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Aspects of the Sedimentology of New Zealand Bryozoans and Mixed Carbonate-Clastic Deposits: a Contribution to the Temperate Shelf Carbonate Model

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"She has been a diver in deep seas, and keeps

their fallen day about her..."

Walter Pater, The Renaissance, 1873

c 1992 Abigail Marion Smith

Abstract

Carbonate sediments are forming on modern shelves in both tropical and temperate latitudes. Temperate shelf carbonate sediments have a distinctive character and, unlike their tropical counterparts, have many poorly understood aspects. Bryozoans are major skeletal components of many temperate carbonate deposits, but very little is known about their sedimentology. Aspects of the sedimentology of New Zealand bryozoans are investigated here. Many temperate carbonates are also closely associated with terrigenous siliciclastic sediments, forming a mixed deposit. A New Zealand example is presented here from the Hauraki Gulf, a semi-enclosed sea in northeastern North Island. The results of these studies are applied to the temperate shelf carbonate model.

Bryozoans are important sedimentologically as producers, stabilizers, encrusters, bioeroders, subjects of diagenesis, and eventually as fossils. Most bryozoans precipitate carbonate at rates of less than 1 g $CaCO_3$/y (mean = 0.07 g $CaCO_3$/y). In the Hauraki Gulf the maximum determined is 0.8 g $CaCO_3$/y and overall production by one bryozoan population is about 24 g $CaCO_3/m^2$/y, generally much less than the few rates published from elsewhere. Bryozoans in New Zealand fall into five mineralogical classes. Calcite may be low-Mg (<3 wt% $MgCO_3$), moderate-Mg (3-5 wt% $MgCO_3$), or high-Mg (5-10 wt% $MgCO_3$). Bimineralic skeletons may be mainly calcite, or mainly aragonite, reflecting two different modes of origin: developmental bimineralism, with discrete age-related layers, or diagenetic bimineralism, where metastable aragonite alters over time. Carbonate mineralogy is most closely linked to higher taxonomic order, while bryozoan colonial growth form is weakly correlated. Isotopes ($\delta^{18}O$ and $\delta^{13}C$)and co-precipitates (Ca, Mg, Sr, Fe, Mn) in bryozoan carbonate are related to mineralogy, taxon, water depth, and degree of terrigenous mixing. Bryozoans precipitate carbonate close to isotopic equilibrium with sea water, and thus reflect their temperate climate.

After death, bryozoan carbonate is subject to abrasion, bioerosion, and dissolution. Different bryozoan colonial growth forms are more or less resistant to abrasion, and the less resistant forms may produce large quantities of carbonate mud. Bryozoans are active in biological diagenesis, as borers, encrusters, and as substrate. Dissolution of bryozoans depends on mineralogy and on morphology. Depth, hydraulic energy, and substrate are all important controls on bryozoan distribution and on diagenesis. Bryozoan assemblages, therefore, reflect these environmental factors. Destructive diagenesis reduces and limits this relationship.

Sediments in the Hauraki Gulf are highly variable spatially, and are a good example of *in situ* mixing of terrigenous and biogenic material. Four sediment facies are described: high-carbonate gravel (64% $CaCO_3$), muddy sand (38% $CaCO_3$), sand (31% $CaCO_3$), and mud (15% $CaCO_3$). The patchy distribution of these facies is controlled by water depth, water energy, source of sediment, and by substrate availability. Bivalves are the dominant carbonate-producers, with bryozoans, gastropods, and barnacles subdominant. Holocene sea-level rise has reworked sediments, and much is palimpsest. The degree of carbonate-clastic mixing appears to influence temperate assemblage in New Zealand carbonates, such that foramol and mollusc assemblages predominate when terrigenous material is abundant, while the bryomol assemblage is more common in high-carbonate settings.

Early marine diagenesis of temperate carbonates includes constructive and destructive processes, but destruction predominates. Abrasion is controlled by hydraulic energy, and indirectly by climate. Biological diagenesis is evident in Hauraki Gulf shells, and operates on a time scale of 100s to 1000s of years. Bioerosion is controlled by biota, thus by environment and climate, and by substrate. Carbonate mud may indicate its origin by mineralogy or by particle morphology. Dissolution is controlled by sea-water chemistry, and the mineralogy and morphology of grains. Constructive processes such as encrustation and local cementation do occur in temperate shelf sediments. Nevertheless, most temperate carbonates, including bryozoan-dominated ones, are subject mainly to destructive processes, often over a long time due to low sediment accumulation rates. Temperate carbonates thus may have a relatively low preservation potential, and could be under-represented in the fossil record.

Extended Abstract

This thesis investigates aspects of modern temperate shelf carbonate sediments from New Zealand. Temperate carbonates, unlike their tropical counterparts, have many processes about which little is known. An important aspect in which temperate carbonates are different from tropical ones is the skeletal biota. Organisms that produce $CaCO_3$ in temperate waters tend to be bryozoans, molluscs, and foraminifera (the bryomol and foramol assemblages), fundamentally different from the predominantly green algae and corals (chlorozoan assemblage) of tropical carbonates. Of the major temperate carbonate-producers, bryozoans are by far the least studied, particularly from a sedimentological viewpoint. Another distinctive character of temperate carbonates is that they are seldom wholly carbonate. The association of terrigenous or siliciclastic sediment with carbonate bryomol and foramol assemblages is typical of temperate carbonates.

The New Zealand shelf, at 33° to 49°S latitude, covers a wide range of the temperate zone. Although most of the shelf sediments are predominantly terrigenous, reflecting the tectonic position of the country astride an actively converging plate margin, two large (each >10,000 km^2) carbonate deposits and several smaller concentrations occur. New Zealand shelf carbonates are entirely skeletal, dominated by bryozoans and molluscs (the bryomol assemblage), and usually mixed to some degree with land-derived siliciclastic sediment. New Zealand shelf sediments are excellent subjects for study of temperate carbonates, particularly for this study of bryozoans and carbonate-clastic mixtures.

The thesis is divided into three parts. The first discusses some sedimentological aspects of bryozoans in New Zealand, the second examines in detail a representative New Zealand shelf carbonate deposit in the Hauraki Gulf (northeastern North Island, New Zealand), and the third explores the temperate shelf carbonate model, particularly with respect to bryozoans and carbonate-clastic mixtures.

Bryozoans, like many marine organisms, precipitate $CaCO_3$ in an organized exoskeleton. Although growth rates are known for some bryozoans, either as increases in zooid number over time or increases in size, little is known about calcification rates. An attempt is made here to recalculate published data to determine production rates of bryozoan carbonate. Most studied bryozoans calcify at less than 1 g $CaCO_3$/y, although in ideal conditions individuals may produce up to 46 g $CaCO_3$/y. An *in situ* study carried out at 14 m water depth at Cape Rodney in Hauraki Gulf gives even slower rates: many species produce less than 0.05 g $CaCO_3$/y, although the mean is 0.07 g $CaCO_3$/y. The highest rate of production recorded was about 0.8 g $CaCO_3$/y. Over the area of the experiment, total bryozoans produced carbonate at a rate of 24 g $CaCO_3/m^2$/y. This is much less than other published sediment production rates for bryozoans (100 to 8000 g/m^2/y). A comparison of the living fauna on the submerged wreck *Rainbow Warrior* with sediments around the wreck indicates that in the four years since its sinking, little bryozoan material from the wreck has been deposited into the adjacent bottom sediments. Bryozoans die and produce sediment through senility, predation, competition, abrasion, or environmental change. Slow production of $CaCO_3$ by bryozoans is reflected in the long time it takes for them to register in the bottom sediment.

