depositional areas were actually diachronous. These findings, particularly with regard to McGugan's correlation of the lower Trent River Formation in the north and the Haslam Formation in the south, were supported by Crickmay and Pockock (1963) and Jones (1963).

Muller and Jeletzky (1970) were the first to propose a unified formational nomenclature for the Nanaimo Group, and provided a refined biostratigraphic subdivision based on teilzones and range zones of ammonites and inocerami. These writers subordinated the numerous non-marine and coal-bearing formations of previous writers of the Nanaimo Basin into a single formation, the Extension-Protection Formation, and indicated that coal-bearing strata in the Comox and Nanaimo Basins are not correlative.

Sliter (1973) analyzed foraminiferal occurrences from several stratigraphic successions in the Nanaimo Group, and correlated them with foraminiferal zones in the California Upper Cretaceous. Scott (1974) also studies Nanaimo foraminifera, but from the Haslam formation only.

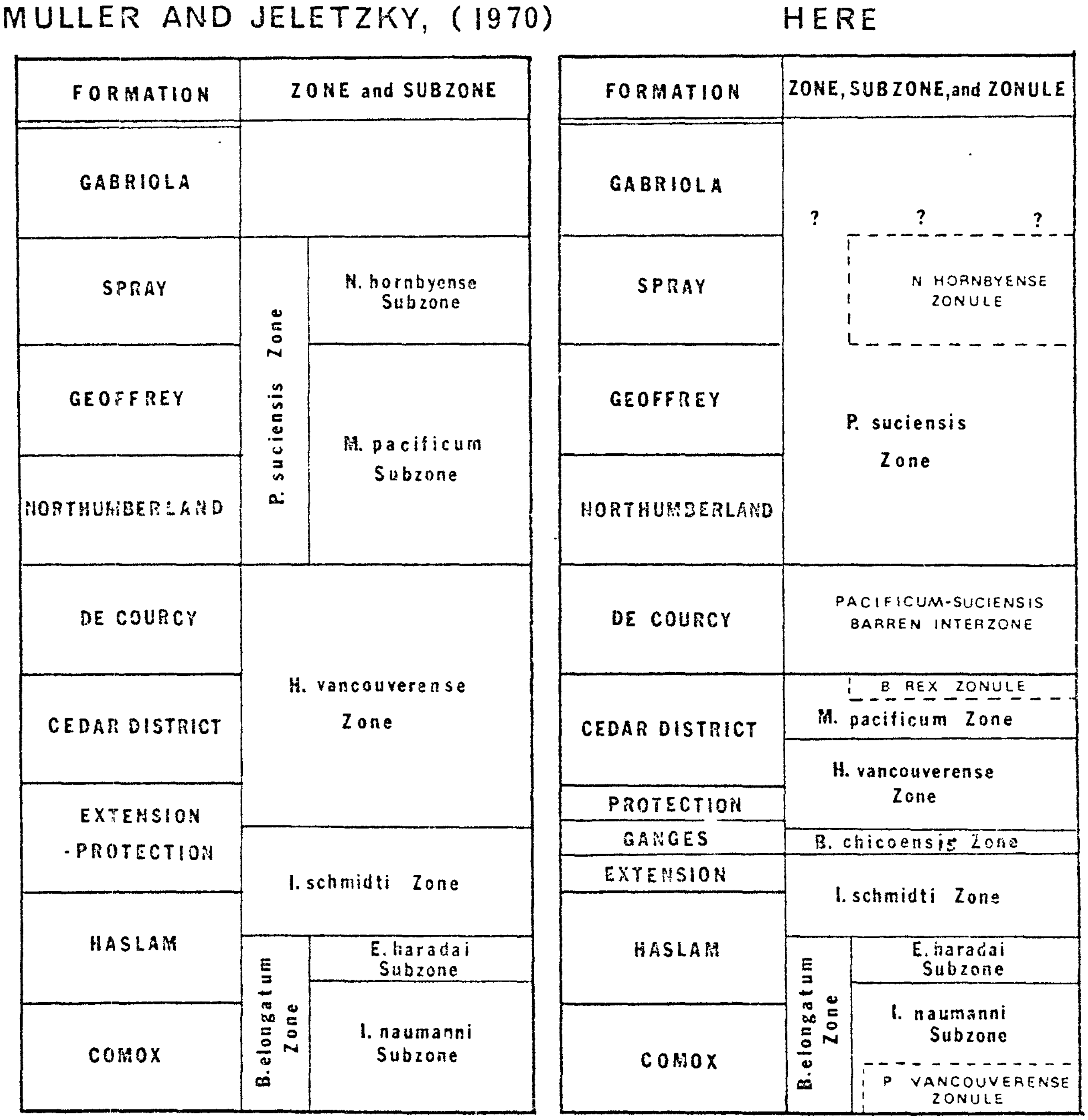
Although the Upper Cretaceous successions in the San Juan Islands of Washington State had been recognized as southerly equivalents of the Nanaimo Group (McLellan, 1927), no differentiation of these units had been accomplished except on Sucia Island. Ward (1974) first correlated other Upper Cretaceous sections on Orcas, Waldron and Stuart Islands with the formational and biostratigraphic subdivisions of Muller and Jeletzky (1970).

The formational succession as recognized in this work is compared with the succession of Muller and Jeletzky (1970) in Figure 2.1.2, and briefly described below. As most of these formations have been described in detail by previous writers (cf. Usher, 1952; Muller and Jeletzky, 1970), descriptive emphasis has been placed on the lithologies in the poorly described Cowichan, Saanich Peninsula, Gulf Island and San Juan areas. Major changes with previously published formational successions and descriptions are an amended description of the Haslam Formation, to include unrecognized turbidite facies present in the Cowichan Valley, Saanich Peninsula and San Juan Islands; and re-recognition and definition of the Ganges Formation, which was recently suppressed by Muller and Jeletzky (1970). The exceedingly complex, intertonguing relationships between turbidites of the Cedar District and Northumberland Formations and coarse, massive sandstones and conglomerates of the De Courcy and Geoffrey Formations are also described.

2.2 Nanaimo Group Formational Succession

2.2.1 Comox Formation

The Comox Formation rests with angular unconformity on basement volcanics and igneous intrusives. The formation was first defined by Clapp (1912a, b) for the coaliferous strata of the Comox Basin area; Muller and Jeletzky (1970) expanded the definition to include the basal Upper Cretaceous beds in the southern Nanaimo Group as well. Dominant



MULLER AND JELETZKY, (1970)

FORMATION	ZONE and SUBZONE	
GABRIOLA		
SPRAY	P. suciensis Zone	N. hornbyense Subzone
GEOFFREY		M. pacificum Subzone
NORTHUMBERLAND		
DE COURCY	H. vancouverense Zone	
CEDAR DISTRICT		
EXTENSION -PROTECTION	I. schmidti Zone	
HASLAM	B. elongatum Zone	E. haradai Subzone
COMOX		I. naumanni Subzone

HERE

FORMATION	ZONE, SUBZONE, and ZONULE	
GABRIOLA	? ? ?	
SPRAY	P. suciensis Zone	N HORNBYENSE ZONULE
GEOFFREY		
NORTHUMBERLAND		
DE COURCY	PACIFICUM-SUCIENSIS BARREN INTERZONE	
CEDAR DISTRICT	B REX ZONULE M. pacificum Zone H. vancouverense Zone	
PROTECTION		
GANGES	B. chicoensis Zone	
EXTENSION	I. schmidti Zone	
HASLAM	B. elongatum Zone	E. haradai Subzone
COMOX		I. naumanni Subzone P VANCOUVERENSE ZONULE

FIGURE 2.1.2 Comparison of formational schemes

lithologies include pebble conglomerates and coarse, trough-cross bedded sandstones with interbedded coal seams.

North of Lake Cowichan, on Meade Creek, the Comox Formation is comprised of an unknown thickness of cobble conglomerate. To the east, in the Saanich Peninsula area, it is exposed as a thick (estimated at 700 - 1000m) succession of fluviatile sandstones, pebble conglomerates, and carbonaceous shales with thin coal seams. A gradational transition from coarse sandstones to marine fossiliferous siltstones is exposed immediately west of the Government ferry landing at Swartz Bay on Saanich Peninsula.

In the San Juan Islands, the formation is exposed on Stuart and Orcas Islands. On Stuart Island (section 73-1, Figure 2.2.1; Figure 2.2.2), Comox equivalents are mainly pebble and cobble conglomerates interbedded with coarse sandstones of at least 100 metres thickness, gradationally overlain by proximal turbidites. Because of their interbedded relation with the turbidites, the conglomerates may be resedimented conglomerates (cf. Walker, 1976), rather than shallow marine or non-marine strata, as everywhere else in the Comox Formation. On Orcas Island (section 73-3, Figure 2.2.1; Figure 2.2.3), 30 m of poorly sorted, coarsely grained lithic subarkose with abundant carbonaceous materials on bedding planes are interbedded with conglomerates composed of rounded quartz and metamorphic rock cobbles. This section is overlain by thin, distal turbidites of the succeeding Haslam Formation.

2.2.2 Haslam Formation

The stratotype of the Haslam Formation at Haslam Creek (Clapp, 1912) is composed of massive, thickly bedded siltstones and shales;

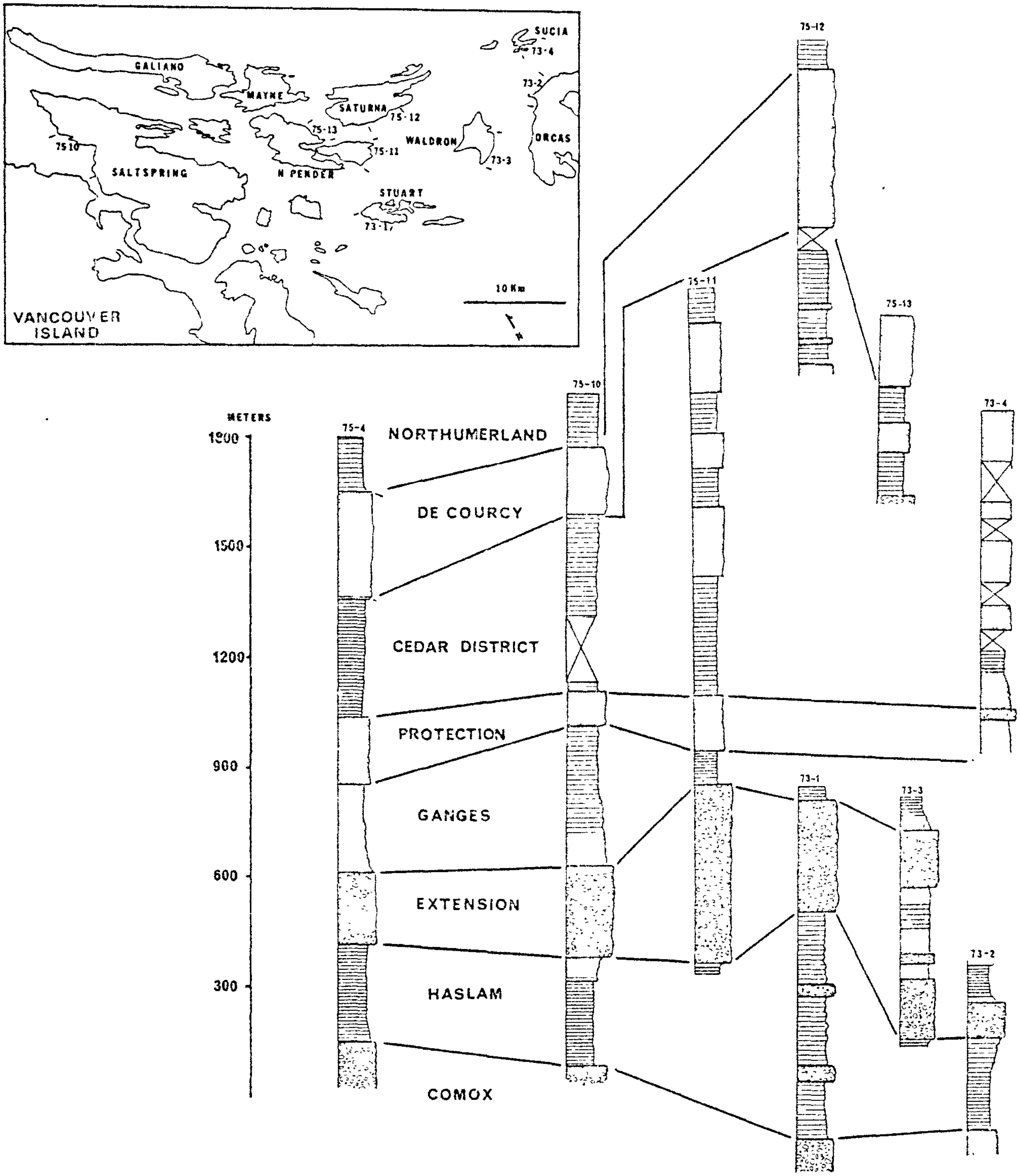


FIGURE 2.2.1 Measured sections, Gulf Island region. Section 75-4 is a composite section from Nanaimo River, taken in part from Clapp (1912), Muller and Jeletzky (1970) and my measurements.

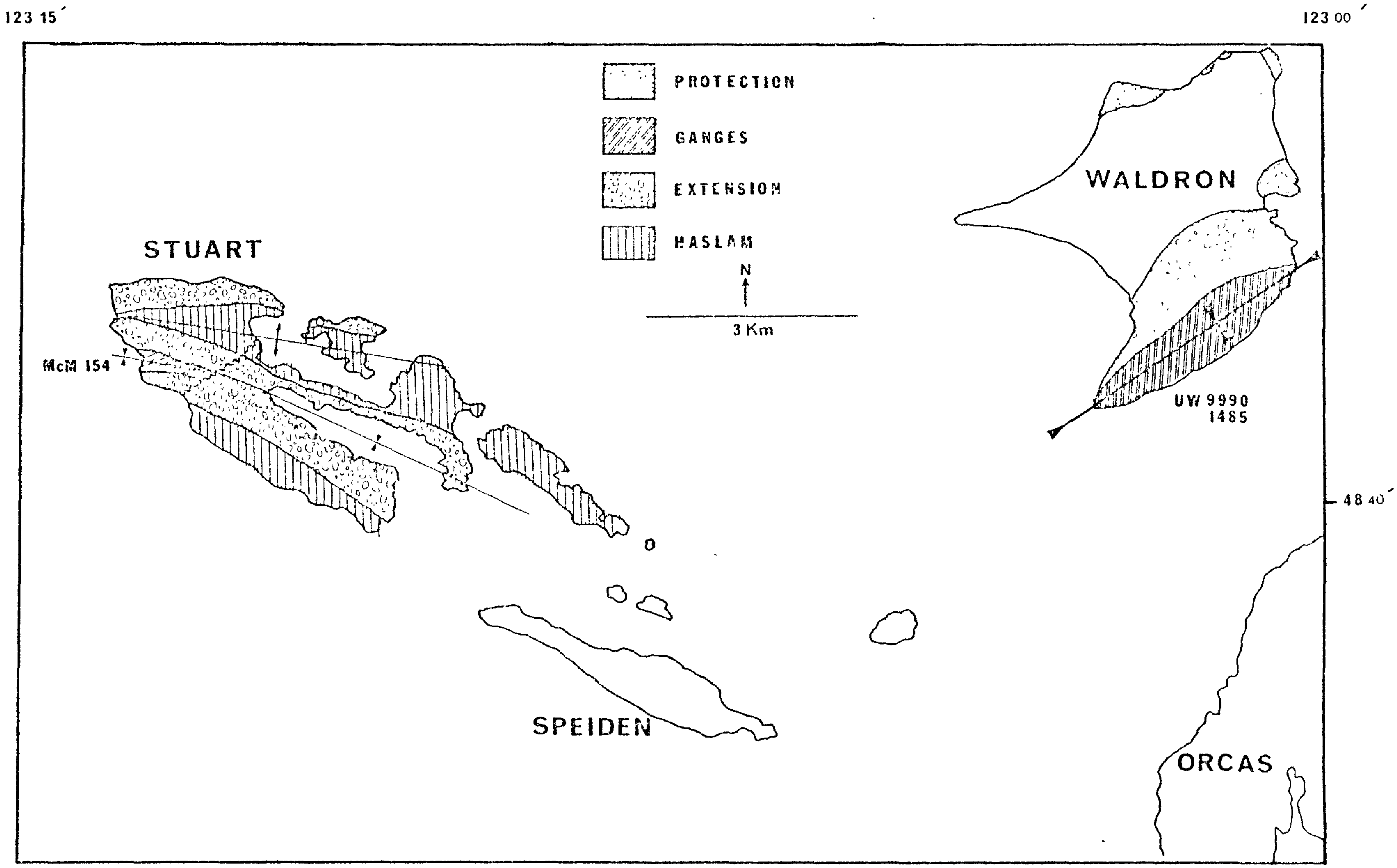


FIGURE 2.2.2 Formational map of Stuart and Waldron Islands.

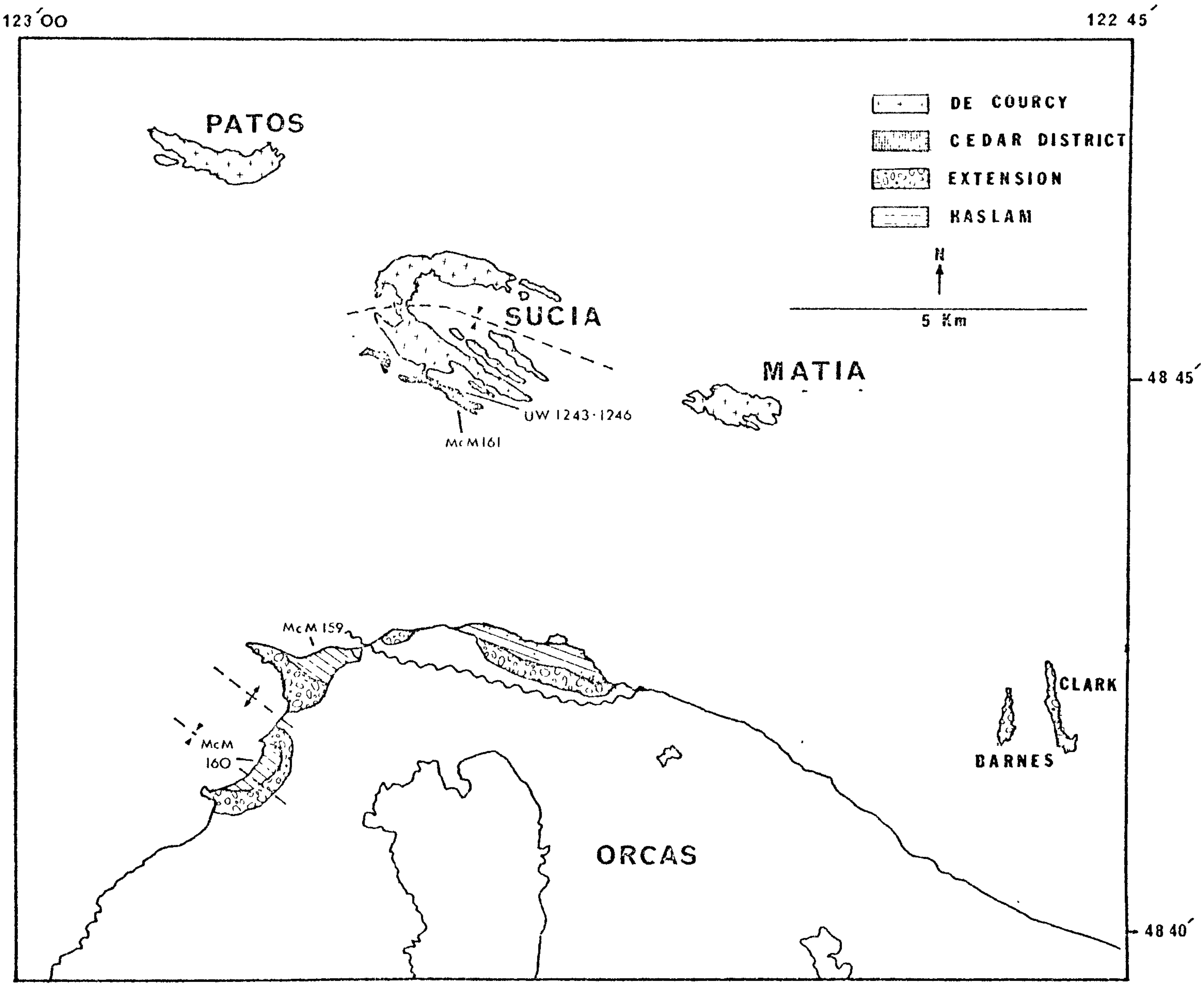


FIGURE 2.2.3 Formational map for Orcas and Sucia Islands.

according to Muller and Jeletzky (1970) and Scott (1974), no turbiditic correlatives of the formation are present in the Nanaimo Group. These same writers indicated a maximum thickness for the Haslam Formation of approximately 200 m. My observations in the Southern Nanaimo Group depositional areas show the presence of a large (60 km largest dimension) turbidite basin, extending from the Upper Chemainus and Cowichan Rivers in the west to Orcas Island in the east. The majority of strata in this area are distal and proximal turbidites which can be paleontologically correlated with the Haslam Formation stratotype. A maximum thickness of 600 m of the Haslam Formation correlatives have been measured.

At Marie Canyon, Cowichan River (section 75-7, Figure 2.2.4), approximately 500 m of distal and proximal turbidites conformably overlay thinnly bedded silty shales. In the turbidite section solemarks are common on the bottoms of beds thicker than .5 m; according to the model of Bouma (1962), the majority of turbidite units can be classified as either AB, ACD, or CD. Invertebrate megafossils are rare, but present throughout the section. Reconstructed current directions from the A-bed solemarks indicate both E-W and W-E paleocurrents. An unmeasured but lithologically similar section is present on the Upper Chemainus River. Unfortunately, no invertebrate fossils were recovered from this section.

In the Saanich Peninsula area (Figure 2.2.5), a thick succession of turbidites are present on Pym and Piers Islands. The strata are distal in nature, as no Bouma A-division beds were observed and beds as thick as one metre were rare; most divisions initiate with shales showing interval convolute bedding and, more rarely, climbing ripples (Division C), succeeded by thin, parallel beds (Division D or E). An average flow

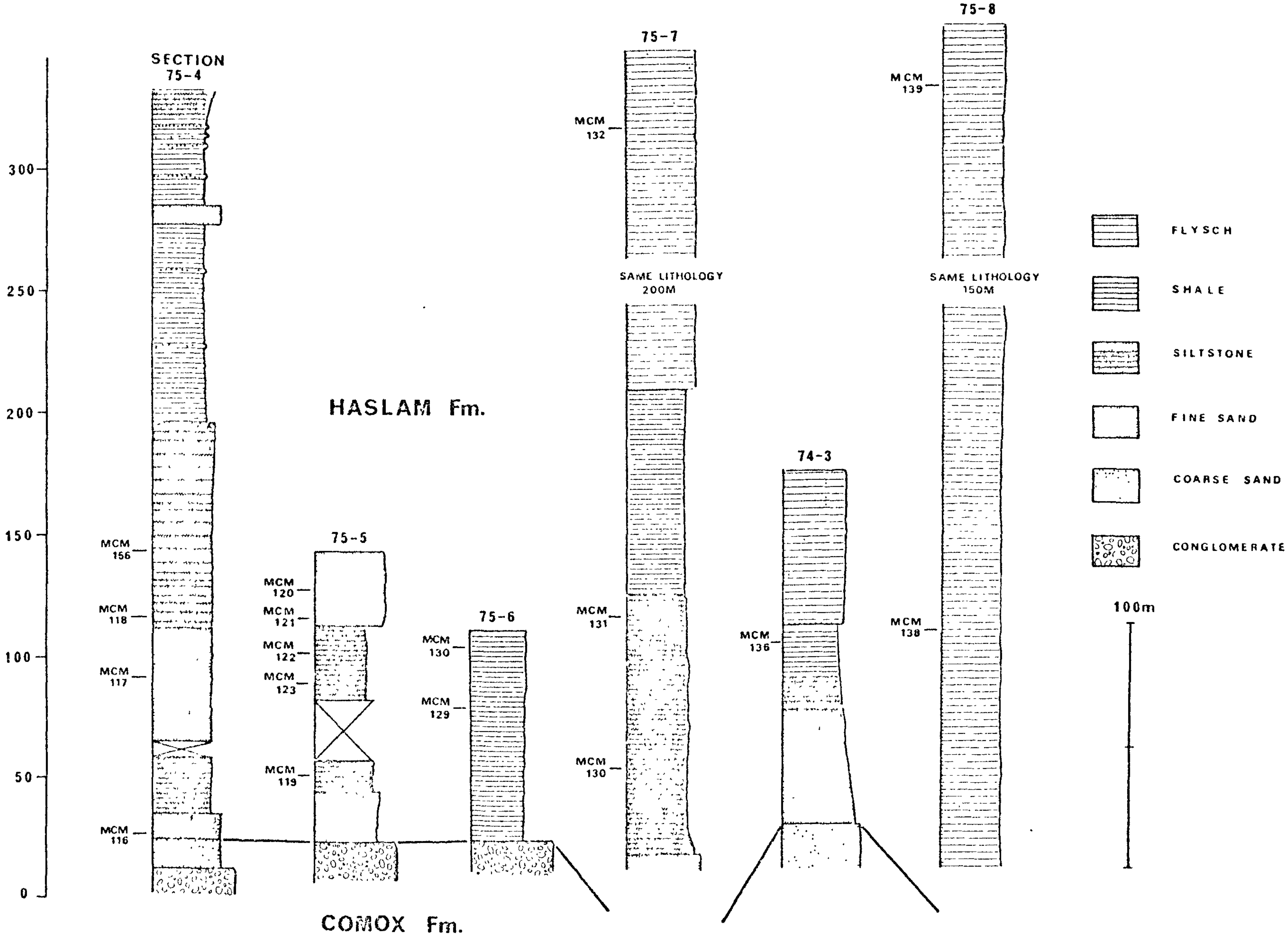


FIGURE 2.2.4 Measured sections, western Nanaimo Basin.

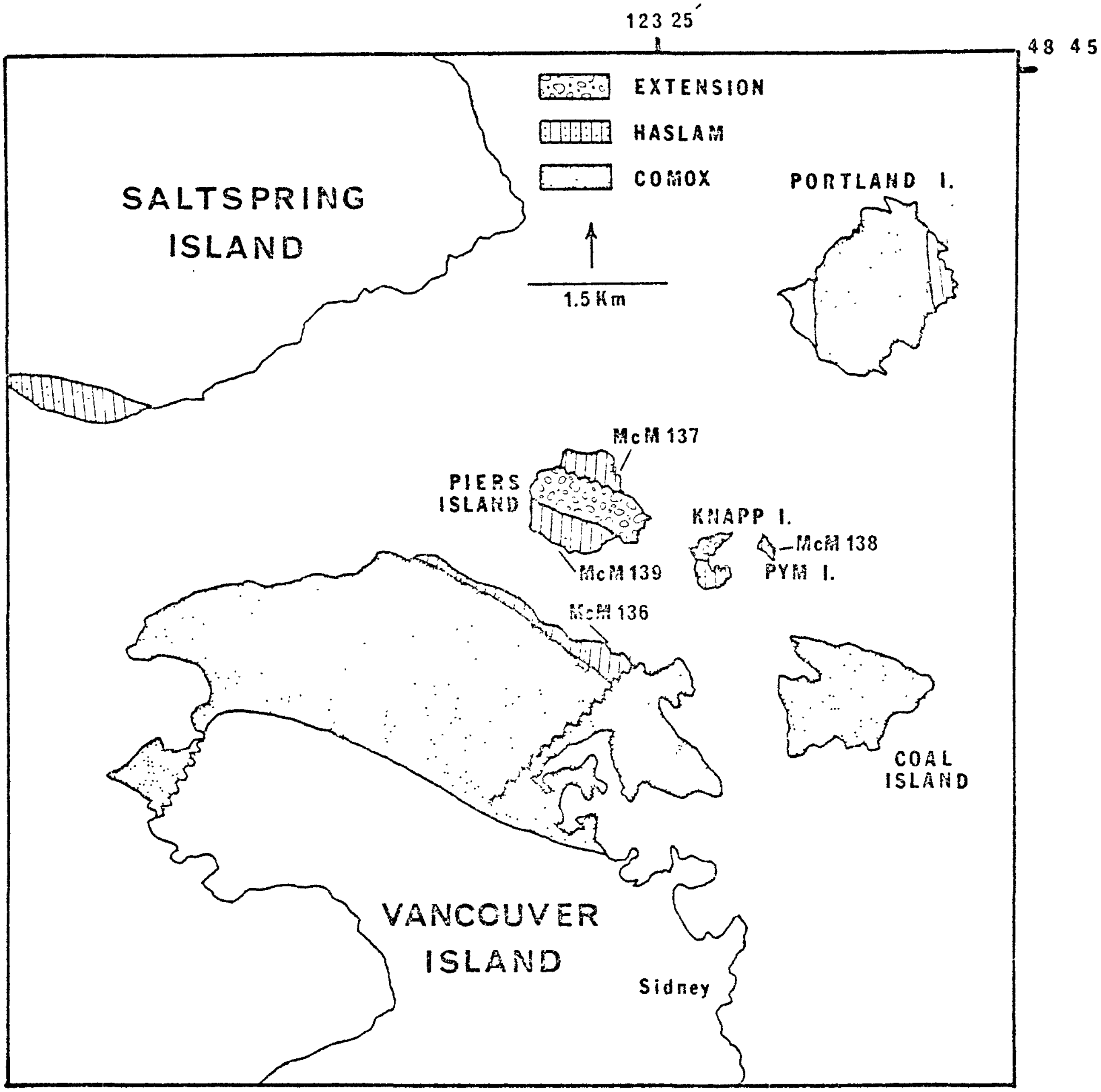


FIGURE 2.2.5 Formational map, Saanich Peninsula area.

regime relatively lower than for the Chemainus River beds is indicated. On Pym Island (section 75-8, Figure 2.2.4), 423 m of uninterrupted section was measured. Fossils are relatively common throughout, and establish the beds as correlative to the Haslam Formation stratotype. A lithologically similar, but incomplete section of approximately 400 m was measured on nearby Piers Island.

Ten kilometres to the east of Piers Island, on Stuart Island, 600 m of mainly proximal turbidites are interbedded with cobble conglomerates. The majority of beds could be characterised as Bouma AB and AC beds. Sole marks are present on most Bouma A beds; paleocurrent directions are primarily NW. The most southeasterly exposures of Haslam Formation equivalents, on Orcas Island, are more distal than on Stuart Island in the lower parts of the section, but become increasingly proximal higher in the section. The Orcas Island stratigraphy has been discussed previously by this author (Ward, 1974, 1976).

In summary, Haslam Formation equivalents are comprised of distal and proximal turbidites, and possibly in some sections by resedimented conglomerates in a previously unrecognized, east-west trending turbidite basin of large geographic extent (See Chapter 5). I propose that the definition of the Haslam Formation be amended to include these lithologically distinct, but coeval facies.

2.2.3 Extension Formation

The Extension Formation (Clapp, 1912) is mainly conglomeratic, but includes interbeds and lenses of sandstone and shale, and coal seams. The formation varies in thickness between north and south, averaging 200 m north of Nanaimo, and 400 m to the south.

In the Gulf and San Juan Islands clast sizes vary between pebble and large boulders. Most common clast lithologies are silicified volcanics (mainly andesites), granites and metagranites, basic plutonics, jasperoid chert and meta-sediments. The matrix consists of rock fragments and quartz, with subordinate amounts of feldspar, in a calcareous cement. An abundance of jasper gives the weathered matrix a reddish or greenish hue.

The contact with the underlying Haslam Formation is everywhere unconformable, and often shows large channelling.

2.2.4 Protection Formation

The Protection Formation (Clapp, 1914) is comprised of massive, white to grey, medium to fine-grained sandstones. The formation is only known south of the town of Nanaimo.

In the Gulf Islands, the lithology is somewhat different than that described by Clapp. The distinctive, well-sorted white sandstones of the north are replaced in the Gulf Islands by poorly-sorted lithic wackes, locally with shale interbeds. Carbonaceous material is common on bedding planes.

Differences in formational thicknesses between northern and southern exposures are also pronounced. Usher (1952, p.14) characterized the Protection Formation as "the most uniform in thickness of any of the Nanaimo Formations, ranging between 600 and 750 feet, and averaging 650 feet". On South Pender Island a similar thickness has been measured; on nearby North Pender, however, the formation thickens to the northwest, such that a thickness of nearly 400 m has been measured on the west side of the Island.

Ganges Formation

The Ganges Formation was defined by Clapp (1917) for thinly bedded sandy shales overlying the Extension Formation in the southern Nanaimo Basin. Outcrops exposed along the shores of Ganges Harbor, Saltspring Island, were designated stratotype. Clapp considered the Ganges Formation as the lateral equivalent of the Newcastle and Cranberry Formations, which have stratotype sections near the town of Nanaimo. Because of their limited extent, the Cranberry and Newcastle Formations are here subordinated as facies of the Ganges Formation.

The Ganges is well exposed in the San Juan Islands and Gulf Islands. On Waldron Island and Stuart Island, approximately 100 m of fine-grained sandstones and siltstones are exposed. Slightly finer grained facies of similar thickness are exposed on North and South Pender Island. On Saltspring Island Clapp estimated approximately 200 m of section in the stratotype area. On Vancouver Island the Ganges Formation is exposed on the lower Cowichan River near the town of Duncan as sandstones grading upward into shales in an unknown thickness. To the north of this section, the Ganges coarsens as described by Clapp (1917).

In the Comox Basin,shales exposed on the lower reaches of Trent and Puntlege Rivers and on Texada Island are here placed within the Ganges Formation. These strata have been mapped as Cedar District Formation by Muller (in Muller and Jeletzky, 1970), but differ in lithology from typical Cedar District (which is dominantly turbiditic), and are of different age. On Trent River nearly 150 m is exposed. The Ganges Formation sections on Puntlege River and Texada Island are not measured.

The basal contact of the Ganges Formation with the underlying Extension Formation is exposed on Waldron, Stuart, North and South Pender, Saltspring, Islands, and on the Cowichan and Nanaimo Rivers in the Nanaimo Basin. In the Comox Basin the lower contact is exposed on Trent River and Texada Island.

The Ganges Formation is often richly fossiliferous. One paleontological characteristic of the formation is the first mass occurrences of the coarsely ribbed inocerami of the Inoceramus vancouverensis-subundatus group. The index ammonites Baculites chicoensis Trask and Submortoniceras chicoense Trask are also restricted to the Ganges Formation.

2.2.5 Cedar District Formation

The Cedar District Formation stratotype (Clapp, 1912) on Dodds Narrows is comprised of concretionary shales with occasional sandstone dykes. Similar lithologies are exposed on the west coast of Denman Island, and on Sucia Island. At these three areas, the Cedar District shales are unconformably overlain by massive, cross-bedded sandstones with conglomeratic interbeds (De Courcy Formation).

Elsewhere in the Nanaimo Group, Cedar District Formation correlatives are quite different in lithology, being composed of proximal and distal turbidites. On North and South Pender Islands and Saltspring Island (Figure 2.2.6), the majority of beds initiate with the Bouma-C division. Climbing ripple drift and convolute laminations are common. Graded or sole-marked beds characterize the Bouma-A division and are exceedingly rare. On the west coasts of Mayne and Saturna Islands, the turbidites are much more proximal, with sand-shale ratios increasing to an estimated 50%.

In the Gulf Islands, the contact between the Cedar District and De Courcy Formations is difficult to define, for the turbidites are interbedded with from one to several massive sandstone units up to 100 m thick.

The recent Vancouver Island area geological map by Geological Suvey of Canada (Muller and Jeletzky, 1970, Figure 11) differentiates the first of these sandstone units overlaying the turbidites on North and South Pender Islands, Saturna Island and Saltspring Island as the De Courcy Formation. The next succeeding turbidite unit is mapped as the Northumberland Formation. My interpretation of the Cedar District -

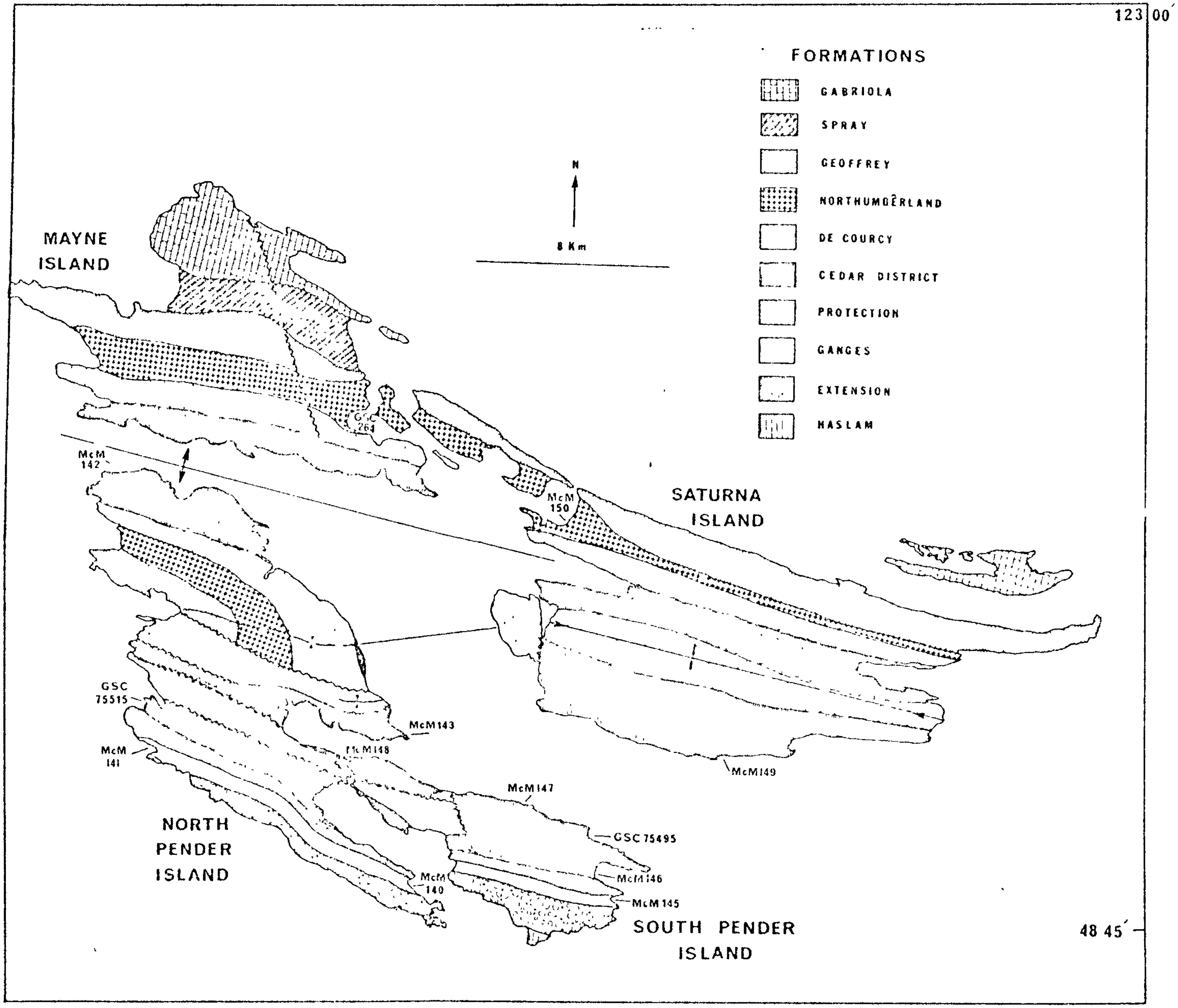


FIGURE 2.2.6 Formational map, Southern Gulf Islands.

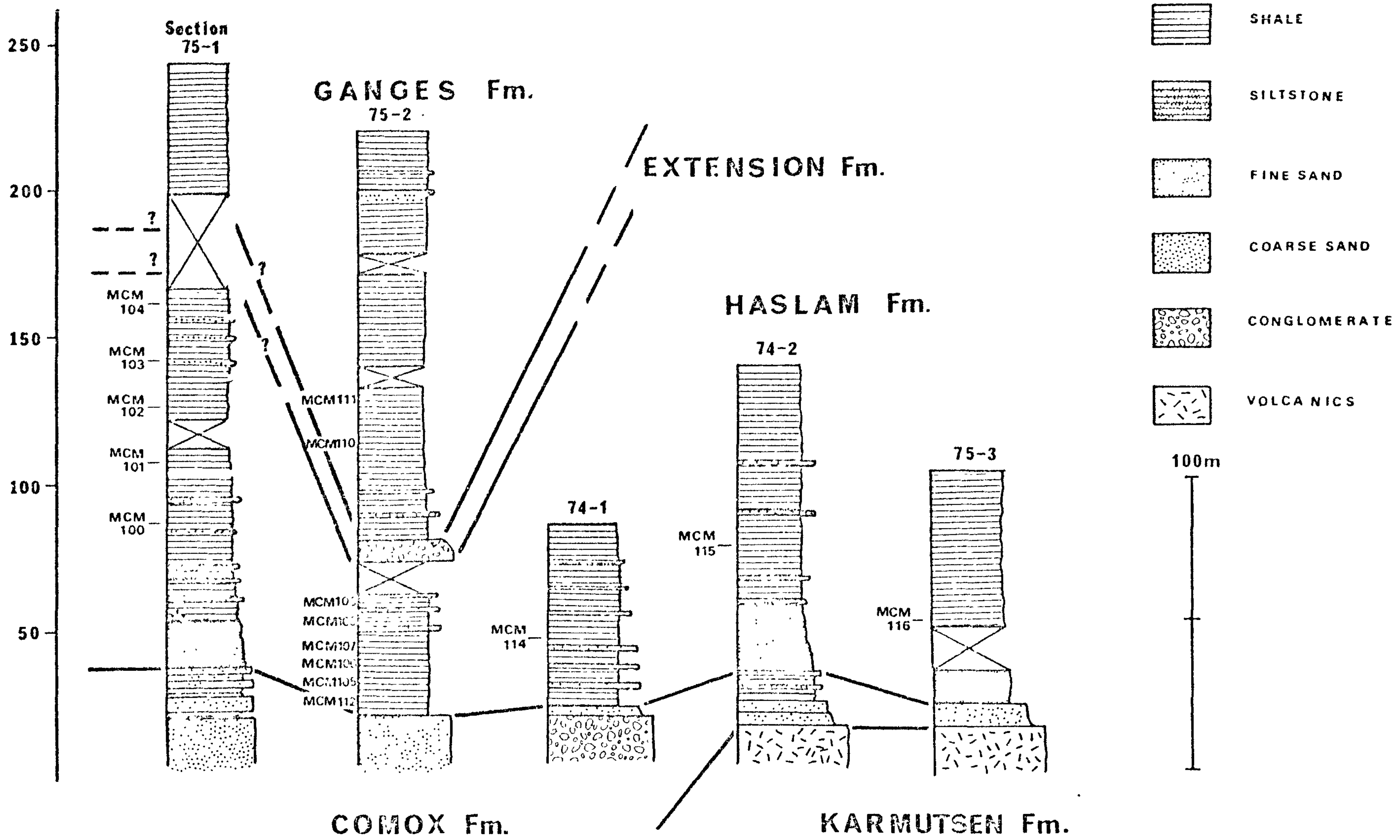


FIGURE 2.2.7 Measured sections, Comox Basin.

De Courcy relationship indicates a much more complex, intertonguing relationship. A revised biostratigraphy for the Nanaimo Group (see Chapter 3) allows biochronologic correlation between individual turbidites units in the Gulf Islands. Correlatives of the Northumberland Formation stratotype on Gabriola Island are of more restricted thickness than interpreted by Muller (in Muller and Jeletzky, 1970); on Saturna Island (section 75-12, Figure 2.2.1) Northumberland time-equivalents are located only on the northeastern half of the Island; on North Pender Island (section 75-11) only in the Port Washington area; and are absent on South Pender Island and the San Juan Islands.

The contact of the Cedar District Formation with the underlying Protection Formation appears to be everywhere gradational. The distinctive conglomerates of Sucia Island and Saturna Island, both composed of rounded, milky quartz cobbles and metamorphic rock fragments were both thought to be coeval and represent, respectively, the base of the Cedar District Formation on these islands (Usher, 1952; Muller and Jeletzky, 1970). On Sucia Island (section 73-4, Figure 2.2.1, Figure 2.2.3), however, approximately 80 m of sandstones underlie this conglomerate, increasing in coarseness low in the section to form a gradational contact with the Protection Formation. The lithologically similar conglomerate on Saturna Island is apparently dissimilar in age to Sucia conglomerate, for it is immediately overlain by a possible grain-flow deposit containing distinctive faunal elements of the latest Campanian (*Baculites rex* Anderson), whereas the strata conformably above the Sucia Island conglomerate contain mid-Campanian faunal elements (*Hoplitoplacenticeras vancouverensis* (Meek), *Baculites inornatus* Meek). This conglomerate lithology is apparently characteristic of southeasternmost Nanaimo Group depositional area, for a virtually identical conglomerate is found in late Santonian Comox Formation deposits of nearby Orcas Island.

2.2.6 De Courcy Formation

The De Courcy Formation (Clapp, 1912a) is comprised of medium- to coarse-grained sandstones and interbedded conglomerates. De Courcy sandstones on Sucia Island, Patos Island, Matia Island and Saturna Island are mainly arkosic, massive and brownish in colour. Fretwork erosion is characteristic of shoreline exposures. Carbonaceous material is disseminated throughout.

2.2.7 Northumberland Formation

The Northumberland Formation was defined by Clapp (1914a) for shales above the De Courcy Formation on Gabriola Island, and for stratigraphically correlative turbidites, sandstones and conglomerates in the southern Gulf Islands. Muller (in Muller and Jeletzky, 1970) interpreted the formation as including only the shales and turbidites; the massive sandstones and conglomerates were included in a newly-defined unit, the Geoffrey Formation. Turbidites exposed on the east shore of Denman Island and on Hornby Island, Comox Basin, were also included by Muller in the Northumberland Formation.

In the southern Gulf Islands, the Northumberland turbidites are generally distal in appearance; the majority of beds can be characterized as Bouma CD beds. Rapidly wedging sandstone bodies of from several metres to several tens of metres are commonly interbedded. Paleocurrent directions inferred from climbing ripples in the turbidites are predominantly western and northwestern.

The entire formation is included in the Pachydiscus suciaensis Zone as defined in Chapter 4.

2.2.8 Geoffrey, Spray and Gabriola Formations

The Geoffrey and Spray Formations were defined by Muller (in Muller and Jeletzky, 1970). The Geoffrey Formation has as its stratotype the thick section of conglomerates along the west shore of Hornby Island; the Spray Formation, the fossiliferous shales immediately overlaying the Geoffrey conglomerates on Hornby Island. The Gabriola Formation, the highest formation of the Nanaimo Group, was named by Clapp (1912a), and was given as its stratotype the conglomerates and arkosic sandstones on the eastern side of Gabriola Island.

On Hornby Island the field differentiation of these formations is clear; in the southern Gulf Islands, however, their correlatives comprise an exceedingly complex assemblage of intertonguing conglomerates, sandstones and turbidites, which make field identification of these formations difficult. On Mayne Island, thick conglomerates exposed on the northeast wedge out into turbidites on the southern side; similar relationships are present on Saturna Island, where coarse sandstones of the southeast side grade into turbidites on the northeast side.

Plate Descriptions, Chapter 2

Plate 2-1, Fig. 1. Haslam Formation turbidites on Stuart Island, Washington. Note hammer for scale.

Plate 2-1, Fig. 2. Large example of Canadoceras newberryanus in Cedar District Formation turbidites, South Pender Island, British Columbia.

Plate 2-1, Fig. 3. Large, sand-filled channel in vertically dipping distal turbidites. Note hammer at base of channel for scale. Haslam Formation, Orcas Island.

Plate 2-1, Fig. 4. Turbidites exposed in Marie Canyon area, Cowichan River. Haslam Formation.

Plate 2-2, Fig. 1. Ripples in turbidites, Stuart Island, Washington. Haslam Formation.

Plate 2-2, Fig. 2. Sandstone dykes (white arrows) in Haslam Formation shales, Trent River.

Plate 2-2, Fig. 3. Concretionary horizon, Haslam Formation, Elkhorn Creek. Concretions up to .5 m diameter.

Plate 2-2, Fig. 4. Channelled, wedging sandstones (white arrows) near top of Haslam Formation, Puntlege River.

Plate 2-3, Fig. 1 Protection Formation, South Pender Island.

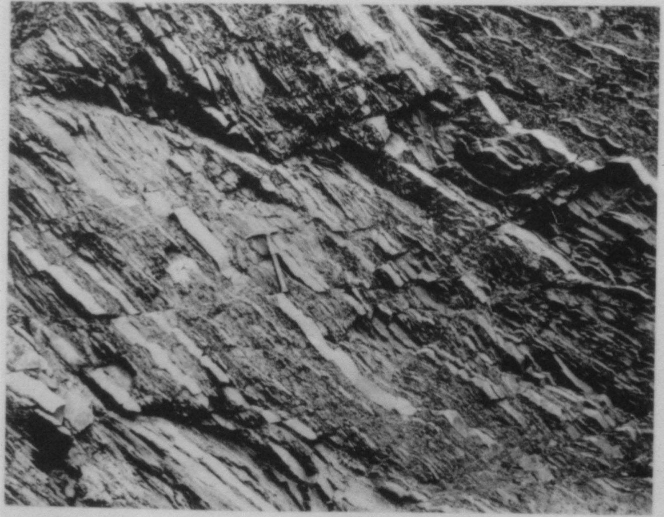
Plate 2-3, Fig. 2. Protection Formation near type area, town of Nanaimo. Bulldozer for scale.

Plate 2-3, Fig. 3. Thin distal turbidites, Pym Island, British Columbia (Saanich Peninsula area). Haslam Formation.

Plate 2-3, Fig. 4. Ganges Formation sandstones overlying Extension Formation conglomerates (lower left side of picture). Waldron Island, Washington.

Plate 2-3, Fig. 5. Extension Formation conglomerate, Orcas Island, Washington.

2-1



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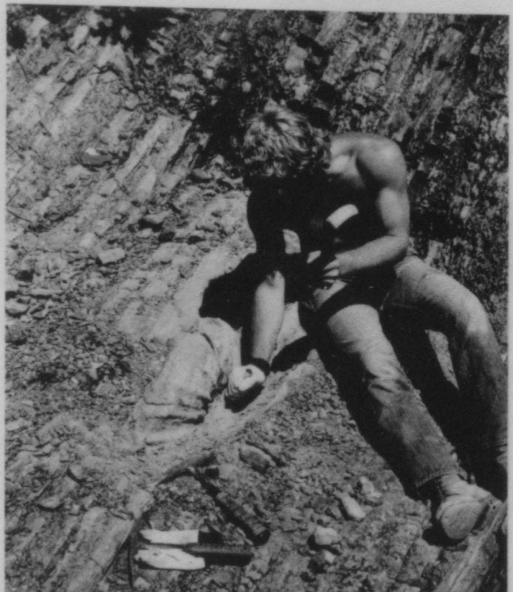

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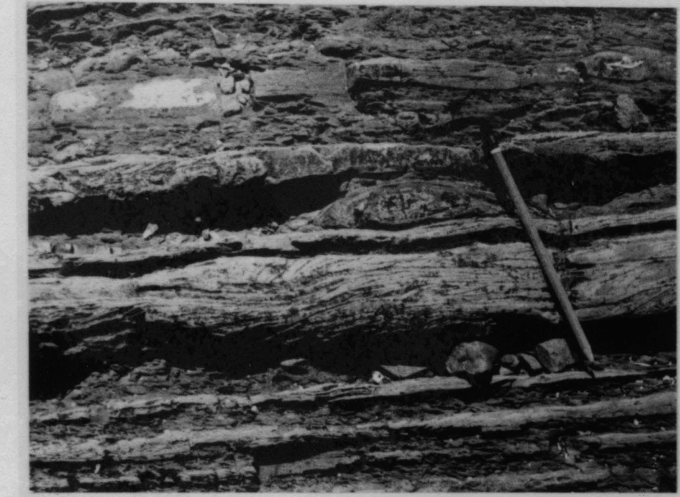

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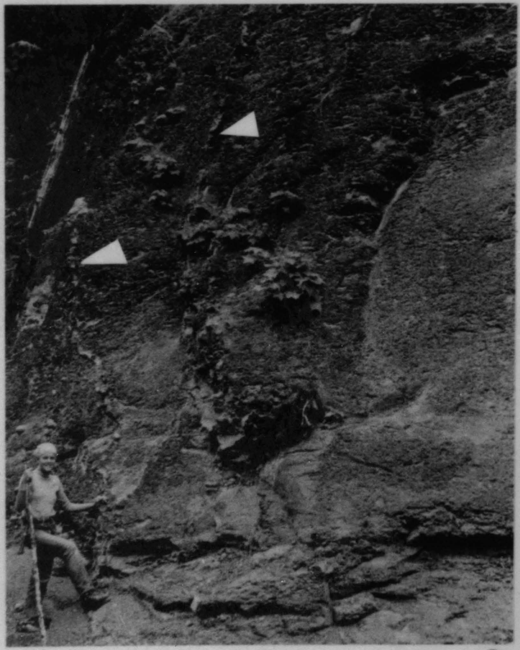

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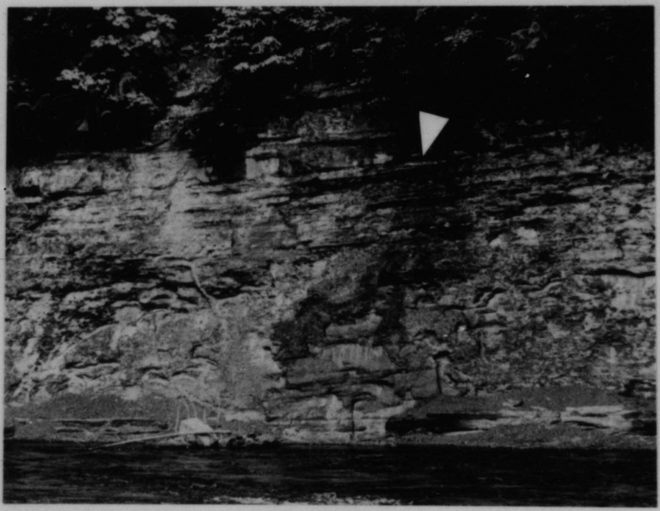

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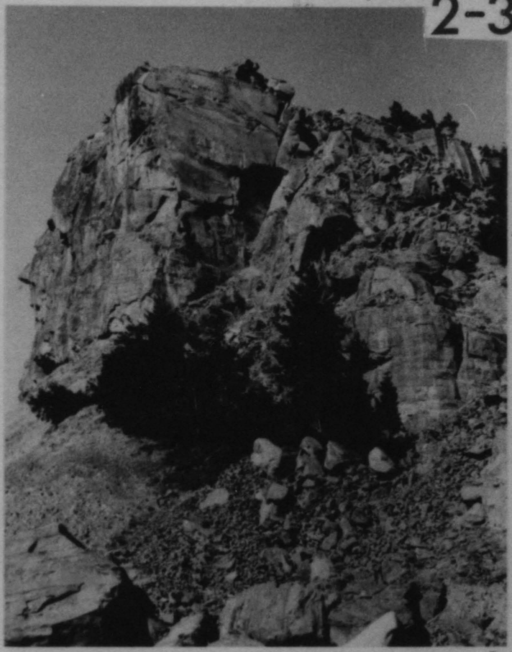
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5

CHAPTER 3

BIOSTRATIGRAPHY

3.1 Introduction

The North Pacific Province was defined by Jeletzky (1965) for Pacific slope (north of Mexico) faunas of late Berriasian to mid-Valanginian age; Jeletzky later (1970a, 1971) broadened the definition to include this geographic area during the entire Cretaceous.

Biostratigraphic differentiation of regions in this province during the Santonian to Maastrichtian Stages has been established in Alaska (Jones, 1963); British Columbia and northernmost Washington State (Jeletzky, in Muller and Jeletzky, 1970) and in California (Popenoe *et al*, 1960; Matsumoto, 1960).

In Alaska, Jones (1963) differentiated two faunal zones: the Campanian *Inoceramus schmidti* Zone, characterizing Member 3 of the Matanuska Formation, as well as the Chignik Formation; and the *Pachydiscus kamishakensis* Zone of the Kaguyak Formation, and the upper part of Member 3 of the Matanuska Formation. Both zones are defined by the local ranges of the index species.

Although no formal zonation of the California Cretaceous based on ammonites has been proposed, Matsumoto (1960) and Popenoe *et al* (1960) have listed a number of ammonite occurrences which they considered biochronologically useful. *Pseudoschloenbachia* aff. *P. boulei* (Basse) and

Baculites capensis Woods were designated as upper Santonian markers; *Submortoniceras chicoense* (Trask) and *Baculites chicoense* Trask marked the lower Campanian; a mid-Campanian marker was not indicated, and *Metaplacentiaras pacificum* (Smith) was designated an upper Campanian marker. The lower Maaestrichtian was characterized by *Baculites rex* Anderson and *Pachydiscus catarinae* (Anderson and Hanna).

Nanaimo Group biostratigraphic zonation based on macroinvertebrate fossil ranges has been proposed by Usher (1952), with ammonite faunizones and in the preliminary report by Muller and Jeletzky (1970), with teilzones and biozones (= range zones) of ammonites and inocerami.

Jeletzky (in Muller and Jeletzky, 1970) subdivided the Nanaimo Group into four zones, listed from oldest to youngest:

1. Elongatum Zone - Defined by the teilzones of *Didymoceras (Bostrychoceras) elongatum* (Whiteaves) and *Glyptoxoceras subcompressum* (Forbes). This zone was further subdivided into a lower subzone (Naumanni subzone) based on mass occurrence of *Inoceramus naumanni* Yokoyama and an upper subzone (Haradai subzone) defined by the range of *Eupachydiscus haradai* Usher.
2. Schmidti Zone - Defined by the range zones of the divergently ribbed inocerami of the *I. schmidti* group, including *I. schmidti* Michael, *I. sachalinensis* Sokolov and *I. elegans* Sokolov. Two subzones were proposed: the *I. elegans* subzone and superjacent *I. schmidti* s.s. subzone.

3. Vancouverense Zone - Defined by the range of *Hoplitoplacenticeras vancouverense* (Meek), and the mass occurrence of *I. vancouverense* Shumard, *I. subundatus* Meek, and *Baculites chicoense* Trask sensu Usher.

4. Suciaensis Zone - Defined by the range of *Pachydiscus suciaensis* (Meek), this zone was further subdivided into a lower subzone based on the occurrences of *Metaplacenticeras* cf. *pacificum* (Smith), and an upper subzone based on the occurrence of *Nostoceras hornbyense* (Whiteaves).

Figure 3.1.1 compares these zonations of the Upper Cretaceous North Pacific Province.

In each of the zonations cited above, biostratigraphic differentiation has been through a continuous or non-continuous succession of local range - zones, which can also be considered teilzones. Teilzone has been defined by Arkell (1933) as the visible proportion (local range) of the total worldwide stratigraphic range (biozone) of a fossil taxon.

Local range zone has been defined by the Stratigraphical Code Sub-committee of the Geological Society of London (1967) as: "a body of strata in a specific geographical section or area characterized by the occurrence of a specified fossil group." This type of zonation has been discussed by Jeletzky (1968) with reference to the method of choosing the most useful range - zone taxon, or "index fossil".

As has been suggested by Matsumoto (1960), the local ranges of Late Cretaceous North Pacific Biotic Province ammonites and inocerami may encompass, in different regions, varying proportions of the taxon's

European Stages		ALASKA Jones, 1963	BRITISH COLUMBIA Muller & Jeletzky, 1970		CALIFORNIA Matsumoto, 1960	CALIFORNIA, OREGON, WASHINGTON Muller & Jeletzky, 1970
MAESTRICHTIAN					Baculites rex	
		- ? - ? - ? - ? - ? - ? -	- ? - ? - ? - ? - ? - ? -			- ? - ? - ? - ? - ? - ? -
		Pachydiscus kamishakensis		Nostoceras hornbyensis		Pachydiscus catarinae
CAMPANIAN	UPPER	Inoceramus schmidti	Pachydiscus suciaensis	Metaplacenticeras pacificum	Metaplacenticeras pacificum	Metaplacenticeras pacificum
			Hoplitoplacenticeras vancouverense			Hoplitoplacenticeras vancouverense
	LOWER		Inoceramus schmidti		No indicator	Patagiosites and Anapachydiscus
		- ? - ? - ? - ? - ? - ? -				
			Bostrychoceras elongatum	Pachydiscus haradai	Submortoniceras chicoense	Submortoniceras chicoense
					No indicator	
SANTONIAN				Inoceramus naumanni	Pseudoschloenbachia aff. P. boulei	No indicator
			- ? - ? - ? - ? - ? - ? -			Baculites capensis

FIGURE 3.1.1 Previous Upper Cretaceous Zonal Classifications, Pacific Slope

complete biozone. Examples include the range of Glyptoxoceras subcompressum (Forbes), which ranges only into the lower Campanian in the Nanaimo Group (Muller and Jeletzky, 1970), but is found in the Maastrichtian of California (Matsumoto, 1960); Baculites rex Anderson, which is restricted to the late Campanian of the Nanaimo Group, but which occurs in the Campanian and Maastrichtian of California (Matsumoto, 1960); and Inoceramus schmidti Michael, which occurs in mid-Campanian rocks in California (Matsumoto, 1960) compared to the lower Campanian in the Nanaimo Group (Muller and Jeletzky, 1960). These differences, when unrecognized, can lead to misinterpretations of interregional correlation; as will be demonstrated below, this situation has occurred with the heterochronous teilzones of I. schmidti in Alaska, British Columbia and California.

3.2 Biostratigraphic Revisions of the Nanaimo Group

Since the publication of the report by Muller and Jeletzky (1970), a large number of newly-collected fossils from the Nanaimo Group have become available. These fossils are now reposited at the University of British Columbia, collected by Mr. C. Pharo and student parties; at the University of Washington, collected by Dr. V. Mallory, collected by student field parties, and myself as part of a Master's Program conducted at that school; and at McMaster University, collected by my field parties. With these new data, and detailed examination of previous collections, Nanaimo Group zonation and correlation can be refined as suggested below. A checklist of Nanaimo Group localities is listed in Table 3. 1 ; comparisons of the Nanaimo Group zonation with that of Muller and Jeletzky (1970) is shown in Figure 2.1.2.

TABLE 3.2

	MCM 106	MCM 129	MCM 137	MCM 125	MCM 108	MCM 103	MCM 104	MCM 135	MCM 159	MCM 122	MCM 115	MCM 131	MCM 117	MCM 132	MCM 118	MCM 156	MCM 155	MCM 110	MCM 111	MCM 141	MCM 140	MCM 145	UWA 9990	MCM 154	GSC 77457	GSC 75515	MCM 146	UWB 1245	UWB 1246	UWB 1243	GSC 60846	GSC 75495	GSC 77458	MCM 147	MCM 148	MCM 149	UBC 203	MCM 143	MCM 151	GSC 259	MCM 150	GSC 284	GSC 264	GSC 266	GSC 109	GSC 110	GSC 112	GSC 114
Phyllopachyceras forbesianum (d'Orbigny)																																													R	R	R	R
Nostoceras hornbyense (Whiteaves)																																							R									R
Didymoceras cooperi Gabb																																													R	R	R	R
Pachydiscus ootacodensis (Stoliczka)																																							R					R	R	R	R	R
Pachydiscus suciaensis (Meek)																																							?	R	R	R	R	R	R	R	R	R
Baculites occidentalis Meek																													R						A		C								A	A	A	A
Pseudophyllites indra (Forbes)																													R										R					R	C	C	C	C
Diplomoceras notabile Whiteaves																																													R	R	R	R
Baculites rex Anderson																																A	A		C	C	C	R										
Menuites sp. indet.																																		R														
Gaudryceras denmanense Whiteaves																															C	R					R											
Neophylloceras lambertense Usher																																		R											R	R	R	R
Canadoceras cf. *newberryanus* (Meek)																																							R									
Baculites anceps pacificus Matsumoto																																R	R						A									
Anapachydiscus nelchinensis Jones																																						C										
Metaplacenticeras cf. *pacificum* (Smith)																															R			R														
Baculites inornatus Meek																												A	A	A																		
Hoplitoplacenticeras vancouverensis (Meek)																												C	C	C																		
Hoplitoplacenticeras sp.																									R	R																						
Pachydiscus neevesi (Whiteaves)																											R																					
Pseudoxybeloceras lineatum (Gabb)																											R	R	R																			
Canadoceras newberryanus (Meek)																	R	R	R	C	R	R	R	R	R		C	C	C	C																		
Pachydiscus cf. *jaquoti* Seynes																	R																															
Submortoniceras chicoense (Trask)																		R	R																													
Pseudoxybeloceras nanaimoense Ward & Mallory																		R	R																													
Baculites chicoense Trask																	R	C	C	C	R	R	C	R																								
Canadoceras yokoyamai (Jimbo)											C	R	R	R	A	C																																
Canadoceras multisulcatus (Whiteaves)											C	R	R	R	A	C																																
Pseudoxybeloceras sp. indet.												R																																				
Pseudoschloenbachia brannani Usher																																																
Baculites boulei Collignon																																																
Baculites bailyi (Wood)	R		A		A	R	R				R																																					
Hauericeras gardeni (Baily)	C	R		R	C	C	C	R		R	R																																					
Epigoniceras epigonum (Kossmat)	R			R	R	R	R				R																																					
Desmophyllites diphylloides (Whiteaves)	R					R																	R					C	C	C	R																	
Diplomaceras cf. *notobile* Whiteaves					R																							R																				
Damesites damesi Matsumoto	R			R																																												
Gaudryceras sp.						R	R				R																	R	R																			
Neophylloceras ramosum (Meek)	R					R	R				R	R	R	R														R	R	R																		
Mesopuzosia densicostatum Matsumoto					R																																											
Kitchinites japonicum (Matsumoto)	R																																															
Ryugasella ryugasensis Wright & Matsumoto	A		C			R	R																																									
Pachydiscus buckhami Usher						R	R	C		C																																						
Eupachydiscus haradai Usher								R		R																																						
Eupachydiscus perplicatum (Whiteaves)	C				C																																											
Pachydiscus binodatus Whiteaves	R																																															
Didymoceras elongatum (Whiteaves)	R	R	R	C	R	C	C	C	C	A																																						
Didymoceras otsukai (Yabe)				R	R	R	R																																									
Glyptoxoceras subcompressum (Forbes)	R	R	C	A	C	C	C	C	C	C																																						
Polyptychoceras vancouverensis Whiteaves	A	A																																														
	1										2						3								4						5									6								

KEY - R = rare, 1 - 5 specimens

C = common, 5 - 10 specimens

A = abundant, >10 specimens

Table 3.2 Check-list of localities. 1. Elongatum Zone 2. Schmidti Zone 3. Chicoense Zone 4. Vancouverense Zone 5. Pacificum Zone 6. Suciaense Zone

3.2.1 Elongatum Zone

As noted by Jeletzky (Muller and Jeletzky, 1970, p.40), the Elongatum Zone faunal assemblage is the oldest known macrofauna of the Nanaimo Group. Recent collecting has shown that with the exception of *Eupachydiscus perplicatum* (Whiteaves), *E. haradai* (Usher) and *Polyptychoceras vancouverense* (Whiteaves), all known Elongatum fauna ammonites range through the zone. *P. vancouverense* was previously known from three localities: as a mass occurrence near the base of the Haslam Formation of Trent River, and as single occurrences near the Haslam Formation base at Puntlege and Browns Rivers. Recent collecting near Lake Cowichan, in the Nanaimo Basin, has yielded numerous conspecific forms from a narrow stratigraphic horizon also near the base of the Haslam Formation. The Lake Cowichan occurrences of *P. vancouverense* are in lithologic facies similar to the horizon of Trent River with *P. vancouverense*; at both areas the lithology consists of shales containing numerous, small concretions packed with small inocerami and *Anomia*.

The restriction of *P. vancouverense* to strata immediately above the Comox - Haslam Formation boundary suggests that it may be biochronologically useful; however, its restriction to a particular facies within the Haslam Formation indicates that its occurrence is also controlled by environmental factors. Consequently, the occurrence of *P. vancouverense* is defined as a zonule in the sense of Fenton and Fenton (1928).

Based on the evidence at hand at that time, Jeletzky (in Muller and Jeletzky, 1970, p.47) placed the Santonian-Campanian Boundary in the Nanaimo Group at the base of the Haradai subzone of the Elongatum Zone.

The following evidence accumulated since then indicates that this boundary might be better placed at, or very near, the top of the Haradai subzone,

1) Based on co-occurrences of foraminiferans in both regions, Sliter (1971) has correlated the Haradai subzone with the lower part of the Upper Marlife Formation in California. Ammonite localities in this part of the formation (listed by Matsumoto, 1960) have yielded numerous specimens of *Baculites capensis* Woods and *Inoceramus naumanni*, both Santonian markers (Matsumoto, 1960, Plate 1).

2) *Inoceramus schmidti*, index of the superjacent zone in the Nanaimo Group is, in Japan, a marker of the Santonian-Campanian boundary (Matsumoto, 1959, p.87; Tanabe, 1973, and personal communication, 1975). In the Nanaimo Group strata bearing *I. schmidti* conformably overlay the Haradai subzone on Nanaimo River, Haslam Creek and Benson (Brannon) Creek.

3) *Didymoceras (Bostrychoseras) otsukai* and *Mesuopusosia densicostatum*, previously each known from the Nanaimo Group by single occurrences, have now been recovered at a number of different localities and levels throughout the Elongatum Zone. Each of these species is restricted to the 'Neourakawan stage' in Japan (Santonian plus lowest Campanian) (Matsumoto, 1954, 1960).

Faunal similarity suggests that stratal correlatives of the Haradai subzone in the Upper Cretaceous of California include Member VI of Popenoe (1943) on Cow Creek, and Unit IIb on Chico Creek (Matsumoto, 1960). Correlatives of the Naumanni subzone appear to include the upper part of Member V on Cow Creek, and possibly part of Member VI, and Unit IIa on Chico Creek (Matsumoto, 1960).

Because of the association of *I. schmidti* with *Canadoceras yokoyami*, but not *C. newberryanum*, it appears that the Schmidti Zone in the Nanaimo Group is equivalent to the lower two-thirds of the upper half of the type section of the Chicoense Zone on Chico Creek, California, where *C. yokoyami* is most common in the lower two-thirds, and *C. newberryanus* first occurs in the upper one-third (Matsumoto, 1960). Although Dr. D. Jones (personal communication) informs me that there is no known association of *I. schmidti* with diagnostic elements of the California Chicoense Zone, Dr. L. Saul (written communication, March 18 and April 21, 1975) adds additional support to this correlation through examination of the ranges of molluscan species common to both regions. Dr. Saul has examined specimens of *Yaadia tryoniana* (Gabb) from Northwest Bay, Vancouver Island, where it was associated with *C. yokoyami*, *C. multisulcatum* and *I. schmidti*; these trigoniids were found to be conspecific with *Yaadia tryoniana* which is restricted to the teilzone of *Submortoniceras chicoense* as proposed by Matsumoto (1960) on Chico Creek.

In the Nanaimo Group, the Elongatum range-zone and Schmidti range-zone are continuous in that the last occurrence of *Didymoceras (Bostrychoceras) elongatum* coincides with the first occurrences of *Inoceramus ex.gr. schmidti*.

3.2.3 Chicoensis Zone

The Ganges Formation contains an ammonite assemblage which is here proposed to define an Oppel zone continuous with the subjacent Schmidti Zone and superjacent Vancouverense Zone. The zone is named the Chicoensis Zone, after its most common species, *Baculites chicoensis* Trask.

The zonal base is defined by the first occurrence of B. chicoensis Submortoniceras chicoense (Trask) and Canadoceras newberryanum. The top of the zone is defined by the first occurrence of the genus Hoplitoplacenticeras. The Ganges Formation section on Trent River is designated stratotype.

The stratotype section was previously placed in the Cedar District Formation and Vancouverense Zone by Muller and Jeletzky (1970) and Sliter (1973). Sliter's placement of the section in the Palmula tricarinella - Praebulimina venusae concurrent range foraminiferal zones, thus correlating these zones with the Vancouverense Zone seems incompatible, since Douglas (1969b) has shown the foraminiferal zones to be lower Campanian, while the macrofaunal Vancouverense Zone is early Upper Campanian (Muller and Jeletzky, 1970, p.55). The recovery of several Submortoniceras chicoense (Trask) from the lower parts of this section (McM - loc. 110, 111) verifies its lower Campanian age.

The contact between the Nanaimo Group Chicoensis Zone and the underlying Schmidti Zone can be recognized only on Texada Island, where a conglomerate with I. schmidti is overlain by shales containing B. chicoensis. Because these specimens of I. schmidti are within a conglomerate, and hence may be re-worked, the two zones may not share a common boundary. Everywhere else in the Nanaimo Group the teilzone of I. schmidti is separated from strata with B. chicoensis by the non-marine, unfossiliferous Extension Formation. Hence, a barren interzone (Hedberg, 1972) may separate the two zones.

The ChicoensisZone is continuous with the superjacent Vancouverense Zone at the stratotype on Trent River (Ganges Formation), where strata with *Baculites chicoensis*and *Submortoniceras chicoense* are overlain by strata with *Hoplitoplacenticeras* cf. *vancouverense* (Jeletzky, personal communication). Elsewhere in the Nanaimo Group, the two zones are separated by the unfossiliferous Protection Formation.

The ChicoensisZone is well-developed in the San Juan and Gulf Islands. Ganges Formation exposures on North Pender, South Pender, Waldron and Stuart Islands have yielded numerous specimens of *B. chicoensis* and *C. newberryanum*; *C. newberryanum* plesiotypes GSC 10030, from GSC loc. 277, and GSC 10032, from GSC loc. 281 are both from the Chicoensis Zone on North Pender Island.

The evidence at hand suggests that the Nanaimo ChicoensisZone is only partially correlative with the Chicoense Zone of California, as defined by Popenoe *et al* (1960) and Matsumoto (1960). In the type section of the Californian Chicoense Zone, on Chico Creek, Sacramento Valley, *C. newberryanum* occurs only in the upper third of the range of *S. chicoense* and *B. chicoensis*, while *I. subundatus* is found only in the youngest localities (Matsumoto, 1960). Since these species range throughout the local Nanaimo range zone of *B. chicoensis*, the two zones are inferred to be slightly diachronous; the Nanaimo ChicoensisZone is correlated with the upper third of the Californian stratotype, and also includes beds in the biozones of *Submortoniceras chicoense* and *Baculites chicoensis* which are stratigraphically higher than those preserved in California.

3.2.4 Vancouverense Zone

The Vancouverense Zone was defined by Jeletzky (in Muller and Jeletzky, 1970) by the local ranges of *Hoplitoplacenticeras spp.* in the Nanaimo Group; *H. vancouverense* (Meek) was designated index fossil. Other diagnostic features of the Vancouverense Zone listed by Jeletzky are the presence of numerous "*Baculites chicoense* Trask sensu Usher", mass occurrences of *I. ex.gr. vancouverensis* Shumard and *I. ex.gr. subundatus* Meek, and the prevalence of *Canadoceras newberryanum* over *C. yokoyami* and *C. multisulcatum* (Whiteaves).

With the differentiation of "*B. chicoense* sensu Usher" into *B. chicoensis* and *B. inornatus* (see Chapter 4), and subsequent definition of the Chicoensis Zone in the Nanaimo Group, the Vancouverense Zone as recognized here is a local range zone defined by *H. vancouverense* in Cedar District Formation strata on Sucia Island, Washington. The zone is also defined by the Nanaimo Group ranges of *H. plasticum* Paulke, *Hoplitoplacenticeras* cf. *vancouverensis* and *B. inornatus*.

Except on Sucia Island, *Hoplitoplacenticeras* is rare in the Nanaimo Group, and Jeletzky's interpretation of the zone has for some localities relied on his diagnostic features. The synonymy of *B. chicoensis* and *B. inornatus* as "*B. chicoense* sensu Usher" has resulted in his amalgamation of the Chicoensis Zone and Vancouverense Zone as recognized here.

Because of the absence of the zonal marker *Hoplitoplacenticeras vancouverense* in California, Alaska and Japan, correlation between these areas and the Vancouverense Zone of the Nanaimo Group has proven controversial. Popenoe *et al* (1960) considered this zone to be younger than the Metaplacenticeras beds of California. Conversely, Matsumoto (1960) considered them contemporaneous, while Jeletzky (in Muller and Jeletzky, 1970) placed the Metaplacenticeras teilzones of California and the Nanaimo Group above the Vancouverense Zone, based on the observed ammonite succession of the Nanaimo Group.

More recent information about non-ammonite macroinvertebrate fossil ranges supports Jeletzky's interpretation. Saul (1974) noted that Cympophora suciensis (Whiteaves) ranges through the Vancouverense Zone in the Nanaimo Group and through the California Submortoniceras chicoense Zone, but is replaced by a descendent species, C. triangulata (Waring) in the Metaplacenticeras pacificum Zone of California. Secondly, several specimens of Turritella from the Vancouverense stratotype on Sucia Island represent, according to Dr. Saul (personal communication, April 21, 1975), a new species intermediate between T. chicoense, confined to the California Chicoense Zone, and T. pescaderoensis, diagnostic of the Metaplacenticeras Zone.

Because of the co-occurrences of Patagiosites arbucklensis, Baculites inornatus and Canadoceras newberryanum, the lower Forbes Formation localities in the Rumsey Hills of California may be correlative with the Vancouverense Zone. Since Inoceramus schmidti was found associated with P. arbucklensis at several of the Forbes Formation localities, Jeletzky correlated them with the Nanaimo Group Schmidti Zone. As indicated earlier, however, I. schmidti shows differences in its local ranges in the North Pacific Biotic Province, and hence is unreliable as a province-wide index fossil.

3.2.5 Pacificum Zone

Marine strata above the Vancouverense Zone are dominated by poorly fossiliferous turbidites; the biostratigraphy is therefore based on less evidence than for the lower zones.

Usher (1952) differentiated a single faunizone above his Cedar District Faunizone (= Vancouverense Zone) which he named the Northumberland-Lambert Faunizone. Diagnostic species included *Pachydiscus ootacodensis* (Stoliczka), *Pachydiscus suciensis* (Meek), *Psuedophyllites indra* (Forbes), *Anisoceras cooperi* Gabb and *Nostoceras hornbyense* (Whiteaves).

Jeletzky (in Muller and Jeletzky, 1970) renamed the equivalent of Usher's Northumberland-Lambert Faunizone the Suciaensis Zone, after the zonal index *P. suciaensis*. The Suciaensis Zone was subdivided into two subzones: a lower, *Metaplacenticeras* cf. *pacificum* subzone, and an upper, *Nostoceras hornbyense* subzone. The former species had not previously been recovered from the Nanaimo Group, and its recovery from several localities by Geological Survey of Canada field parties provided an important link with Upper Cretaceous beds of California, where *M. pacificum* is short-ranged, and has been regarded as a zonal index (Popenoe *et al*, 1960).

Even though *M.* cf. *pacificum* was not known to be associated in the Nanaimo Group with other diagnostic elements of the Suciaense Zone, Jeletzky (1970) included its occurrence within the Nanaimo Group teilzone of *P. suciaensis* for several reasons:

1) One Nanaimo Group example of *M.* cf. *pacificum* was recovered from GSC loc. 75495, South Pender Island, in strata mapped as Northumberland Formation. Since the Suciaensis fauna was

known to range throughout the Northumberland Formation at its stratotype (Usher, 1952), Jeletzky considered this occurrence of M. cf. pacificum as from within the P. suciaensis zone.

2) Jeletzky (Muller and Jeletzky, 1970, p. 56) noted that M. pacificum was known to be associated in California with some faunal elements of the Suciaensis Zone (although this zone is undefined in California and, indeed, the zonal index P. suciaensis has never been recovered there).

Fossil collection in the Nanaimo Group subsequent to Muller and Jeletzky's publication has yielded several more examples of M. cf. pacificum, and numerous ammonites of the Suciaensis fauna. The evidence now at hand suggests that the Nanaimo Group teilzone of M. pacificum does not overlap with the younger teilzones of the diagnostic Suciaensis faunal members P. suciaensis, P. ootacodensis (Stoliczka), Didymoceras vancouverensis (Gabb) (Anisoceras cooperi of Usher), or Nostoceras hornbyense in the Nanaimo Group. Pseudophyllites indra (Forbes) was also considered by Jeletzky (in Muller and Jeletzky, 1970) to be diagnostic of the Suciaensis Fauna; however, it has been recovered in the older Vancouverense Zone on Sucia Island (loc. UWA 1246) and is thus proven to be long-ranging in the Nanaimo Group. The turbidites of GSC loc. 75495 are here regarded as part of the Gulf Islands Cedar District Formation turbidite complex, rather than the Northumberland Formation (see Chapter 2, Figure 2.2.1, section 75.11). M. pacificum is therefore restricted to a portion of the Cedar District Formation, while the Suciaensis Fauna is found only in the succeeding Northumberland and Spray Formations.