Bryozoan skeletons may be calcite, aragonite, or both. 48 New Zealand species were collected from a range of shelf locations and depths, and their mineralogy determined using x-ray diffraction (XRD) . The use of multiple analyses allowed for an investigation of sources of variation. There is more variation among populations than within colonies and within populations. No systematic trend with latitude or depth was found. Five categories were found to include all New Zealand specimens: low-Mg calcite (<3 wt% $MgCO_3$), moderate-Mg calcite (3 to 5 wt% $MgCO_3$), high-Mg calcite (>5 wt% $MgCO_3$), bimineralic/calcite (50 to 100% calcite), and bimineralic/aragonite (0 to 10% calcite). The two bimineralic classes have different causes, developmental (bimineralic/calcite) and diagenetic (bimineralic/aragonite). In the former case, calcite

is first precipitated, then an aragonite layer as secondary strengthening. In the diagenetic case, metastable aragonite begins to slowly change to calcite. Mineralogical variation is linked to major bryozoan taxa. Cyclostomes are low to moderate-Mg calcite. Cheilostomes are more variable, with anascans having an overall lower Mg content than ascophorans. Some colonial growth forms have fairly consistent mineralogies, others are more variable (particularly encrusting forms). State of preservation of bryozoan skeletons was not found to have an effect on their mineralogy. Bryozoans cover a wide range of mineralogies, and the mineralogy of bulk sediments made up of bryozoans must vary considerably, depending on what bryozoans they contain.

Marine carbonates are seldom pure $CaCO_3$. Co-precipitation of small amounts of other elements from sea water is common. 92 New Zealand bryozoans were tested using atomic absorption (AA) for Mg, Sr, Mn, and Fe. Mn and Sr contents are strongly related to mineralogy and taxon of bryozoans. Fe and Mn increase with increasing terrigenous mixing in sediments. The same specimens were analyzed for oxygen ($\delta^{18}O$) and carbon ($\delta^{13}C$) stable isotopes using mass spectrometry. Bryozoans secrete $CaCO_3$ near isotopic equilibrium with sea water, so that the $\delta^{18}O$ composition of New Zealand bryozoans reflect their water temperature and therefore the temperate climate. Mineralogy is related to isotopic ratios, the aragonitic bryozoans being enriched in both isotopes relative to calcitic ones. $\delta^{18}O$ values of bryozoan skeletons increase with water depth, reflecting cooler temperatures.

After bryozoan carbonate is deposited, it is subject to a range of diagenetic processes. Early sea-floor diagenesis, here taken to include abrasion, bioerosion, encrustation, and dissolution, takes place at or near the sediment-sea water interface. The role and response of bryozoans in physical, biological, and chemical diagenesis have been investigated. In a tumbling experiment, different bryozoan growth forms were found to respond differently to abrasion. In additon, old and degraded skeletons were more susceptible than fresher ones. This limits their use as indicators of transport or age,

and may bias the fossil record. Some bryozoans subject to abrasion may produce large quantities of carbonate mud; almost 50% of multilaminar encrusting forms were converted to mud in 127 h tumbling. Bryozoans may be agents of biological diagenesis, as encrusters or as borers. As substrate, they may be encrusted or overgrown, and may also be subject to bioerosion. Little bioerosion occurred over the course of a year's immersion in sea water in the free-living *Otionella squamosa*. A laboratory acid-bath experiment was run to determine the influences on dissolution rate of bryozoans. Morphology, mineralogy, and initial size were found to be important predictors of dissolution history. Bryozoans that were small, delicate, and aragonitic dissolved faster than large, compact, calcitic ones. The traditional assumption that mineralogy alone affects dissolution rate must be widened in bryozoans to include morphology. The fossil record is likely to reflect both influences.

In the context of temperate carbonate sediments and temperate limestones, bryozoans are important as producers of carbonate, stabilizers of sediment, encrusters and bioeroders, subjects of diagenesis, and eventual fossils. A qualitative budget for bryozoans as sediment indicates that carbonate produced is often greater than that deposited, and that diagenetic processes may account for the disparity. Bioerosion, abrasion, and dissolution are all important in reducing bryozoan carbonate available for lithification. Environmental interpretation of bryozoan faunas is described. Study of Hauraki Gulf faunas indicates that depth, hydraulic energy, and substrate character and extent are important controls on the distribution of bryozoans. The effect of diagenesis in temperate waters is mainly to remove information from the ultimate fossil record. Bryozoans are not particularly strong, and are susceptible to abrasion. The interaction of habitat choice and variability in resistance to abrasion results in distinctive faunas in areas of different degrees of hydraulic energy. Low-energy faunas may be retained intact, but high-energy faunas may be represented only by fragments of the strongest forms. The extent of bioerosion of bryozoans is unknown, but is likely to enhance the destructive effects of abrasion and dissolution. Mineralogy and morphology both affect dissolution history, both early sea-floor

dissolution and later diagenetic dissolution. The interaction of these processes is discussed, and theoretical resultant faunas described. Several of these are found in New Zealand Tertiary limestones, and the combination of paleoenvironmental interpretation with diagenetic change is used to explain fossil faunas.

A second aspect of temperate carbonates, that of mixing of carbonate and clastic sediments, is explored in an investigation of the sediments in the Hauraki Gulf. Small patches of carbonate were sampled and studied as to texture, biota, carbonate content, and age. These were used to determine four sediment facies. The majority of the area of the Gulf is blanketed by a muddy sand, with about 30% carbonate. In several small patches, a high-carbonate (>60%) gravel facies is found. This facies coincides with both topographic highs and high-velocity tidal currents, suggesting that water energy is a distributional control. A terrigenous sand facies is found near shore, and a mud facies occurs in more sheltered areas to the south. Substrate type appears to be a primary control on biota, in which bivalves are dominant, but bryozoans, barnacles, and gastropods are subdominant. Bulk skeletal sediments range in age from 1750 to 8250 years old, indicating that some are palimpsest sediments, reworked in the late Holocene sea level rise that ended 6,500 years ago.

Biological diagenesis in the Hauraki Gulf was investigated by enclosing bivalve shells in fine mesh and immersing them in the sea for 3 to 12 months. Encrustation was important, and many shells gained weight over time. Bioerosion appeared to outweigh encrustation after longer periods of immersion. Bioerosion is a longer-term process than encrustation. Four bioeroders were identified and described: clionid sponges, green algae, fungi, and some prokaryotes. Season and substrate age affected bioerosion rate, while mineralogy of substrate appeared to have little influence.