Reasonable doubt also exists about the co-occurrence of *M. pacificum* with the Suciaensis fauna in California, since the co-occurring "diagnostic elements of the Northumberland-Lambert Faunizone of Usher" discussed by Jeletzky (in Muller and Jeletzky, 1970, p.54) are *Pseudophyllites indra*, which has been shown to be long-ranging, and an ammonite collected by Anderson (1902) and identified by Popenoe *et al* (1960) as *Didymoceras cooperi*. This co-occurrence has not been reduplicated at any of the numerous California localities yielding *M. pacificum* since Anderson's collection.

Since, in the Nanaimo Group at least, the range of *M. pacificum* appears to be non-overlapping with diagnostic elements of the Suciaensis Zone, it is here proposed that the *Metaplacenticeras* cf. *pacificum* subzone proposed by Jeletzky be elevated to zonal status. Contact with the older Vancouverense Zone is nowhere recorded in the Nanaimo Group, although both include parts of the Cedar District Formation. The Cedar District Formation on Denman Island is proposed as stratotype.

The uppermost beds of the Cedar District Formation on Denman Island, North Pender Island, South Pender Island, Prevost Island, Saltspring Island and Saturna Island have all yielded numerous specimens of *Baculites rex*. Several of these localities have also yielded lesser numbers of *B. anceps pacificus* Matsumoto and *B. occidentalis* Meek. The two former species, both restricted to the Cedar District Formation, have not previously been recorded from the Nanaimo Group, although they are well known in California, where *B. rex* is, according to Matsumoto, diagnostic of the Maastrichtian and the highest Campanian (1959a, p.142).

In California, it has been found associated with *Metaplacenticeras pacificum* at loc. UCLA 2415 in the Santa Ana Mountains, and slightly above *M. pacificum* and *B. anceps pacificus* at loc. LSJU 3357 in Arroyo del Valle, as well as in association with younger faunal constituents, including elements of the Suciaensis Zone at numerous localities. In the Nanaimo Group, however, *B. rex* is apparently very short-ranged, as it has only been recovered slightly above the range of *M. pacificum* and below the first occurrences of the Suciaensis Zone faunal indices at the base of the Northumberland Formation. Because of its undoubted occurrence with *M. pacificum* in California, the range of B. rex is tentatively regarded as a zonule in the Nanaimo Group; however, additional collecting may show the need for elevation of its range to zonal status.

Baculites anceps pacificus Matsumoto is common at Shelter Point, Vancouver Island, where it was identified as *B. inornatus* (Richards, 1975). Additional ammonites listed by Richards included *Pachydiscus* cf. *suciaensis*, *Phyllopachyceras forbesianum* (d'Orbigny) and *Pseudophyllites indra*. Examination of the single specimen of *P.* cf. *suciaensis* from this locality by Dr. Jeletzky and myself precludes positive assignment to *P. suciaensis*, since it consists of only a poorly preserved living chamber fragment. My re-collection of the locality during 1975 yielded several *Canadoceras* cf. *newberryanum*, indicating a better assignment of the Shelter Point strata to either the Vancouverense Zone or Pacificum Zone. On the basis of this information, Richards' assignment of the Shelter Point locality to the Spray Formation is doubtful.

The thick, well-exposed section on Dodds Narrows (Chapter 2, Figure 2.2.1, section 75.4) was defined by Muller and Jeletzky (1970) as the stratotype of the Cedar District Formation. Based on comparisons of foraminifera, Sliter (1972) noted that this section was younger than the shales exposed on lower Trent River (Ganges Formation of this work). However, since he mistakenly correlated all of the lower Trent River section with the Vancouverense macrofaunal zone, his placement of the Dodds Narrows section entirely within the Metaplacenticeras pacificum subzone of Jeletzky may also be in error. Unfortunately, no macrofaunal evidence is available from the Dodds Narrows sections; based on Sliter's microfaunal evidence, it seems possible, however, that portions of both the Vancouverense and Pacificum Zones are present there, since diagnostic elements of the Gyroidinoindes benthic foraminiferal zone, concurrent with the Metaplacenticeras pacificum zone in California (Douglas, 1969b), are only present in the upper part of the section at Dodds Narrows (Sliter, 1972, p.180).

3.2.6 SuciaensisZone

The SuciaensisZone is restricted to the Northumberland and Spray Formations. Additional subdivision of the zone may prove necessary, since faunal differences are apparent between the two formations. Northumberland macrofossil localities have not yielded several common elements of the Spray Formation on Hornby Island, such as Didymoceras vancouverense, Nostoceras hornbyense, Phyllopachyceras forbesianum and Baculites occidentalis. These differences may be due to environmental, rather than chronological factors, however, since the Hornby Island sections represent the only non-turbiditic facies of the Suciaensis Zone.

A contact between the Suciaense Zone and the subjacent Pacificum Zone is nowhere exposed, and it is not known if the zonal boundaries are contiguous. A barren interzone, named the Pacificum-Suciaense Barren Interzone is proposed for the De Courcy Formation, the coarsely clastic, unfossiliferous formation which separates Pacificum Zone strata from Suciaense Zone strata.

Widespread correlatives are present in California, including CAS 29108, 9, where *Pachydiscus ootacodensis* is associated with *Diplomoceras* sp. and *Neophylloceras ramosum* CAS 29664 and 29666, Puerto Creek, where *P. ootacodensis* is associated with *Didymoceras* ? *hornbyense* (*Nostoceras hornbyense*?) and *D.*?*vancouverense*; at CAS 2362, 6, 8, LSJU 1628 and LSJU 3345 where *P. ootacodensis* occurs with *D. vancouverensis*, *D.*?*hornbyense* and *Baculites occidentalis*; loc. CAS 31368, 31366 and 33702, San Joaquin Valley, where *Nostoceras* sp. is associated with *B. occidentalis*; and at UCLA 3268, Baja, California, where *Nostoceras* sp. is associated with *B. occidentalis*.

The *Pachydiscus kamishakensis* Zone of Alaska (member 3, Matoruska Formation, Jones, 1963) also appears to be correlative.

3.3 Interregional Correlation - Current Problems

Figure 3.3.1 shows the zonal correlations favoured here for the North Pacific Province during late Santonian through early Maaestrichtian time.

Further fieldwork is obviously needed in Alaska, British Columbia, California and Baja, California, to better understand the stratigraphic relationships in these areas.

<table>
<tr><th rowspan="2">European Stages</th><th colspan="4">LOCAL RANGE ZONES</th></tr>
<tr><th>ALASKA</th><th colspan="2">NANAIMO GROUP</th><th>CALIFORNIA</th></tr>
<tr><td rowspan="2">MAESTRICHTIAN</td><td></td><td colspan="2"></td><td>Pachydiscus catarinae</td></tr>
<tr><td rowspan="2">- ? - ? - ? - ? - ? -
Pachydiscus kamishakensis</td><td colspan="2" rowspan="2">? - ? - ? - ? - ? - ? -
Pachydiscus suciaensis</td><td rowspan="2">Pachydiscus ootacodensis</td></tr>
<tr><td rowspan="3">UPPER CAMPANIAN</td></tr>
<tr><td rowspan="6">Inoceramus schmidti
- ? - ? - ? - ? - ?</td><td colspan="2">Metaplacenticeras pacificum</td><td>Metaplacenticeras pacificum</td></tr>
<tr><td colspan="2">Hoplitoplacenticeras vancouverense</td><td>Inoceramus schmidti</td></tr>
<tr><td rowspan="2">LOWER CAMPANIAN</td><td colspan="2">Baculites chicoensis</td><td rowspan="2">Baculites chicoensis</td></tr>
<tr><td colspan="2">Inoceramus schmidti</td></tr>
<tr><td rowspan="2">SANTONIAN</td><td rowspan="2">Didymoceras elongatum</td><td>Pachydiscus haradai</td><td rowspan="2">Baculites capensis
- ? - ? - ? - ? -</td></tr>
<tr><td>Inoceramus naumanni</td></tr>
</table>

FIGURE 3.3.1 Correlations and Zonations Suggested Here

In Alaska, the thick _I. schmidti_ zone contains faunal elements of most of the British Columbia and California zones; unfortunately, according to Jones (1963), ammonites are very rare.

In British Columbia, there is as yet no known macrofaunal correlation between the Nanaimo Group of Vancouver Island and islands in the Strait of Georgia, and mainland British Columbia and Washington State. Detailed examination of lithofacies patterns on Sucia, Patos, Matia and Lummi Island in the state of Washington offer, in my opinion, the best chance of correlation between Nanaimo and Chuckanut Formation strata. The thick Suciaensis Zone can probably also be biostratigraphically subdivided through renewed collection efforts in the Gulf Islands.

In California, detailed re-collection of the _I. schmidti_-bearing strata must be initiated to better understand that species' biochronologic value. Re-collection of the _Pachydiscus_ silt, Moreno Formation, and Chico Creek areas is also needed to better correlate the eastern and western sides of the Sacramento Valley.

TABLE 3.2 List of Localities

McM 100	Browns River, latitude 49°41'40"N, longitude 125°03'25"W. In shales along river. Haslam Formation, Elongatum Zone, Naumanni subzone.
McM 101	Browns River, latitude 49°41'25"N, longitude 125°02'55"W. Intersection of Browns and Puntlege Rivers. Haslam Formation, Elongatum Zone, Naumanni subzone.
McM 102	Puntlege River, latitude 49°41'23"N, longitude 125°01'55"W. In shale banks on opposite side of river from city of Courtney pumping station. Elongatum Zone, Naumanni subzone?
McM 103	Puntlege River, latitude 49°41'05"N, longitude 125°01'45"W. In shale banks on river at first major bend in river downstream of Courtney pumping station. Elongatum Zone, subzone unknown.
McM 104	Puntlege River, latitude 49°41'10"N, longitude 125°01'45"W. In shale banks approximately 200 m downstream of locality McM 103. Haslam Formation, Elongatum Zone, Haradai subzone.
McM 106	Trent River, latitude 49°35'30"N, longitude 124°59'20"W. In shales at Van logging bridge. Equivalent to GSC loc. 60839. Haslam Formation, Elongatum Zone, Haradai subzone, *Polyptychoceras vancouverense* zonule.
McM 107	Trent River, latitude 49°35'25"N, longitude 124°59'20"N. Downstream 200 m from Van logging bridge. Equivalent to GSC loc. 60843. Haslam Formation, Elongatum Zone, Naumanni subzone.

TABLE 3.2 (Continued)

McM 108	Trent River, latitude 49°35'30"N, longitude 124°59'30"W. At top of large waterfall. Haslam Formation, Elongatum Zone, Naumanni subzone.
McM 109	Trent River, latitude 49°35'45"N, longitude 124°59'15"W. Approximately 200 m downstream of large waterfall. Haslam Formation, Elongatum Zone, Naumanni subzone?
McM 110	Trent River, latitude 49°36'20"N, longitude 124°59'00"W. Approximately 500 m west of Trent River-Bloedel Creek intersection. Equivalent to loc. UWB 2051. Ganges Formation, Chicoense Zone.
McM 111	Trent River, latitude 49°35' "N, longitude 124°58'30"W. Approximately 200 m upstream of Bloedel Creek-Trent River intersection. Equivalent to UWB 2051. Ganges Formation, Chicoense Zone.
McM 112	Trent River, latitude 49°35'25"N, longitude 124°59'30"W. In shale immediately above contact with Comox Formation. Equivalent to GSC loc. 60837. Haslam Formation, Elongatum Zone, Naumanni subzone.
McM 113	Tsable River, latitude 49°30'50"N, longitude 124°52'40"W. Haslam Formation, Elongatum Zone, Haradai subzone?
McM 114	Little Qualicum River, latitude 49°19'45"N, longitude 124°33'10"W. Downstream from lower suspension bridge, Little Qualicum Falls Park. Equivalent to GSC loc. 57584. Haslam Formation, Elongatum Zone.

TABLE 3.2 (Continued)

McM 115	Englishman River, latitude 49°15'10"N, longitude 124°20'45"W. Downstream of lower falls, Englishman River Provincial Park, in shales along river. Haslam Formation, Schmidti Zone.
McM 116	Nanaimo River, latitude 49°04'19"N, longitude 123°59'42"W. Equivalent to GSC loc. 64932. Haslam Formation, Elongatum Zone, Haradai subzone.
McM 117	Nanaimo River, 65 m stratigraphically above McM 116. Haslam Formation, Schmidti Zone.
McM 118	Nanaimo River, 20 m stratigraphically above McM 117. Haslam Formation, Schmidti Zone.
McM 119	Elkhorn Creek, latitude 49°03'15"N, longitude 123°59'50"W. 10 m stratigraphically above Comox Formation conglomerates. Haslam Formation, Elongatum Zone.
McM 120	East Elkhorn Creek, latitude 49°03'04"N, longitude 123°59'00"W. Equivalent to GSC loc. 69485. Haslam Formation, Elongatum Zone.
McM 121	East Elkhorn Creek, 100 m downstream from McM 120. Haslam Formation, Elongatum Zone.
McM 122	Elkhorn Creek, latitude 49°03'30"N, longitude 123°59'45"W. In siltstones along river. Haslam Formation, Elongatum Zone, Haradai subzone?
McM 123	Elkhorn Creek, 100 m downstream of McM 122.

TABLE 3.2 (Continued)

McM 133	Cowichan River, latitude 48°46'15"N, longitude 123°53'30"W. Downstream 500 m from Marie Canyon Railroad Bridge. Haslam Formation, Schmidti Zone.
McM 134	Maple Bay, latitude 48°48'45"N, longitude 123°36'30"W. In shales on wave cut platform and in cliffs. Haslam Formation, Elongatum Zone, Haradai subzone.
McM 135	Saltspring Island, latitude 48°46'20"N, longitude 123°26'20"W. On beach near mouth of Cusheon Creek. Equivalent to GSC loc. 75431. Haslam Formation, Haradai subzone.
McM 136	Saanich Peninsula, latitude 48°41'25"N, longitude 123°24'50"W. Immediately west of Swartz Bay ferry terminal. Equivalent to GSC loc 75484. Haslam Formation, Elongatum Zone, Naumanni subzone.
McM 137	Piers Island, latitude 48°42'35"N, longitude 123°24'40"W. Northeast corner of island on beach exposure. Haslam Formation, Elongatum Zone.
McM 138	Pym Island, latitude 48°42'55"N, longitude 123°23'20"W. Southeast corner of island on beach exposure. Haslam Formation, Elongatum Zone, Naumanni subzone.
McM 139	Piers Island, latitude 48°42'00"N, longitude 123°25'05"W. South side of island on beach exposure. Haslam Formation, Elongatum Zone.

TABLE 3.2 (Continued)

McM 133	Cowichan River, latitude 48°46'15"N, longitude 123°53'30"W. Downstream 500 m from Marie Canyon Railroad Bridge. Haslam Formation, Schmidti Zone.
McM 134	Maple Bay, latitude 48°48'45"N, longitude 123°36'30"W. In shales on wave cut platform and in cliffs. Haslam Formation, Elongatum Zone, Haradai subzone.
McM 135	Saltspring Island, latitude 48°46'20"N, longitude 123°26'20"W. On beach near mouth of Cusheon Creek. Equivalent to GSC loc. 75431. Haslam Formation, Haradai subzone.
McM 136	Saanich Peninsula, latitude 48°41'25"N, longitude 123°24'50"W. Immediately west of Swartz Bay ferry terminal. Equivalent to GSC loc 75484. Haslam Formation, Elongatum Zone, Naumanni subzone.
McM 137	Piers Island, latitude 48°42'35"N, longitude 123°24'40"W. Northeast corner of island on beach exposure. Haslam Formation, Elongatum Zone.
McM 138	Pym Island, latitude 48°42'55"N, longitude 123°23'20"W. Southeast corner of island on beach exposure. Haslam Formation, Elongatum Zone, Naumanni subzone.
McM 139	Piers Island, latitude 48°42'00"N, longitude 123°25'05"W. South side of island on beach exposure. Haslam Formation, Elongatum Zone.

TABLE 3.2 (Continued)

McM 140	North Pender Island, latitude $48^{\circ}44'30''$N, longitude $123^{\circ}14'25''$W. In small bay west of Hay Point, Bedwell Harbour. Equivalent to GSC loc. 75516, 77031. Ganges Formation, Chicoense Zone.
McM 141	North Pender Island, latitude $48^{\circ}45'30''$N, longitude $123^{\circ}17'25''$W. Shoreline exposure, west side of island. Equivalent to GSC loc. 75496. Ganges Formation, Chicoense Zone.
McM 142	North Pender Island, latitude $48^{\circ}49'15''$N, longitude $123^{\circ}18'20''$W. North end of island. Cedar District Formation, Pacificum Zone.
McM 143	North Pender Island, latitude $48^{\circ}46'15''$N, longitude $123^{\circ}14'45''$W. Shoreline exposure, both sides of Razor Point. Cedar District Formation, Pacificum Zone. *Baculites rex* zonule.
McM 144	South Pender Island, latitude $48^{\circ}45'15''$N, longitude $123^{\circ}14'45''$W. Shoreline exposure. Cedar District Formation, Vancouverense Zone?
McM 145	South Pender Island, latitude $48^{\circ}44'15''$N, longitude $123^{\circ}11'00''$W. Shoreline exposure in shales east of Gowlland Point. Equivalent to GSC loc. 75453. Ganges Formation, Chicoense Zone.
McM 146	South Pender Island, latitude $48^{\circ}44'30''$N, longitude $123^{\circ}11'15''$W. In shales of Camp Bay. Cedar District Formation, Vancouverense Zone.
McM 147	South Pender Island, latitude $48^{\circ}45'30''$N, longitude $123^{\circ}12'10''$W. Shoreline exposure. Cedar District Formation, Pacificum Zone.

TABLE 3.2 (Continued)

McM 148	South Pender Island, latitude 48°46'00"N, longitude 123°14'55"W. Near entrance to Port Browning, shoreline exposure. Equivalent to GSC loc. 75459. Cedar District Formation, Pacificum Zone. *B. rex* zonule.
McM 149	Saturna Island, latitude 48°45'40"N, longitude 123°09'15"W. Shoreline exposure close above contact with quartz conglomerate. Equivalent to GSC loc. 75440, 75441. Cedar District Formation, Pacificum Zone. *B. rex* zonule.
McM 150	Saturna Island, latitude 48°48'35"N, longitude 123°11'15"W. Shoreline exposure, Winter Cove. Northumberland Formation, Suciaensis Zone.
McM 151	Shelter Point, Vancouver Island, latitude 49°56'20"N, longitude 125°11'10"W. Formation and zone unknown.
McM 152	Sucia Island, latitude 48°44'55"N, longitude 123°54'40"W. In pebble conglomerate, south side of island. Protection Formation, Vancouverense Zone.
McM 153	Puntlege River, latitude 49°41'26"N, longitude 125°02'12"W. Across river from pumping station. Equivalent to GSC loc. 60848. Haslam Formation, Elongatum Zone, Naumanni subzone?
McM 154	Stuart Island, latitude 48°40'40"N, longitude 123°13'50"W. Shoreline exposure in small bay approximately 1000 m south of Turn Point. Ganges Formation, Chicoense Zone.

TABLE 3.2 (Continued)

McM 155	Texada Island, latitude 49°39'00"N, longitude 124°24'30"W. In shales on Moatt Creek. Equivalent to GSC loc. 79264, 79265. Ganges Formation, Chicoense Zone.
McM 156	Nanaimo River, 30 m stratigraphically above McM 118. In shales by river. Haslam Formation, Schmidti Zone.
McM 157	Bloedel Creek, latitude 49°35'45"N, longitude 124°58'45"W. Haslam Formation, Elongatum Zone.
McM 158	Parker Reef, Orcas Island, latitude 48°43'25"N, longitude 122°54'00"W. Haslam Formation, Elongatum Zone.
McM 159	Orcas Island, latitude 48°43'05"N, latitude 122°56'00"W. Immediately above contact with Comox Formation, east of Pt. Doughty. Equivalent to UWB 1482. Haslam Formation, Elongatum Zone.
McM 160	Orcas Island, latitude 48°41'45"N, longitude 122°50'55"W. East of Freeman Island, shoreline exposure. Equivalent to UWB 1487. Haslam Formation, Elongatum Zone.
McM 161	Sucia Island, latitude 48°44'55"N, longitude 122°54'30"W. Below conglomerate. Protection Formation, Vancouverense Zone.

CHAPTER 4

SYSTEMATIC PALEONTOLOGY

Order AMMONOIDEA

Family BACULITIDAE Meek, 1876

Genus *Baculites* Lamarck, 1799

Baculites bailyi Woods 1906

Plate 4-2; figs. 1, 2; Text fig. 4-1

1963 *Baculites bailyi* Woods, in Matsumoto and Obata, p. 35-38, Pl. 20, figs. 1, 2; Pl. 21, Fig. 5: text figs. 88, 89, 116-120, 140-142.

1970 *Baculites chicoense* sensu Usher, Jeletzky, p. 38.

Material - Well-preserved material includes GSC 77410, MCMK1047a-f, MCM1023c.

Description - Shell ornamentation is lacking, or consists only of subdued, closely spaced ridges and furrows on venter which attach to ribs projecting adorally only along flanks. These ribs do not extend onto dorsum.

Whorl section varies between inflated elliptical to egg-shaped, with narrower ventral half. The taper is very gradual. All observed specimens are small: largest observed body chamber whorl diameter ∿19 mm; largest observed phragmacone diameter is 14 mm.

The suture is moderately incised. The lobes are narrower than the saddles, the saddles are very broad; ventral saddle is approximately half the height and width of lateral saddles.

Remarks - *B. bailyi* is closest in ornamentation and suture to *B. inornatus*; Matsumoto (1959a) considered *B. bailyi* to be immediately ancestral. Differences between the two are seen in the smaller size, more inflated cross-section, and non-phylloid, less incised septal sutures of *B. bailyi* (see text fig. 4-1).

B. bailyi is readily distinguished from *B. chicoense* by its simplified, quadrate septal sutures and more inflated cross-section.

The complete synonymy of *B. bailyi* is listed by Matsumoto and Obata (1963, p. 35).

Variation - *B. bailyi* from the Nanaimo Group vary with specimens from Japan and South Africa in having a slightly less incised suture and apparently greater average size.

Occurrence - *B. bailyi* has been recovered from various levels of the Elongatum and Schmidti Zones in the Nanaimo Group, but is most common in the Naumanni Subzone of the Elongatum Zone.

In summary the Nanaimo Group representatives range from upper Santonian into the lower Campanian. Their range is slightly longer than that of the conspecific forms in South Africa and Japan, which are restricted to the Santonian (Woods, 1906; Matsumoto and Obata, 1963).

Measurements -

Specimen	B	H	B/H	Distance
MCMK1023c	8.4	10.8	.77	33
	9.8	12.4	.79	
GSC77410	6.8	7.7	.	135
	11.6	13.6	.85	

Measurements (cont'd)

MCMK1047e	7.7	9.8	.78	25
	8.3	10.2	.81	
MCM1047b	8.4	10.8	.77	45
	10.4	13.6	.76	
MCM1047c	13.7	17.4	.78	64
	14.2	19.0	.75	
MCM1047f	8.6	10.5	.94	34
	9.1	11.2	.93	
MCMK1047g	9.7	12.8	.76	11
	10.0	13.2	.76	
			M = .81	

Baculites cf. boulei Collignon 1931

1959 Baculites boulei Collignon, Matsumoto, p. 118-121,
p. 118-121, Pl. 32, fig. a-c. Pl. 33, figs. 4a-c,
5a, b, 6a-d, 7a, b: Text figs. 27a, b, 28-32.

Description - The shell is slowly tapering, the cross-section is higher than broad, with siphonal area more narrowly rounded than the antisiphonal. The shell is ornamented with prominent crescentic nodes connected to ribs which are markedly prorsiradiate. No septal suture is preserved.

Remarks - In its ornamentation and cross-section, this single specimen most closely conforms to B. boulei. The shape of the nodes excludes it from B. capensis, while the short inter-node distance excludes it from B. tanakae Matsumoto and Obata.

Complete synonymy by Matsumoto (1959b, p. 118).

Occurrence - GSC loc. 225, Schmidti Zone, Haslam Formation, Nanaimo River.

Measurements -

	W	H	L	W/H
GSC15L80	7.0	9.6	28	.73
	8.0	10.2		.76

Baculites chicoensis Trask, 1856

Plate 4-1; figs. 3, 4; Text fig. 4-1

1959 Baculites chicoensis Trask, Matsumoto, p. 145-150, Pl. 36, fig. 2a-d, Pl. 37, fig. 1a-d: Text figs. 59a-d, 60a, b, 62a, b, 63a, b.

1963 Baculites chicoensis Trask, Matsumoto and Obata, p. 66 - 70, Pl. 21, figs. 2, 4: Text figs. 159, 163, 164.

1970 Baculites chicoense sensu Usher, Jeletzky, p.33, part.

Material - MCM1101 from loc. MCM145, MCM1107 from loc. MCM140, UW47796 from loc. UWA9990, GSC79265.

Description - No shell ornamentation present on any of the Nanaimo specimens. Whorl section shows prominent keel along ventor, at all preserved growth stages. In later growth stages this keel is bordered by faint grooves. The remainder of the section is inflated and elliptical.

The septal sutures are deeply incised. The first lateral saddle is very narrow and more constricted at base than second, The folioles are non-phylloid. The median lobules in the saddles incise half-way to the base of saddle. The dorsal saddle is nearly same height as laterals.

Remarks - *Baculites chicoensis* is similar to *B. bailyi* and *B. inornatus* in its low degree of ornament, but is easily differentiated on cross-sectional and sutural characteristics. Whereas the latter two species possess septal sutures with quadrate or trapezoidal lobes of low incision, the septal sutures of *B. chicoense* are deeply incised and complex.

The complete synonymy is listed by Matsumoto (1959b, p. 145).

Occurrence - *B. chicoensis* has been recovered from a number of localities at various horizons within the Ganges Formation (Chicoense Zone), including: UWA9990, Waldron Island; MCM154, Stuart Island; MCM140,141, North Pender Island; MCM145, South Pender Island; MCM111,112, Trent River; and GSC79265, Texada Island.

Measurements -

Specimen	W	H	L	W/H Length
GSC79265	9.2	12.3	74	.75
	12.4	16.8		.74
MCMK1101a	7.9	11.9	35	.66
MCMK1101b	14.1	18.7	78	.75
	15.2	21.0		.72

Baculites inornatus Meek, 1862

Plate 4-1; figs. 1, 2; Text fig. 4-1

1959 *Baculites inornatus* Meek, Matsumoto, p. 155-161, Pl. 38, fig. 1a-c, Pl. 43, fig. 5a-c; Text figs. 72a, b, 73a-d, 74-79.

1963 *Baculites inornatus* Trask, Matsumoto and Obata, ________ .., p. 78-80, Pl. 22, fig. 1, Pl. 24, fig. 6, Pl. 26, figs. 4-6; Text figs. 169, 170, 187-190.

1970 Baculites chicoense sensu Usher, Jeletzky, p. 38, part.

Material - Numerous specimens from loc. UW1390, Sucia Island.

Description - Shell ornamented with numerous, crowded striae which occasionally cross ventor with projection. Whorl section is oval in some specimens, with ventral portion slightly narrower than dorsal. Shell reaches moderate size; maximum height of 40 mm observed in body chamber (with rostrum); maximum height of 25 mm for collected phragmocones. Tapering most rapid in early portions of phragmocone.

Septal suture comprised of broad, moderately incised rectangular saddles. Folioles have prominent phylloid terminals. The dorsal saddle is slightly smaller than lateral saddles. Incisions of medial lobules extend about 1/3 of way to base of saddle.

Remarks - B. inornatus is similar to B. bailyi in ornament, but differs greatly in size and sutural type. Septal sutures in B. inornatus are strongly phylloid, as compared to a lack of phylloid foliole terminals in B. bailyi and B. chicoens .

The complete synonymy of B. inornatus is listed by Matsumoto (1959, p. 155).

Occurrence - B. inornatus has only been recovered from Cedar District Formation beds on Sucia Island, where it is restricted to the Vancouverense Zone.

Measurements -

Specimen	W	H	L	W/H
MCMK1102a	21.5	29.0	133	.74
	27.7	37.8		.73
MCMK1102b	27.8	37.4	147	.74
	30.8	42.7		.72
MCMK1102c	19.0	25.8	74	.74
	21.7	30.9		.70
MCMK1102d	15.8	22.6	84	.70
	18.9	27.4		.69
MCMK1102e	16.4	23.7	89	.69
	9.8	28.8		.69
MCMK1102f	16.7	23.5	85	.71
	19.2	28.0		.69
MCMK1102g	11.8	15.8	209	.75
	20.6	30.6		.67
UW65391a	6.7	9.2	99	.73
	10.0	15.3		.65
UW65391b	7.2	9.4	65	.76
	9.8	14.4		.68

Baculites anceps pacificus Matsumoto and Obata 1963
Plate 4-2; figs. 3, 4, 5; Text fig. 4-2

1963 *Baculites anceps pacificus* Matsumoto and Obata, p. 59-63, Pl. 20, fig. 3; Text figs. 145, 146, 156.

Material - MCMK1100 A-E from loc. MCM 151, Shelter Point; GSC90888b, GSC77458a, both from Denman Island.

Description - Flank ornamented with crescentic ribs of varying prominence. These ribs run forward, disappear on shoulder, then re-appear, crossing the ventor with projection. The vent r has a very corrugated appearance. The dorsum is smooth; the rostrum projects past most anterior part of dorsum for a distance of about one-half the length of the whorl diameter. The whorl section is compressed oval, much higher than broad. The suture is moderately incised. The saddles are broadly rectangular. The folioles are slightly phylloid. The ventral saddle is much smaller than laterals.

Remarks - The ornamentation, cross-section and short rostrum serve to differentiate this species from the other Nanaimo baculites. The suture is less phylloid than in *B. inornatus* and *B. occidentalis*, but more complex than *B. bailyi*.

The species conforms well to the description of the Californian and Japanese conspecific forms.

Occurrence - Associated with *Metaplacenticeras pacificum* on Denman Island, and with a *C.* cf. *newberryanus* at Shelter Point (cf. Richards, 1975). From these occurrences, the species seems to range through some part of the Pacificum Zone, and possibly part of the Vancouverense Zone.

Measurements -

Specimen	W	H	L	W/H
MCMK1100A	9.7	15.2	90	.64
	15.7	21.3		.74
MCMK1100B	9.5	13.8	152	.68
	15.8	23.5		.67

	W	H	L	W/H
GSC90888b	14.0	-	70	
	18.1	23.7		.76
GSC77458a	7.7	10.5	61	.73
	8.8	12.2		.72

Baculites rex Anderson, 1958

Plate 4-1; figs. 5, 6, 9; Text fig. 4-2

1963 Baculites rex Anderson, Matsumoto and Obata, p. 64-65, Pl. 19, fig. 3; Text figs. 158, 165.

1970 Baculites chicoense sensu Usher, Jeletzky, p. 33. part.

Material - Numerous specimens from locs. GSC92066, 77458, Denman Island; MCM 148, South Pender Island and MCM 149, Saturna Island.

Description - The shell is unornamented except for fine growth lines, and slight corrugation on venter in some specimens. The taper is rapid and some small specimens show slight bending. The shell reaches large size (up to 50 mm diameter). The whorl section is egg-shaped throughout growth. The septal suture is greatly incised and extremely complex, even at early growth stages, with non-phylloid folioles. The first lateral saddle is very narrow at its base, the second lateral saddle wider than the first, and less incised at base. The dorsal lobe is approximately one-half as deep as the lateral lobes.

Occurrence - Baculites rex is restricted to the Pacificum Zone of the Cedar District Formation. It has been found associated with Gaudryceras denmanense, Neophylloceras sp., Baculites anceps pacificum and Anapachydiscus nelchinensis. Localities with B. rex are known from Saturna, Saltspring, North and South Pender, Denman and Prevost Islands.

Measurements -

Specimen	H	W	L	W/H
GSC77458	14	10.2	80	.59
	8.2	6.1		.74
MCMK1104	43	--		--
	34	--	109	--

Baculites occidentalis Meek 1862

Plate 4-1; figs. 8, 9; Text fig. 4-2

1959 Baculites occidentalis Meek, Matsumoto, p. 150-155, Pl. 35, figs. 2a-d, 3a-d; Pl. 36, figs. 1a-d, Pl. 41, figs. 1a-d; Pl. 42, figs. 1a-c, 2a-c; Text figs. 64, 65a,b; 66, 67-71.

1963 Baculites occidentalis Meek, Jones, U.S.G.S. Prof. Paper 432, p. 82-85, Pl. 23, fig. 3; Pl. 25, fig. 1; Pl. 26, figs. 1-3; Pl. 27, figs. 2-5, 8; Text figs. 172-186.

1970 Baculites occidentalis, Jeletzky, p.33

Material - UW65918 from loc. UW 1390, Sucia Island, numerous specimens from Hornby Island, loc. GSC 15570, 15567, 15565.

Description - Flank ornamental with crescentic nodes; weak on juveniles, but very pronounced on adult living chambers. Nodes interdispersed with approximately 10 - 12 prominent growth lines. The whorl section is compressed; egg-shaped in early stages and becoming more compressed in later stages, often with pronounced fastigation and flattened dorsum. The septal suture is very similar to B. inornatus in general outline, but slightly more incised, and with less phylloid folioles.

Remarks - B. occidentalis is easily differentiated from B. inornatus by whorl cross-section and ornamental differences; the similarity in septal suture is, however, striking. B. occidentalis has similar, but more pronounced ornamentation than B. anceps pacificus, but is easily differentiated from that species on sutural and cross-sectional differences.

Occurrence - Previously, all known specimens have been from the Spray Formation, Hornby Island, except for a single specimen collected from Sucia Island almost a century ago. Jones (1963) and Jeletzky (in Muller and Jeletzky, 1970) have discussed this apparently anomalous find, and have suggested that it may have been found elsewhere and mislabelled. The occurrence of B. occidentalis from Sucia Island can be substantiated, however, for several well-preserved specimens of B. occidentalis collected on Sucia Island by Dr. P. Popenoe and identified by D. R. Matsumoto are present in the collections at UCLA (loc. UCLA 1397, Spec. No. UCLA 43811). Additionally, I have collected two well-preserved specimens (UW 65918 from loc. UW 1390) from the highest megafossil localities on Sucia Island (Vancouverense Zone).

Measurements

Specimen	W	H	L	W/H
GSC 5952a	8.6	12.3	131	.70
	17.3	23.2		.74
GSC 5952b	14.1	20.8	67.7	.68
	--	29.4		
MCMK1103a	12.2	18.0	97	.68
	16.0	25.2		.64

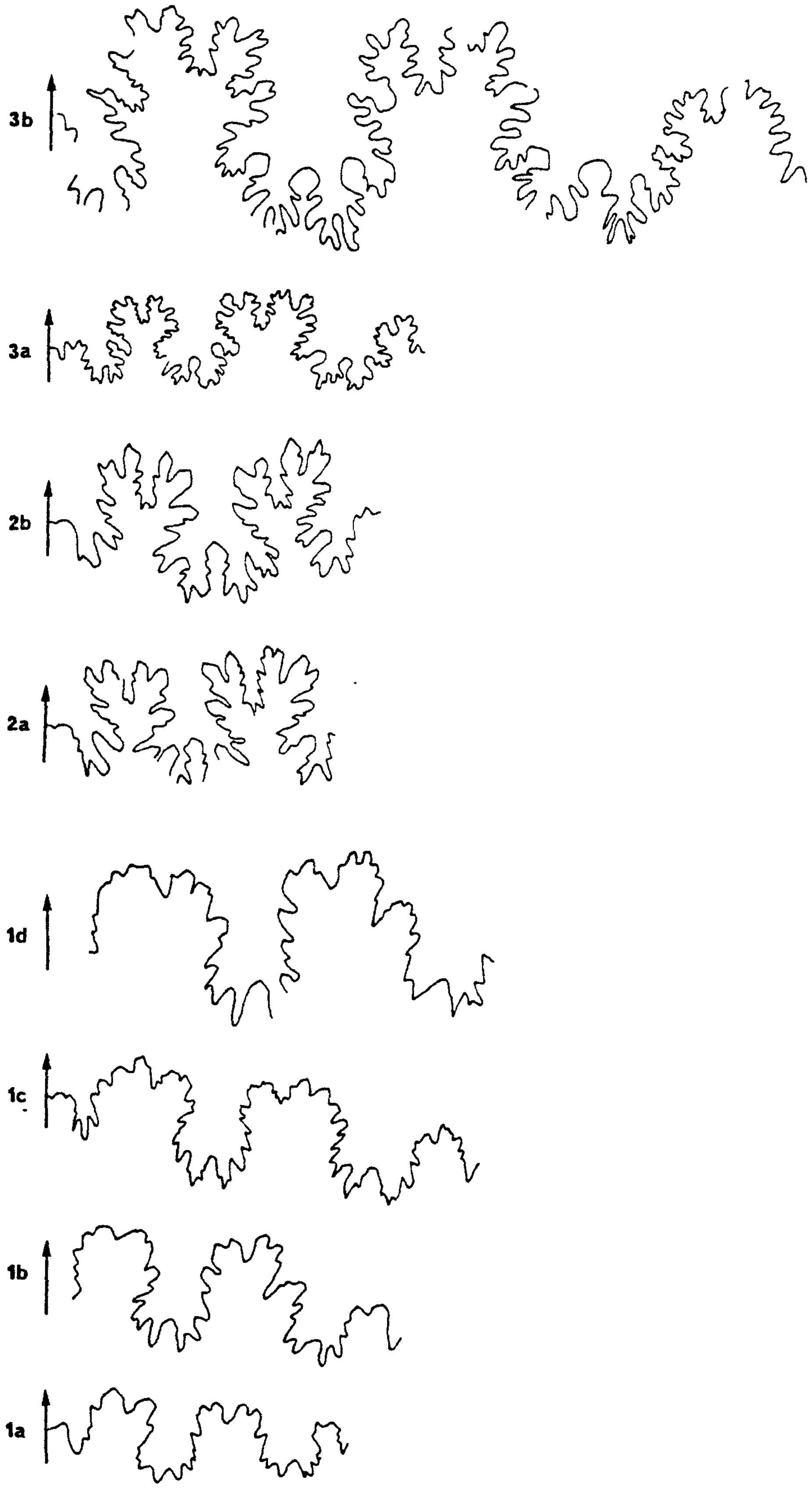


FIGURE 4.1 *Baculites* suture lines. 1. *B. bailyi*; a. MCMK1047B, 5 mm; c. same, 10.4 mm; b. MCMK1023B, 8.0 mm; d. same, 14.2 mm. 2a. *B. chicoense*, MCMK 3a. *B. inornatus*, UW65391, 10 mm; b. same, 16 mm.