Hauraki Gulf is an example of how an alleged incompatibility of carbonate and siliciclastic sedimentation is disproved in many temperate sediments and limestones. *In situ* mixing, where allochthonous terrigenous material is mixed with autochthonous

skeletal carbonate, occurs in the Hauraki Gulf, and other New Zealand carbonates. Generally, low rates of terrigenous supply allow this to occur, as does disequilibrium. Rate of terrigenous supply appears to affect temperate assemblages, with foramol and mollusc sediments occurring in sediments high in terrigenous material, and bryomol sediments requiring lower terrigenous input. Mixing also increases abrasion rate. Mixing in New Zealand Tertiary limestones is described, and two possible lithologies for a hypothetical future Hauraki Gulf formation are proposed. In one case, sea-level rise would result in an upward increase in $CaCO_3$, until the Gulf sediments became those of a typical New Zealand bryomol limestone. If sea level fell or remained the same, such that terrigenous material dominated, the Hauraki Gulf deposit would more likely resemble the Upper Jurassic Redwater Shale of Wyoming, USA, a fine terrigenous deposit with shoestrings and lenses of bivalve-dominated carbonate.

Early marine diagenesis in temperate carbonates is described and several models are proposed. Destructive and constructive processes are identified. Abrasion is wholly destructive, controlled by hydraulic energy, which is only indirectly influenced by climate. Temperate shelf sediments are lacking some of the protective features of tropical ones (e.g., reefs, seagrass beds, rimmed shelves). Mixing with terrigenous sediment increases the effect of abrasion. Biological diagenesis is controlled by biota, which is affected by season, environment, and climate. Substrate "appeal" is another important factor, seen in New Zealand sediments as preferential boring of some bivalves. Biological processes may be destructive (bioerosion) or constructive (encrustation) or both (bioturbation). Abrasion and bioerosion both have been invoked as producers of carbonate mud in temperate carbonates, particularly in the absence of the typical tropical sources (codiacean green algae and inorganic precipitation). Coccolithophores may also form carbonate mud deposits. The difference between these sources may be indicated by their mineralogy, and by SEM examination of particle morphology. Chemical diagenesis is a spectrum, with dissolution and precipitation as end-members. In temperate carbonates, dissolution may predominate. Sea-water chemistry is the primary control, and temperature, pH, salinity, and hydraulic energy

all affect it. Mineralogy, morphology, and porosity of sediment control the response to dissolution. Early cementation is rare in temperate carbonates, but examples of intertidal and sea-floor cementation do occur, both requiring strong agitation and water flow. The temperate skeletal assemblage plays a role in temperate diagenesis. Bryozoans occupy a particularly wide range of mineralogies and morphologies, and consequently have a diversity of responses to diagenetic processes. Overall, temperate bryozoan carbonates are exposed to mainly destructive processes. They are rather vulnerable to these processes, and may be exposed at the sediment-sea water interface for a long time. These carbonates have a lower preservation potential than tropical carbonates, and as a consequence may be under-represented in the fossil record.

Despite the gains made here, much remains to be learned about temperate carbonates. Those of particular interest include: carbonate production rates in different taxa and at different latitudes; representation of living assemblages in sediment, and rates and mechanisms of death and damage; production and fate of carbonate mud; rates of diagenetic processes in nature; effects of grain size, shape, and chemistry on bioerosion; and similarities and differences between polar and temperate carbonates.

Dedicated to the memory of Dr Anne Elliott Smith

and to Dr Arthur C. Smith

with thanks for everything

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Introduction

"The Sea never changes and its works, for all the Talk of men, are wrapped in mystery."
J. Conrad, Typhoon, 1902

A. BACKGROUND

Geologists study modern sediments in order to understand processes and relationships that may be applied to ancient sedimentary rocks. Carbonate sediments have been rather extensively investigated, at least in part because of their occurrence as reservoirs in oil-bearing deposits (e.g., Milliman, 1974; Scoffin, 1987). The resulting shelf carbonate sedimentary models, however, have mainly been based on a few important reef-bearing localities, including the Bahamas, the Red Sea, Bermuda, and the Great Barrier Reef. The consideration of only these reefs, despite their undeniable importance, has led to a one-sided, tropically-biased understanding of carbonate sediments. Tropical carbonates (dominantly made up of coral and algal skeletons, along with extensive inorganically-precipitated carbonate) are considered the norm. Descriptions of carbonate production, mineralogy, geochemistry, and diagenesis have largely been based on these tropical reef carbonate settings.

It has become clear throughout the 1970s and 1980s, however, that the temperate and even polar shelves also contain carbonate deposits, sometimes very extensive, such as those on the southern Australian shelf (Gostin et al., 1988). Research has shown that these are very different from tropical carbonates. Temperate carbonates are entirely skeletal, and the carbonate-producing organisms are usually molluscs, bryozoans, foraminifera, and barnacles. Production, mineralogy, geochemistry, and diagenesis in temperate carbonate shelf sediments are quite different from the processes occurring in tropical reefs. Temperate shelf carbonate sediments are often found mixed with terrigenous siliciclastic sediments, increasing their complexity. The temperate carbonate shelf sediment model (described in detail in Chapter 10) explains some limestones far more accurately than does the more traditional tropical one (e.g., Nelson, 1978).

One of the recurring themes in the temperate shelf carbonate literature is the lack of recognition that temperate carbonates receive. Modern texts (e.g., Morse and Mackenzie, 1990) continue to refer to "carbonates" as though all are tropical reefs. Little or no mention of nontropical carbonates is made in alleged overviews (e.g., Tucker and Bathurst, 1990). Somehow, despite regular publication in major sedimentary journals, the temperate carbonate message is not getting through.

Another common observation by temperate carbonate workers is how little is known about many aspects of temperate carbonate sedimentology. Many areas of the model are still untested or unexplained. It is the aim of this thesis, then, to continue to focus attention on temperate carbonates by exploring aspects of temperate carbonate shelf sediments that are poorly known. Many New Zealand carbonates are dominantly made up of bryozoan skeletons, and most are mixed with terrigenous material to some degree. This thesis will examine these two aspects: bryozoans and mixed carbonate-clastic deposits.

B. BRYOZOANS

Part I of this thesis deals with the sedimentology of bryozoans. Bryozoans are colonial organisms, comprising many small individuals (zooids). In most bryozoans, the zooidal body wall is calcified, so that the colony (or zoarium) that remains after the decay of soft parts is the skeleton. Although geologists are primarily concerned with the dead calcareous skeleton, a basic knowledge of the biology of living bryozoans is relevant.

Bryozoans are suspension-feeders. Many are intertidal; still more live subtidally. The soft parts of normal feeding zooids (autozooids) consist mainly of an open funnel of tentacles (lophophore) and a gut (alimentary canal) (Figure IB.1). Some bryozoans have specialized heterozooids, which may be active in reproduction, protection, locomotion, or cleaning. These heterozooids rely on the autozooids for nutrients.