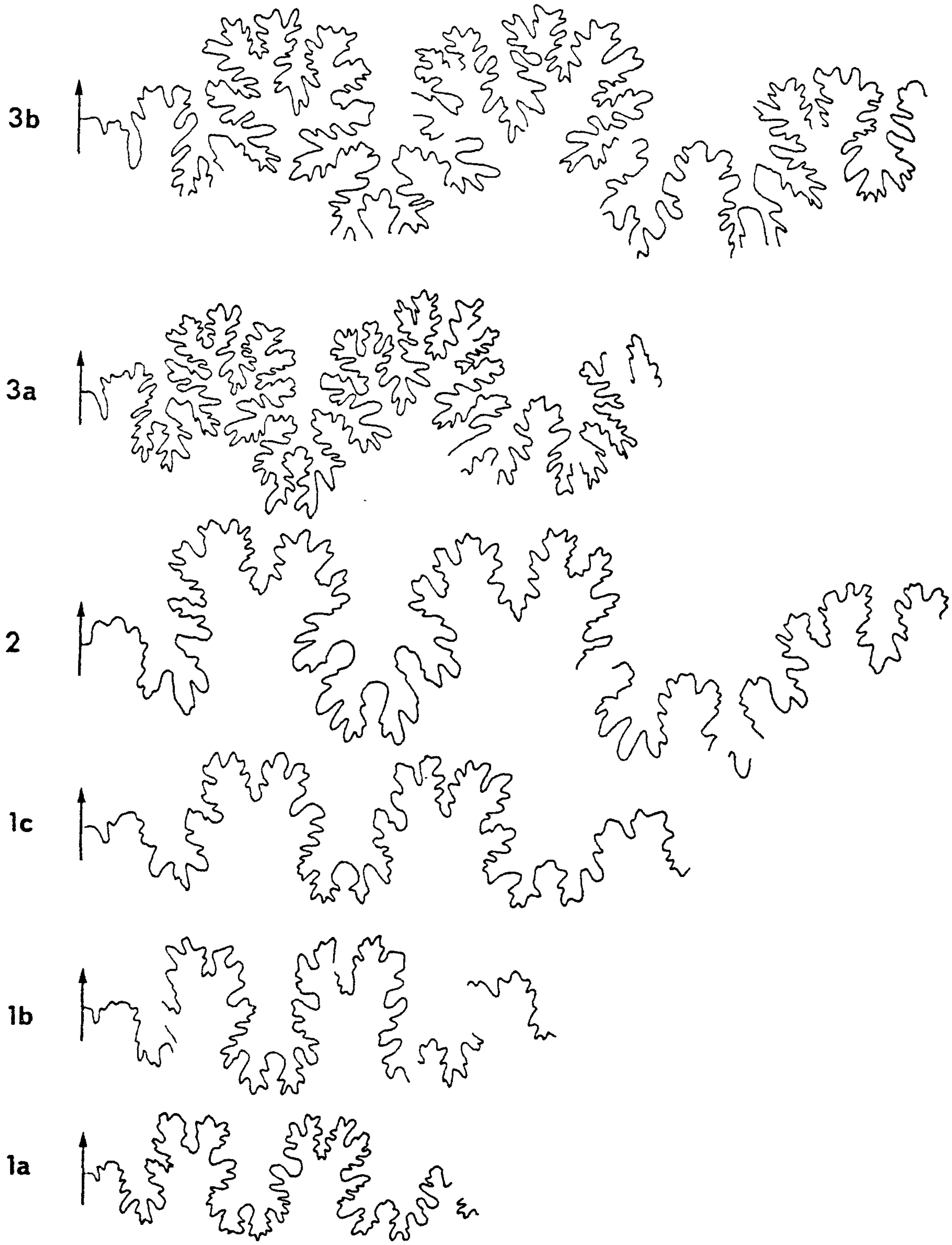


FIGURE 4-2. *Baculites* suture lines. 1a. *B. anceps pacificus*, MCMK1100a, 9 mm; b. same, 12.0 mm; c. same, 14.2 mm. 2. *B. occidentalis*, MCMK1103a, 18 mm; 3. *B. rex*, GSC92066a, 17 mm; b. same, 23 mm. **Venter to left.**

Family DESMOCERATIDAE Zittel, 1895

Genus *Kitchinites* Spath, 1922

Subgenus *Neopuzosia* Matsumoto, 1954

Kitchinites (Neopuzosia) japonica (Spath, 1922)
Plate 4-3; fig. 7; Text fig. 4-3

1954 *Neopuzosia japonica* (Spath), Matsumoto, p. 91-94, Pl. 17, 18, 22; Text fig. 4.

Material - MCMK1053a, b, c from loc. MCM 106, Trent River, Haslam Formation, Elongatum Zone.

Description - Shell moderately evolute, ornamented with rounded ribs which curve adapically on venter and deeper constrictions. Ornament on large specimens is unknown. There are between 6 and 9 constrictions per whorl in early stages. Suture line as described by Matsumoto (1954).

Remarks - Complete synonymy and diagnosis given by Matsumoto (1954).

Occurrence - All specimens in the McMaster collections have been collected in the *Polyptychoceras vancouverense* zonule on Trent River; one specimen in the collections of the Geological Survey of Canada has been collected from the Comox Formation on Haslam Creek (GSC loc. 77383).

Measurements -

Specimen	D	H	W	W/H	U	U/D
MCMK1053a	85	34	25	.74	30	.35
MCMK1053b	--	28	20	.71	20	--
MCMK1053c	--	29	20	.69	--	--

Genus Mesopuzosia Matsumoto, 1954

Mesopuzosia densicostata Matsumoto 1954

Plate 4-3; figs. 4a, b

1954 Mesopuzosia densicostata Matsumoto, p. 87-88, Pl. 22.

1970 Parapuzosia sp. Jeletzky, in Muller and Jeletzky, p. 35.

Material - MCMK1078 from loc. MCM 157, Bloedel Creek; MCMK1074 from loc. MCM 109, Trent River.

Description - All known specimens are very large (maximum size 1.5 m), unornamented; inner whorls are ornamented with fine, sinuous ribs and broader constrictions. Suture line as described by Matsumoto (1954).

Occurrence - Both collected specimens are from the Naumanni Subzone, Elongatum Zone. One uncollected specimen was observed in the Haradai Subzone, Elongatum Zone, on Elkhorn Creek (loc. MCM 122).

Measurements -

Specimen	D	H	W	W/H	U	U/D
MCMK1078	190	85	50	.59	46	.24
MCMK1074	--	75	46	.61	43	--

Family PACHYDISCIDAE Spath, 1922

Genus Anapachydiscus Yabe and Shimizu, 1926

Anapachydiscus nelchinensis Jones, 1963

Plate 4-3; figs. 5a, b, 6; Text fig. 4-3

1963 *Anapachydiscus nelchinensis* Jones, p. 67 - 68,
Pl. 32; Pl. 35, figs. 4, 7-9, Text fig. 23.

Material - MCMK 1106a, b, c from loc. MCM 143, North Pender Island.

Description - All specimens were dissected from extremely large, secondarily compressed and tectonically deformed specimens of .5 to .75 m diameter. No ornament on large specimens was observed. Smaller specimens are smooth, except for between 6 and 8 umbilical bullae and fine striae. The specimens appear identical in ornament and suture line to the examples figured by Jones.

Occurrence - All specimens come from a single locality in the Cedar District Formation of North Pender Island, where they were found associated with *Baculites rex*. This occurrence is placed within the *B. rex* zonule of the Pacificum Zone.

Measurements -

Specimen	D	H	W	W/H	U	U/D
MCMK1106a	61	29	32	1.10	18	.30
MCMK1106b	40	18	23	1.28	6	.33
MCMK1106C	51	21	28	1.33	14	.27

Menuites Spath, 1922

Menuites sp. indet.

Plate 4-3; figs. 8a, b; Text fig. 4-3

Material - A single specimen, MCMK1105 from loc. MCM 147.

Description - Shell involute with steep umbilical wall, cross-section broader than high. Shell ornamented with large, blunt ventrolateral and shoulder tubercles, weak ribs intercalate between tubercles. Septal suture composed of four external saddles per side; saddles complex and deeply incised.

Remarks - This specimen is referred to Menuites because of its quadrituberculation and depressed cross-section. Most of the phragmocone is crushed, however, and the body chamber is apparently incomplete, rendering specific identification impossible.

Occurrence - The single specimen was found with Metaplacenticeras cf. pacificum in the Cedar District Formation on South Pender Island.

Measurements

	D	H	W	W/H	U	U/D
MCM1105	--	35	47	1.34	15	--

Family COLLIGNONICERATIDAE Wright and Wright, 1951

Subfamily TEXANITINAE Collignon, 1948

Submortoniceras chicoensis (Trask, 1856)

Plate 4-3; figs. 1, 2, 3

1959 Submortoniceras chicoense (Trask), Matsumoto, p. 126, Pl. 32, fig. 1; Pl. 33, fig. 1, Pl. 34, figs. 1-3; Pl. 35, figs. 1, 2.

1963 Submortoniceras chicoense (Trask), Young, p. 106, Text figs. 11e, f, 12d; Pl. 57, figs. 1-3.

1966 Submortoniceras chicoense (Trask), Howarth, p. 61-62, Text figs. 3a, 5, 6.

Material - MCMK1109 from loc. MCM 111, UW13907 and UW65762 from loc. UWB 2051.

Description - Three complete specimens and several fragmentary ones have been recovered. All have been secondarily compressed, so that true whorl thicknesses are not known, and the venters are not visible. All specimens are moderately involute. Ornamentation is coarse, consisting of primary, flexuous ribs originating from prominent umbilical tubercles. Secondary ribs intercalate with the primaries, originating approximately two-thirds of the distance from the umbilical shoulder to the venter, and continuing to the ventrolateral tubercles. On the larger two specimens, each primary rib bears three lateral tubercles in addition to the umbilical and ventrolateral tubercles. On the smaller specimen, only these latter two tubercles are developed. No septal sutures are preserved.

Remarks - The two larger specimens conform well with Matsumoto's forma α (1959b, p. 129); the smaller specimen seems closest to forma γ, although its lack of ornamentation may be due to immaturity.

Occurrence - All specimens are from the Chicoense Zone, Ganges Formation, on lower Trent River, where they were associated with *Baculites chicoensis*, *Canadoceras newberryanum* and *Pseudoxybeloceras (Cyphoceras) nanaimoense*.

Measurements -

	D	H	U	U/D	Tubercles Umbilical	 Ventral
MCMK1109	34.7	16.6	7.6	.22	12	44
UW13907	86	39	21	.24	12	48
UW65762	124	54	30	.24	--	--

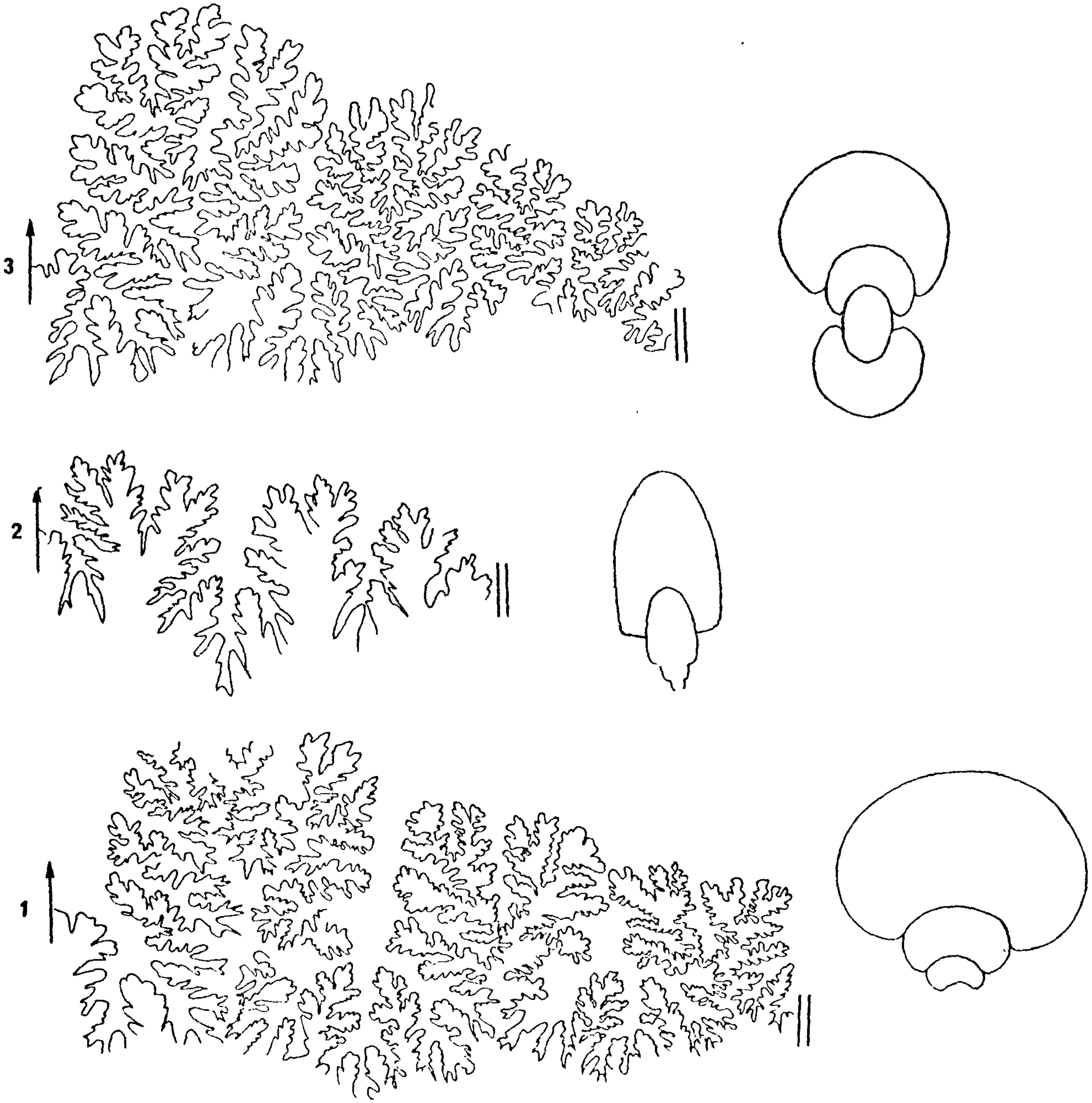
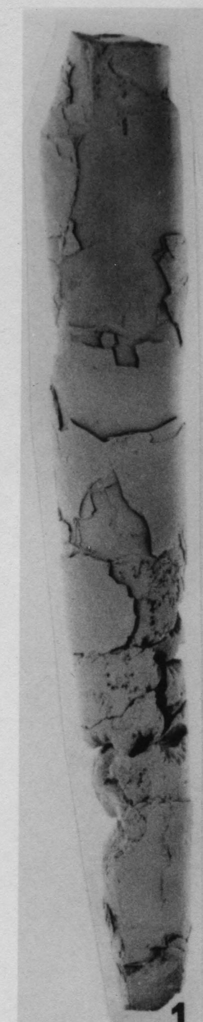


FIGURE 4.3. 1. *Menuites* sp., MCM1105, H = 25 mm. 2. *Kitchinites japonica*, MCM1053, H = 24 mm. 3. *Anapachydiscus nelchinensis*, MCM1106, H = 14 mm.

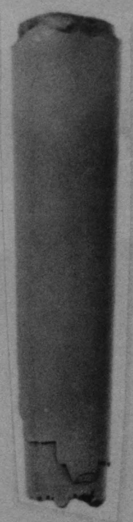
4-1

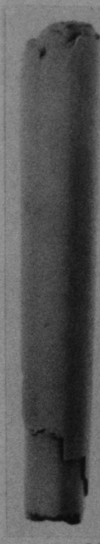

1


2

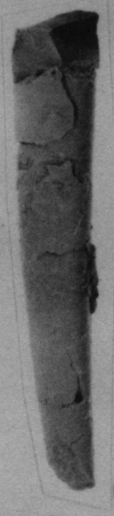

3a


3b


4a


4b

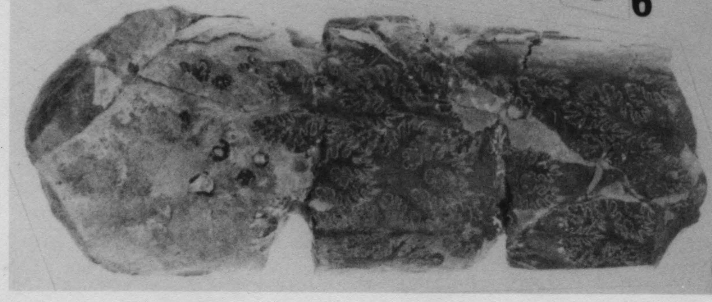

5


6


7a

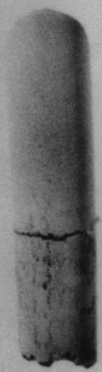

7b


8

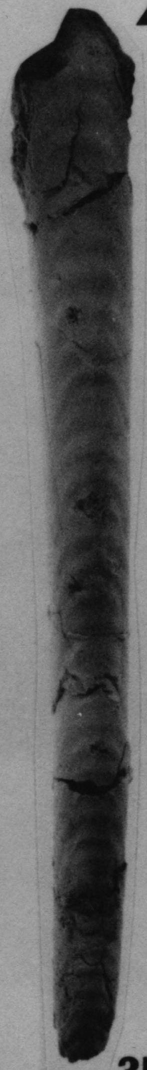

9

4-2


1


2


3a


3b

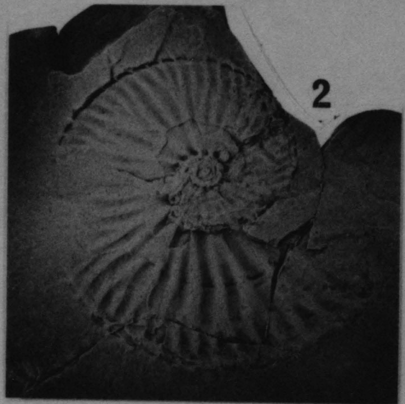

4a


4b

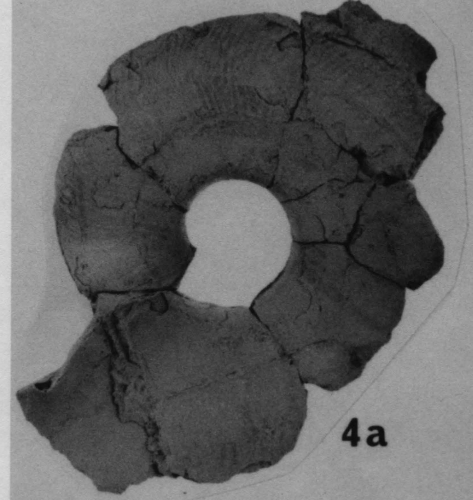

5

4-3

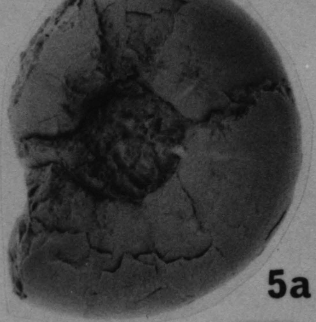

1


2


3


4a

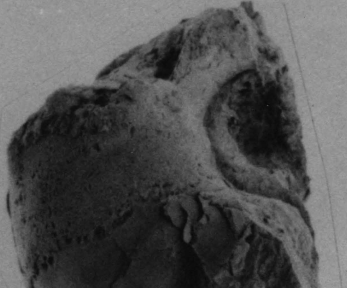

4b


5a


5b


6


7


8a

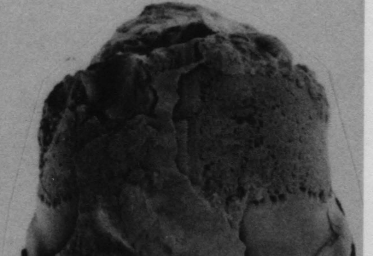

8b

Plate Descriptions, Chapter 4

Plate 4-1, Fig. 1, 2. *Baculites inornatus* Meek.

Fig. 1, MCMK 1102g, X.75; Fig. 2, MCMK 1102b, X.75

Plate 4-1, Fig. 3,4. *B. chicoensis* Trask.

Fig. 3a, b, UW47791, X1.; Fig. 4a, b, GSC 79265, X1.

Plate 4-1, Fig. 5, 6, 9. *B. rex* Anderson.

Fig. 5, MCMK 1107a, X1.; Fig. 6, GSC 77458, X1.;
Fig. 9, MCMK 1104, X1.

Plate 4-1, Fig. 7, 8. *B. occidentalis* Meek.

Fig. 7a, b, MCMK 1103a, X1.; Fig. 8, UW 65918, X1.

Plate 4-2, Fig. 1, 2. *Baculites bailyi* Woods.

Fig. 1, MCM 1023c, X1.5; Fig. 2, MCM 1047f, X1.5.

Plate 4-2, Fig. 3, 4, 5, 6. *Baculites anceps pacificus* Matsumoto.

Fig. 3a, b, MCMK 1100B, X1.25; Fig. 4, GSC 77458a, X1.25;
Fig. 6, MCMK 1100C, X1.

Plate 3, Fig. 1, 2, 3. *Submortoniceras chicoense* (Trask).

Fig. 1, UW 65762, X.5; Fig. 2, UW 13907, X.5;
Fig. 3, MCMK 1109, X1.

Plate 3, Fig. 4a, b. *Mesopuzosia densicostata* Matsumoto.

MCMK 1078, X.4.

Plate 3, Fig. 5a, b, 6. *Anapachydiscus nelchinensis* Jones.

Fig. 5a, b, MCMK 1106a, X1.; Fig. 6, MCMK 1106 , X1.

Plate 3, Fig. 7. *Kitchinites (Neopuzosia) japonica* Spath.

MCM 1053a, X.9.

Plate 3, Fig. 8. *Menuites* sp. indet. MCM 1105 X1.

CHAPTER 5

PALEOGEOGRAPHY

5.1 Introduction

Eisbacher (1974) has described the Nanaimo Group, or Georgia Assemblage (after the Strait of Georgia, which separates Vancouver Island from the mainland) as an example of an epieugeosyncline, or "successor basin", as defined by Kay (1951), which was deposited during the gradual establishment of the Georgia Depression between Vancouver Island and the mainland of British Columbia. These deposits were considered to mark the first time mainland source areas contributed sediments to Vancouver Island region stratal accumulation.

The Georgian Depression itself is thought to have formed in response to westward stepping of eastward dipping subduction zones during the Cretaceous (Monger _et al_, 1972), causing a crustal downwarping which was repeatedly transgressed by seas entering from the southwest. Jeletzky, however (personal communication), disagrees with this interpretation and advocates isostatic, rather than plate-tectonic mechanisms for the genesis of the Georgian Depression.

A number of depositional basins within the Georgian Depression have been defined; there has been disagreement, however, as to what extent these are defined by structural deformation and post-depositional erosion. Clapp (1912) and Sutherland Brown (1966) defined two separate depositional basins; Muller (in Muller and Jeletzky, 1970) indicates one large basin. Evidence in the Nanaimo area suggests to me that northern and southern depositional areas, corresponding to Clapp's Comox and Nanaimo Basins were present, since strata thin and coarsen markedly near Nanaimo, suggesting a topographic high of pre-Cretaceous rocks was influencing sedimentation, and separating two depositional regimes.

To the southeast of Vancouver Island, Miller and Misch (1963) and Griggs (1970) defined the Bellingham Basin for those areas near the city of Bellingham, Washington, which accumulated over 3000 m of the Chuckanut Formation. The lower 2000 m of this formation has been shown to be Upper Cretaceous in age (Griggs, 1970), and hence probably correlative with the upper Nanaimo Group Formations. Deposition probably occurred subaerially on a wide alluvial plain close to sea level (Griggs, 1970). The strongly arkosic composition of the Chuckanut Formation suggests that unroofing of the coast range granitic intrusives to the north and east was well underway at this time.

Muller (in Muller and Jeletzky, 1970) interpreted the Nanaimo Group as the preserved record of five transgressive-regressive cycles, each progressing from fluvial to deltaic and/or marine, to offshore marine conditions. The first cycle was initiated by Comox Formation deposition, followed by the Haslam Formation. The second cycle was initiated by the Extension-Protection Formation, followed by the marine Cedar District Formation. The third depositional cycle started with the De Courcy Formation, followed by the Northumberland Formation. The fourth cycle initiated with the Geoffrey Formation, followed by the Spray Formation. The fifth cycle was judged incomplete, consisting only of the Gabriola Formation.

Muller's model, in light of information presented here on the stratigraphy and biochronology in the Nanaimo Group, is oversimplified. First, in Muller's model, the Extension-Protection Formation is considered as the non-marine and shallow marine deposits of the second cycle; however, Clapp (1912) recognized that a marine sandstone and shale unit, which he named the Ganges Formation, was stratigraphically between the name members of Muller's Extension-Protection Formation. I have traced the Ganges Formation throughout the Nanaimo Group, so that according to Muller's model, a sixth cycle would have to be recognized.

Secondly, the stratigraphic patterns in the Gulf Islands in the upper formations do not lend themselves into categorization as either offshore marine shales or non- and marginal-marine conglomerates and sandstones. The alternation of sandstones and shales of the Cedar District to Geoffrey Formations near the town of Nanaimo cannot be recognized in the Gulf Islands; because several more shale and sandstone units were preserved on the very complete North and South Pender Island sections, Muller mapped these islands as consisting of the same formations of the stratotype areas, repeated by faulting or overturned (see Figures 2.2.5, 2.2.6, and compare with Muller and Jeletzky, 1970, text, Figure 11). Paleontological and preliminary sedimentological evidence indicates that the strata in the Gulf Islands are correlative with the type areas near Nanaimo, but consist of a greatly thickened aggregate of turbidites and grain flows, as well as possible re-sedimented conglomerates. In this area, widespread regression may not have occurred during the Vancouverense, Pacificum and Suciensis Zones.

5.2 Lithofacies Patterns

Figures 5.2.1 - 5.2.5 illustrate the distribution of marine lithologies presently observable in the Nanaimo Group for the Elongatum, Schmidti, Chicoensis, Vancouverense, Pacificum and Suciaensis Zones.

A large-scale paleogeographic feature unrecognized by previous workers is the large turbidite trough present in the southwestern part of the Nanaimo Basin during the Elongatum and Schmidti Zones, and possibly after. Turbidites biochronologically correlative with the Haslam Formation stratotype extend from Orcas Island in the southeast to Lake Cowichan in the southwest, a distance of over 80 km. Only several km. north of these deposits, biochronologic correlatives are comprised of massive shales rather than flysch (Figure 5.2.1, 5.2.2).

Sediment transport and paleocurrent directions are only known from scattered measurements in the Haslam Formation turbidites. Sole marks in the Marie Canyon section of the Cowichan River showed mainly western, eastern and northeastern directions of flow (Schmidti Zone), while numerous sole marks on Stuart Island (Elongatum Zone) showed mainly northwestern directions.

Nanaimo Basin geometry apparently altered in post-Schmidti Zone time. Eisbacher (1974) noted that overall sediment transport is predominantly westward in the Cedar District and younger formations, and mainly eastward in the older Nanaimo Group formations. Rahmanni(1972) found predominantly westward and northwestward paleocurrents in turbidites of the Cedar District Formation.

The area of marine sedimentation during deposition of the Chicoense Zone (Figure 5.2.3) was apparently nearly, or as, extensive as during the Elongatum Zone deposition. Flysch sedimentation seems to have been restricted to the Saltspring Island region, however. In the Cowichan Valley, the Chicoense Zone is comprised of massive silty shales, while in the San Juan Islands, the predominant lithologies are fine-grained sandstones and sandy siltstones. In the Comox Basin, thick sections of shales are present on the Trent and Puntlege Rivers and Texada Island.

Major regression associated with widespread uplift to the east and southeast of the Georgian Depression may have begun in late Chicoense time. The Protection Formation, which succeeds the Ganges Formation, is in its stratotype a well-sorted, massive white sandstone which I interpret as having been deposited in near-shore, high energy conditions. In the Gulf Islands, however, correlatives of the stratotype are more poorly sorted, less massive and, on Saltspring and North Pender Island, under- and overlain by turbidites, indicating that the Protection Formation here may have been deposited in deeper water by gravity flow mechanisms.

In the Comox Basin, there is no record of the Protection Formation. Since strata with Chicoense fauna conformably underlies Vancouverense-bearing fauna, no regression may have occurred in the northern regions of the Georgian Basin. Muller (in Muller and Jeletzky, 1970) shows a connection to the sea for the first time during his second transgressive cycle; the absence of the Protection Formation in the Comox Basin, and hence evidence of continued marine conditions in the north during regression in the south, may be indirect evidence of this seaway during Chicoense time.

Areal extent of the Vancouverense Zone and later strata is, with the exception of the Nanaimo area and the small Shelter Point area near the town of Cambell River, restricted to island exposures in the Strait of Georgia.

During this time the area of turbidite deposition expanded greatly in the Gulf Islands (Figures 5.2.4 - 5.2.6). In the Comox Basin, turbidites are only known from the Northumberland Formation exposed on the eastern shore of Denman Island and the western shore of Hornby Island.

5.3 Paleodepth Indicators

The depth of Nanaimo Group sediment deposition has been discussed for several Nanaimo Group Formations by Sliter (1973) and Scott (1974), using different aspects of formaminiferal assemblages as estimators.

Sliter based his bathymetries on his previous models (Sliter, 1972a, b; Sliter and Baker, 1972). The Haslam Formation on Trent River was found to contain mainly agglutinated forms indicative of an outer shelf-slope environment of about 200 m depth. The Cedar District beds immediately above the Haslam Formation on Trent River (Ganges Formation of this work) wereinterpreted as having been deposited in considerably deeper water, at depths between 800 and 1000 m. A similar depth of deposition was indicated for the Cedar District Formation on Dodds Narrows near the town of Nanaimo. The Northumberland Formation of Denman Island was assigned a depth of 300 - 400 m, and the Spray Formation of Hornby Island a depth of 500 to 600 m.

Based on co-occurring molluscan assemblages, I consider these estimates to be on the high side. Dr. A. McGugan, who has published several papers on the Nanaimo Group foraminiferal assemblages (1962, 1964) has concurred in a personal communication, and considers all of Sliter's estimates too deep.

Scott analyzed the Haslam Formation foraminiferal assemblages in detail from sections of both the Nanaimo and Comox Basins. Depth estimates were relative, rather than empirical estimates such as Sliter proposed, and were based on the ratios of calcareous to agglutinated forams, mean diversity and percentage of planktonic forms present in each sample. The deepest water was found to have occurred in the Tsable River area, Haslam Creek area and Qualicum-Englishman River areas during Elongatum and Schmidti Zone times. Unfortunately, no samples were taken from the southern Haslam Formation turbidite deposits.

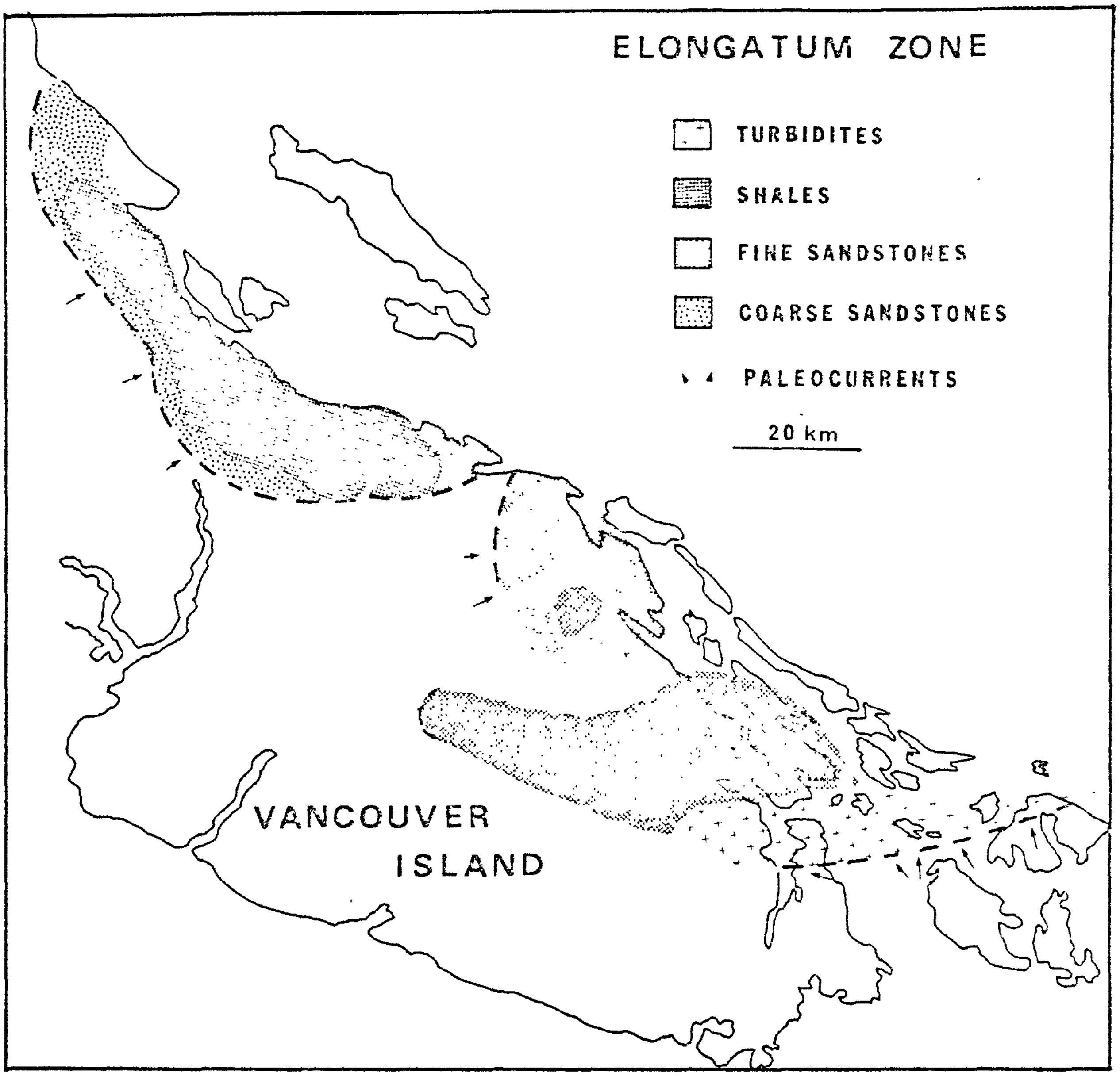


FIGURE 5.1. Elongatum Zone lithofacies. Dashed lines infer shorelines. Paleocurrent directions in all maps generalized from Muller and Jeletzky (1970), Rahmanni (1970), Sutherland-Brown (1966) and my measurements.

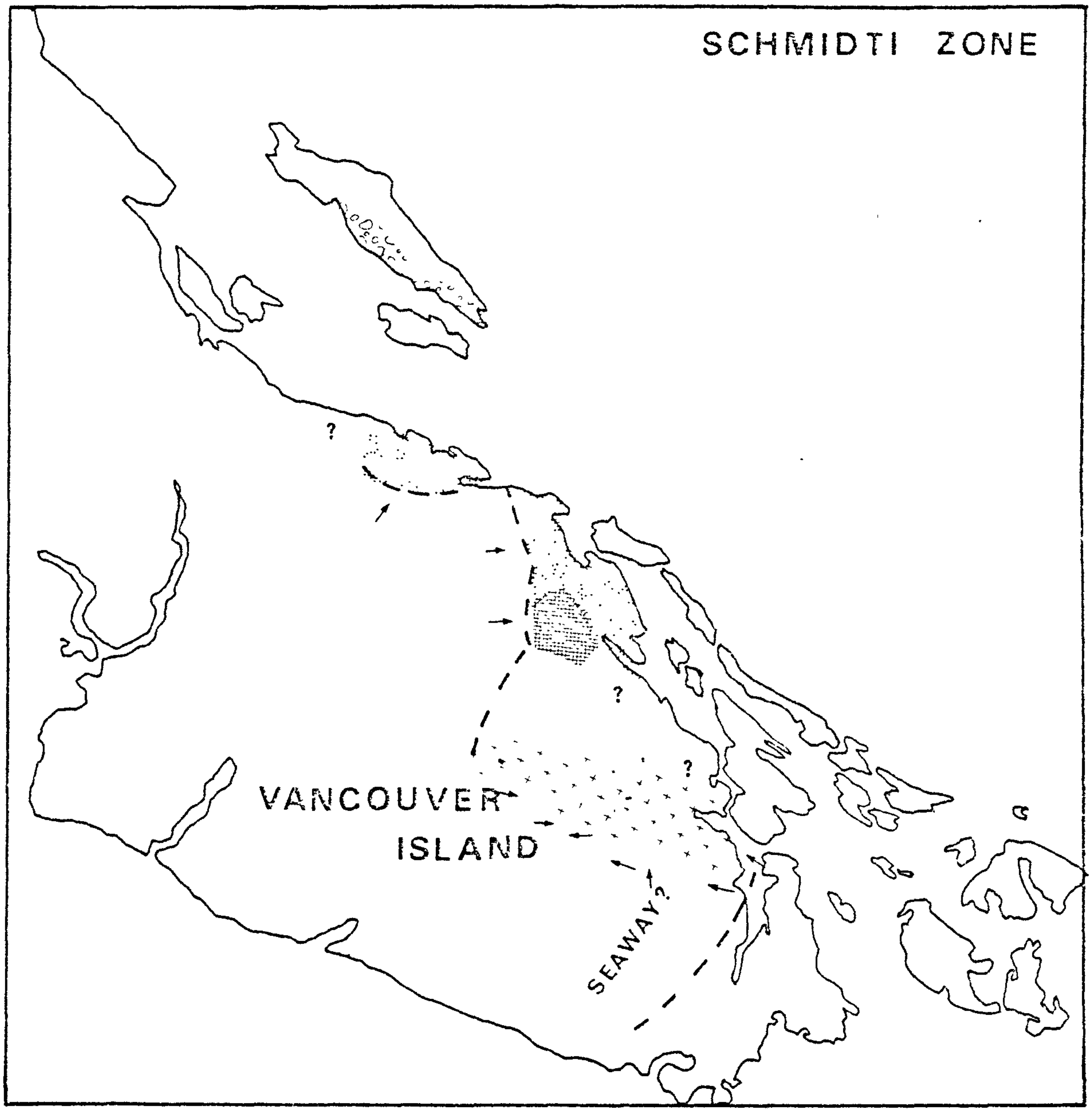


FIGURE 5.2. Schmidti Zone lithofacies.

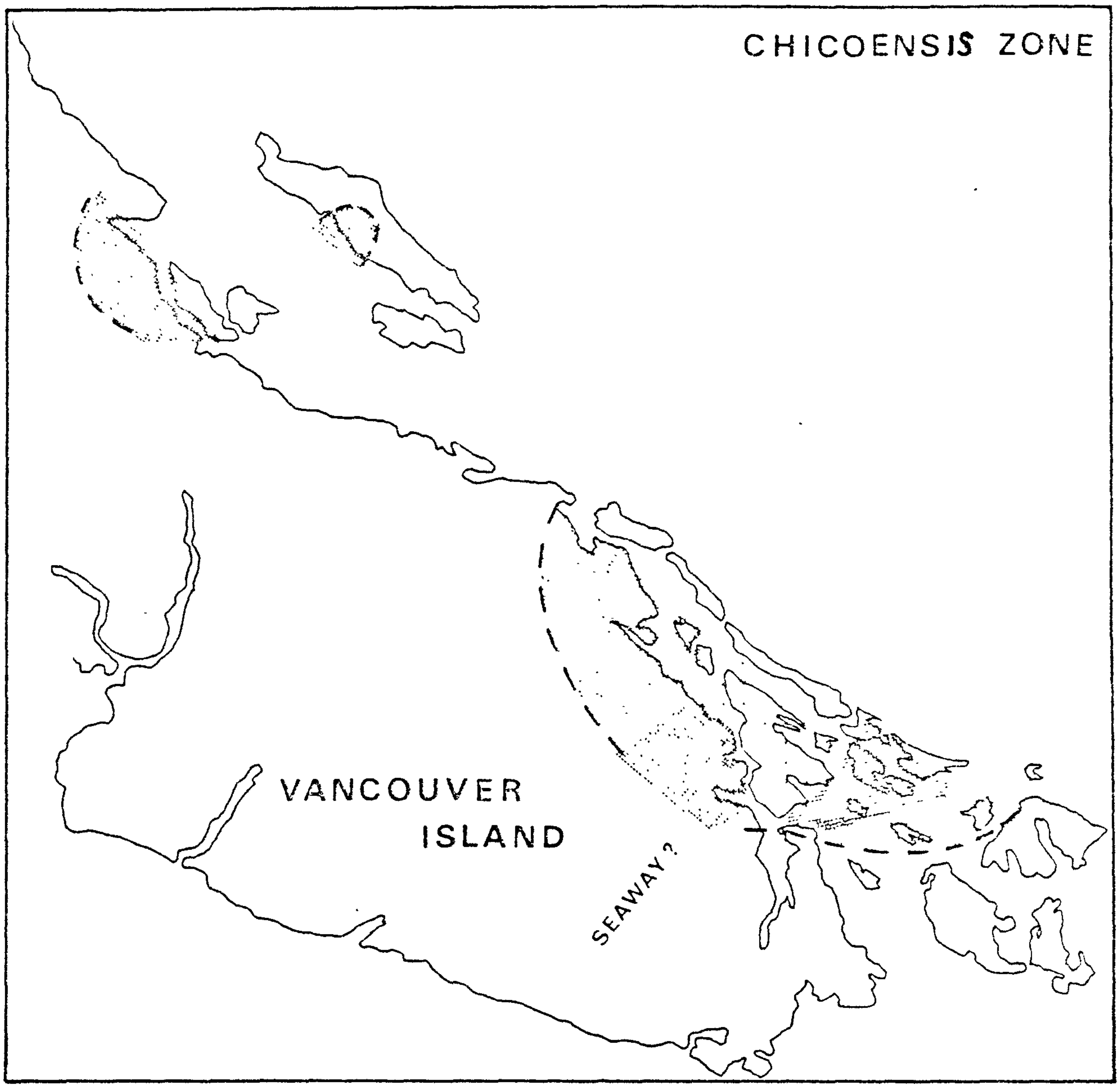


FIGURE 5.3. Chicoensis Zone lithofacies.