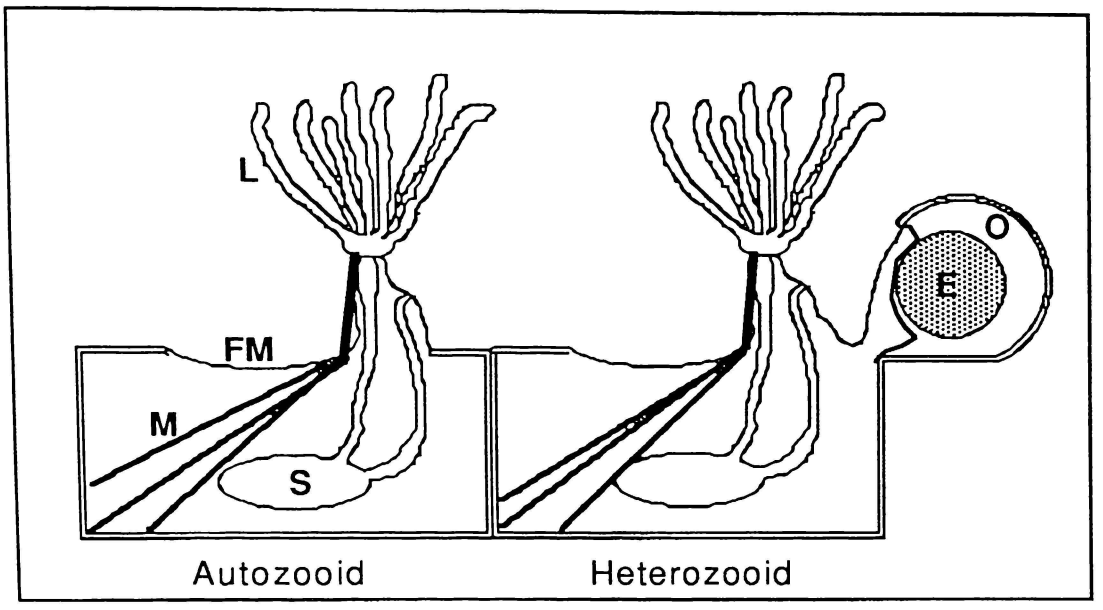


Figure IB.1: Cross-section of generalized anascan cheilostome, showing autozooid and reproductive heterozooid (after Ryland, 1970). Double line indicates zooecium, i.e, the calcified part of the body wall.
E - embryo; FM - frontal membrane; L - lophophore; M - lophophore retractor muscles; O - ovicell; S - stomach.

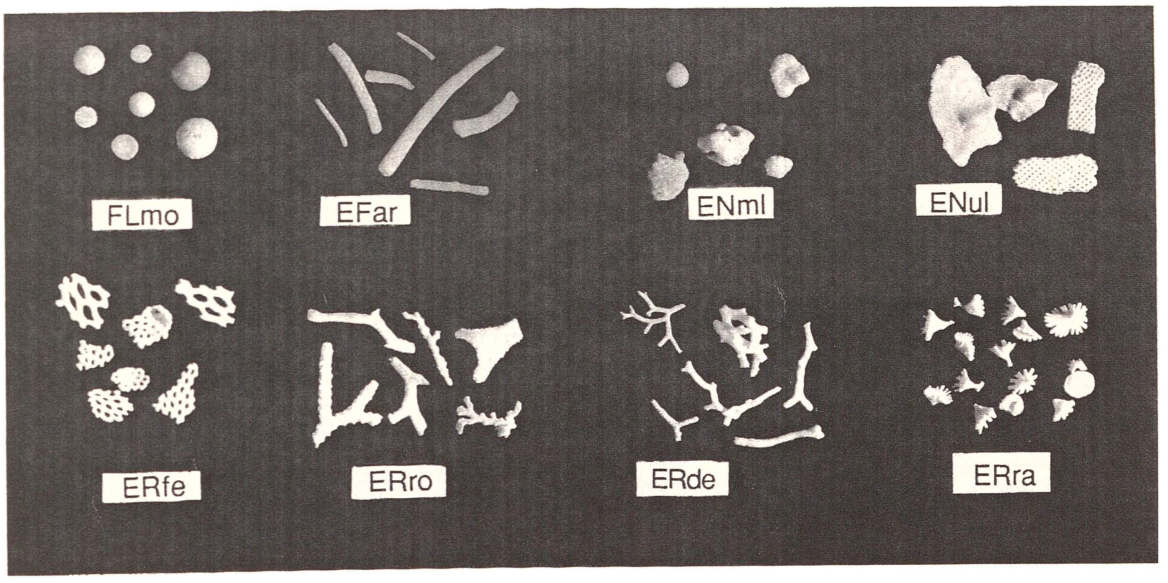


Figure IB.2: New Zealand examples of common zoarial growth forms. Abbreviations defined in Figure IB.3.

A colonial life habit means that a single colony may contain reproductive zooids, newly-added zooids, very old zooids, and dead zooids. This makes the lifespan and growth rate of bryozoans rather difficult to measure.

Zooids have particular features that identify the species, including spines, surface structure, and size and shape of pores. Differentiating species in bryozoans, particularly from damaged or old ones, is difficult. Preparation of bryozoans for identification usually involves removing organic material by bleach or H_2O_2. The organization of the colony, including the arrangement of zooids may also be helpful. There are relatively few types of arrangement found in bryozoans; they are called colonial or zoarial growth forms (Figure IB.2). A complex nomenclature has arisen in bryozoology (summarized in Schopf, 1969). A simpler growth-form classification of bryozoans specifically for the use of geologists has been proposed by Nelson et al. (1988a), adapting earlier schemes (e.g., Stach, 1936). A slightly modified version will be used in this thesis (Figure IB.3).

An encrusting habit is probably most common in bryozoans. Zooids may be attached to a flat surface as runners (uniserial), in a circular disc (radiate), or in sheets (unilaminar). Sometimes they cover a small nucleus with numerous layers (multilaminar). A few species are free-living: they may live rooted in sand or they may be quite unattached and may even be motile. Most bryozoans, however, are attached. Among erect growth forms, colonies may be rigid or flexible. Flexible growth forms may be made up of short branches with flexible nodes (articulate) or of a group of rigid branches attached only at the base (rooted). Some lightly calcified forms are flexible despite being non-articulate - both delicately branched and foliose types occur. Erect rigid forms may be branching, foliose, fenestrate, massive, or radiate. Each growth form has an abbreviation (as given in Figure IB.3) which will be used throughout the text. Not all the growth forms listed are important contributors to carbonate sediments (e.g., the lightly calcified types, particularly EFde and EFfo).

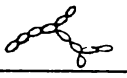
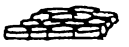
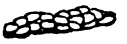
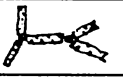
Life habit	Zooid arrangement	Abbrev.	New Zealand example	Schematic diagram
ENCRUSTING	uniserial	ENus	*Platonea sp.*	
	radiate	ENra	*Lichenopora sp.*	
	unilaminar	ENul	*Chaperia acanthina*	
	multilaminar	ENml	*Celleporaria agglutinans*	
ERECT FLEXIBLE	articulated	EFar	*Cellaria immersa*	
	rooted	EFrt	*Steginoporella neozelanica*	
	delicate branching	EFde	*Bugula sp.*	
	foliose	EFfo	*Beania sp.*	
ERECT RIGID	delicate branching	ERde	*Galeopsis porcellanicus*	
	robust branching	ERro	*Adeonellopsis sp.*	
	massive	ERma	*Celleporina grandis*	
	foliose	ERfo	*Arachnopusia unicornis*	
	fenestrate	ERfe	*Hippellozoon novaezelandiae*	
	radiate	ERra	*Telopora buski*	
FREE LIVING	rooted	FLrt	*Conescharellina angulopora*	
	motile	FLmo	*Otionella squamosa*	

Figure IB.3: Classification of bryozoan colonial growth forms (modified from Jackson, 1979 and Nelson et al., 1988a).