FIGURE 5.4. Vancouverense Zone lithofacies.

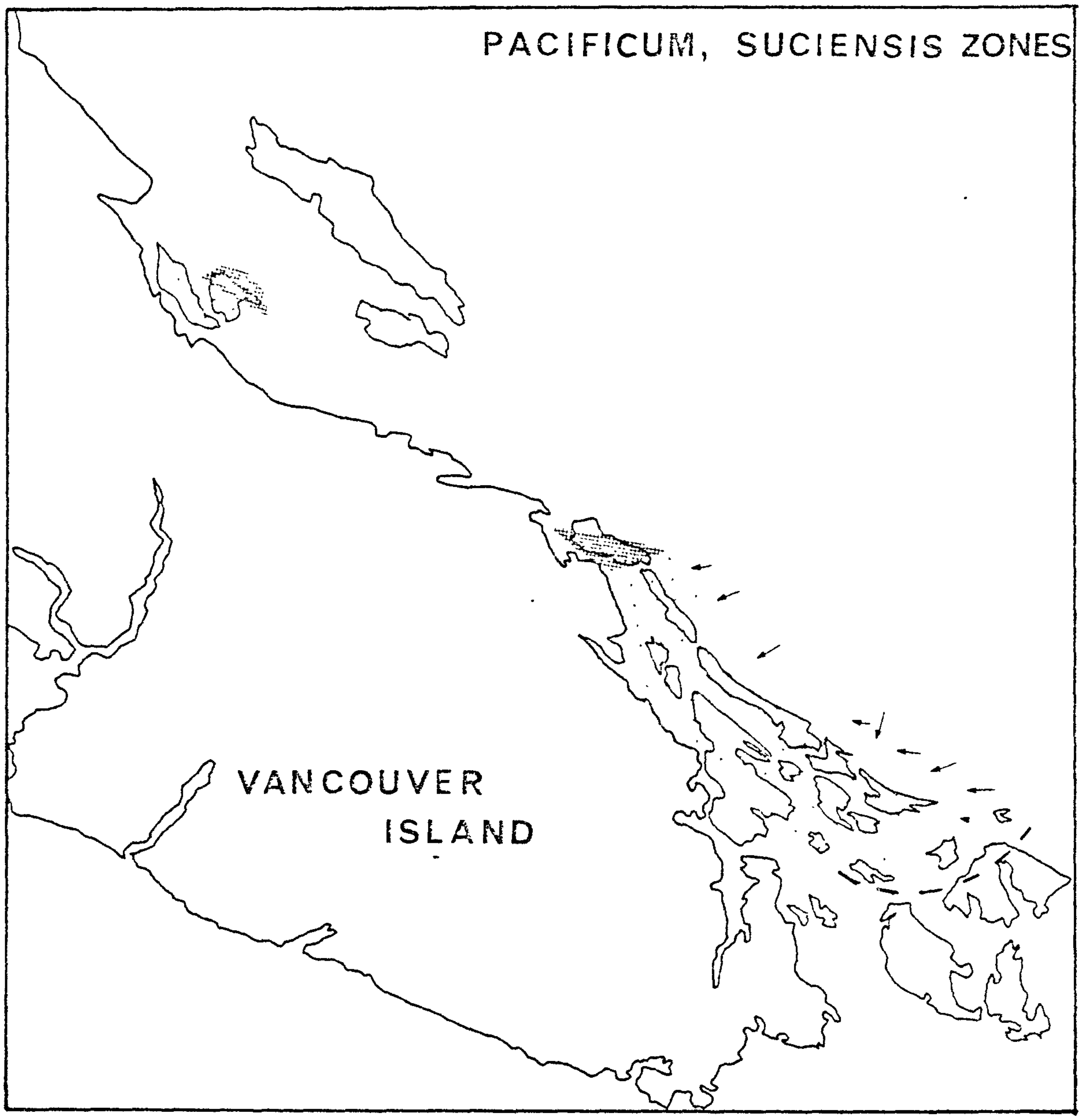


FIGURE 5.5. Pacificum, Suciaense Zone lithofacies.

CHAPTER 6

PALEOECOLOGY

6.1 Introduction

The ammonoidea are poorly understood from a paleobiological standpoint, in spite of a long history of investigation. No consensus has been reached on such ecologic aspects as their trophic position, swimming ability, larval ecology, predators and prey, or major competitors. Ammonoid paleoecology at the community level has remained especially ambiguous because of the possibilities of common and lengthy post-mortal drift, from inference with the well-known dispersal of empty Nautilus shells. In spite of these problems, however, some ammonite biofacies have been recognized.

European workers have long recognized that the phylloceratids and lytoceratids, or "leiostracans", are most common in strata deposited in deep, offshore environments of the Tethyan region: recent studies include those of Zeiss (1969), Ziegler (1970), Geyer (1971) and Geczy (1967, 1971). Scott (1940) proposed that ammonoids other than leiostracans could be correlated with specific sedimentary environments or habitats. Upper Cretaceous ammonites from the Texas area were categorized as either 1) smooth, involute, obese; 2) smooth, evolute, obese; 3) smooth, ovate; 4) sculptured; 5) tenuous, involute, lightly sculptured; 6) tenuous, involute, unsculptured, or 7) heteromorphic.

Based on his personal experience of their common occurrences, Scott correlated groups 5 and 6 with epineritic environments; groups 4 and 7 with epineritic environments; group 3 with the infraneritic, and groups 1 and 2 with the infrabathyal. Scott's ammonite morphotype biofacies have not been widely recognized outside of his study area. The concept of ammonite shell morphology as adaptive response to specific habitat factors was, nevertheless, germinal.

Kauffman (1967) utilized several of Scott's morphotype concepts in an examination of ammonite and other macroinvertebrate distributions in Upper Cretaceous lithofacies of the North American Western Interior. Coarsely ornamented ammonites were found to occur most commonly in calcarenites and dark clay muds of the middle shelf; small, finely ribbed forms and baculitids were most common in outer shelf carbonate assemblages; scaphitids and compressed forms were found to be widely facies ranging, while the greatest diversity of heteromorph ammonites was from middle and outer shelf lithofacies.

Young (1973) examined the occurrences of endemic and cosmopolitan ammonites from the Cretaceous of Texas, finding that endemic forms were usually compressed (oxycones), and suggested that the endemism was caused by geographic restriction of the Texas depositional area from the remainder of the Tethys region. The endemic ammonites were usually found in specific sediment types.

Scott (1976) examined diversity trends among invertebrate fossils of the Washita Stage (Cretaceous) of Texas and the Western Interior. Diversity of various ammonite morphotypes was tabulated in different geographical areas and related briefly to sedimentological factors.

In this Chapter, possible relationships between specific ammonite taxa and morphotypes and other faunal and sedimentary parameters are examined. Numerous occurrences of ammonites within a restricted paleogeographic and temporal setting (Elongatum Zone of the Georgian Basin, British Columbia) have been noted, and patterns of characteristic co-occurrences with associated macrofossil assemblages and lithofacies searched for with statistical associative techniques.

6.2 Study Area

The Nanaimo Group was chosen as field area for several reasons. I had a working knowledge of the ammonite taxonomy, stratigraphy and geography of Vancouver Island at the inception of the study, thereby saving a great deal of time over a novel area. Secondly, the results of previous workers in the area indicated that the depositional basin was surrounded on three sides by land area, and therefore was probably a discrete, small-scale paleogeographic feature. Finally, the observations of previous workers (e.g., Usher, 1952) that certain Nanaimo Group ammonite species had restricted geographic ranges within single zones indicated that differentiable ammonite biofacies were possibly present.

Exposures within the Nanaimo Group are generally good. Rapidly eroding shoreline exposures, carved by the Vashon glaciation approximately 13,000 years ago, are present along the coast of Vancouver Island, the Gulf Islands and the San Juan Islands. Inland, Vancouver Island itself is heavily forested, but a large number of deeply cut river ravines provide adequate exposure.

The stratigraphy and biostratigraphy of the Nanaimo Group has been discussed above in Chapters 2 and 3. In order to reduce the temporal effects of species replacement as much as possible, a single zone was sampled. The Elongatum Zone of the Haslam Formation was chosen because it is the most arealy extensive and has the largest number of ammonite species in the Nanaimo Group.

Even though temporal bias has been reduced by utilizing a single zone, certain ammonite and inocerami species, and possibly as yet unknown bivalve or gastropod species range only partially through the Elongatum Zone, and thus introduce temporal bias into the associative techniques. As detailed in Chapter 3, Polyptychoceras vancouverense is the shortest ranging of the ammonites, being restricted to the lower levels of the Naumanni subzone. Other short-ranging ammonites are Eupachydiscus perplicatum and E. haradai. According to Jeletzky (in Muller and Jeletzky, 1970), the latter species is descendent, and completely replaces the former in the latest Santonian or early Campanian. They may also be somewhat facies-dependent, for E. perplicatum is known only from the Comox Basin, while E. haradai, although also known from several Comox Basin sections, is much more common in the Nanaimo Basin.

6.3 Sampling Techniques

Several methods of sampling were employed for this study. Since fossils were found to be present in varying numbers at nearly all levels and sections of the Haslam Formation, a random sampling procedure was initially used, in which sampling localities were chosen with random number tables for 10 m horizons of measured sections. When a locality was found to be reasonably devoid of fossils, a second horizon was chosen. A more serious problem was the poor accessibility of many river cut exposures. The Vancouver Island region is heavily forested, and access to many exposures was by logging road only. The bulk of material necessarily collected from each locality and the difficulty of its transport necessitated the restriction in sampling of some sections.

Each locality consisted of beds not exceeding 20 m in stratigraphic thickness. Within this area, as many fossils as possible were collected or noted, with a minimum number of 100 as goal. In many river sections the prevailing eastern dip of the Nanaimo Group coincided with the river direction, resulting in bedding-plane exposures of large areal extent. An effort was made to note every megafossil regardless of size, including imprints.

For two localities (GSC 77383 and 69453), counts were made on bulk material collected by other workers.

6.4 Fossil Data

Data collected for this Chapter are listed in Tables 6.1 - 6.3.

Table 6.1 lists the taxa of the Elongatum Zone in binary presence-absence form; x = presence, and 0 = absence for a taxon from any given locality. Ammonites and inocerami are differentiated and listed at the species level, since their taxonomy has been recently revised (i.e., Usher, 1952; Matsumoto, 1959a, 1959b; Ward, 1976). Other bivalves and gastropods are differentiated to the generic level only, since their systematics at the species level has not been re-examined or revised since the work of Whiteaves (1890, 1901, 1912).

TABLE 6.1 Presence - absence occurrences (x indicates presence)

	Acila	Anomia	Cymbophora	Cymprima	I. ezoensis	I. naumanni	I. orientalis	Nucula	Nuculana	Ostrea	Parallelodon	Tellina	Thracin	Trigonia	Yoldia	Dentalium	Hemiastum	Acteonina	Gyrodes	Cirostrema	Cylichnida	Helcion	Hindsia	Solariella	Tessolarex	Vanikoropsis	Rhynchonella	Baculites	D. elongatum	D. otsukai	Damesite	Desmophy.	Diplomaceras	Epigoniceras	Gaudryceras	Glyptoxoceras	Hauericeras	Kitchinites	Mesopuzosia	Neophylloceras	P. binodo	P. buckhami	E. haradai	E. perplic.	Polyptych.	Ryugasella	Nautilus
GSC 69455			x	x	x	x						x	x	x		x				x										x						x											
GSC 69456				x		x						x	x	x				x		x																											
MCM 100					x	x	x	x								x							x					x	x							x	x							x			
MCM 101	x				x	x	x	x								x							x						x	x						x	x							x			
MCM 102	x	x			x	x	x	x	x		x	x				x								x		x		x	x	x					x	x	x				x						
MCM 103	x				x	x	x	x	x		x					x										x		x	x	x		x		x	x	x	x			x		x				x	x
MCM 104	x	x			x	x	x	x			x					x				x									x	x				x	x	x	x						x				
MCM 112	x	x			x	x		x																				x			x	x		x			x	x						x		x	
MCM 106	x	x			x	x		x								x					x			x				x	x			x		x	x	x	x	x		x				x	x	x	
MCM 107		x	x		x	x		x								x						x	x					x	x							x	x							x		x	
MCM 108	x				x	x	x	x	x		x				x	x									x	x		x					x	x		x			x					x			
MCM 109	x				x	x		x	x		x				x	x	x						x		x				x								x		x					x			
MCM 157					x	x	x	x	x						x													x	x							x	x		x					x			x
MCM 114					x	x	x	x				x										x	x	x					x							x	x						x				x
MCM 116			x		x		x	x				x	x	x		x										x			x							x											
MCM 121'			x	x	x	x	x			x		x	x	x	x	x		x	x				x	x												x											x
MCM 120			x	x	x	x					x	x	x	x		x		x	x					x		x			x							x	x										
MCM 122	x				x	x	x	x			x	x				x			x				x			x			x	x						x						x					
MCM 123	x				x	x	x	x	x						x	x			x				x	x		x			x							x						x					

TABLE 6.1 (Continued)

	Acila	Anomia	Cymbophora	Cymprima	I. ezoensis	I. naumanni	I. orientalis	Nucula	Nuculana	Ostrea	Parallelodon	Tellina	Thracin	Trigonia	Yoldia	Dentalium	Hemiastum	Acteonina	Gyrodes	Cirostrema	Cylichnida	Helcion	Hindsia	Solariella	Tessolarex	Vanikoropsis	Rhynchonella	Baculites	D. elongatum	D. otsukai	Damesite	Desmophy.	Diplomaceras	Epigoniceras	Gaudryceras	Glyptoxoceras	Hauericeras	Kitchinites	Mesopuzosia	Neophylloceras	P. binodo	P. buckhami	E. haradai	E. perplic.	Polyptych.	Ryugasella	Nautilus
MCM 124	x				x	x	x	x	x		x				x	x			x										x							x											x
MCM 125	x				x	x		x			x				x	x													x					x		x	x										
MCM 126		x			x	x	x	x								x					x								x							x										x	x
MCM 127					x	x	x	x													x								x	x				x		x											
MCM 128					x		x	x	x													x	x	x		x	x							x		x											
MCM 129		x			x	x		x																x					x							x	x							x		
MCM 130	x	x			x	x	x										x												x							x	x							x		
MCM 137	x				x	x	x	x																					x							x	x								x	
MCM 138	x				x	x	x	x																				x	x						x	x									x	
MCM 135					x	x	x	x									x					x							x							x	x					x	x				
MCM 158	x				x	x	x	x			x					x	x												x							x							x				
MCM 136	x	x	x			x	x	x									x											x								x	x								x		
MCM 159		x			x	x	x	x								x	x			x				x					x							x											
MCM 160					x	x	x	x									x			x									x							x											
GSC 77383			x	x	x	x		x		x		x	x	x		x			x	x	x			x		x										x		x									

TABLE 6.2 Percent Morphotype Occurrences.

	Orthocones	Torticones	Gyrocones	Ptychocones	Evolute - obese	Involute - obese	Pachydiscid	Compressed	Anomia	Small Inoceramus	Giant Inoceramus	Trigonia	Deposit-feeding clams	Suspension-feeding clams	Gastropods	TOTAL
MCM 100	.008	.040	.072	0	0	0	.065	.008	0	.75	.04	0	.008	0	.008	124
MCM 101	.032	.096	.032	0	0	0	.016	.016	0	.56	.096	0	.096	0	.048	62
MCM 102	.009	.019	.145	0	.009	.02	.01	.02	.05	.479	.117	0	.08	.03	.029	103
MCM 103	.012	.113	.069	0	.013	.025	.006	.031	0	.547	.031	0	.120	.02	.018	159
MCM 104	0	.138	.063	0	.005	.037	.052	.023	.011	.41	.196	0	.02	.003	.017	173
MCM 112	.07	0	0	0	0	.03	.04	.03	.50	.25	.01	0	.04	0	.04	100
MCM 106	.056	0	.002	.1	.002	.006	.020	.018	.55	.228	.002	0	.006	0	.028	500
MCM 107	.061	.02	.01	0	0	0	.01	.005	.595	.269	.015	0	.026	0	.020	193
MCM 108	.152	.011	.045	.002	0	.011	.028	.022	0	.224	.073	0	.370	.008	.056	177
MCM 157	.035	.007	.154	0	0	0	.034	.021	0	.467	.028	0	.168	0	.014	143
MCM 113	.020	.065	.137	0	.007	.007	.021	.026	.007	.60	.060	0	.06	0	.014	190
MCM 114	0	.036	.09	0	0	0	.018	.018	0	.508	.127	0	.145	0	.054	55
MCM 116	0	.018	.027	0	0	0	0	0	0	0	.675	.129	.005	.119	.027	108
MCM 120	0	.017	.017	0	0	0	0	.009	.009	.026	.474	.086	.006	.175	.163	116
MCM 119	0	.04	.03	0	0	0	0	0	.03	.14	.10	.03	.03	.33	.21	103
MCM 121	0	0	.01	0	0	0	0	0	0	0	.05	.13	.03	.70	.09	110
MCM 122	0	.138	.053	0	0	0	.053	0	0	.136	.106	0	0	.39	.106	126
MCM 123	0	.025	.040	0	0	0	.005	0	0	.060	.091	0	.020	.39	.127	197

TABLE 6.2 (continued)

	Orthocones	Torticones	Gyrocones	Ptychocones	Evolute - obese	Involute - obese	Pachydiscid	Compressed	Anomia	Small Inoceramus	Giant Inoceramus	Trigonia	Deposit-feeding clams	Suspension-feeding clams	Gastropods	TOTAL
MCM 124	0	0	.027	0	0	0	0	.037	0	.249	.083	0	.300	.10	.120	108
MCM 125	0	.045	.081	0	0	.009	0	0	0	.081	.063	0	.35	.10	.171	111
MCM 126	.04	.08	.08	0	0	0	0	0	.26	.28	.04	0	.14	0	.01	50
MCM 127	0	.055	.095	0	0	.01	0	0	0	.756	.030	0	.04	0	.01	198
MCM 128	0	0	.089	0	0	.012	0	0	.009	.397	0	0	.022	.020	.078	89
MCM 129	0	.008	.033	.050	0	0	0	.008	.206	.430	.033	0	.225	0	.01	121
MCM 130	0	.010	.010	.040	0	0	0	.010	.206	.380	.040	0	.170	.02	.13	100
MCM 137	.010	.010	.090	0	0	0	0	.010	0	.827	.020	0	.030	0	0	58
MCM 139	.122	.009	.052	0	.009	0	0	0	0	.72	0	0	.034	0	.017	101
MCM 135	0	.092	.118	0	0	0	.026	.131	0	.619	.065	0	.013	0	.092	76
MCM 158	0	.137	.086	0	0	0	0	0	0	.430	.086	0	.206	0	0	58
MCM 136	.060	0	.017	0	0	0	0	.009	.130	.121	.034	0	.626	0	0	115
MCM 159	0	.095	.059	0	0	0	0	0	0	.701	.047	0	.047	0	.036	84
MCM 160	0	.051	.076	0	0	0	0	0	0	.340	0	0	.38	.03	.01	96
GSC 77383	0	0	.02	0	0	.01	0	0	0	.046	.10	.09	.03	.74	.10	90
																4,194

	B. bailyi	D. otsukai	D. elongatum	Damesites	Desmophy.	Diplomaceras	Epigoniceras	Gaudryceras	Glyptoxoceras	Hauericeras	Kitchinites	Mesopuzosia	Neophylloceras	P. binodo	P. buckhami	E. haradai	E. perplicatum	Polyptychoceras	Ryugasella	Eutrephoceras	
MCM 100	.024	.024	.073	0	0	0	0	0	.292	.048	0	0	0	0	.024	0	.536	0	0	0	41
MCM 101	.08	.12	.16	0	.04	0	0	0	.28	.24	0	0	.04	0	0	0	.04	0	0	0	25
MCM 102a	0	0	.11	0	0	0	.055	0	.55	.055	0	0	0	.055	0	0	.166	0	0	0	18
MCM 103	.025	.051	.41	0	.026	0	.076	.026	.282	.075	0	0	.026	0	.026	0	0	0	.026	.026	40
MCM 104	0	.017	.42	0	.035	0	.052	.017	.192	.070	0	0	.035	0	0	.158	0	0	0	0	57
MCM 112	.29	0	0	.059	.059	0	.059	0	0	.176	.059	0	.059	0	0	0	.117	0	.117	0	17
MCM 106	.027	0	.016	.005	.005	0	.022	0	.011	.005	.011	0	.005	.005	0	0	.065	.60	.148	0	183
MCM 107	.478	0	.17	0	0	0	0	0	.043	.08	0	0	0	0	0	0	.173	0	.043	0	23
MCM 108	.418	.016	.016	0	0	.029	.029	0	.134	.089	0	.029	0	0	0	0	.194	0	0	0	67
MCM 157	.138	0	.027	0	0	0	0	0	.61	0	0	.027	0	0	0	0	.138	0	0	0	36
MCM 114	0	0	.27	0	0	0	0	0	.45	.09	0	0	0	0	0	0	.09	0	0	0	11
MCM 113	0	0	.22	0	0	0	.037	.037	.415	.151	0	0	0	0	0	0	.057	0	.075	0	53
MCM 122	0	.023	.336	0	0	0	0	0	.166	.023	0	0	0	0	.143	0	0	0	0	.046	42
MCM 123	0	.064	.612	0	0	0	0	0	.1	.1	0	0	0	0	.1	0	0	0	0	.03	31
MCM 124	0	.077	.29	.015	0	0	.015	0	.54	.061	0	0	0	0	0	0	0	0	0	.015	65
MCM 125	0	0	.26	0	0	0	.05	0	.47	.21	0	0	0	0	0	0	0	0	0	0	19
MCM 127	0	0	.35	.02	0	0	0	0	.54	0	0	0	0	0	0	0	0	0	0	0	27
MCM 130	0	0	.11	0	0	0	0	0	.28	.11	0	0	0	0	0	0	0	.50	0	0	18
MCM 158	0	0	.625	0	0	0	0	0	.312	0	0	0	0	0	0	.061	0	0	0	0	16
MCM 135	.02	.02	.387	0	0	0	0	0	.367	.041	0	0	0	0	.102	.061	0	0	0	0	49
MCM 139	.54	0	.04	0	0	0	0	.04	.33	0	0	0	0	0	0	0	0	0	.04	0	24
MCM 137	0	0	.083	0	0	0	0	0	.75	.083	0	0	0	0	0	0	0	0	.083	0	12
MCM 160	0	0	.60	0	0	0	0	0	.40	0	0	0	0	0	0	0	0	0	0	0	28
MCM 102b	.03	0	.125	0	0	0	0	.03	.53	.094	0	0	0	0	0	0	.187	0	0	0	32
																					810

TABLE 6.3 Percent ammonite occurrences.

Table 6. 2 lists the proportion of ammonite morphotypes (orthocones, gyrocones, torticones, pachydiscids, evolute obese forms, involute obese forms, hamitids and compressed forms), bivalve feeding types (infaunal suspension feeders, infaunal deposit feeders), inocerami by size, gastropods and anomiids. Each of these variables represents a proportion of the total fauna collected from the localities. To approximate normality of the variables for each locality, a requisite of all multivariate analyses, the listed percentages have been transformed with the expression

$$X_{ab} = \arcsin \sqrt{Y_{ab}}$$

where Y_{ab} is the proportion of the a_{th} species from the b_{th} locality. This transformation has been used to transform the binomial distributions inherent in many biological populations to normality by Goodall (1954), Cassie and Michael (1968), and has been discussed in detail with regard to paleoecologic applications by Buzas (1972).

Table 6 .3 lists the percentage of each Elongatum Zone ammonite species from Nanaimo Group localities. These data were compiled by recording the numbers of specimens at the University of Washington, University of British Columbia, and Geological Survey of Canada in Ottawa collections from localities which are equivalent to McMaster localities recorded in Table 3.2 , Chapter 3. Only those localities with sufficient geographic and stratigraphic control to allow close identity with McMaster collections were utilized. These data were transformed as in Table 6 .2 above.

6.5 Statistical Methods

The association of fossil occurrences as models of paleocommunities, and the differentiation of biofacies have been the frequent goals of numerous paleoecological studies in recent years: Buzas (1972) lists a history of past studies. Most have relied on some form of multivariate statistical techniques, the most frequent being principal components analysis, factor analysis, ordination and the family of cluster analyses.

Relative advantages and disadvantages of each method are discussed in Sokal and Sneath (1973) and Valentine (1973). Because cluster analyses have the advantage of a compact, two-dimensional visualization of the cladistic or ecologic relationships with the phenogram, and of discriminating slightly dissimilar variables (Rohlf, 1972), the technique has been used here.

Sokal and Sneath (1970) have discussed the various types of clustering techniques available. In most ecologic and paleoecological studies to date, either weighted pair group method (WPGM) or unweighted pair group method (UPGM) agglomerative techniques have been utilized. Advantages of each are discussed by Sokal and Sneath (1970), Hazel (1970) and Valentine (1973). Recently, derivation of the cophenetic correlation coefficient (Sokal and Rohlf, 1962) and its analysis with artificial data (Farris, 1969; Rohlf, 1970) has shown that the UPGM yields clusters with less information loss than WPGM. Consequently, the UPGM has been utilized here.

The analyses were performed at the Rochester University Computing Center, using the NT-SYS system of multivariate programs. The data from Table 6 .1 was associated with Jaccards Coefficient; Tables 6 .2 and 6 .3 with the Cosine θ coefficient.

6.6 Data Analyses

The data from Tables 6 .1 - 6 .3 have been analyzed in several ways. Figure 6.6.1 plots the number of ammonite species (lower graph) and total number of species, including ammonites (upper graph) of Table 6 .1 for each locality. Localities are arranged in the order of their geographic position from north to south in the Nanaimo Group; localities 1 - 14 are from the Comox Basin, and 15 - 35 from the Nanaimo Basin. Since sample sizes from each locality are approximately equal, rarefaction effects on diversity (Sanders, 1968) should be neutralized.

A general trend of decreasing numbers in both ammonite species and total taxa is suggested from north to south. Among the ammonites differences in species numbers are more pronounced than among non-ammonites, especially if non-ammonite facies localities (1, 2, 15, 16, 17) are excluded. The mean number of ammonite species present in the northern localities, exclusive of localities 1 and 2, is 6.8; for the southern ammonitiferous localities, the mean is 3.4. Computation of Students T-statistic (t = -5.2695) rejects the hypothesis $\overline{X}_N = \overline{X}_S$ at 99% confidence interval.

6.6.1 Cluster Analyses

The Q-mode (localities) and R-mode (faunal variables) phenograms of each analysis have been grouped together in two-way phenograms

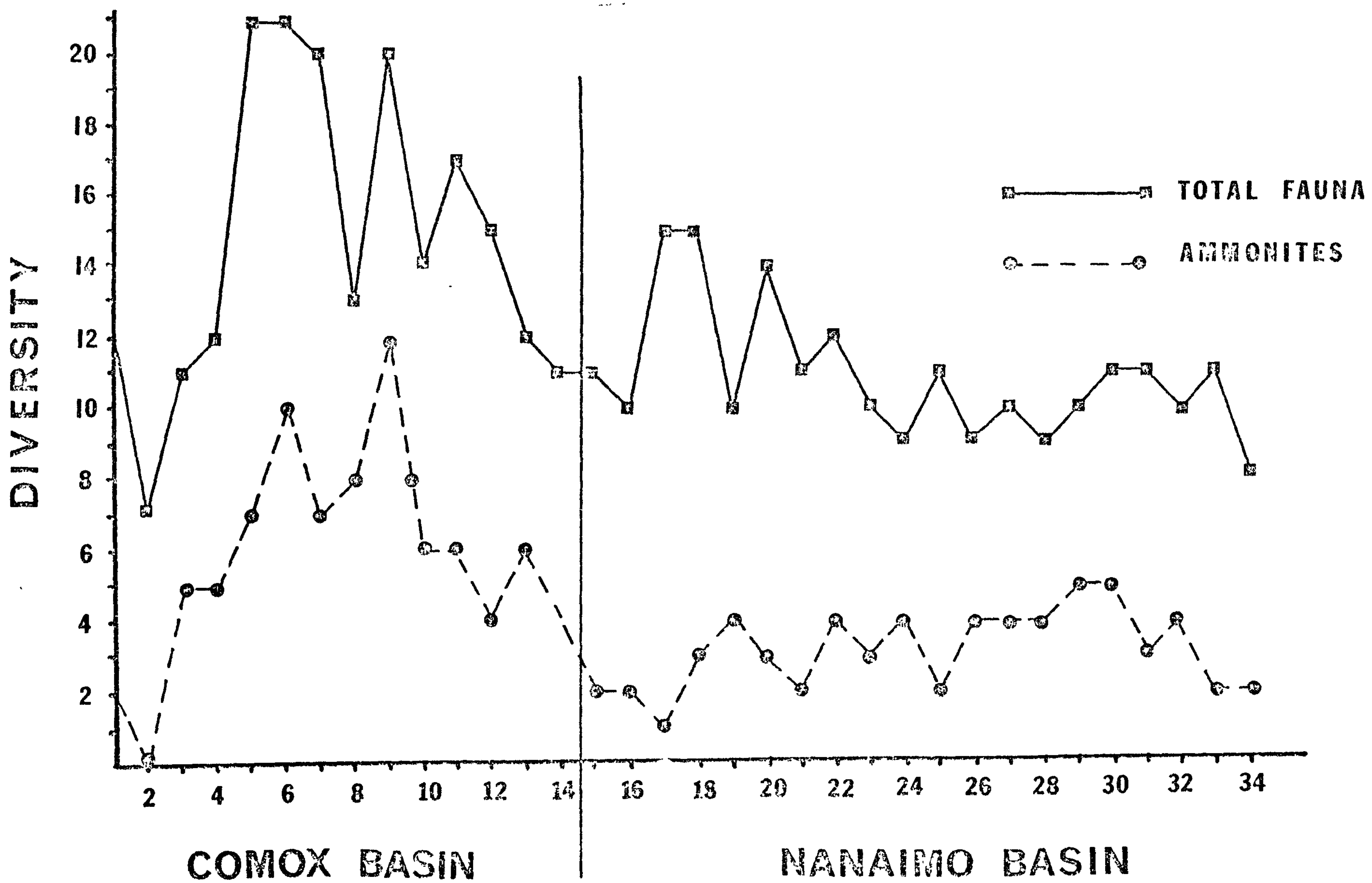


FIGURE 6.6.1. Molluscan Diversity, Nanaimo and Comox Basins.

following the method of Sepkoski and Rex (1974). This graphical method allows simultaneous presentation and intercorrelation of the Q and R mode clusters.

The result of the cluster analyses with the presence-absence data of Table 6 .1 is shown in Figure 6.6.2.

Three major clusters of localities are differentiated in the Q-mode dendogram. Cluster 1 is apparently discriminated from clusters 2 and 3 because of the presence of epifaunal bivalves.

Cluster 2 is comprised of infaunal bivalves and a nearly ubiquitous inoceram -heteromorph ammonite assemblage. This group can be further divided into two sub-groups: cluster 2a, comprised mainly of localities from the Nanaimo Basin (the northern depositional area of the Nanaimo Group), and cluster 2b, mainly northern localities.

Cluster 3 is apparently differentiated on the presence of a number of rare ammonite species, and absence of the zonal index species Glyptoxoceras subcompressum and Inoceramus orientalis. Although represented by only two localities in this phenogram, this group is readily differentiable in the field by distinct lithological and faunal features. Several other localities also belong to this group in my opinion (McM 129, 130, 107), but have been placed in Cluster 2 by the program. The characteristic feature of this biofacies is an abundance of Anomia.

Figure 6.6.3 illustrates a two-way cluster analysis of 33 localities and 15 morphotypes. The groups are numbered as in Figure 6.1.2, with correlative groupings receiving the same number. Cluster 1 is defined as those localities with a high proportion of trigonnids and infaunal suspension-feeding bivalves.

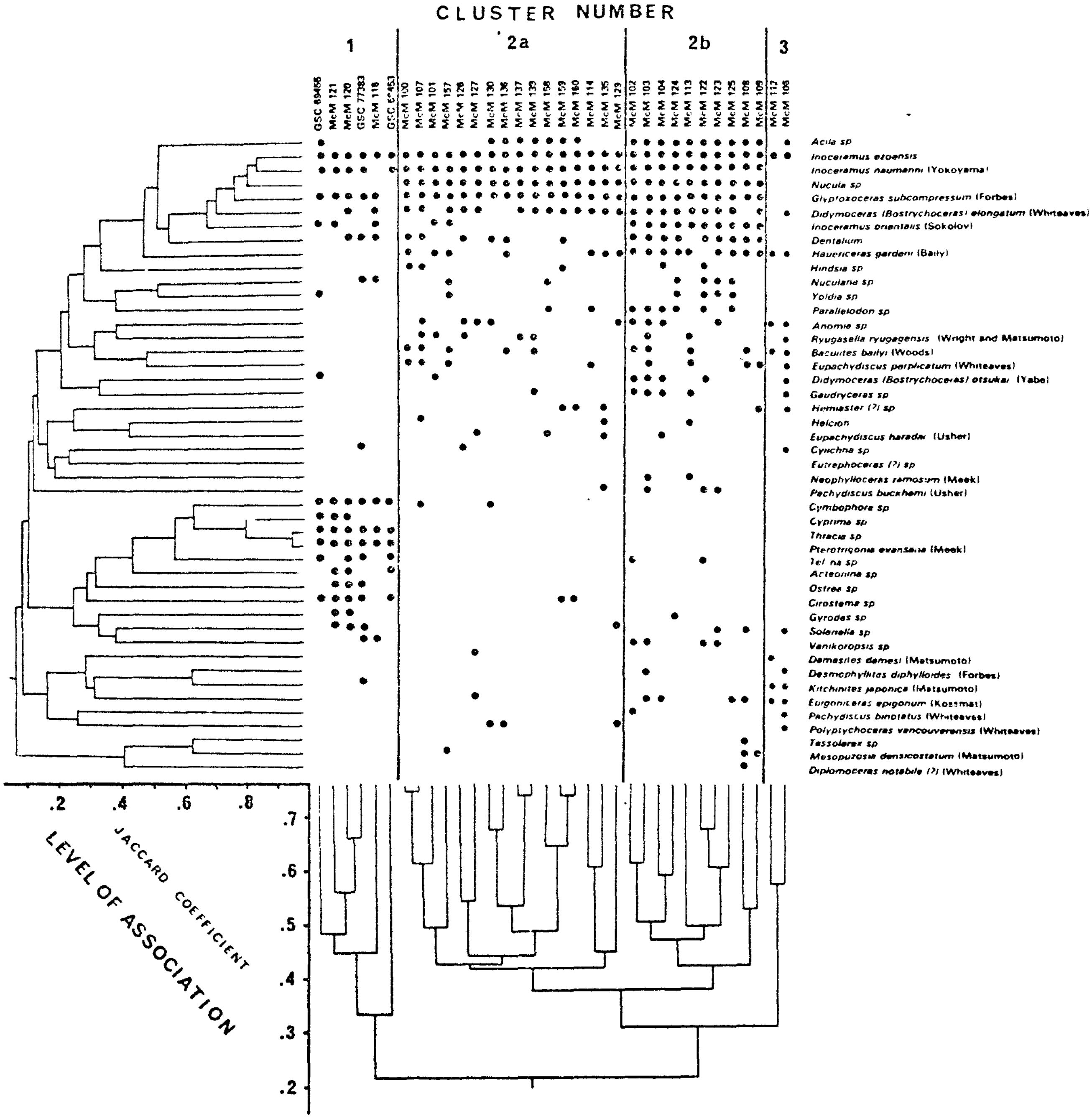


FIGURE 6.6.2. Two-way phenogram, based on presence-absence data.

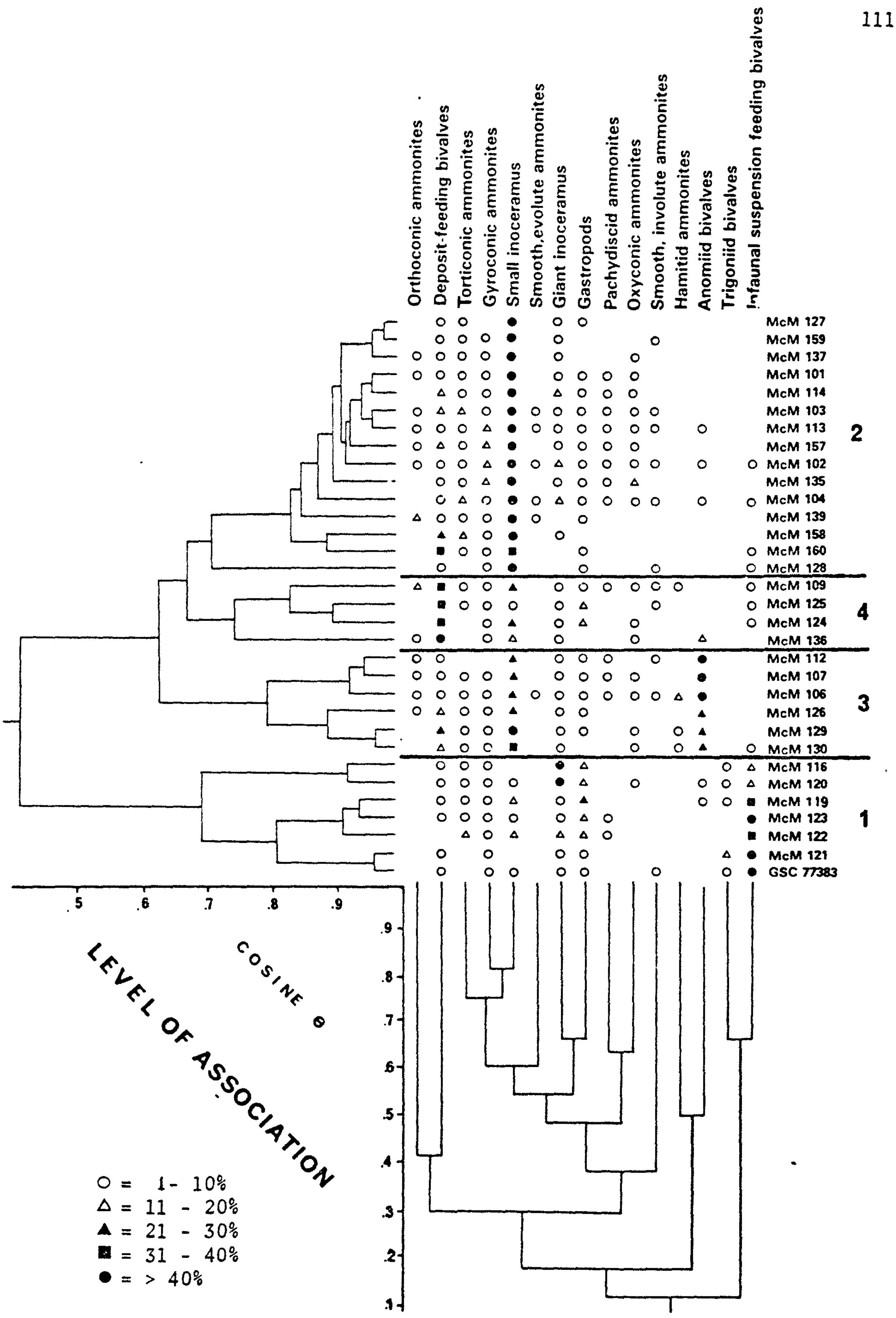


FIGURE 6.6.3. Two-way phenogram, based on percentages of morphotypes.

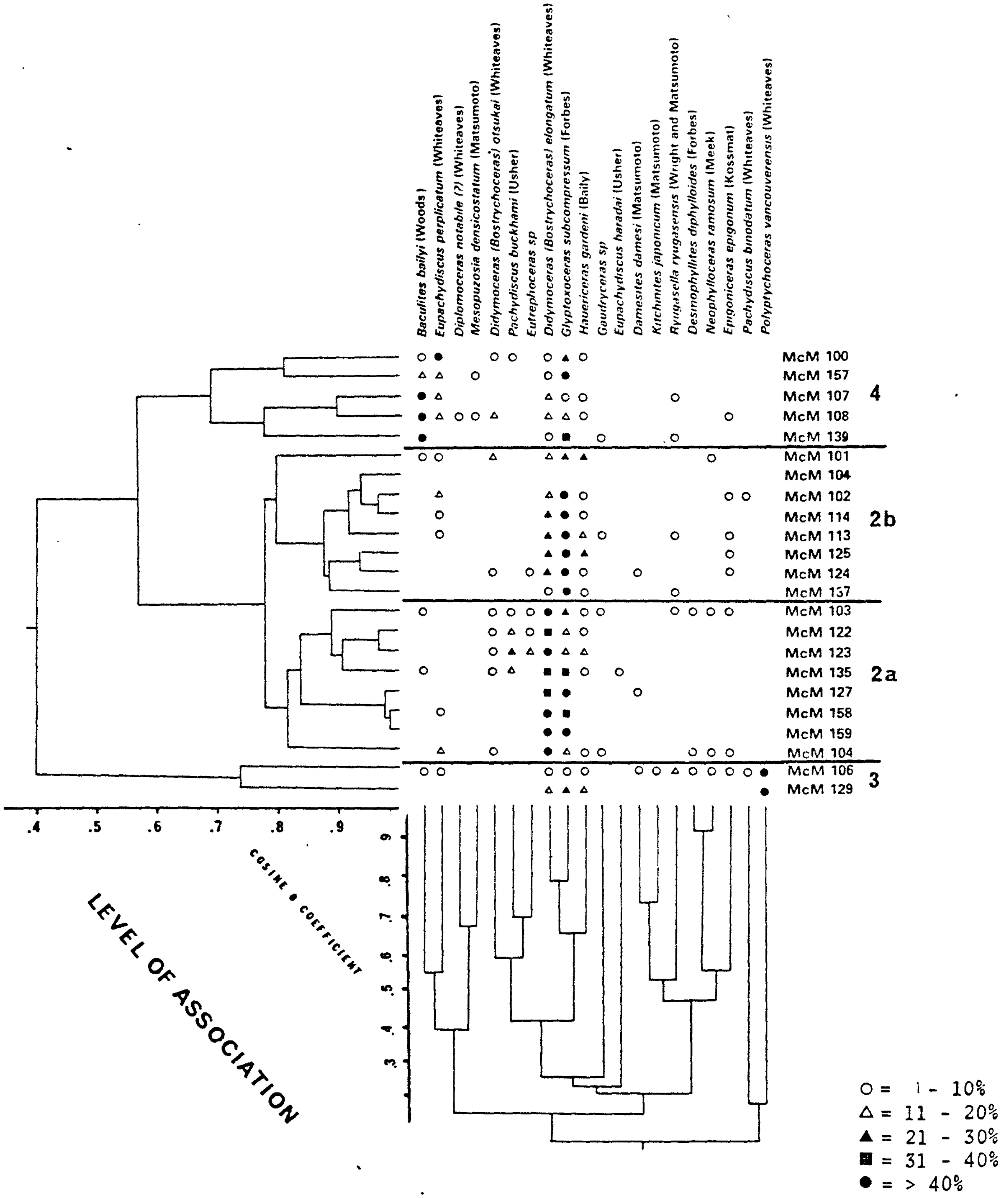


FIGURE 6.6.4. Two-way phenogram, based on percentages of ammonite species.

Group 2 is dominated by torticones (*Didymoceras (Bostrychoceras) elongatum* and *D. (B.) otsukai*), gyrocones (*Glyptoxoceras subcompressum*), small inocerami (*I. naumanni*, *I. orientalis*), and large inocerami (*I. ezoensis*). Also present are significant percentages of pachydiscids (*Eupachydiscus perplicatum*, *E. haradai*), compressed ammonites (*Hauericeras gardeni* , involute ammonites (*Desmophyllites diphylloides*, *Epigoniceras epigonum*, *Neophylloceras ramosum*, *Damesites damesi*), and evolute ammonites (*Gaudyceras* sp. indet.) .

Group 3, comprised of *Anomia*-dominant localities, is equivalent to the same numbered group in Figure 6.1.2, but contains more localities.

Group 4, dominated by infaunal deposit-feeding bivalves, was not differentiated by the presence-absence analysis. Orthoconic ammonites (mainly *Baculites bailyi*) and pachydiscids are also common at these localities.

The final two-way cluster analysis (Figure 6.6.4) utilized fewer localities than the others and also utilized samples of previous collectors. For this analysis, only "ammonitiferous" horizons were sampled, since sandstone facies contained too few ammonites for meaningful analysis.

Since the three major clusters can be related to the groupings of the presence-absence and morphotype phenograms, they have been numbered to correspond with their analogues in the previous analyses.

No analogue of Cluster 1 is present.

Cluster 2 contains the largest number of localities and species and, as in Figure 6.6.2, can be subdivided into subclusters comprised of Comox Basin and Nanaimo Basin localities.

Cluster 3 separates the Polyptychoceras vancouverensis grouping, which is restricted to Anomia localities.

Cluster 4 corresponds with the same numbered cluster of Figure 6.6.3. Dominants include Baculites bailyi and Eupachydiscus perplicatum.

6.7 Correlation of Lithology and Localities

From field observations, the localities in this study can be characterized by one of the following lithofacies:

1. Sandstones, coarse to finely-grained, sorting usually poor, with high clay fraction. Bedding is usually poorly defined, and numerous burrow marks suggest concentrated bioturbation. Colours vary from light grey to olive green. Fossils, mainly thick-shelled gastropods and pelecypods, are generally abundant.
2. Siltstone, high clay fraction, sorting poor. Bedding is usually massive. Concretions may or may not be present. Colour is usually dark grey to olive. Fossils common.
3. Shales, slightly calcareous, with fine sand occasionally disseminated throughout. Bedding is generally massive. Sandstone interbeds and/or concretionary layers often present. Sandstone dykes extremely common. Fossils common to rare.
4. Same as 3), but without sandstone dykes.
5. Distal turbidites, thinnly bedded, composed of Bouma CD and CE divisions. Sand-shale ratios generally .3 - .6, bed thicknesses range between 2 - 20 cm. Fossils common to rare.

6. Shales, with numerous concretions packed with Anomia shells. Shales massive, interbedded with sandstone layers and concretionary layers.

The categorization of localities used in this study with lithotypes and cluster designation from the three cluster analyses is shown in Table 6.7.1. Also included is the geographic position of the locality (either C, for the northern Comox Basin, or N, for the southern Nanaimo Basin).

6.8 Discussion

The cluster analyses based on percentage data (Figure 6.6.3, 6.6.4) showed greater fidelity with field observations in terms of overall biofacies patterns than did the presence-absence analyses; as would be expected, however, the latter were poorer in separating out diversity-related groupings of the northern and southern basins of deposition.

One of the striking features of Figure 6.6.1 is the nearly ubiquitous occurrence of Inoceramus naumanni, I. orientalis, I. ezoensis, Nucula sp., Didymoceras elongatum and Glyptoxoceras subcompressum. These species are present at nearly every locality, regardless of lithofacies. Figure 6.6.2 demonstrates, however, that these species are present in widely varying numbers.

Significant differences are apparent between the Comox and Nanaimo Basin assemblages in terms of diversity, faunal makeup and lithofacies. Sanders (1969) has suggested that habitat stability is one of the prime controlling factors on diversity. Within the Georgian Basin, shown to be a rapidly-filled "successor basin" by Eisbacher (1973),

TABLE 6.7.1

Locality	Lithotope	Cluster, Fig. 6.6.2	Cluster, Fig. 6.6.3	Cluster, Fig. 6.6.4	Basin N=Nanaimo, C=Comox
McM 100	3	2a	--	--	C
McM 101	3	2a	2	2b	C
McM 102	3	2b	2	2b	C
McM 103	3	2b	2	2a	C
McM 104	3	2b	2	2a	C
McM 106	6	3	3	3	C
McM 107	6	2b	3	4	C
McM 108	2	2b	--	4	C
McM 109	2	2b	4	--	C
McM 112	6	3	3	--	C
McM 113	3	2b	2	2b	C
McM 114	3	2a	2	2b	C
McM 116	1	1	1	--	N
McM 120	1	1	1	--	N
McM 121	1	1	1	--	N
McM 122	2	2b	1	2a	N
McM 123	2	2b	1	2a	N
McM 124	2	2b	4	2b	N
McM 125	2	2b	4	2b	N
McM 126	6	2a	3	--	N
McM 127	4	2a	2	2a	N
McM 129	6	2a	3	3	N
McM 130	6	2a	3	--	N
McM 135	4	2a	2	2a	N
McM 136	5	2a	4	--	N
McM 137	5	2a	2	4	N
McM 139	5	2a	2	2b	N
McM 157	3	2a	2	4	C
McM 158	4	2a	2	2a	N
McM 159	4	2a	2	2a	N
McM 160	5	2a	2	--	N
GSC69455	1	1	--	--	C
GSC77383	1	1	1	--	N
GSC69453	1	1	2	--	C

between-habitat differences could be expected from variations in salinity, oxygen content, and probably most importantly, sedimentation type and rates. The comparatively low diversity of Elongatum Zone faunas compared to other Cretaceous invertebrate faunas (cf. Kauffman, 1967; Scott, 1975) could, in part, be due to a low level of dissolved oxygen, as fossils in both the northern and southern siltstone and shale lithotopes show sulphide mineralization. It seems unlikely, however, that dissolved oxygen level differences between basins could completely account for the observed diversity differences.

Two sedimentological differences are present between the Comox and Nanaimo Basins. The Haslam Formation siltstones and shales of the Comox Basin are dissected by numerous sandstone dykes, which are absent at all examined Nanaimo Basin localities. These dykes average from several centimeters to at most a meter in thickness; some can be traced for tens of meters up the walls of river cut exposures. Most are at angles to bedding, and intersection with other dykes is extremely common. Dyke lithology includes fine to coarse, poorly-sorted sandstones. Several dykes on Puntlege River contained numerous thick-shelled bivalves. Mechanisms of sandstone-dyke formations have been discussed by Dzulynski and Walton (1965) and Blatt, Middleton and Murray (1972). Liquifaction of sand, overlain by consolidated muds, was apparently common in the Comox Basin, but relatively rare to the south.

Rates of sedimentation may also have been different.

Similar successions of subzonal indices are present in the northern and southern depositional basins, but in greatly differing thicknesses. On the average, the Elongatum Zone is twice to three times as thick in the Nanaimo Basin as in the Comox Basin, even between sections with grossly similar lithologies. Turbidites, restricted during the Elongatum Zone time to the southern basin, show even greater stratal thicknesses.

6.8.1 Faunal Associations

From field observations and the data interpretation presented above, the following faunal associations are indicated:

1. *Pterotrigonia evansana* Association.

This faunal association is comprised of infaunal suspension-feeding bivalves followed in numerical importance by gastropods, deposit-feeding bivalves, epifaunal suspension feeders and ammonites. The latter are usually extremely rare or absent. Overall fossil density is very high.

The lithology present at all of the localities with this association is equivalent to lithologies 1 to 3 of Kauffman (1967); while faunal association H (ibid) appears similar in faunal composition. This assemblage was considered to have inhabited a near-shore environment of medium to high energy. Modern analogues include sandy and silty upper shelf communities at depths usually not exceeding 15 m.

Rhoads, Speden and Waage (1972) differentiated a number of Cretaceous marine invertebrate associations based on trophic groupings; the Nanaimo Group *Pterotrigonia* assemblage appears to correspond with their *Tancredia-Ophiomorpha* assemblage, comprised of infaunal suspension feeders, and in part to the Lower Timber Lake Member assemblage, comprised of a mixture of deposit and suspension-feeding forms.

Saul (1960) discussed a number of faunal associations from the Upper Cretaceous section on Chico Creek, California. The Nanaimo Group *Pterotrigonia* association contains faunal elements common to three of Saul's associations: the *Gymnarus-Cymbophora* association, *Donax-semele* association and *Calva-Glycymeris* association. All three are dominated by infaunal suspension-feeding forms.

2. *Nucula* Association.

This faunal association is characterized by infaunal deposit-feeding bivalves, including *Nucula*, *Nuculana*, *Yoldia* and *Acila*. Other common constituents include *Inoceramus ezoensis*, *Baculites bailyi* and *Eupachydiscus perplicatum*. Characteristic lithologies are poorly-sorted siltstones with sandstone interbeds; fossil density is variable.

Lithologies and fauna of this association are similar to lithotope and faunal assemblage P of Kauffman (1967). This latter assemblage shows high diversity and lack of a single, numerically dominant taxon. In addition to deposit-feeders, common constituents include large, thin-shelled inocerami, and the heteromorph ammonite *Scaphites*. The entire assemblage was considered by Kauffman as a middle shelf assemblage inhabiting silt-muds in water depth of from 60 to 100 m, by analogy with the depth habitats of presently extant association members.

Assemblage P was observed to intergrade laterally with the more shallow equivalent of Elongatum Zone *Pterotrigionia* Association, Kauffman's assemblage H. A similar, intergradational relationship between the lithotopes and faunas of the *Pterotrigonia* and *Nucula* associations is observable in the Nanaimo Group.

The *Nucula* Association also shares faunal elements with the Trail City Member Association of Rhoads *et al* (1972). In this latter association, the presence of bivalves is correlated with periods of moderate to high sedimentation, with suspension-feeding bysally-attached pterioids and inoceramids feeding well off the bottom.

A third analogous Cretaceous association is the *Nucula-Nuculana* Community of Scott (1974). This association from the lower Cretaceous of Texas is dominated by protobranchs and shows high diversity but low density.

3. *Inoceramus* Assemblage.

The majority of sampled horizons contained an epifaunal suspension-feeding bivalve dominated association here termed the *Inoceramus* Assemblage. Ammonites are the second-most important faunal element, followed by deposit-feeding bivalves.

This assemblage shows diversity differences between the Comox and Nanaimo Basins, but appears trophically similar throughout the Nanaimo Group. The most marked diversity differences are among the ammonites, where common to rare species in the north are rare or absent in the south.

In both the north and south, *Glyptoxeras subcompressum* is the most common ammonite, followed in numbers by the torticonic forms *Didymoceras (Bostrychoceras)* spp. In the south, the third most common ammonites are the oxycones (*Hauericeras gardeni*), while in the north, various pachydiscid species usually rival the compressed forms in numbers. Several leiostracan species are rarely, but persistently present at most northern localities; these species are absent or virtually so in the south.

The lithologies containing the *Inoceramus* Assemblage are, in the Comox Basin, mainly shales with interbedded sandstone or siltstone beds and common sandstone dykes. In the Nanaimo Basin, the assemblage is present in shales without injection phenomena and in distal turbidites.

Generally, the proportion of ammonites to other taxa remains approximately constant throughout the Elongatum Zone, even though ammonites diversity drops markedly from north to south.

The *Inoceramus* Assemblage has parallels in the Cretaceous Western Interior. Assemblages Q, R and S of Kauffman (1967) are all from dark shale facies and, like the Nanaimo *Inoceramus* association, are dominated by inoceramid and ammonite species.

4. *Anomia* Association.

The last major faunal association, named after the most common faunal element, is dominated by the epifaunal suspension-feeding bivalve *Anomia vancouverensis*. Wherever present, this species by far outnumbers all other taxa.

The *Anomia* rarely occur as scattered valves in the shale; most commonly, they occur as shell concentrations in concretions. The concretions are mostly spherical to elongated ellipsoids in shape and are common in the shale layers. Most concretions bear several *Inoceramus naumanni* shells; since most *Anomia* shells within these concretions bear radial ornamentation matching the curvature of the inocerami ribs, it appears that the *Anomia* were attached to the inoceramids, and to each other. Other common constituents of these concretions are the heteromorph ammonites *Ryugasella ryugasensis* and *Polyptychoceras vancouverense*.

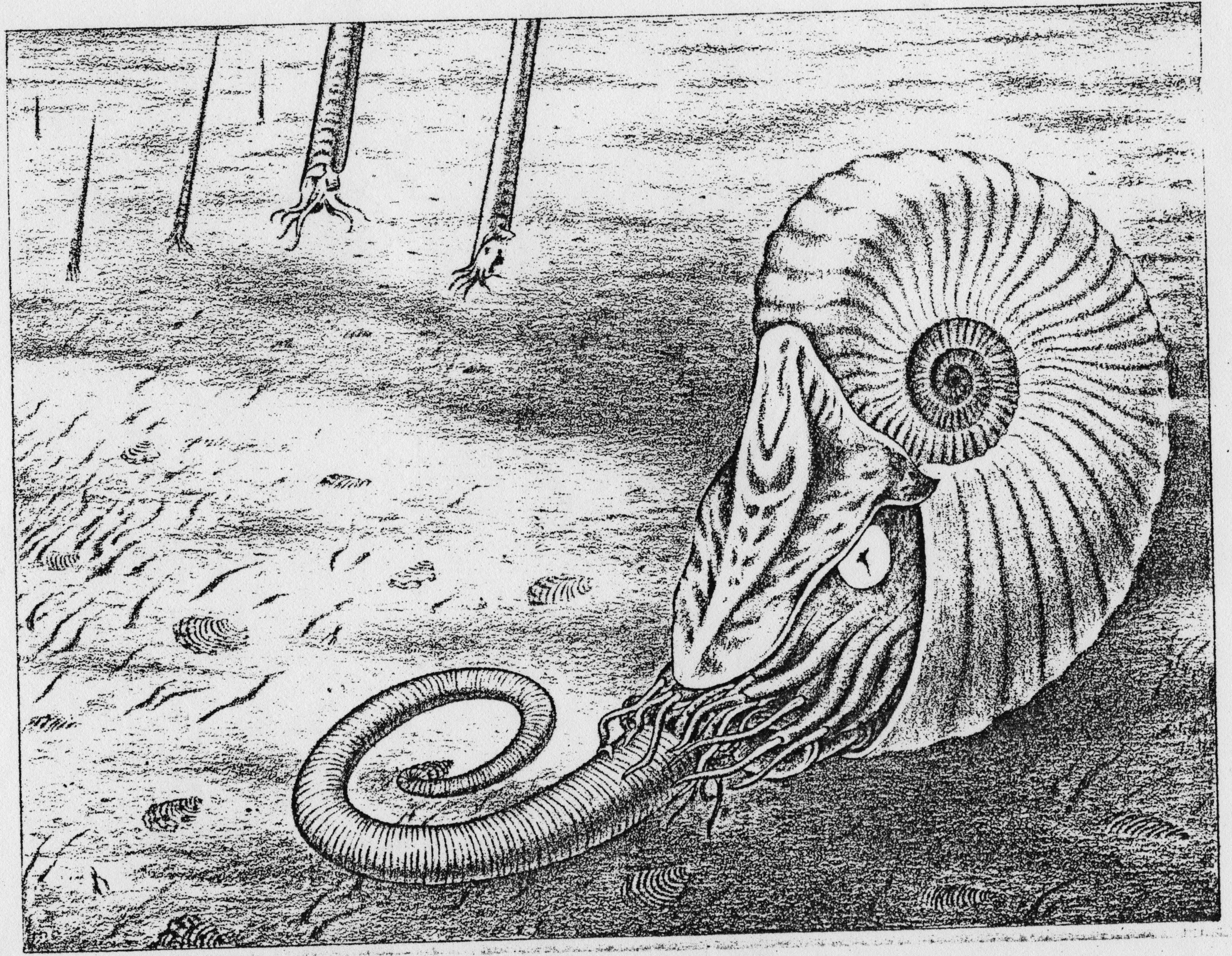


FIGURE 6.8.1. Artist's reconstruction of Nucula association. Eupachydiscus scavenging from Glyptoxoceras conch, Baculites in background

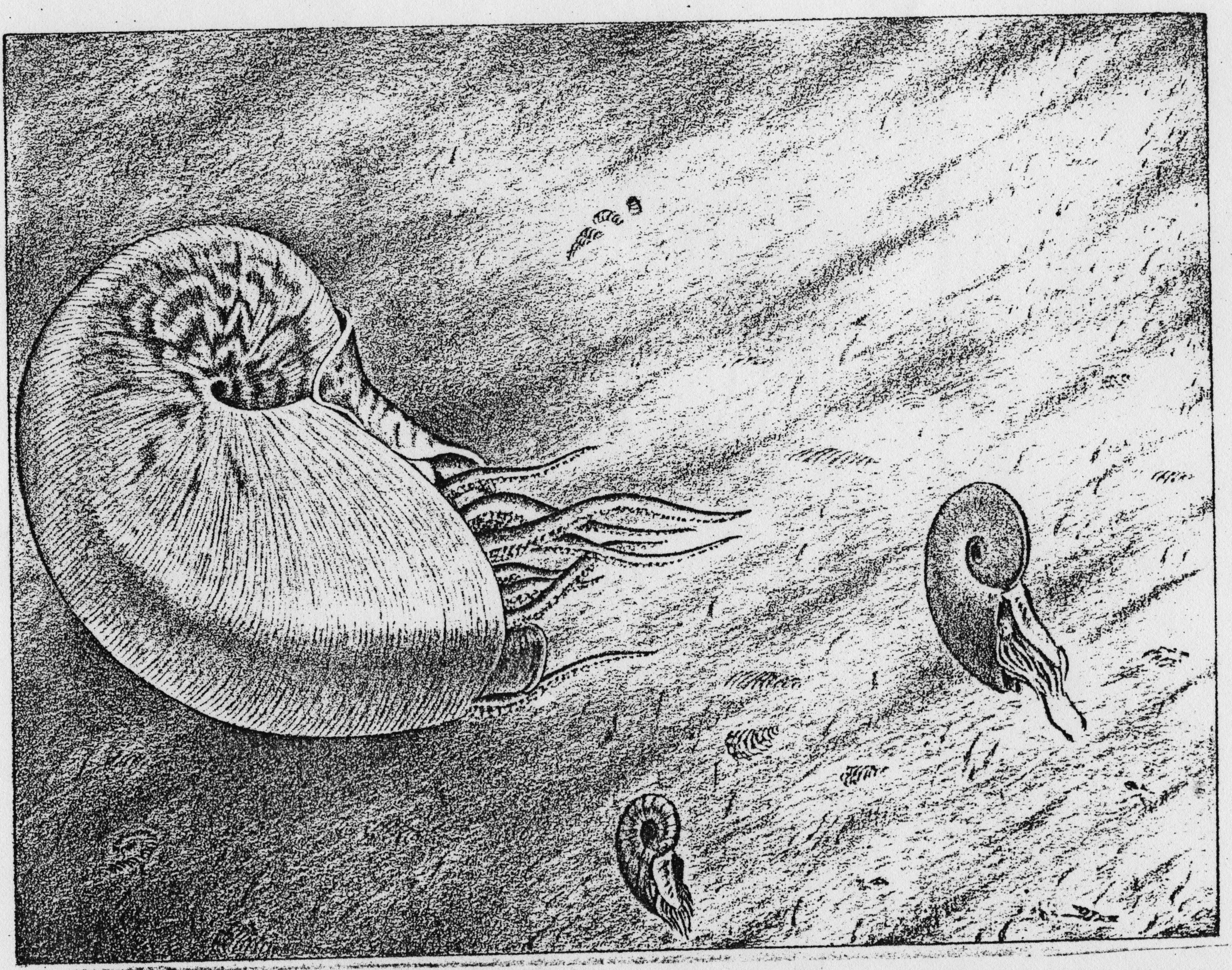


FIGURE 6.8.2. Artist's reconstruction of Inoceramus association, Comox Basin. Neophylloceras in foreground, Hauericeras, Desmophyllites below. Empty Didymoceras, Glyptoxoceras shells below.

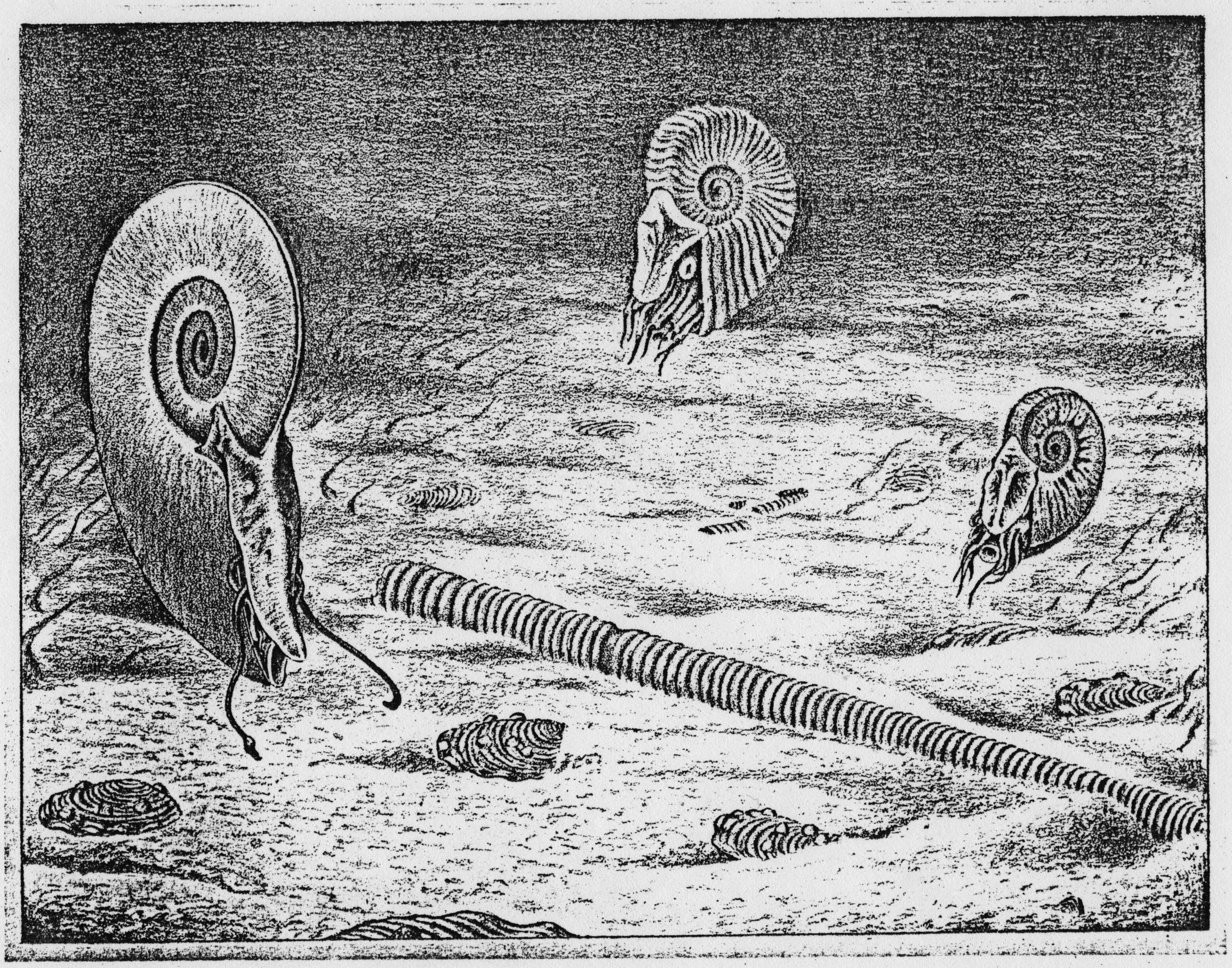


FIGURE6.8.3. Artist's reconstruction of Anomia association. <u>Hauericeras</u> in foreground,

The latter, a hamitid, is restricted to lithologies with the Anomia concretions, but appears free in the shale as well as in the concretions and is by far the most common ammonite at these horizons.

The evidence suggests that the inoceramids provided a settling place for the Anomia, which then completely covered the inocerami and themselves to form tiny, hard bioherms. The sediment between these Anomia concentrations was inhabited by rare deposit-feeding bivalves and gastropods.

Fossils in this facies are generally pyritized.

6.9 Summary

Four main faunal associations are differentiated on the bases of multivariate associative techniques and field observations. The Pterotrigonia Association is comprised mainly of infaunal suspension-feeding bivalves, with secondary numbers of gastropods and deposit-feeding bivalves. A nearshore, medium to high energy sand substrate is indicated.

The Nucula Association is comprised mainly of infaunal deposit feeders, with subordinate numbers of epifaunal suspension-feeding bivalves (mainly inoceramids) and ammonites. The association is associated with poorly-sorted, highly-bioturbated siltstones suggestive of a mid-shelf environment.

The Inoceramus Association is dominated by both small and very large epifaunal suspension-feeding inoceramids and shows the highest numbers of ammonites. Strata enclosing this association are generally shales. An outer shelf depth is indicated.

The *Anomia* Association is dominated by the epifaunal suspension-feeding bivalve *Anomia*, which occurs as shell concentrations in concretions and attached to inoceramids. The ammonite *Polyptychoceras vancouverense* is restricted to this association. The fine shales and presence of deposit-feeding forms suggests a mid- to outer shelf depositional environment.

Diversity differences in overall fauna and, especially, ammonites are related to sedimentological differences between the northern and southern Nanaimo Group depositional basins. In the northern area, the Comox Basin, high diversities may be related to lower rates of sedimentation.

Parallels between these associations and faunal groupings of the Cretaceous Western Interior can be noted. Major differences are also present. The Nanaimo Group has no development of *Ostrea*, *Gryphaea*, scleractinian coral or rudistid associations. Among the ammonites, no scaphitids or sphenodiscids are present. There is also little epifaunal development of bryozoans, serpulids and hydrozoans, which commonly encrust large mollusk shells, even though large inocerami are very common in the Nanaimo Group.

CHAPTER 7

VOLUMES AND LIVING POSITIONS OF NANAIMO HETEROMORPH AMMONITES

7.1 Introduction

Recent work on the extant Nautilus, Spirula and Sepia by Denton and Gilpin Brown (1961a-d, 1966, 1971) has demonstrated that these genera use their chambered shells to maintain neutral or near-neutral buoyancy in the sea, and that buoyancy and living orientation can, so some extent, be regulated by the admission or removal of liquid in the chambers of the shell.

It has been suggested that the ammonoids were probably approximately neutrally buoyant and may have controlled their buoyancy in ways similar to the extant chambered cephalopods. Trueman (1941) derived equations for the ammonid shell and body volume and weight, and computed these values for a number of Mesozoic ammonites, finding near neutral buoyancy in each case; life orientations for both planispiral and a number of heteromorphic species were also estimated. Currie (1957) in similar fashion estimated volumes and specific gravities of several goniatites. Raup and Chamberlain (1968) calculated volumes for planispiral shells with expressions for volume and centre of gravity, based on the equations first proposed by Mosely (1838). Heptonstall (1970) revised several of Trueman's density estimates by substituting new values for the specific gravity of the ammonite test and soft parts, based on studies by Reyment (1958) and Denton and Gilpin Brown (1966), and by revising the equation for the volume of the body chamber. Tanabe (1975) analyzed the volumes and specific gravity of Otoscaphites, alleging that certain ontogenetic stages were negatively buoyant and hence benthonic. This work is critically examined below. Ward and Westermann (in press) made estimates of the volume and specific gravity of the aberrantly coiled Nipponites and concluded that the living organism was capable of a nektonic or planktonic existence.

In this chapter, I present estimated volumes, specific gravities and living orientations of six heteromorph species from the Nanaimo Group. A variety of volume measures are used, including empirical estimates, direct measurements from well-preserved fossil material, and volume measurements from models of specimens. A new technique of modelling ammonite shells using materials simulating the specific gravities of the phragmocone and body chamber of the living animals is introduced. Using this technique, the adult living positions, and change in orientation during growth can be simulated.

7.2 Fossil Material

The following heteromorph species from the Nanaimo Group were measured for volume and density:

Family Diplomoceratidae

Glyptoxoceras subcompressum (Forbes). The conch of this species is an elliptically coiled gyrocone with torticonic early whorls. Its morphology has most recently been described in detail by Ward (1976). An additional morphologic characteristic now recognized is the presence of an orthoconic stage immediately following the protoconch, which is enclosed by the following torticonic section. (See Plate 7.1, Fig.2)

This species is the most commonly preserved ammonite of the Elongatum Zone, was nearly world-wide in distribution and ranged from the Santonian to the late Maestrichtian.

Ryugassela ryugasensis Wright and Matsumoto. The conch of this species is straight in all specimens observed from the Nanaimo Group, although the genus is said to have crytoconic juvenile whorls (Wright and Matsumoto, 1954). The genus is monotypic and known only from the North Pacific Biotic Province (Matsumoto, 1960). Several crushed, but nearly complete, specimens have been recovered from fine shale horizons (Bouma Division E) turbidite facies of the Haslam Formation in the Saanich Peninsula area. In all other facies of the Nanaimo Group, R. ryugasensis is preserved only fragmentarily.

Family Nostoceratidae

Didymoceras (Bostrychoceras) elongatum (Whiteaves). Subsequent to its description, recent evidence (Ward, 1976) has shown that the species is quite variable in size, ornamentation and coiling characteristics. The lectotype (5806) is coarsely ribbed and tightly coiled. Collignon (1971), however, considered loosely coiled specimens with similar ornamentation as conspecific. One specimen from the Nanaimo Group (MCMK1004H; Plate 7.2, Fig. 5) is loosely coiled in early stages and becomes tightly coiled in the body chamber.

Nostoceras hornbyense (Whiteaves). This species has a torticonic shell with U-shaped body chamber. The apical angle is greater than in Didymoceras. The taxonomy of this species was last reviewed by Usher (1952) and is currently in a state of confusion. The species is close to *Didymoceras cooperi* (Gabb) and *Didymoceras vancouverense* (Meek). I have examined the holotype of *N. horbyense* and several examples of the latter species, and consider the three to be conspecific in light of the variability known in other Campanian torticones. This question will be examined in greater detail in a subsequent work. The species has been collected in the Nanaimo Group only from Hornby Island (Suciaense Zone).

Pseudoxybeloceras (Cyphoceras) nanaimoense Ward and Mallory. This species is a hamitid with long arms and U-shaped connectives. The taxonomy and detailed description is in press (Ward and Mallory). The species is known only from Trent River, Chicoense Zone.

Family Baculitidae

Baculites inornatus Meek. This species is described in detail in Chapter 4. It occurs in the Vancouverense Zone, Cedar District Formation.

Baculites anceps pacificus Matsumoto. This species is described in detail in Chapter 4. It occurs in the Pacificum Zone, Cedar District Formation.

7.3 Volume and Density Estimators

The calculation of volumes for heteromorph species with circular cross-section and constant growth is simpler than for planispiral ammonites, since the lack of whorl overlap allows use of simple volume equations. In most species, however, these conditions are not met. In some forms, the cross-section approximates an ellipse, and the equation

$$V = 1/3(ab)^2 h\pi$$

where a and b are radii, can be used as a volume estimate. Since in many ammonite species the expansion rate decreases in the body chamber (Westermann, 1971; Ward and Westermann, 1976), separate estimates for the phragmocone and body chamber, using two different apical angles, are necessary. However, in species in which the cross-section is egg-shaped, or where coarse ornamentation is present on the shell, empirical values of volume cannot be derived within reasonable limits of experimental error. In these cases, the most accurate methods of volume measurement are either from direct measurement of the specimen's volume, or, since most heteromorph species are incomplete, by measurement of partially restored or modelled specimens.

Trueman (1941) showed that the ratio of shell test volume to total volume is equal to the ratio of test area to total area of any given cross-section, assuming that the ratio stays the same throughout growth. In _Nipponites occidentalis_, we showed that this ratio, in fact, decreases with growth, such that the proportion on the late body chamber was less than half the value measured for the early phragmocone. This ratio has been measured for each of the studied Nanaimo Group heteromorphs, with results in most species comparable to those from _N. occidentalis_. To measure this ratio a number of specimens of each species were cut and polished, and acetate peels taken. The resulting peels were enlarged photographically, and the prints analyzed for area using a compensating, zero-resetting planimeter.

The ratios of test area (A_t) to total cross-sectional area (A_{cs}) for a number of heteromorphs are shown in Figure 7.2.1. A trend of decreasing ratios is apparent in all but Baculites anceps pacificus. For the late body chambers of most species, the ratio is about ½ to ¼ of early phragmocone values. As a comparison, Trueman (1941), assuming a constant ratio in all stages, found A_t/A_{cs} values of .09 for Dactylioceras commune and Sigaloceras micans; 0.13 for Asteroceras smithi and 0.03 for Liparoceras cheltiense, all planispiral species.

A second important feature of ammonoid shell morphology which must be taken into account in volume calculations is the relationship between cross-sectional area and shell diameter during ontogeny. Westermann (1971) has shown that planispiral ammonites often show a relative decrease in whorl expansion rate of the body chamber. The only measurements for heteromorphs are by Reyment (1964), who found similar decreases in the body chamber expansion rate of Myloceras davidi.

I have plotted height against ventral length for a number of Nanaimo Group heteromorphs (Figures 7.2.2, 7.2.3, 7.2.4). In almost all cases, the whorl expansion rate shows some decrease on the body chamber.

If the test and total specimen volumes are known, the weight of the test of empty phragmocone and body chamber can be derived using the expression

$$W = \left(A_t/A_{cs}\right) V \rho_1 K_2$$

where

A_t/A_{cs} is the ratio of test area to total cross-sectional area;

V = total specimen volume;

ρ_1 = specific gravity of test (2.6);

K_2 = correction for additional weight of septa and siphuncle (1.06).

Since A_t/A_{cs} varies during ontogeny, separate values for the phragmocone and body chamber estimates increase accuracy.

An estimate for the weight of the soft tissues, assuming the soft parts to fill the body chamber, was derived by Heptonstall (1972):

$$W_a = b/(b+1)\ V(1-a)\ \rho_2$$

where

$$b = \frac{\text{volume body chamber}}{\text{volume phragmocone}}\ ;$$

$$a = \frac{\text{volume test}}{\text{volume specimen}}\ ;$$

and

ρ_2 = specific gravity cephalopod tissue (1.06).

Using a and b, Raup (1973) derived an expression for the proportion of flooding necessary to sink an empty shell:

$$F_s = 1 - \left(\frac{a(b+1)}{1-a}\right) \left(\frac{\rho_1 - \rho_w}{\rho_w}\right)$$

where

ρ_w = specific gravity water (assumed to be 1.0).

The volumes and densities of the studied heteromorphs are shown in Table 7.3. All of the specimens show neutral or positivebuoyancy.