The systematic classification of marine bryozoans is complex and ever-shifting. The two main groups, cyclostomes and cheilostomes, are widely separated taxonomically. They both, however, tend to arrange zooids in similar patterns, allowing the growth-form classification given above to transcend taxa. Appendix AI.1 gives the complete taxonomic classification of New Zealand bryozoans mentioned in this thesis. Figure IB.4 gives a summary of the major groups.

Cyclostomes are the more primitive bryozoans, having rather simple tube-like zooecia. The classification of cyclostomes is still under discussion, and identification is difficult. In many cases, New Zealand cyclostomes have been neither identified nor described (e.g., Gordon, 1984, 1986, 1989). These genera have sometimes been used without a specific name, as the focus of this thesis is not taxonomic.

Cheilostomes, the more advanced group, are traditionally divided into two groups based on the presence or absence of an internal sac (an ascus) for the hydrostatic control of extruding or withdrawing the lophophore. Anascans (comprising the Malacostegina, Neocheilostomina, and some smaller suborders) and ascophorans (Ascophorina) are two commonly-used names for these morphological groups.

When bryozoan species names have been quoted from the literature, they have been referred to as such, even if nomenclatural changes have been made since then. In the text and in figures and tables, scientific names are, of course, italicized. Although non-Latin parts of the names such as "sp." should not be italicized, they are in tables herein because the worksheet program used to produce the tables is unable to change font in mid-entry.

Chapter 1 begins by looking at calcification and carbonate production by bryozoans - a very little-known aspect of their sedimentology. Chapters 2 and 3 explore the chemistry of bryozoan carbonate; its carbonate mineralogy, trace element geochemistry, and stable isotope chemistry. Chapter 4 considers three destructive processes that

PHYLUM	CLASS	ORDER	SUBORDER	SUPERFAMILY or INFRAORDER
Bryozoa	Phylactolaemata FRESHWATER			
	Stenolaemata	Cyclostomida	Tubuliporina	Tubuliporoidea
			Articulina	Crisioidea
			Cancellina	Horneroidea
			Rectangulina	Lichenoporoidea
		Cystoporida EXTINCT		
		Trepostomida EXTINCT		
		Cryptostomida EXTINCT		
	Gymnolaemata	Ctenostomida NOT CALCIFIED	Malacostegina	Membraniporoidea
			Scrupariina	Scruparoidea
		Cheilostomida	Neocheilostomina ("Anascans")	Calloporoidea
				Buguloidea
				Microporoidea
				Cellarioidea
			Ascophorina ("Ascophorans")	Cribriomorpha
				Hippothoomorpha
				Umbonulomorpha
				Lepraliomorpha

Figure IB.4: Higher systematics of bryozoans. Non-marine and uncalcified groups shaded. See Appendix Table AI.1 for details.

modify bryozoan carbonate after deposition: abrasion, bioerosion, and dissolution. Applications of these results and a discussion of theoretical aspects of these subjects are given later, in Chapter 11.

C. THE HAURAKI GULF: MIXED CARBONATE-CLASTIC SEDIMENTS

New Zealand sits astride the convergent boundary between the Pacific and Indo-Australian plates, and consequently is a high-relief landmass (up to 12 00 m), with locally high rainfall (mean rainfall in the Hauraki Gulf area is 1165 mm/y). The potential for erosion is considerable. Most of the New Zealand shelf is thus blanketed by land-derived terrigenous or siliciclastic sediment (Carter, 1975). Two extensive carbonate deposits at the northern and southern extremes of the country (Three Kings Plateau and Snares Platform, respectively) are generally rather distant from major terrigenous sediment sources. Other more restricted carbonate-rich localities may be associated with more terrigenous material, and the relative percentages may vary considerably over small areas (e.g., Wanganui, Hauraki, Otago).

The Hauraki Gulf, located east of Auckland City on the North Island (Figure IC.1), is one such mixed deposit. The outer Gulf, particularly, has patches of sediment that are up to 95% $CaCO_3$. Nearby are muddy sands with less than 30% $CaCO_3$. Part II of this thesis investigates the carbonates of the outer Hauraki Gulf, their character, distribution, texture, and age. Chapter 5 gives an overview of the Gulf, while Chapters 6 and 7 describe sediment characteristics and define sedimentary facies. Chapter 9 summarizes the work on Gulf sediments and, later, Chapter 12 discusses the Gulf in the context of carbonate-clastic mixtures worldwide.

Bioerosion appears to be one of the most active early diagenetic processes on New Zealand shelves (Nelson et al., 1988b). A study of bioerosion rates in the Hauraki Gulf is reported in Chapter 8; early marine diagenesis of temperate carbonates generally is discussed more fully in Chapter 13.

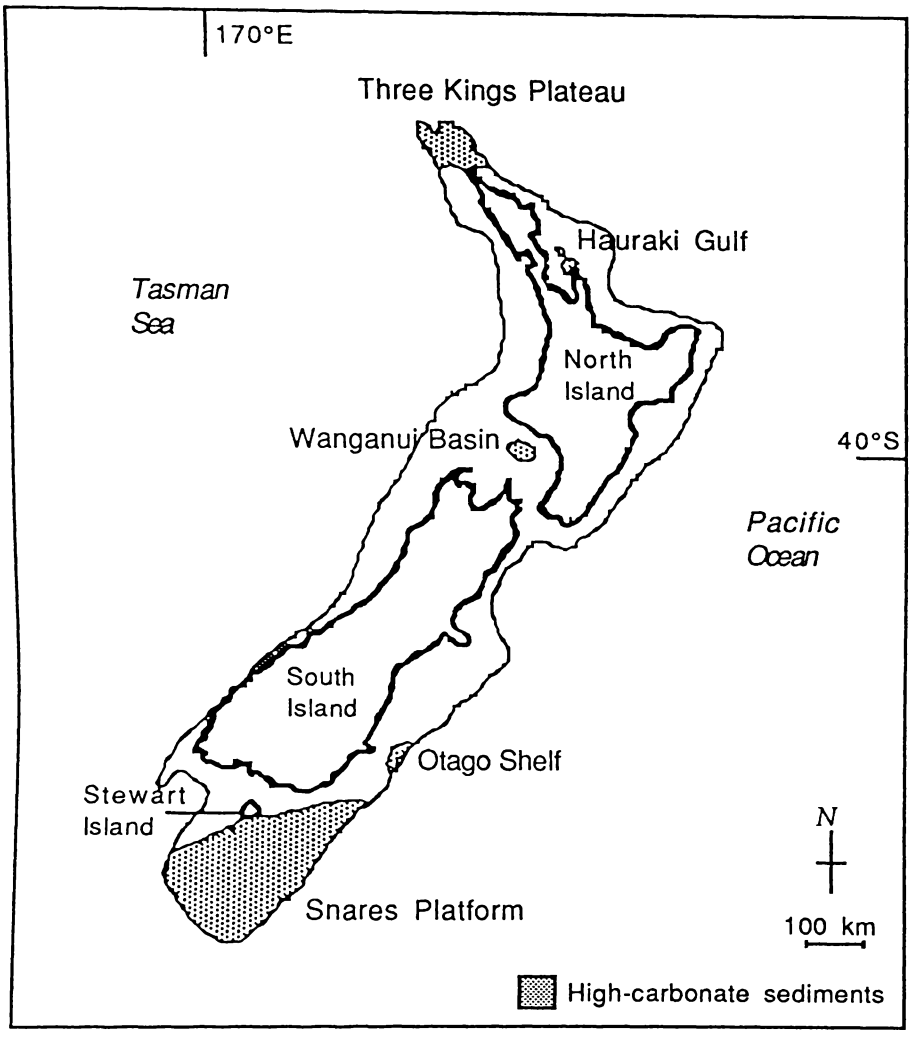


Figure IC.1: Map of New Zealand, showing approximate shelf break (about 200 m water depth) and high-carbonate shelf sediments (after Nelson et al., 1988b, figure 1).