7.4 Living Orientation Demonstrations

Ammonoid studies using life-size or scale models have been presented by Reyment (1973) and Chamberlain (1973). Reyment's models were made of molded plastic, and hence reproduced the internal and external morphology of the modelled ammonite species. According to Reyment,

TABLE 7.3 Volume and density estimates, and model and heavy liquid densities

Specimen	V_p	V_b	V_t	V_s	a	b	F_s	ρ_p	ρ_b	ρ_s	ρ_{mb}	ρ_ℓ
<u>Glyptoxoceras subcompressum</u> (MCMK985)	9.0	21.0	3.5	30.0	.12	2.33	.26	.30	1.24	.96	1.85	1.6
<u>Didymoceras elongatum</u> (GSC 16475)	150	530	58	680	.09	3.53	.27	.33	1.16	.98	1.76	1.57
<u>Ryugasella ryugasensis</u> (MCM 1108a)	16.5	35.4	4.5	51.9	.1	2.14	.43	.36	1.16	.91	--	--
<u>Pseudoxybeloceras nanaimoense</u> (UW 65760)	407	2129	2536	203	.08	5.23	.17	.29	1.17	1.03	1.7_7	1.61
<u>Baculites inornatus</u>	40.0	86.0	16.2	126	.12	2.15	.30	.4	1.25	.93	1.85	1.5
<u>B. anceps pacificus</u>	12.0	21.0	4.4	33.0	.12	1.75	.39	.33	1.24	.91	1.8_4	1.57

V_p = volume phragmocone

V_b = volume body chamber

V_t = volume test material

V_s = total volume of specimen

$a = V_t/V_s$

$b = V_b/V_p$

F_s = proportion of flooding to sink empty shell

ρ_p = density phragmocone

ρ_b = density body chamber

ρ_s = density entire specimen

ρ_{mb} = density model body chamber

ρ_ℓ = density heavy liquid

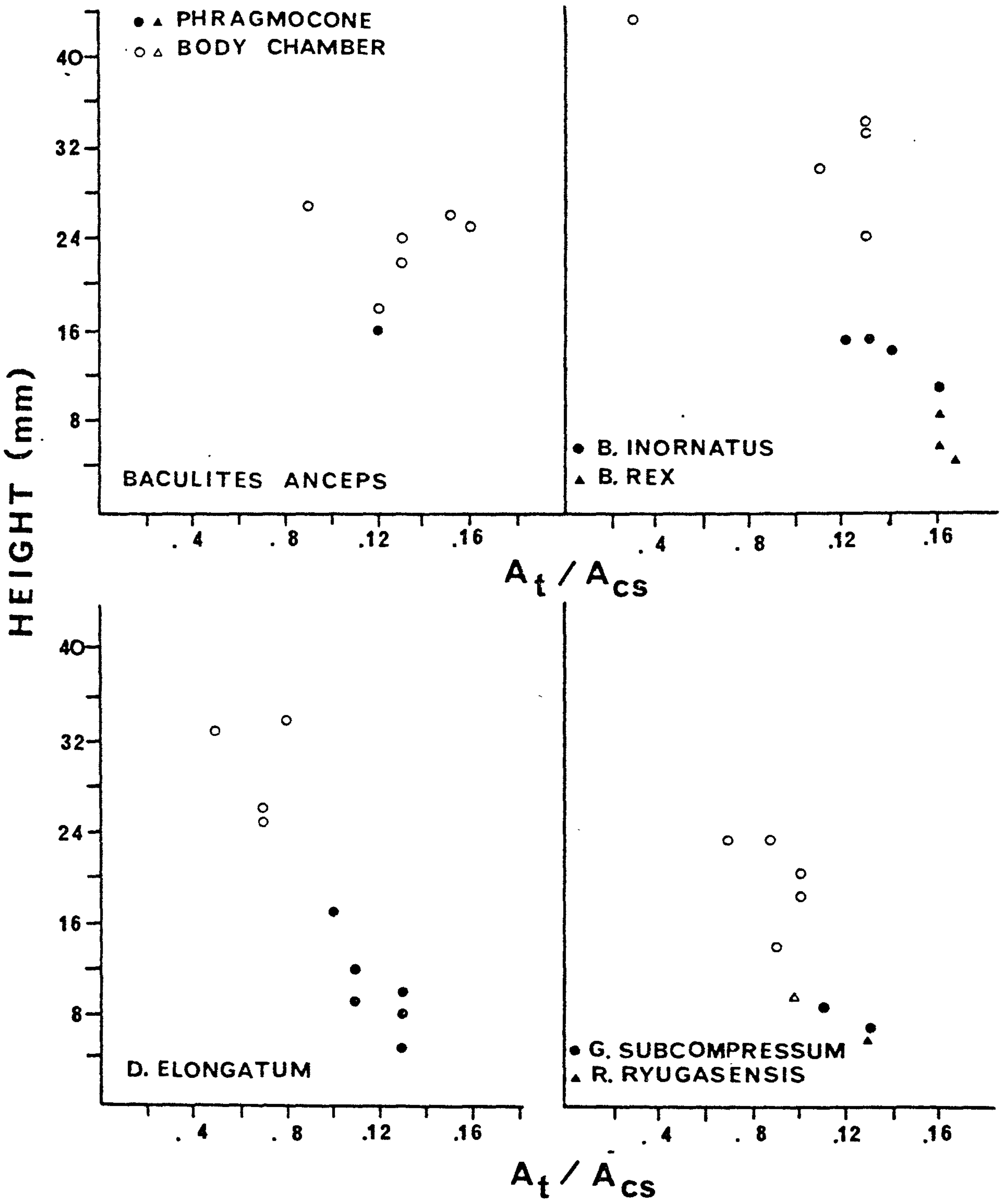


FIGURE 7.2.1. Ratio of test area to total area in cross-section against height.

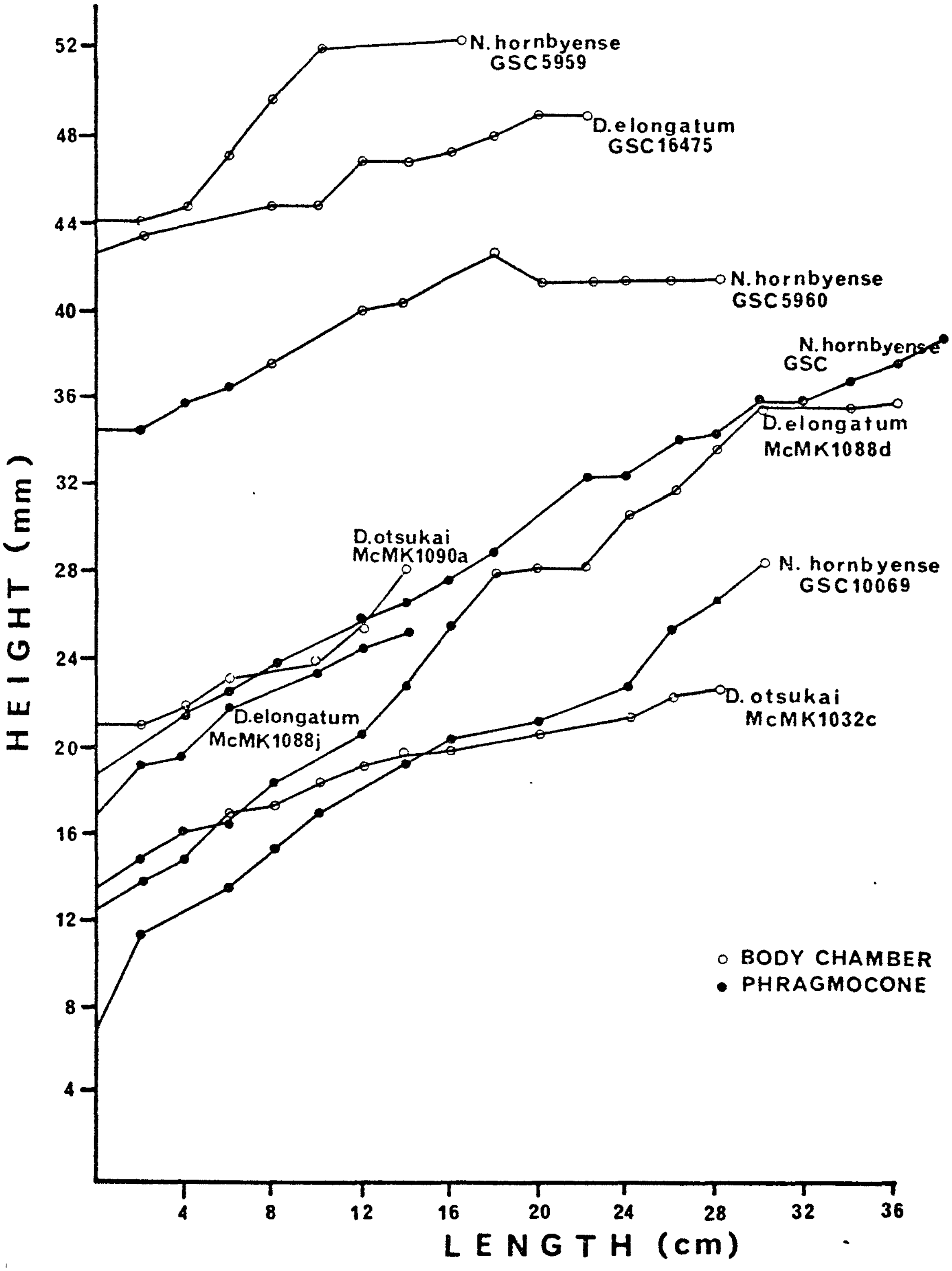


FIGURE 7.2.2. Whorl height vs. ventral length in torticones.

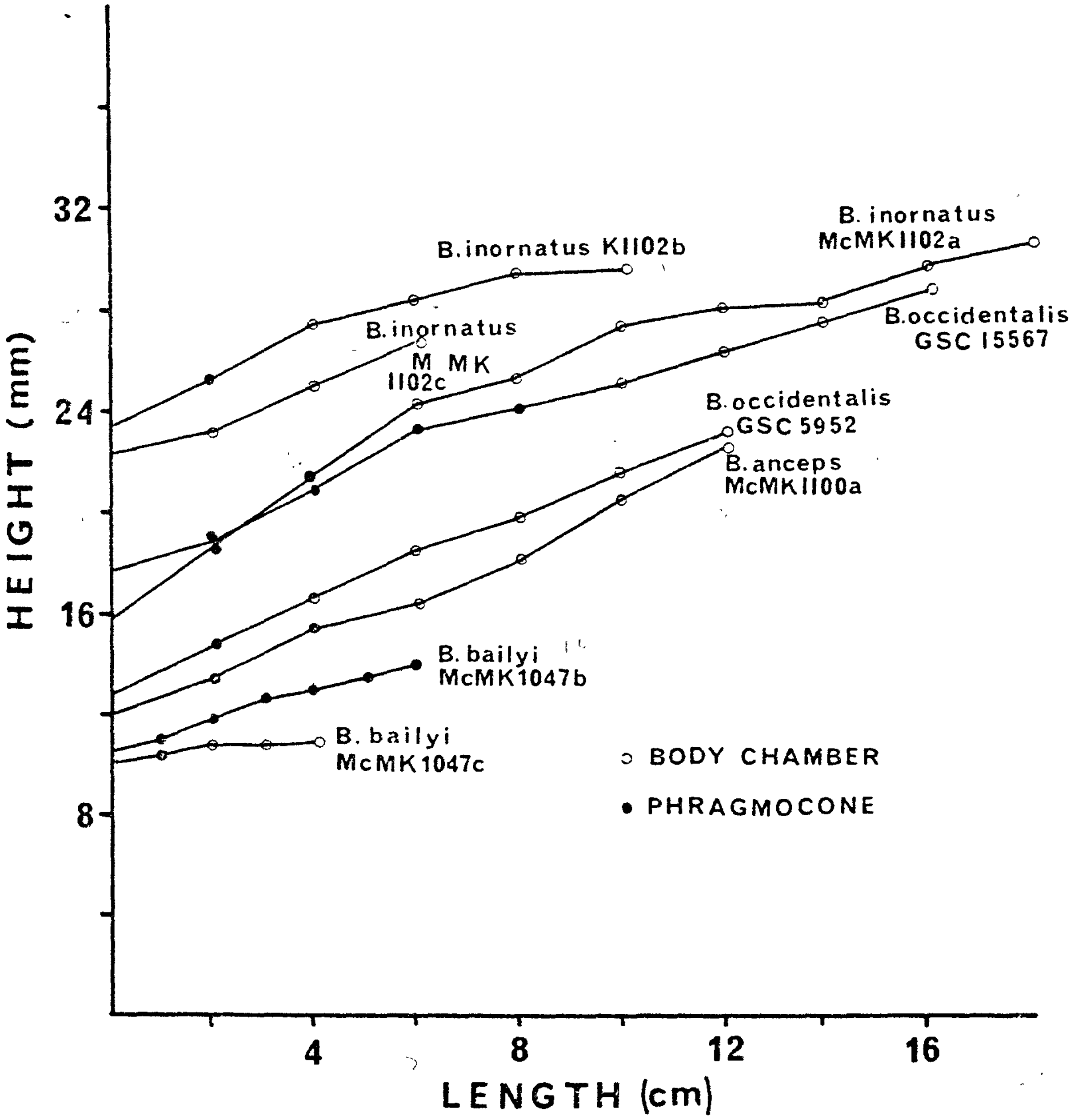


FIGURE 7.2.3. Whorl height vs.ventral length in Baculites.

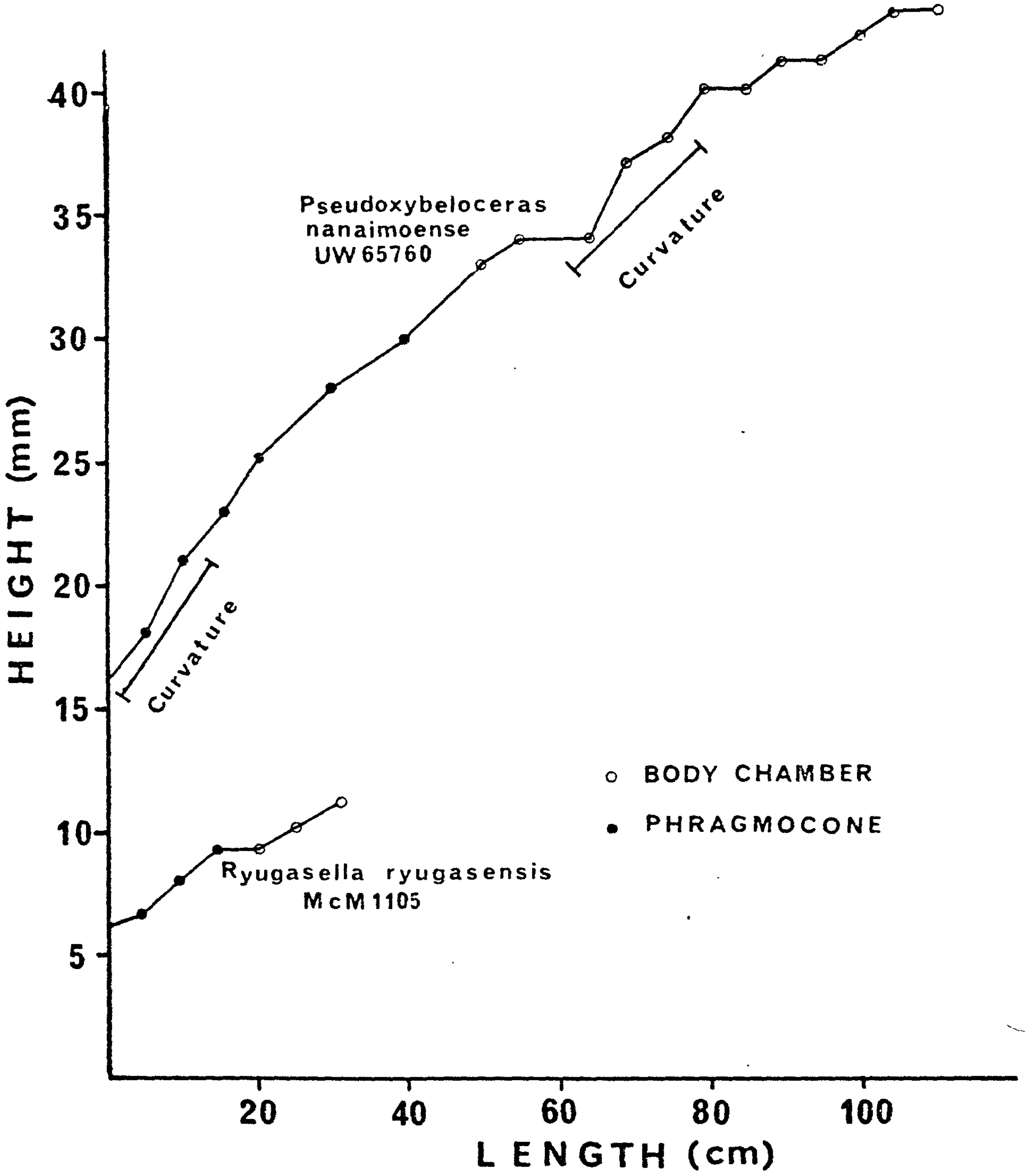


FIGURE 7.2.4. Whorl height vs. ventral length in *Pseudoxybeloceras* and *Ryugasella*.

however, the process is extremely time-consuming and expensive; a single model took a full-time technician several months to fabricate. Chamberlain discussed a method of producing exact models of ideal shells with logarithmic spirals using computer simulation and subsequent construction by plastic laminae. This method, however, is also time-consuming and, presumably, only applicable to ideal, rather than real shells.

I have constructed a number of exact size or scale model heteromorph ammonite replicas from microcrystaline sculpting wax. These models have been either cast from molds of the original specimens, or modelled by hand, following exact measurements. In sculpted specimens, the melted wax is first poured onto a smooth plaster of Paris surface in thin sheets; these sheets are then tightly rolled into a tube to the correct dimensions. Ornament and variations in cross-section can be produced by carving or by melting away with a hot knife. The density of the wax can be increased, so as to simulate the relative densities of the phragmocone and body chamber by the addition of carborundum or metal powder into the melted wax immediately before casting, and by the addition of thin lead or solder strips in the core of the rolled wax. Trained sculptors were easily able to produce even complex forms in one to two days.

In order to simulate the living positions of the species in seawater, the body chambers were of material with higher specific gravities than the phragmacone. The specific gravity of the microcrystalline wax was found to be .90 gm/ml, and since the computed specific gravity of the phragmocones was always much less, the difference had to be added to the computed specific gravity of the reconstructed body chamber, and to the liquid in which the model was floated. For example, the specific gravity estimates for Glyptoxoceras subcompressum (Forbes) (MCM 985) was found to be .30 g/ml for the phragmacone, and 1.24 g/ml for the body chamber. Using plain wax to simulate the phragmocone necessitated adding enough weight to the body chamber model so that its density measured 1.84 g/ml (1.24 g/ml to simulate the weight of shell and animal, and .6 g/ml to compensate for the heavy phragmocone). The entire model was then placed in liquid of density 1.6.

The values for estimated phragmocone and body chamber densities of actual specimens, and the densities of the scaled models and heavy liquid are listed in Table 7.3.1.

The results of flotational experiments are shown in Plates 7-4, 7-5 and 7-6. Experimental error was possibly introduced into the experiments in several ways. Because of a lack of complete juvenile specimens of different growth stages, the relative proportion of body chamber and phragmocone volumes were estimated from the adult shell stages. This may have been erroneous, since in some planispiral species, the body chamber decreases in length relative to the phragmocone in adult stages (Westermann, 1971). A second possible source of error is that shell thickness, and hence overall specific gravity of the shell (without animal), decreases with growth. In the models, separate densities were utilized for the phragmocone and body chamber, rather than using material of continuously changing density.

Another possibility is that the estimates for the specific gravities of the aragonite test of ammonite shells, or of soft tissue may be wrong. However, in spite of these factors, I believe the models give reasonable approximations of heteromorph buoyancy conditions and living positions, and that the technique can be profitably expanded to models of planispiral shells.

7.4.1 Cases

Glyptoxoceras subcompressum

This species shows one of the most complex growth patterns of any known mollusc shell. Its changes in living attitudes may have been equally complex. Figure 7.4.1. illustrates its possible life positions.

Although not modelled, one can make some predicitions about the orientations of the earliest growth stages. The initial stage (up to 1 cm long) is orthoconic. Assuming that the succeeding torticonic stage was not initiated within the egg, and that the phragmocone was filled with air, while the body chamber contained tissue of such specific gravity that the body chamber and tissue together were heavier than seawater, the earliest orientation would have been vertical, with shell apex up. Maintaining the same assumptions, subsequent coiling of the body chamber around the orthocone would have retained the protoconch in a dorsal position, but changed the orientation of the aperture from facing downward (horizontal attitude) to a nearly vertical attitude. Then, presumably, at some stage in the coiling around the initial orthocone, and subsequent septation of the early torticone, the entire shell would flip over, possibly abruptly. At this stage, the apex of the torticone pointed upward, the aperture stayed in the same plane (but the animal would now be upside-down) and the protoconch downward. The change from an orthoconic shell shape to a torticonic shape would presumably also have effects on the anatomy of soft parts, and possibly habitat. Initiation of planispiral, gyroconic coiling probably resulted in gradual changes of apertural orientation as outlined in Plate 7.4.

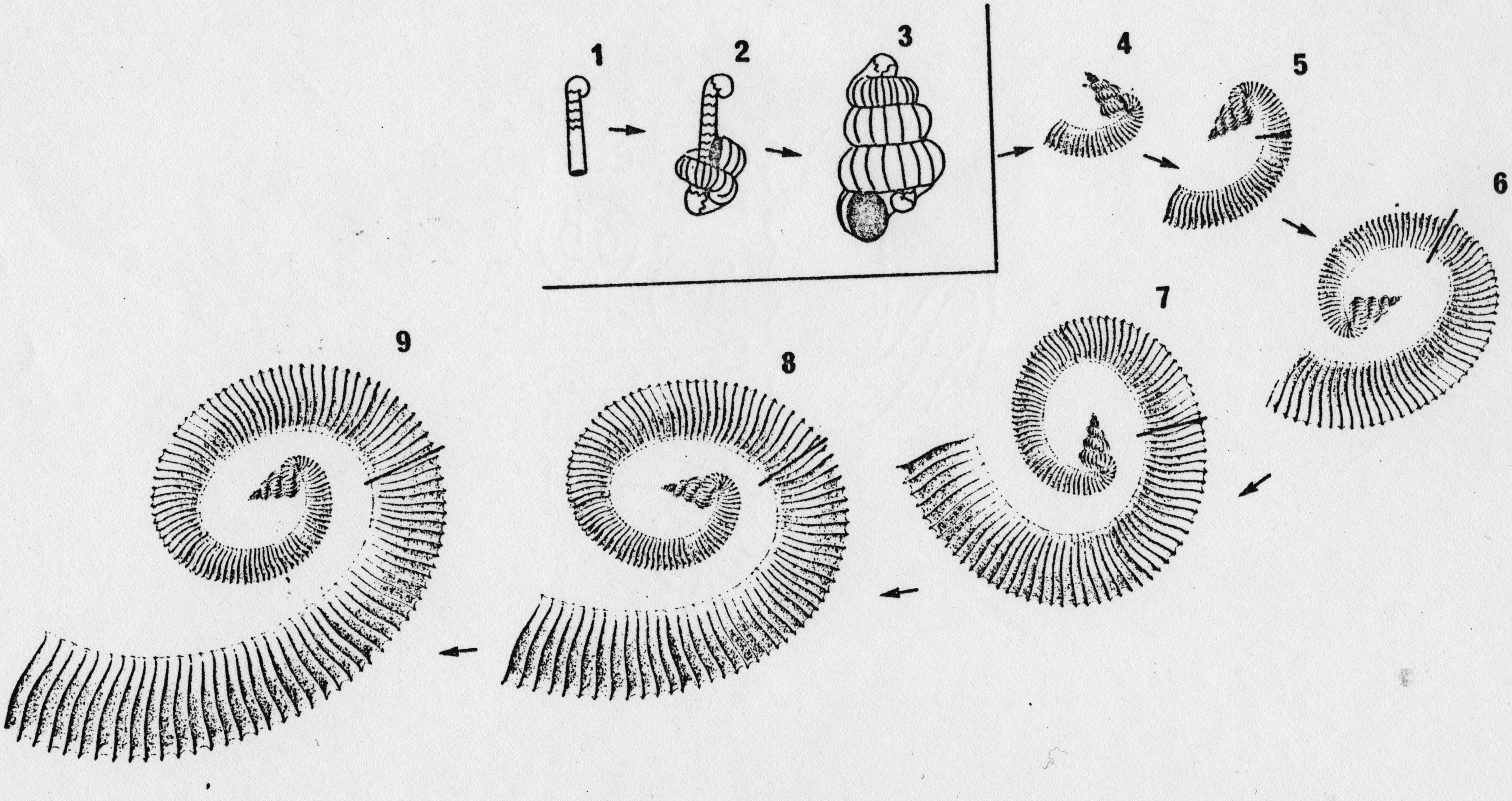


FIGURE 7.4.1. Inferred living positions of *Glyptoxoceras* *subcompressum* during growth.
Line indicates end of phragmocone.

Torticones

In *Didymoceras elongatum* the living animal's attitude was with shell apex upward (from experiments above) throughout much of life. The model for this species shows little change in position even after the U-shaped body chamber grows out of the turreted coiling and coils to one side. The bulk of body chambers in both these species are situated directly below the phragmocone, resulting in high stability.

Turreted coiling is apparently present in all stages of the phragmocone in *D. elongatum*; in all known species of *Nostoceras* and some *Didymoceras*. However, the juvenile stages are orthoconic (Gill and Cobban, 1965).

Striking features of torticonic shell shape include its effects on septal morphology, siphuncular position and possible modifications of soft part morphology.

Septal sutures in all torticonic ammonoids are highly assymmetric on either side of the siphuncle; in most cases the first lateral saddle on the outside of the whorl increases in size, while its counterpart on the inside of the whorl becomes commensurately reduced. Seilacher (1975) has suggested that this morphologic change brings about an effective alternation of lobes and saddles in successive septa, thereby producing a corrugation analogous to the alternating overlap of test elements in fusulinids.

A second important consequence of the torticonic morphology is the U-effect it imposes on siphuncle position. Perhaps the most conservative morphological character of the ammonites, the siphuncle in the

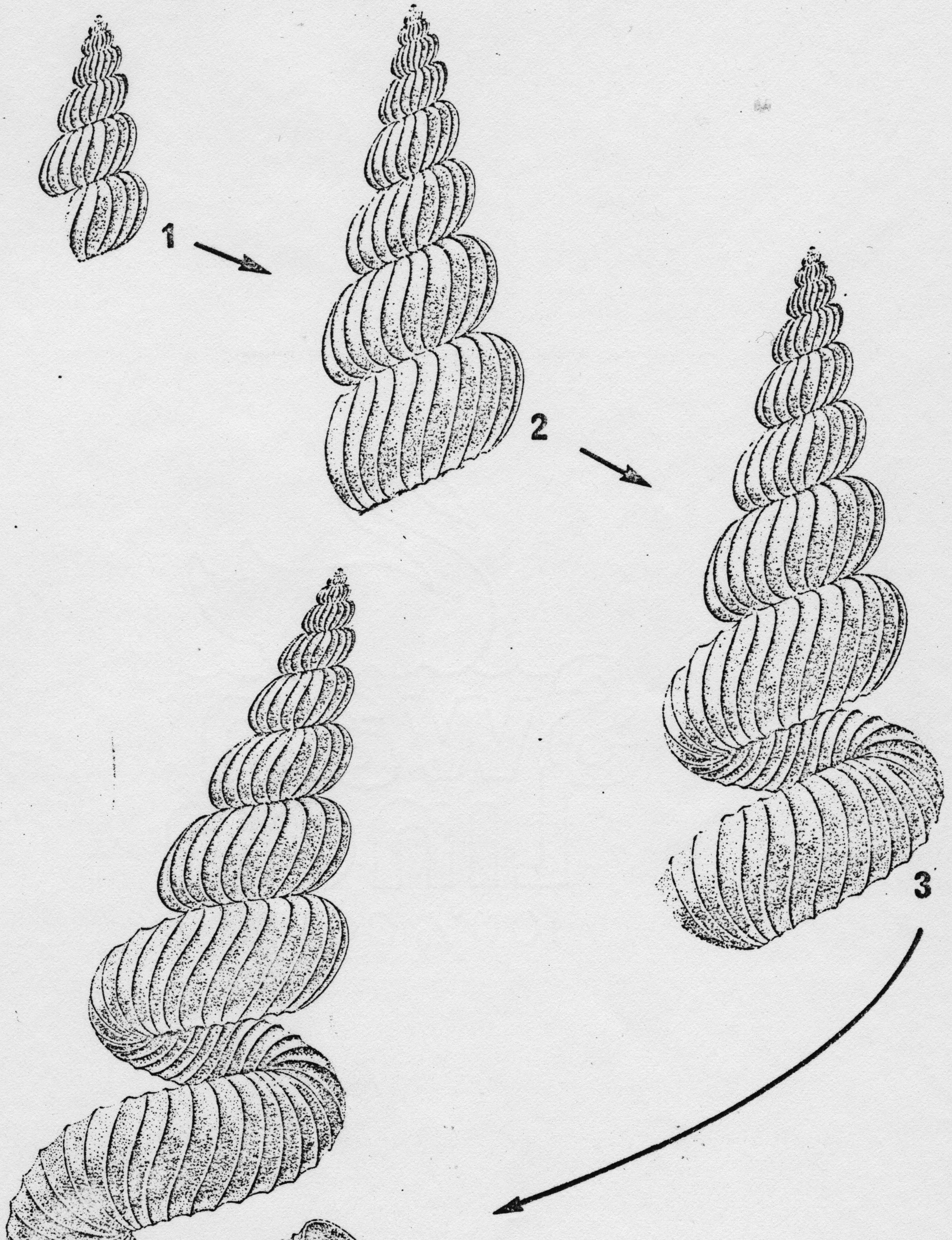


FIGURE 7.4.2 Inferred living positions of Didymoceras elongatum.

torticones is, for the first time, no longer coiled in a vertical plane. Further change is imposed by the modified septal morphology in torticones; since the relative sizes of the sutural elements are changed in torticones, the ventral saddle and siphuncle become displaced upward on the shoulder in shells with low (small) apical angle. This migration of the siphuncle to a more dorsal position on the whorl (with respect to the shell in living position) would presumably have functional ramifications, since it decreases the amount of cameral fluid necessarily removed before siphuncular "de-coupling". The trend is most pronounced in the turrilitids, and less so in the less steeply coiled nostoceratids.

Orthocones

In both species of *Baculites* which I have modelled, and also presumably in *Ryugasella*, the conch maintains a vertical attitude in all growth stages. In all three species, however, estimates of living animal and shell specific gravity are slightly higher than .9, suggesting that a large proportion of the phragmocone would have to be flooded to attain neutral buoyancy. Could this liquid have been positioned in the apical portions of the phragmocone, so as to produce a counterweight effect analogous to the cameral deposits of orthoconic nautiloids? This question is an important one, not only for orthocones, but for all ammonites. In all examined cases, appreciable volumes of liquid are necessary to produce neutral buoyancy in ammonoids, and if the animal were able to position this liquid in selected chambers, great latitude in living orientation could presumably be achieved.

Flower (1955) has discussed the probable orientation of non-planispiral nautiloids in detail, and many of his discussions are pertinent here. From colour patterns it was apparent that many, if not all orthoconic species in which original shell colouration was present were horizontal during life. The widespread presence of calcareous counterweights in orthoconic nautiloids indicated the probable method of counterweighting the shell.

Unfortunately, colour markings, apertural modifications, or cameral deposit which could be used to infer orientation during life are unknown in heteromorph ammonites. If the phragmocones of these ammonites were filled mainly with gas, a body chambers with tissue heavier than seawater, a vertical orientation would have resulted. However, cameral fluid in the apical chambers which was divorced from buoyancy regulatory functions , and/ or tissues of the animals body chamber which were lighter than seawater would have allowed a horizontal orientation. Unfortunately, the writer sees no method of testing these alternate hypotheses.

Hamiticones

These shell shapes go through perhaps the greatest number of orientation changes of the heteromorphs. As the animal grew, and emplaced new septa along the straight shell portions, the entire conch would periodically turn over. The aperture would mainly alternate between facing downward or facing upward; only during growth of the U-shaped connectives would the apertural orientation vary.

One interesting result of modelling experiments on this shell shape was my observation of the low stability of these forms. The very long body chamber often "surrounded" the inner whorls in such a way that the characteristic separation of gravity and buoyancy centres was not as

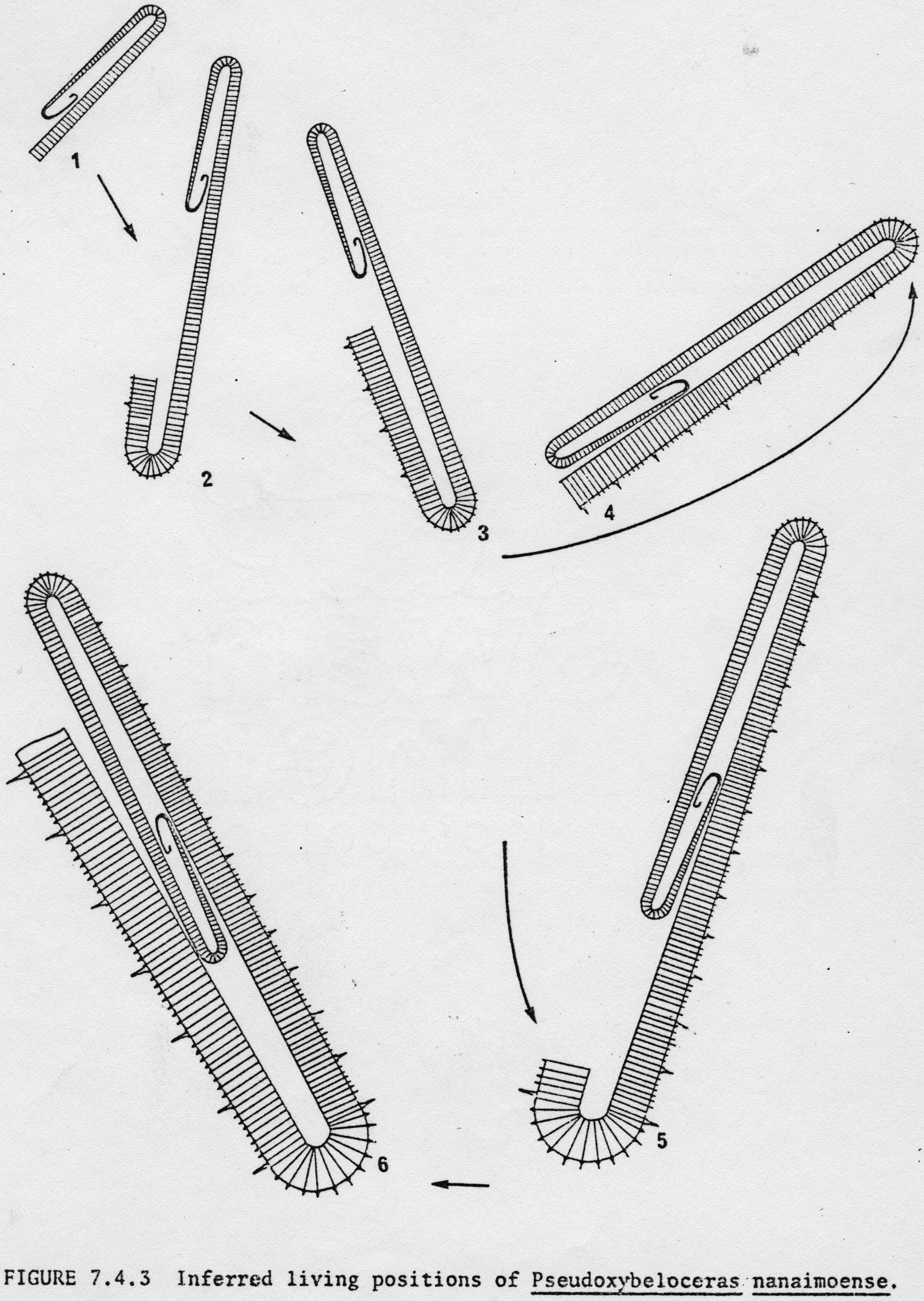


FIGURE 7.4.3 Inferred living positions of Pseudoxybeloceras nanaimoense.

pronounced as in the other heteromorphs studies. If the living animal did not completely fill the body chamber, but was capable of some movement within the body chamber, it seems possible that the entire shell could change orientation by change in the position of the animal within (or extending out of) the body chamber.

Plate Descriptions, Chapter 7

Plate 7-1 *Glyptoxoceras subcompressum* (Forbes).

Fig. 1, GSC 89541, X1.; Fig. 2, GSC 89541, X3.;
Fig. 3, GSC 64936a, X2.; Fig. 4, GSC 649366, X2.;
Fig. 5, MCMK 985a, X1.

Plate 7-2 *Didymoceras (Bostrychoceras) elongatum* (Whiteaves).

Fig. 1, GSC 15694, X1.; Fig. 2, GSC 16475, X.5;
Fig. 3, MCMK 1088D, X ; Fig. 4, UBC 68, X1.;
Fig. 5, GSC 15679, X.5; Fig. 6, MCMK 1004h.

Plate 7-3. *Pseudoxybeloceras nanaimoense* Ward and Mallory;
Ryugasella ryugasensis Wright and Matsumoto.

Fig. 1, *R. ryugasensis*, MCM 1108a, X.75;
Fig. 2, UW 65760B, X.5; Fig. 3, UW 65760A, X.25.

Plate 7-4. Models of *G. subcompressum*.

Plate 7-5. Models of *P. nanaimoense*.

Plate 7-6. Models of *B. inornatus*, *D. elongatum*.

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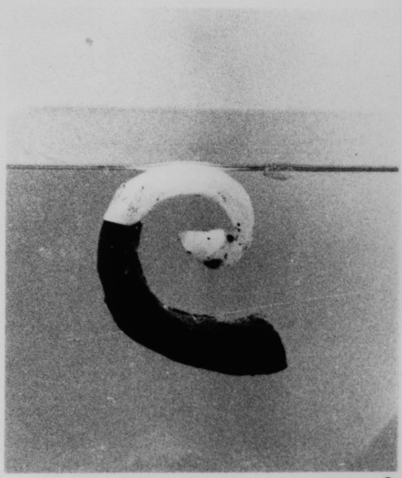
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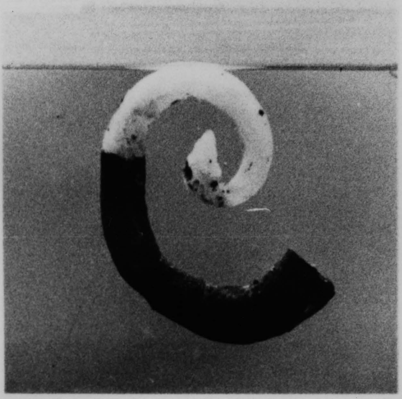
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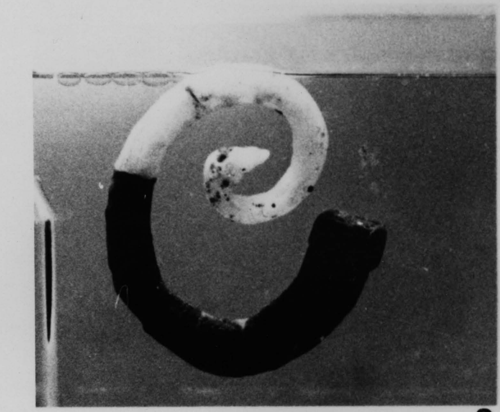
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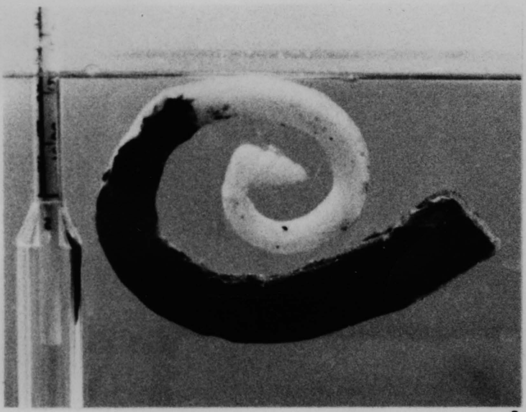
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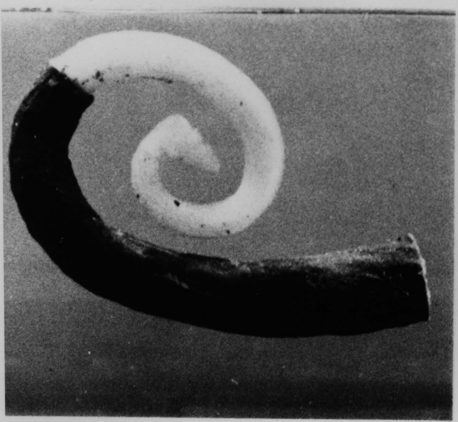
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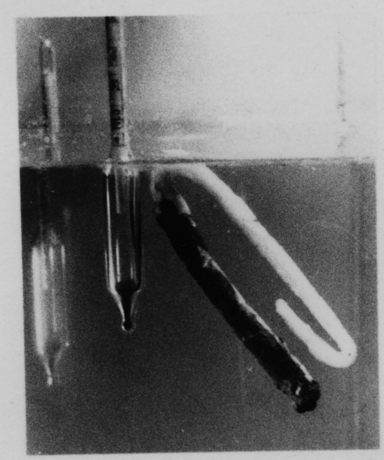
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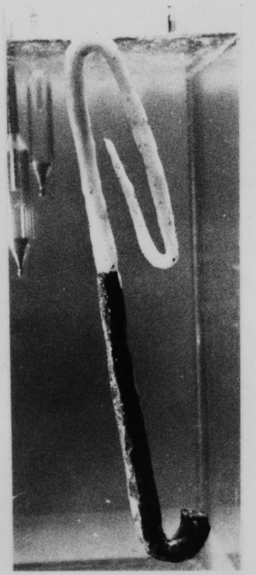
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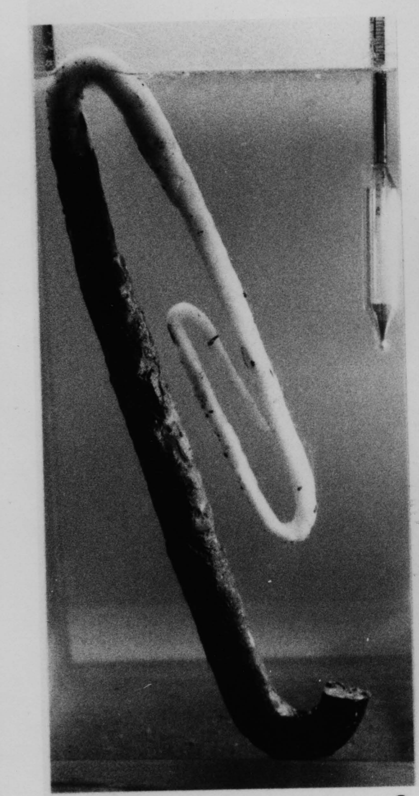
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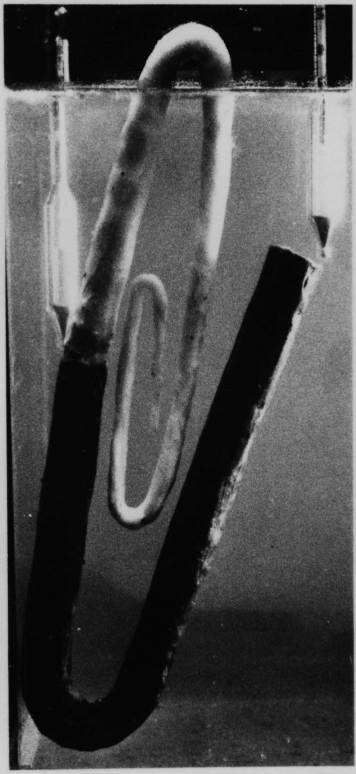
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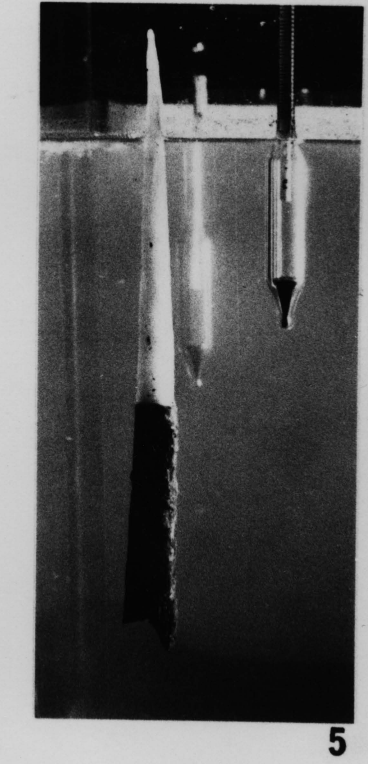

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CHAPTER 8

SOME GENERAL CONSIDERATIONS OF HETEROMORPH FORM AND FUNCTION

Heteromorph ammonoids can be categorized by the following morphotypes:

1) Gyrocones: Circular or elliptical coiling in one plane where the whorls are not in contact. Examples: Crioceras, Glyptoxoceras.
2) Torticones: Helical or trochoid coiling, whorls may or may not be in contact. Examples: Turrilites, Didymoceras.
3) Ancylocones: Planispiral or gyroconic phragmocone with hook-like (U-shaped) body chamber. Examples: Ancyloceras, Macroscaphites.
4) Hamiticones: Straight or slightly curved shells connected with U-shaped sections. Examples: Hamites, Polyptychoceras.
5) Orthocones: Straight shells. Examples: Sciponoceras, Baculites.
6) Vermeticones: Irregular coiling followed by U-shaped body chamber. Examples: Nipponites, Madagascarites.
7) Crytocones: Arcuate shells of less than one whorl. Example: Spiroceras.

The stratigraphic distribution of these morphotypes has been tabulated for the Mesozoic from data compiled in the Treatise on Invertebrate Paleontology (Part 4) and is illustrated in Table 8.1. Wiedmann (1969) has reviewed the evolution of the heteromorph families, and concluded that many of the shell shapes evolved iteratively from a long-ranging lytoceratid stem , or polyphyletically from a number of sources. In many genera the convergence in form is striking; notable examples include Ancyloceras of the Barremian and Eoscapaphites of the Albian, Protancyloceras of the Berrasian and Hamites of the Aptian, and Crioceras of the Valanginain and Neocrioceras of the Campanian.

The repeated evolution of similar heteromorph morphotypes listed above suggests that each may be an adaptation to a particular niche. Similar niches may also have been present during the Paleozoic, for torticones, gyrocones, orthocones and cyrtocones were all evolved by the Paleozoic nautiloids (Table 8.2, from data compiled in Treatise on Invertebrate Paleontology, Part 3). In my opinion, however, no satisfactory explanation of adaptive advantages, or the nature of the niches exploited by the particular heteromorph morphotypes has yet been advanced. Most past workers have inferred a benthonic existence, primarily on such teleological arguments as an apparent lack of swimming ability, and in the case of the torticones, the striking, but possible misleading, parallelism with the gastropod shell.

The work of Trueman (1941) and living position experiments described in Chapter 7 suggest several generalizations about the heteromorph conchs: Most can be characterized by greater separation of centres of buoyancy and gravity than in planispiral forms. Secondly, many forms were oriented with the aperture pointed upward. Because of the high stability of the conchs, it is difficult to conceive of these forms being manoeverable, or able to attain a variety of attitudes in the sea. Third, most heteromorph species may have undergone significant changes in living position, and possibly habit and habitat during growth. For example, many ancylocones were "normal" planispirals during much of their growth; the regression and eventual recurvature of the body chamber, however, undoubtedly caused change in attitude.

Another consequence of heteromorphic coiling is the restriction of cross-section to non-overlapping shapes. It is not unreasonable to conceive of ammonites with radically different cross-sections, and hence body chamber morphologies as also being anatomically distinct, while forms with similar body shapes may have been grossly similar anatomically (position of gills, shape of alimentary canal, size of hyponome).

In cross-section and body chamber length relative to the phragmocone, the heteromorphs are most similar to the planispiral serpenticones. These latter forms have been suggested to be extremely unstable because of the proximity of their centres of gravity and buoyancy (Trueman, 1941) and, consequently, poor swimmers. It is interesting to note that in preliminary tabulation of ammonoid morphotypes for each stage of the Jurassic and Cretaceous (cadicones, oxycones, sphaerocones, serpenticones, planulates, intermediates, heteromorphs), I have noted that declines in numbers of serpenticones during the late Jurassic and early Cretaceous are coincident with the heteromorph radiations. Mutvei and Reyment (1973) have suggested that the dactylioceratids moved mainly upward or downward in the water column; the evidence presented above suggests to me that the Jurassic serpenticones and Cretaceous lytoceratid heteromorphs with long body chambers may have been anatomically, and ecologically, similar, with the difference that the heteromorphs were much more stable, and probably able to descend to greater depths (based on siphuncular strength studies, Westermann, 1971).

Another interesting aspect of the heteromorphs is their often wide geographic distribution. Even though many were probably poor swimmers, some form of effective larval or post-mortal distribution was apparently present in the Cretaceous. Matsumoto (1973) has noted that *Turrilites costatus*, and several species of *Sciaponiceras* and *Scaphites* are virtually world-wide in distribution. Other species with wide geographic extent include *Hyphantoceras venutsum*, *Baculites anceps* and *Glyptoxoceras subcompressum*.

To further examine this generalization, I have categorized the Turonian-Maestrichtian ammonites listed in the Treatise as either oxyconic, smooth involute, smooth evolute, coarsely ornamented, or heteromorphic. The occurrence of each genus in the following paleogeographic units was then tabulated for each genus, and the resultant mean distribution in units compared for each morphotype. The paleogeographic units are comprised of the following:

1) Tethys - includes European Tethys, the Near East, the North American Gulf region, and Mexico and Central America;
2) South Atlantic - includes western, central and northwestern Africa, and eastern South America;
3) South Pacific - includes Australia, New Zealand;
4) Indopacific - includes Madagascar, India, Japan and far east Siberia;
5) Northeast Pacific - includes Alaska, British Columbia, westernmost United States and Baja California;
6) North American Western Interior - includes western interior of United States and Canada;

7) Boreal - includes northern Canada, Arctic islands and Russian platform.

The units are qualitative, and have been differentiated because they represent major endemic centres among foraminifera (Dilley, 1973), bivalves (Kauffman, 1973), and ammonites (Matsumoto, 1973; Jeletzky, 1971).

Although for a restricted time range, based on genera rather than species, and necessarily including areas which do not show a complete Turonian-Maestrichtian record, the resulting figures (Table 8.3) are somewhat surprising. Oxyconic genera, seemingly the best adapted for swimming, show the highest degree of endemism. The heteromorphs show a low degree, suggesting that 1) they could tolerate a variety of environmental conditions (especially latitudinal gradients); 2) they were capable of wide geographic dispersal, because of morphologic or ecologic (or a combination of both) considerations.

In conclusion, Packard (1968) has suggested that the heteromorphs were adapted for mespelagic habitats, where they passively floated or migrated vertically in much the same way as the Cranchid squids exist today. For many heteromorph species this hypothesis seems reasonable, in light of their apparent buoyancy capabilities and living positions, and wide dispersal. However, it is probably as misleading to characterize all heteromorphs as planktonic as it was to uncritically relegate them to the benthos. The rich variety and morphologic complexity argues instead for adaptation to many different habits and habitats, which may only be elucidated by careful biofacies analysis and functional studies for many different species.

TABLE 8.1 Morphologic Distribution of Heteromorph Ammonites During Stages of Cretaceous

Stage	Orthocone	Cyrtocone	Gyrocone	Torticone	Ancylocone	Hamiticone	Vermeticone	% of total Ammonite genera	Total number heteromorph genera
Maestrichtian	2	2	2	4	0	1	0	.33	11
Campanian	2	4	5	7	1	5	0	.31	24
Santonian	2	2	2	4	1	3	0	.21	11
Coniacian	2	1	1	2	2	2	1	.14	11
Turonian	2	1	0	2	3	3	2	.16	13
Cenomanian	1	0	0	8	1	1	1	.15	12
Albian	1	0	0	7	7	7	3	.16	25
Aptian	1	0	0	0	10	3	0	.22	14
Barramian	1	0	5	0	11	5	0	.28	22
Hauterivian	1	0	4	0	2	1	0	.17	8
Valanginian	1	1	0	0	0	0	0	.02	2
Berriasian	1	1	0	0	0	0	0	.06	2

TABLE 8.2 Morphologic Distribution of Heteromorph Cephalopod Genera in Paleozoic and Mesozoic

Period	Orthocone	Cyrtocone	Gyrocone	Torticone	Ancylocone	Hamiticone	Vermeticone
Cretaceous	7	12	16	18	18	20	6
Jurassic	3	1	3	0	0	0	0
Triassic	3	1	0	1	0	0	0
Permian	20	6	0	0	0	0	0
Pennsylvanian	0	2	0	0	0	0	0
Mississippian	21	12	3	0	0	0	0
Devonian	48	31	26	6	0	0	0
Silurian	48	48	6	9	0	0	0
Ordovician	152	73	18	1	0	0	0
Cambrian	1	2	0	0	0	0	0

TABLE 8.3

Paleogeographic Units

Taxa	Tethys	Indopacific	Northeast Pacific	South Pacific	South Atlantic	North American	Boreal	Total	Cosmopolite	Endemic
Heteromorphs										
Hyphantoceras	x	x	x	x				4		
Nipponites	x	x	x					3		
Polyptychoceras	x	x	x	x	x			5		
Ryugasella		x	x	x	x			4		
Scalarites	x	x	x					3		
Didymoceras	x	x	x		x	x	x	6	x	
Nostoceras	x	x	x		x	x		5		
Exiteloceras		x	x		x	x		4		
Solenoceras	x	x	x	x	x	x		6	x	
Neocrioceras	x	x	x	x		x		5		
Pseudoxybeloceras		x	x	x	x	x		5		
Glyptoxoceras	x	x	x	x	x	x		6	x	
Diplomoceras	x	x	x	x			x	5		
Scaphites	x	x	x	x		x	x	6	x	
Otoscaphites	x	x	x			x		4		
Hoploscaphites	x			x	x	x	x	5		
Discoscaphites	x					x	x	3		
Acanthoscaphites	x					x	x	3		
Rhaeboceras						x	x	2		
Baculites	x	x	x	x	x	x	x	7	x	
Eubaculites		x	x	x		x		4		
Madagascarites		x						1		x
Sciponiceras	x	x	x	x	x	x		6	x	
Pravitoceras	x							1		x
Anisoceras	x	x	x			x		4		
Allocrioceras	x					x		2		
Joaniceras	x							1		x
27 genera						$\bar{X}$ = 4.07		110	6	3

TABLE 8.3 (continued)

Taxa	Tethys	Indopacific	Northeast Pacific	South Pacific	South Atlantic	North American	Boreal	Total	Cosmopolite	Endemic
Evolute, inflated										
Zealandites	x	x		x				3		
Gaudryceras		x	x	x	x			4		
Epigoniceras		x	x					2		
Saghalinites		x					x	2		
Anagaudryceras	x	x	x	x	x			5		
Vertebrites	x	x	x	x				4		
Pseudokossmatticeras	x	x		x	x			4		
Brahmaites	x	x						2		
Jacobites	x							1		x
Jimboiceras		x						1		x
10 genera $\overline{X}$ = 2.08								28	0	2
Oxyconic										
Proplacenticeras				x				1		x
Pseudoplacenticeras				x				1		x
Stantonoceras	x							1		x
Diplacmoceras	x							1		x
Haresiceras						x	x	2		
Hoplitoides	x				x			2		
Coilopoceras	x				x	x		3		
Binneyites					x			1		x
Paramammites	x							1		x
Pleisotissotia	x							1		x
Choffaticeras	x	x			x			3		
Glebosoceras					x			1		x
Pseudoschloenbachia	x	x	x				x	4		
Eulophoceras	x	x			x			3		
Hauericeras	x	x	x	x				4		

(Continued)

TABLE 8.3 (continued)

Taxa	Tethys	Indopacific	Northeast Pacific	South Pacific	South Atlantic	North American	Boreal	Total	Cosmopolite	Endemic
Oxyconic (Cont'd)										
Epengoniceras	x						x	2		
Metaplacenticeras		x	x					2		
Placenticeras	x	x				x	x	4		
Coahuilites	x					x		2		
Daradiceras	x							1		x
Libycoceras	x							1		x
Indoceras	x							1		x
Sphenodiscus	x	x				x	x	4		
Binneyites						x		1		x
24 genera						$\overline{X}$ = 1.96		47	0	12

TABLE 8.3 (continued)

Taxa	Tethys	Indopacific	Northeast Pacific	South Pacific	South Atlantic	North American	Boreal	Total	Cosmopolite	Endemic
Involute, inflated										
Hypophylloceras	x	x	x	x	x	x		6	x	
Phyllopachyceras	x	x		x			x	4		
Desmophyllites	x	x	x				x	4		
Pachydiscus	x	x	x	x	x			5		
Patagiosites	x	x	x	x				4		
Teshioites		x						1		x
Anapachydiscus	x	x	x	x	x			5		
Neodesmoceras		x	x					2		
Eupachydiscus	x	x	x		x			4		
Canadoceras		x	x			x		3		
Gunnarites		x		x				2		
Maorites		x		x				2		
Kossmatticeras		x		x				2		
Pachydesmoceras	x	x	x	x	x			5		
Parapuzosia	x	x	x			x		4		
Kitchinites		x	x	x				3		
Damesites	x	x	x		x			4		
Pseudophyllites	x	x	x	x	x		x	6	x	
Nigericeras	x				x			2		
Spathites						x		1		x
Gombeoceras	x							1		x
Ezilloella					x			1		x
Pachyvascoceras	x				x			2		
Vascoceras	x				x			2		
Paramammites	x							1		x
Plesiovascoceras	x					x		2		
Pseudotissotia	x				x	x		3		
Choffaticeras	x	x			x			3		
Lenticeras	x							1		x
Paralenticeras	x							1		x
30 genera							$\overline{X} = 2.87$	86	3	7

TABLE 8.3 (continued)

Taxa	Tethys	Indopacific	Northeast Pacific	South Pacific	South Atlantic	North American	Boreal	Total	Cosmopolite	Endemic
Ornamented										
Romaniceras	x	x	x	x				4		
Dunveganoceras						x	x	2		
Mammites	x	x			x	x		4		
Pseudoaspidoceras	x	x			x	x	x	5		
Fagesia	x	x			x			3		
Collignoniceras	x	x	x		x			4		
Prionocycloceras	x	x	x		x			4		
Peroniceras	x	x						2		
Prionocyclus		x				x		2		
Subprionocyclus	x	x	x					3		
Hoplitoplacenticeras	x	x	x	x	x	x		6	x	
Romaniceras	x	x	x		x			4		
Watinoceras	x				x	x		3		
Metasigaloceras	x							1		x
Benuites					x			1		x
Gauthiericeras	x	x						2		
Reesideites		x						1		x
Subprionotropsis	x				x			2		
Protexanites	x	x				x		3		
Texanites	x	x	x		x	x		5		
Behavites		x						1		x
Submortoniceras	x	x	x	x				4		
Menabites	x	x				x		3		
Calycoceras	x	x	x	x	x	x		6	x	
Eucalycoceras	x	x	x		x	x		5		
Kanabiceras	x				x			2		
Neocardioceras	x				x			2		
Metoicoceras	x				x			2		
29 genera							$\bar{X}$ = 3.66	106	3	3

CHAPTER 9

CONCLUSIONS

Based on the preceding results and discussions, the following conclusions are drawn:

1. The Haslam Formation of the Upper Cretaceous Nanaimo Group, Vancouver Island region, is correlative with previously unrecognized distal and proximal turbidites in southern Vancouver Island and northwestern Washington State.

2. The Ganges Formation, subordinated into the Extension-Protection Formation by Muller and Jeletzky (1970) because of their inability to recognize it outside of the stratotype region near Nanaimo, is distinguishable and mappable throughout the Nanaimo Group. The Extension, Ganges and Protection Formations all deserve formational differentiation.

3. Two new biostratigraphic zones are recognized in the Nanaimo Group. The older, here named the Chicoens Zone, is defined by the first occurrence of *Baculites chicoensis* Trask (base) and the first occurrence of *Hoplitoplacenticeras* spp. (top), and hence is an oppel zone. Other diagnostic features include the occurrence of *Submortoniceras chicoense* (Trask) and the first Nanaimo Group occurrences of *Inoceramus* ex.gr. *subundatus* - *vancouverensis*, *Canadoceras newberryanum* (Meek) and *Pachydiscus* cf. *jaquoti* Seynes. The zone is limited to part of the Ganges Formation.

The younger of the new zones, named the Pacificum Zone, is a range zone based on the Nanaimo Group range of *Metaplacenticeras* cf. *pacificum* (Smith). Other characteristic faunal elements are *Baculites rex* Anderson and *B. anceps pacificus* Matsumoto. The zone is restricted to the upper Cedar District Formation.

4. Within the Nanaimo Group Elongatum Zone, four characteristic macrofaunal associations can be distinguished. In sandstone lithologies an infaunal suspension-feeding bivalve association is characteristic. Siltstones characteristically contain a deposit-feeding bivalve association. Shales contain an ammonite-inocerami association, or an anomiid association.

5. Ammonite biofacies can be distinguished within the Elongatum Zone. In the northern part of the Nanaimo Group, ammonite assemblages are characterized by high diversity of planispiral forms as well as heteromorphs; in the southern areas, diversity is low, and the majority of ammonite occurrences are either *Glyptoxoceras subcompressum* (Forbes) or *Didymoceras (Bostrychoceras) elongatum* (Whiteaves), both heteromorphs. This difference between northern and southern areas may be mainly due to sedimentological differences between the two areas; the northern are is characterized by shelf sediments, the southern by turbidites.

6. Volume and specific gravity estimates for the Nanaimo Group heteromorphs *Baculites anceps pacificus*, *B. inornatus*, *Didymoceras elongatum*, *Glyptoxoceras subcompressum*, *Pseudoxybeloceras nanaimoense* and *Ryugasella ryugasensis* suggest slightly positive buoyancy for complete animal and conch without cameral fluid.

7. A new method of modelling complete ammonites using microcrystalline sculpting wax appears promising for simulating living positions of planispiral and heteromorph species. Of the heteromorphs tested, orthocones and torticones show virtually identical orientations throughout growth, while elliptically coiled gyrocones and hamiticones have a constantly changing apertural position during growth. All heteromorphs are characterized by high shell stability.

8. Based on buoyancy and living position studies, and occurrence patterns both within the Nanaimo Group and on a broader, world-wide scale, it appears that many heteromorph species were adapted to a planktonic habit and habitat, rather than to the benthos, as inferred by many previous writers.

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APPENDIX I

MEASURED SECTIONS

Localities of measured sections presented in this thesis:

Section Number	Locality
75-1a	Browns River
75-1b	Puntlege River
75-2	Trent River
74-1	Tsable River
74-2	Little Qualicum River
75-5	Englishman River
75-4	Nanaimo River
75-5	Elkhorn Creek
75-6	Meade Creek
75-7	Cowichan River
74-3	Saanich
75-8	Pym Island
75-9	Nanaimo River
75-10	Saltspring Island
75-11	South Pender Island
73-1	Stuart Island
73-2	Waldron Island
75-12	Saturna Island
73-3	Orcas Island
73-4	Sucia Island
75-13	Skutz Falls
75-14	Piers Island

	Formation	Zone, Subzone, Zonule	Pym Island (Section 75-8)
423.4	Haslam	Elongatum Zone	Covered by water.
408.0	Haslam	Elongatum Zone	Medium to coarsely-grained sandstones, grey to grey-green in color, average bed thickness 1 m, interbedded with thin shale beds. No fossils.
374	Haslam	Elongatum Zone	Interbedded sandstone and shale, sand-shale ratio approximately 50%, average bed thickness 2 - 4 cm. Fossils rare.
320	Haslam	Elongatum Zone	Interbedded sandstones and shales (turbidites), sand-shale ratio approximately 30%, bed thicknesses of 2 - 4 cm, most beds commence with Bouma C. Large, ellipsoidal, non-septarian concretions present in shales. Fossils rare.
246	Haslam	Elongatum Zone	Thinnly interbedded sandstones and shales (turbidites), sand-shale ratio of approximately 10 - 20%. Most beds 1 - 2 cm thick, commence with Bouma C. Small, non-septarian limestone concretions common. Fossils common on bedding planes of shales.
215	Haslam	Elongatum Zone	Thinnly interbedded sandstones-shales, sand-shale ratio approximately 10 - 20%. Large, ellipsoidal limestone concretions and light grey limestone interbeds. Fossils common in shales.
197	Haslam	Elongatum Zone	Thinnly interbedded sandstones and shales (turbidites). Bed thickness averages 3 - 7 cm, occasional thicker sandstone beds up to 1 m in thickness. Majority of beds commence with Bouma C division, thicker sandstones commence with Bouma A division. Fossils rare to common.
185	Haslam	Elongatum Zone	Thinnly interbedded sandstones and shales (turbidites), sand-shale ratio approximately .6, bed thicknesses average 5 - 15 cm. Most beds commence with Bouma C division. Fossils rare to common.

	Formation	Zone, Subzone, Zonule	Pym Island (continued)
129	Haslam	Elongatum Zone	Thinnly interbedded sandstones and shales (turbidites), sand-shale ratio approximately .3, bed thicknesses average 2 - 6 cm, majority of beds commence with Bouma division C. Interbedded limestone concretions and thin layers present. Fossils common.
98	Haslam	Elongatum Zone	Thinnly interbedded sandstones and shales (turbidites), sand-shale ratio .5, average thickness of bed 2 - 4 cm. Fossils common.
64	Haslam	Elongatum Zone	Interbedded sandstones and shales (turbidites), average bed thickness 2 - 4 cm, sand-shale ratio approximately .3. Bouma divisions CD predominate. Fossils common.
20	Haslam	Elongatum Zone	Interbedded sandstones and shales (turbidites). Sandstone beds up to .5 m in thickness, sand-shale ratio approximately .7. Fossils rare. Beds initiate with Bouma division C, rare Bouma A.
0	Haslam	Elongatum Zone	Interbedded sandstone and shales (turbidites), sand-shale ratio approximately .5, bed thicknesses 4 - 10 cm. Fossils rare.
			Base of section covered by water.
			Nanaimo River (Section 75-4)
297			Covered by alluvium.
258	Haslam	Schmidti Zone	Interbedded sandstone and siltstone. Sandstones are medium to finely grained, poorly sorted, grey in colour. Contact with subjacent unit is markedly channelled. Bed thicknesses average 10 cm - 1 m. No fossils.
252	Haslam	Schmidti Zone	Siltstone, thinnly bedded, average bed thickness 10 - 20 cm. No fossils.
248	Haslam	Schmidti Zone	Sandstone, medium to finely grained, bed thicknesses 20 cm to 1 m. Interbedded with thin siltstone and shale beds. No fossils.

	Formation	Zone, Subzone, Zonule	Nanaimo River (continued)
215	Haslam	Schmidti Zone	Shale, with numerous septarian concretions which show pyritization. No fossils.
106	Haslam	Schmidti Zone	Interbedded sandstones and siltstones, thinnly interbedded. Bed thicknesses average 10 to 50 cm. Large and small inocerami, pachydiscids common.
63	Haslam	Schmidti Zone	Siltstones, thinnly bedded with occasional medium to fine-grained sandstone interbeds. Average bed thicknesses of 5 - 10 cm. Large and small inocerami, pachydiscids common.
57	Haslam	Elongatum Zone	Sandstone, fine-grained, thinnly bedded, concretionary. Bed thicknesses average 10 - 20 cm. Rare lenses of pebbles interbedded with sands. Fossils common.
14	Haslam	Elongatum Zone	Interbedded sandstones and siltstones, concretionary. Bedding thicknesses average 5 - 10 cm. Fossils common.
11	Haslam	Elongatum Zone	Sandstone, finely grained, thinnly bedded, concretionary. Fossils rare.
0	Comox	Elongatum Zone	Sandstone, coarsely grained, grey-green in colour, occasional large cobbles and pebbles in sandstone matrix.
Base			Conglomerate, poorly sorted, comprised of pebbles to boulders, grey sandstone matrix.
			North Pender Island (Section 75-13)
425	De Courcy		Top of section, base of De Courcy Formation.
340			Covered.
186	Cedar District	Rex Zonule	Interbedded siltstones and sandstones (turbidites), sand beds 2 - 10 cm thick, show ripple drift. Shales and sands show numerous horizontal burrows. Beds can be characterized by Bouma CD and CE divisions. Large Inoceramus present.
184	Cedar District	Rex Zonule	Sandstone, massive, medium-grained, non-graded.

	Formation	Zone, Subzone, Zonule	North Pender Island (continued)
100	Cedar District	Rex Zonule	Interbedded sandstones and shales (turbidites), thinnly bedded, sandstone beds average 2 - 4 cm in thickness, sand-shale ratio approximately .5. Fossils rare.
98	Cedar District	Rex Zonule	Sandstone, massive, medium-grained. No visible sedimentary structures.
62	Cedar District	Rex Zonule	Interbedded sandstones and shales (turbidites), sand layers up to 20 cm in thickness, show ripple drift. Sand-shale ratio approximately .5 - .6.
6	Cedar District	Rex Zonule	Interbedded sandstone and shale (turbidites), sandstone beds 2 - 4 cm in thickness, rippled. Sandstones intensively burrowed. Large Pachydiscid ammonites (up to 1 m diameter) moderately common; also Inoceramus.
0	Cedar District	Rex Zonule	Sandstone, massive, medium to coarsely grained, beds up to 5 m thick, show channelled bases.
			Base of section, covered by water.

	Formation	Zone, Subzone, Zonule	South Pender Island (Section 75-11)
1937			Top of section, covered by water.
1910	Cedar District	Pacificum Zone, Rex Zonule	Interbedded sandstones and shales (turbidites), bed thicknesses 5 - 10 cm, occasional medium-grained sandstone interbeds up to .5 m in thickness. Base of sand beds broadly undulating to form channels with E-W trending axes.
1839	Cedar District	Pacificum Zone, Rex Zonule	Shales, interbedded with rare sandstone beds up to 10 cm thick. Sandstone beds strongly rippled. Shales contain calcareous concretions. Baculites common on bedding planes.
1655	Cedar District	Pacificum Zone	Sandstone, massive, medium to coarsely grained, bed thicknesses average 1 - 5 m, bases of beds strongly channelled.
1537	Cedar District	Pacificum Zone	Interbedded sandstones and shales (turbidites). Sandstones show ripple-drift lamination, convolute lamination. Bed thin, average 2 - 10 cm, sand-shale ratio approximately 50%.
1429	Cedar District	Pacificum Zone	Sandstone, massive, medium to coarsely grained, bases of beds strongly channelled. Fossils absent. Bed thicknesses up to 5 m. Sandstones interbedded with thin shales.
1337	Cedar District	Pacificum Zone	Interbedded sandstones and shales (turbidites), sand-shale ratio approximately .5, beds average 5 - 10 cm in thickness. Fossils rare. Beds can be characterized by Bouma CD and CE divisions.
1152	Cedar District	?	Sandstones, massive, coarsely grained, interbedded with pebble conglomerates. Bases show channelling into underlying beds.
1107	Cedar District	?	Shale, with rare interbeds of fine grained sandstone. Poorly exposed.
1072			Covered.
931	Cedar District	?	Interbedded sandstones and shales (turbidites), sandstone layers up to .3 m thick, approximately .3 to 2 m apart. Sandstones are bluish-grey in colour, poorly sorted, medium to fine grained, with high clay fraction. Fossils rare or absent.

	Formation	Zone, Subzone, Zonule	South Pender Island (continued)
858			Covered.
792	Cedar District	Vancouverense Zone	Interbedded sandstones and shales (turbidites), sandstone layers up to .3 m thick, show ripple-drift lamination. Beds mainly Bouma CD and CE.
784	Cedar District	Vancouverense Zone	Shale, concretionary, with interbedded sandstone layers averaging 2 - 3 m apart, up to .5 m thick. Shales have sand disseminated, appear intensively bioturbated. Fossils rare.
643	Protection	?	Sandstone, massive, whitish to buff in colour, non-graded, bases of beds, where distinct, show channelling into underlying beds. Sandstones show distinct honeycomb weathering. No fossils.
628			Covered.
597			Sandstone, massive, whitish to grey to buff, channelled bases. No fossils.
594	Ganges	Chicoense	Siltstone, fairly massive, pale blue, thin limestone interbeds and concretionary layers. Poorly sorted, with fine sand disseminated throughout. Fossils common to abundant.
563			Covered.
538	Ganges	Chicoense	Siltstone, blocky and massive, poorly bedded. Fossils common.
505	Extension	?	Sandstone, coarsely-grained, poorly sorted, buff to tan in colour, variable bedding thicknesses, interbedded pebble conglomerate layers.
462	Extension	?	Conglomerate, matrix greenish, calcareous, sandy; conglomerate clasts poorly sorted cobbles and pebbles, poorly developed cross-bedding.
405			Covered.
378	Extension	?	Conglomerate, pebbles to cobbles, matrix red in colour. Conglomerate clasts poorly sorted, well-rounded, mainly granitics.
332			Covered.

	Formation	Zone, Subzone, Zonule	South Pender Island (continued)
	?	?	Conglomerate, pebbles and cobbles, reddish matrix.
288	Extension	?	Siltstones, grey in colour, numerous pebbles scattered throughout, trough cross-bedding.
257	Extension	?	Conglomerate, comprised of cobbles and boulders, matrix red in colour.
215	Extension	?	Interbedded conglomerate and sandstone. Conglomerate composed of pebbles and cobbles. Sandstones coarse-grained, poorly sorted, grey in colour.
123	Extension	?	Conglomerate, comprised of red matrix, and cobbles to boulders. Large-scale cross-bedding, indicating westward paleocurrents. No obvious orientation to clasts in conglomerate.
92			Covered.
65	Extension	?	Conglomerate, comprised mainly of cobbles in green sandstone matrix. Clasts rounded, well sorted.
46			Covered.
8	Haslam	Elongatum ?	Shale, interbedded with siltstones and sandstones. Sandstones are graded, but flute marks are absent. Fossils rare.
0	Haslam	Elongatum ?	Sandstone, massive, light grey in colour, poorly sorted, mainly medium to finely grained.
			Base of section, covered by water.

Level	Formation	Zone	Skutz Falls (Section 75-13)
65			Covered by alluvium (top of section)
49	Haslam	Schmidti	Sandstone, medium-grained, poorly sorted, thinnly bedded (average thickness 2-10 cm). Broken shell material common.
3	Haslam	Schmidti	Interbedded sandstone and siltstone, sand-shale ratio approximately .5, bed thicknesses average 4-10 cm, concretionary. Base of sandstones channelled; sandstone beds occasionally show grading (Bouma division). *A. inoceramus* common.
0	Haslam	Schmidti	Sandstone, fine-grained, poorly sorted, greyish-green in colour, thinnly bedded. Beds average .5 to 1 m in thickness. No fossils. Covered by alluvium.
			Marie Canyon, Cowichan River (Section 75-7)
432			Top of section - covered by alluvium.
268	Haslam	Schmidti	Interbedded sandstones and shales (turbidites). Sand-shale ratio approximately .6, sandstone bed thicknesses up to 1 m. Beds characterized by Bouma divisions ACD and CD, sole marks common on undersides of beds, climbing ripple drift and convolute lamination common in C division beds. Base of beds characterized by large-scale (5 - 10 m wave-length) channelling. Sole marks show predominantly EW and WE paleocurrent directions. Fossils rare.
263	Haslam	Schmidti	Interbedded sandstones and shales (turbidites). Sandstone-shale ratio approximately .7 to .8, sandstone beds graded, average .5 to 1.5 m in thickness, contain small pebbles and shell debris. Sole marks common, Bouma division AC beds predominate.
252	Haslam	Schmidti	Interbedded sandstones and shales (turbidites), sand-shale ratio approximately .5, bed thicknesses average 4 to 50 cm.
126	Haslam	Schmidti	Interbedded sandstones and shales (turbidites), sandstone medium to coarsely grained, shale fisile, bed thicknesses average 2 - 10 cm, sand-shale ratio approximately .5, sole marks common on base of sand beds, beds characterized by Bouma divisions AC and ABC, climbing ripples, convolute lamination in C division beds. Fossils rare.

Level	Formation	Zone	Marie Canyon (Continued)
31	Haslam	Schmidti	Sandstone shale (turbidites), sand-shale ratio approximately .3, bed thicknesses average 4 - 10 cm, shale is silty, laminated in appearance. Beds characterized by Bouma divisions CD or CE, no sole marks or graded bedding.
0	Haslam	Schmidti	Siltstone, interbedded with thin sandstone beds. Concretions present. Sandy interbeds graded, show channelled contacts with underlying siltstones. Sandstones 2 - 4 cm thick. Base of section covered by alluvium.
			Piers Island (Section 75-14)
770			Top of section, covered by water.
738	Haslam	Elongatum	Interbedded sandstones-shales (turbidites), sand-shale ratio approximately .7, bed thicknesses average 10 - 50 cm, beds characterized by Bouma divisions CD, sandstones contain climbing ripple drift. Fossils rare. Sandstones medium to coarsely grained.
701	Haslam	Elongatum	Interbedded sandstones-shales (turbidites), sand-shale ratio approximately .2 to .4. Beds thin (4 - 6 cm), characterized by Bouma CD divisions, sandstones finely grained.
579			Covered by alluvium.
480	Haslam	Elongatum	Sandstone, massive, medium to coarsely grained, occasional thin shaley interbeds. Plant material present on bedding planes.
473			Covered.
388	Haslam	Elongatum	Sandstone, massive, grey in colour, medium to coarsely grained with interbedded lenses of pebble conglomerate.
370			Covered.
358	Haslam	Elongatum	Conglomerate, poorly sorted, comprised of pebble- and cobble-size clasts in grey sandstone matrix. Most clasts are dark metamorphic rocks and mafic igneous rocks; little granitic, gneissic or quartzy components. Sorting poor.

Level	Formation	Zone	Piers Island (Continued)
320	Haslam	Elongatum	Sandstone, grey, interbedded with siltstones. Bases of beds are channelled.
261			Covered.
253	Haslam	Elongatum	Shale, thinnly bedded, no sandstone interbeds.
247			Covered.
227	Haslam	Elongatum	Interbedded sandstone and shale (turbidites), bed thicknesses 4 - 8 cm, characterized by Bouma CD divisions, fossils common.
221	Haslam	Elongatum	Sandstone, massive, thin lense of pebbles near base, little bedding apparent.
215	Haslam	Elongatum	Interbedded sandstones and shales (turbidites), thinnly bedded, predominantly Bouma divisions CD, fossils rare.
128			Covered.
34	Haslam	Elongatum	Interbedded sandstones and shales (turbidites), bed thickness averages 4 - 8 cm, beds characterized by Bouma CD divisions, sand-shale ratio approximately .3 - .4. Fossils common.
0	Haslam	Elongatum	Interbedded sandstones and shales, bed thicknesses 2 - 4 cm, beds characterized by Bouma CD divisions, sand-shale ratios approximately .2 - .4. Flattened elongated concretions common in shale. Fossils common. Base covered by water.
			Elkhorn Creek (Section 75-5)
			Top of section, covered by alluvium.
65	Haslam	Elongatum	Sandstone, fine grained, massive, poorly sorted, large clay fraction, numerous concretions, fossils common.
45			Covered.
15			Siltstone, thinnly bedded to massive, poorly sorted, concretions common, fossils abundant. Siltstone, massive, concretionary, fossils common.
0	Haslam	Elongatum	Sandstone, thinnly bedded, medium to fine grained, concretionary, fossils common. Base of section - conglomerate, comprised of pebbles and small cobbles, poorly sorted, matrix grey sandstone, fossils absent. Unmeasured thickness.

Level	Formation	Zone & Subzone	Browns River (Section 75-1a)
60			Top of section - intersection with Puntlege River (base of Section 75-2).
32	Haslam	Elongatum (Naumanni Subzone)	Shale, massive, poorly bedded, dark grey, concretionary, hackly fracture, interbedded with sandstone layers up to .5 m thick. Sandstone dykes common, fossils rare to common.
20	Haslam	Elongatum (Naumanni Subzone)	Siltstone, massive, interbedded with occasional sandstone interbeds averaging .1 - .5 m thick, concretionary, sandstone dykes common. Fossils rare to common.
17	Haslam	Elongatum (Naumanni Subzone)	Siltstone, thinnly bedded, interbedded with sandstone layers up to 1 m thick, base of sandstone beds channelled. Fossils rare.
6	Haslam	Elongatum (Naumanni Subzone)	Interbedded siltstones and sandstones, bed thicknesses .1 to 1 m in thickness, no concretions or sandstone dykes, fossils rare. Sandstones poorly sorted, show evidence of intense bioturbation.
0	Haslam	Elongatum (Naumanni Subzone)	Sandstone, fine grained, bed thicknesses average 1 - 2 m, interbedded with thin siltstones. Fossils rare.
			Base of section, sandstones medium grained, massive, bioturbated. Unmeasured thickness of medium to coarse sandstones below this point.
			Puntlege River (Section 75-1b)
			Top of section, covered by alluvium.
185	Ganges	Chicoense?	Shales, massive, dark grey, hackly fracture, concretionary. Fossils absent.
155			Covered.
124	Haslam	Elongatum (Haradai Subzone)	Shale, with silt and sand disseminated throughout, interbedded with fine grained sandstone beds of 2 - 10 cm in thickness, concretionary, numerous sandstone dykes. Base of sandstone interbeds channelled. Fossils common, concretions phosphatic.

Level	Formation	Zone & Subzone	Puntlege River (Continued)
115	Haslam	Elongatum (Haradai Subzone)	Silty shales, interbedded with channelled, fine to medium grained, poorly sorted sandstones averaging 5 - 10 cm in thickness, concretionary layers, composed of phosphatic, argillaceous limestone. Fossils common.
106	Haslam	Elongatum (Subzone Unknown)	Silty shales, massive, hackly fracture, numerous concretions and concretionary layers, interbedded with fine to medium grained sandstone interbeds up to 1 m thick, numerous sandstone dykes, fossils common.
100			Covered.
60	Haslam	Elongatum (Naumanni Subzone)	Silty shales, interbedded with fine to medium grained sandstones up to 1 m thick, sandstone dykes common.
			Base of section - top of Section 75-1a.