D. ORGANIZATION

The thesis is divided into three parts, dealing with bryozoans (Part One), Hauraki Gulf sediments (Part Two), and their implications for the temperate shelf carbonate sediment model (Part Three). Chapters are sequentially numbered, with major sections lettered. Figures and tables are given the chapter number (or I for Introduction) and section letter as well as a sequential number within the section (i.e., Figure 1B.6 is the sixth figure in section B of Chapter 1). Many data tables and a few figures have been relegated to the Appendix; they are identified with A for appendix followed by the chapter number and a sequential number (i.e., Appendix Table A6.3 is the third appendix table for Chapter 6).

Abbreviations have been used sparingly. When necessary, they are identified the first time used, and again in Appendix Table AI.2.

In most cases, methodology is given in each chapter, as appropriate. If cumbersome, methodological detail is given in Appendix AI.3.

Part One Bryozoans in New Zealand Sediments

Bryozoans are major components of many of New Zealand's shelf carbonates. Despite this, as sediments, bryozoans have not been investigated in detail.

Chapter 1 begins by looking at calcification and carbonate production by bryozoans - a very little-known aspect of their sedimentology. Chapters 2 and 3 explore the chemistry of bryozoan carbonate; its carbonate mineralogy, trace element geochemistry, and stable isotope chemistry. Chapter 4 considers three destructive processes that modify bryozoan carbonate after deposition: abrasion, bioerosion, and dissolution. Applications of these results and a discussion of theoretical aspects of these subjects are given later, in Chapter 11.

Chapter 1 Carbonate Sediment Production by Bryozoans

"They shall build houses, and inhabit them."
Isaiah 65:21, Old Testament, King James Version, 1611

A. INTRODUCTION

The study of carbonate-producing organisms often begins with a description of sediments in which their skeletal remains are found. This sort of description is too late; several important processes have already done their work, and the sediment is the result (Figure 1A.1).

An extremely important process, in fact the birth of skeletal sediments, is calcification. Organisms remove Ca^{2+} and CO_3^{2-} ions from sea water (along with other ions, especially Mg^{2+}) and form calcium carbonate into shell material. This process usually continues throughout the life of the organism as it grows. The process of biological calcification results in a calcium carbonate skeleton, which may be aragonite or calcite or both, and may reflect the environment of growth in its geochemistry.

The skeleton thus produced becomes subject to other forces. Breakage or other damage that does not kill the organism but does contribute some portion of it to the sediment may occur. Eventually death by predation or another cause ends whatever organic protection the living organism may have given its skeleton. The skeleton becomes sediment, subject to the many marine processes of sedimentation, and ultimately perhaps to lithification.

The purpose of this chapter is to examine the processes of calcification and growth, leading to carbonate production, and the processes of death and damage, which lead to the formation of carbonate sediments, particularly with reference to bryozoans. There will be considerable literature review, but this is justifiable as there will be re-interpretation of the biological literature for geological purposes. Experiments with New Zealand bryozoans will be described and discussed.

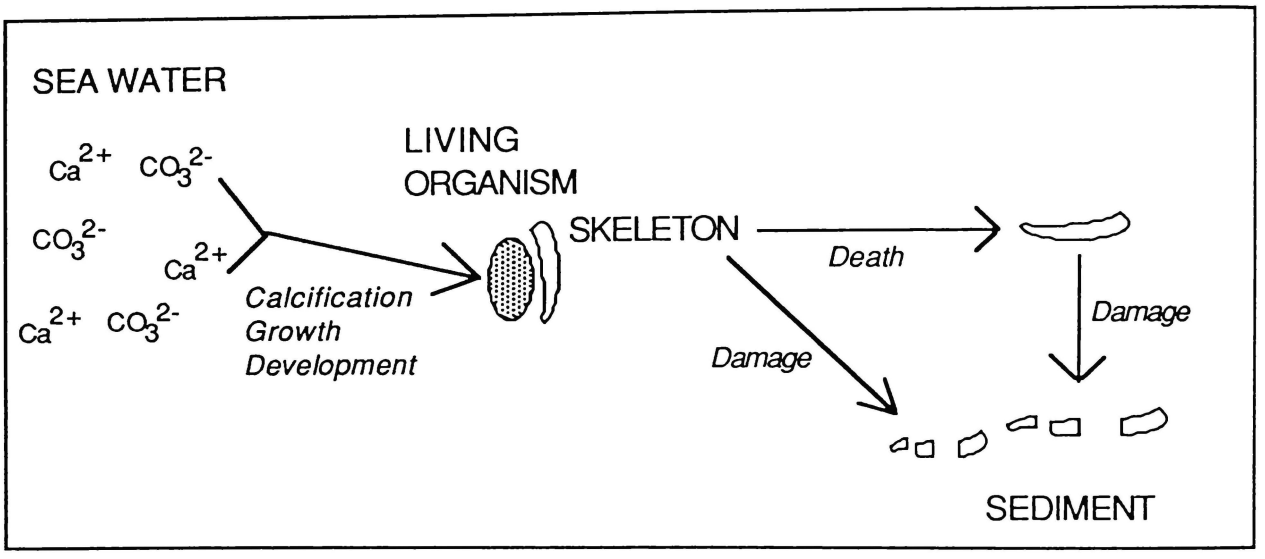


Figure 1A.1: Stages and processes in the formation of skeletal carbonate sediments. Processes in italics.

Production of carbonate can be measured in many ways (e.g., see Smith, 1970; Chave et al., 1972), and it is worthwhile to define the measurements that will be used here. The simplest measurement of calcification is a transformation of total size of the individual taking into account how much of the organism is skeletal. Thus individual carbonate production (ICP) is a simple measurement by weight of the carbonate in an organism at death (or when calcification stops):

$$ICP = (\text{volume in } cm^3)(\text{density: g } CaCO_3/cm^3).$$

If one knows the lifespan of the organism (in y), then the inverse (called turnover; see Smith, 1970) can be used to transform ICP into a production rate. The individual carbonate production rate (ICPR) is thus given in g $CaCO_3$/y, for an individual:

$$ICPR = (ICP)(\text{turnover in } 1/y).$$

In order to summarize the ICPR for an area, population density of the species over the area must be used to generate the areal production rate (APR) in g $CaCO_3/m^2/y$:

$$APR = (ICPR)(\text{population density organisms}/m^2).$$

This is equivalent to potential production (Chave et al., 1972).

The distributionally weighted sum of all the APR's for all the species in the area gives gross production rate (GPR), which can have losses of carbonate from the area subtracted to give net production rate (NPR), also called sedimentation rate (Smith, 1988).

In this chapter, the most common measurement of production as calcification rate will be ICPR. If no turnover rate is available, ICP will be used. Rates of destruction will be presented in % weight lost, wherever possible.

B. CALCIFICATION

1. Calcification by marine invertebrates

Many marine plants and animals secrete a mineralized skeleton. The energy cost of mineralization, which may actually limit body growth and/or reproduction according to Palmer (1981) is matched by the advantages of structure and protection. Calcareous skeletons are most common and, among the invertebrates, they are mainly exoskeletons.

Ca^{2+} and CO_3^{2-} are removed from sea water and transported to the surface cells by intercellular and intracellular pathways. There, $CaCO_3$ is secreted in one of three locations: extracellular, intercellular, and intracellular (Watabe and Kingsley, 1989).

Extracellular calcification takes place on the outer surfaces of cells. Although it may occur within body tissues, forming internal skeletal structures such as spicules, extracellular calcification generally occurs outside the body, resulting in a test or shell. Most major carbonate producers among the marine invertebrates secrete their shell or test extracellularly (e.g., molluscs, barnacles, corals, and bryozoans).

Intercellular calcification is not common. It takes place between cells and usually results in spicules. Intracellular calcification, when $CaCO_3$ is actually precipitated within a cell, may also result in spicules (e.g., gorgonian corals) or in specialized structures which are extruded from the cell (e.g., echinoid spines). Unicellular organisms often have intracellular calcification (e.g., coccolithophores) (Watabe and Kingsley, 1989).

2. Calcification by bryozoans

Within the bryozoans, calcification is extracellular. An outer acellular layer, the cuticle, is produced by the epithelium. It grows into the appropriate shape and $CaCO_3$ is laid down on its inner surface by the epithelium (Figure 1B.1). Decalcification

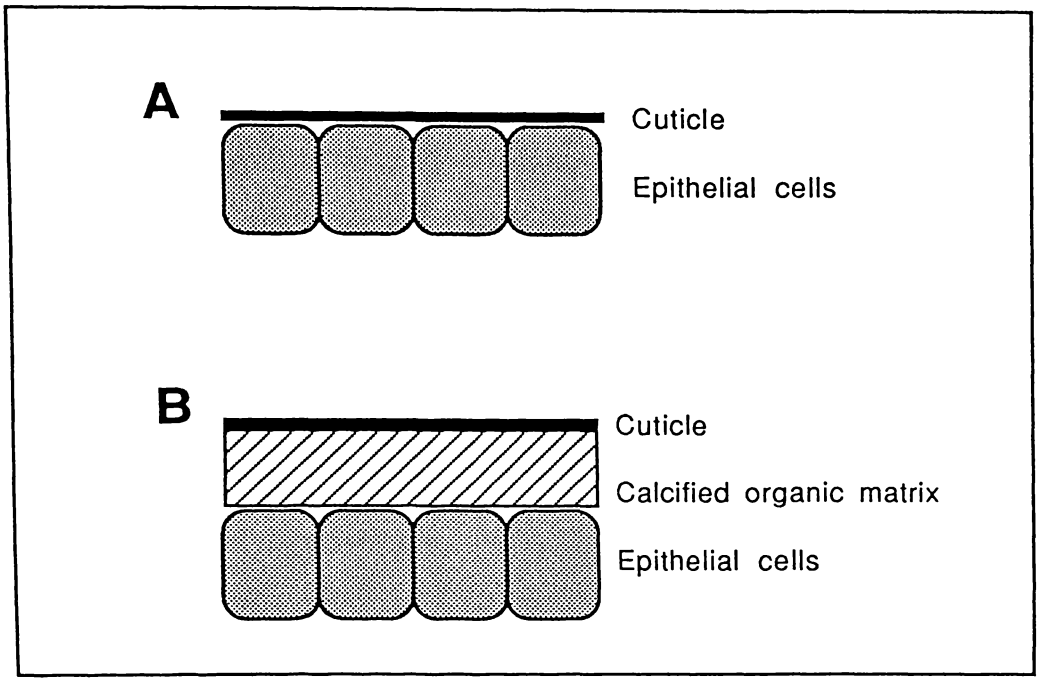


Figure 1B.1: Idealized model of formation of cellular wall layers in (A) a newly budded zooid and (B) a mature adult zooid (after Lutaud, 1983).

reveals an organic matrix within the skeletal layer (Lutaud, 1983). The cuticle is chitinous and proteinaceous, and in a mature zooid up to 85% of the exoskeleton may be $CaCO_3$ (Hunt, 1972). At first there are spherical crystals against the cuticle, then lamellar bands of primary calcification, sometimes followed by fibrous secondary calcification (Schneider, 1963). Exterior walls are generally formed first, then internal walls divide up the enclosed space (Schopf and Travis, 1968).

Crystallites may be tabular, rhombic, acicular, or massive. In general, lamellar structures are interpreted to be calcite, whereas fibrous and spherulitic textures tend to be aragonite (Sandberg, 1983). Ryland (1970) notes that in perforate cheilostomes, a calcitic frontal wall may become overlaid with aragonite over time. This is more likely to occur in erect forms which require secondary support (Schopf and Travis, 1968). Generally, less advanced organisms (i.e., cyclostomes) have a simpler skeletal structure than more complex ones. Cheilostomes tend to have three or four layers of calcification whereas cyclostomes mostly only have two.

Tavener-Smith (1969) made the distinction between colonial calcification and zooidal calcification, where some $CaCO_3$ seems to be colony-wide in its growth and some is associated only with individual zooids.

Calcification in marine bryozoans is thus rather complex. It varies among growth forms, and among taxa. Aragonite or calcite may be laid down, sometimes in sequence within a single colony (see Figure 2B.27). Crystallites vary in form, and the distribution of layers varies between species (Milliman, 1974). Rates of calcification are not likely to be consistent among all this variation.

Indeed, calcification rates have not been reported for bryozoans. Growth rates (in term of zooids or area) are known for some, and some can be calculated using published data.

It is, however, possible to convert growth rate to carbonate production rate using a conversion factor, either zooids/g $CaCO_3$ or area/g $CaCO_3$. This factor will vary depending on degree of calcification, measurement technique, species, and growth form. The calculated production rates, therefore, will be rather limited in their accuracy. Nevertheless, in the absence of measured calcification rates, roughly calculated ones must serve.

C. GROWTH RATES AND LIFESPANS

1. Growth rates of bryozoans

The measurement of growth and lifespan in bryozoans is complicated by their coloniality. Within a healthy, growing colony a physiological gradient exists. Some zooids may be dead, some may be reproductive, some may be dying, some may be resting, and some may be feeding. In encrusting species these stages may be in concentric bands. It is not uncommon to find an encrusting bryozoan that has died in the middle and is actively growing on the margins, not only extending the colony outwards but overgrowing its own dead center (Ryland, 1970). In addition to this potentially eternal growth mode, colonies of some species may reproduce themselves by fragments. Broken pieces may anchor and begin a new colony, genetically identical to its "parent" (that is, a clone). The combination of colonial growth and cloning is such that a bryozoan may be considered "nominally immortal" (Palumbi and Jackson, 1983). It is clearly difficult to define the beginning and end of life in such a situation.

Nevertheless, most colonies are not immortal. Sexually-reproduced larvae settle, begin to grow and, most often, die (Keough, 1984). A small percentage of settled larvae survive to become "adult" colonies. The life cycle of bryozoan colonies can be annual or sub-annual (lifespan less than 1 y), biennial, or perennial. Some colonies have been shown to be more than 12 years old (Stebbing, 1971)! Eventually a colony may die, either from severe physical disturbance, overgrowth, predation, or senility (Figure 1C.1)

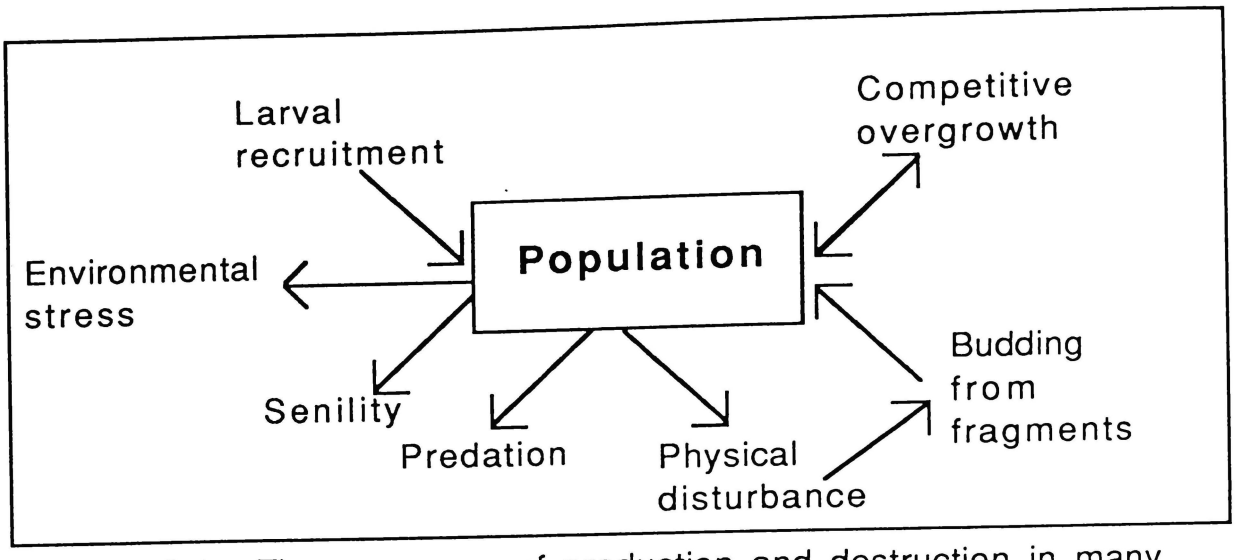


Figure 1C.1: The processes of production and destruction in many benthic invertebrate populations.

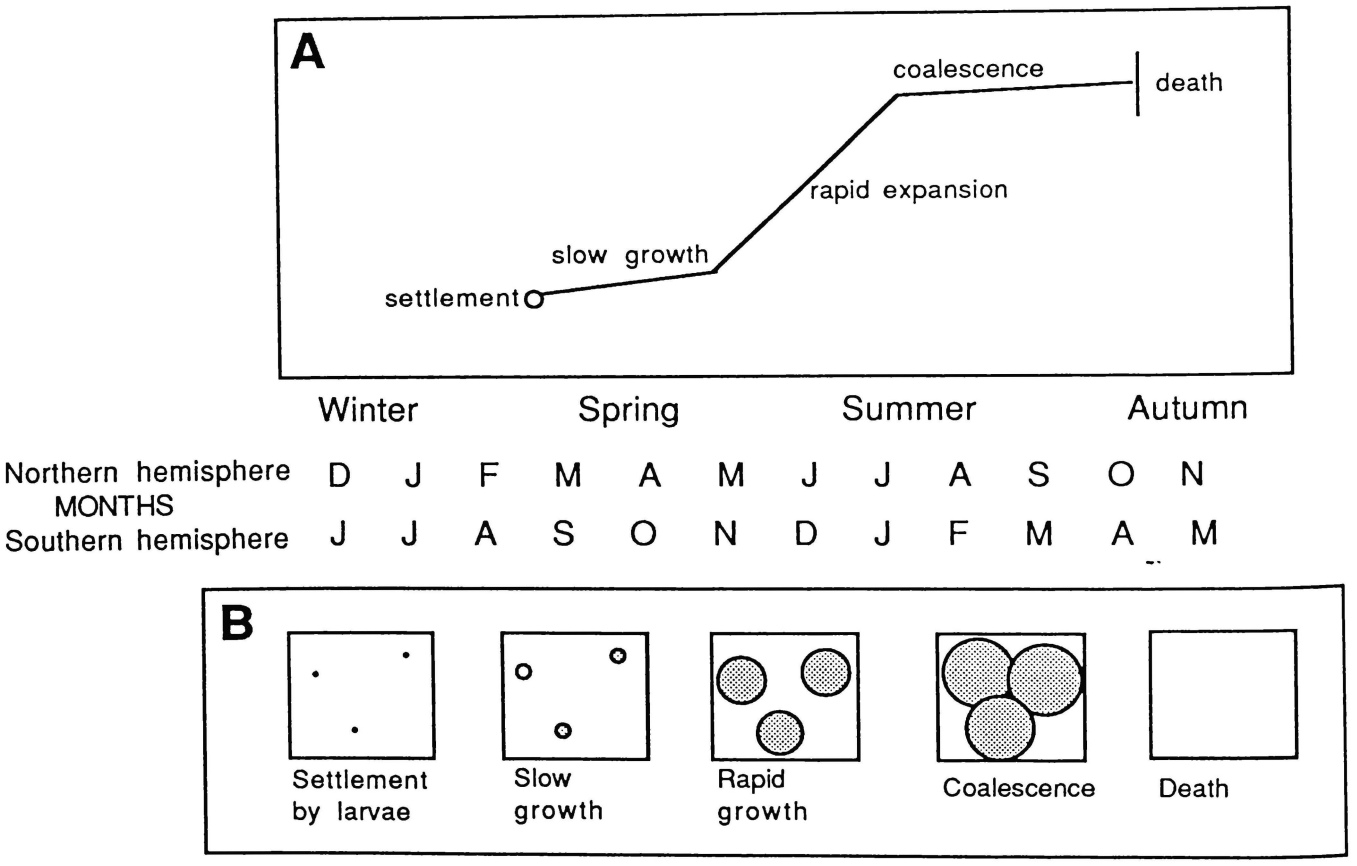


Figure 1C.2: Seasonal growth in annual encrusting bryozoans. A - generalized growth curve over time. B - idealized plan view of stages.

There is a strong seasonal effect in bryozoan growth rates. This is obviously a feature of short-lived bryozoans (e.g., Figure 1C.2) such as *Bugula neritina* (Keough, 1986), *Cryptosula pallasiana* (Osman, 1977), and *Microporella ciliata* (Humphries, 1973). It also appears to be important in perennial species. *Flustra foliacea*, for example, shows annual bands where growth slows in winter (Stebbing, 1971).

Growth rates reported in the literature usually take the form of an indication of size increase over a period of time, or an increase in zooid number over time. Appendix Table A1.1 lists growth rates from the literature as they appear in publication. They are rather difficult to compare, and a first step must be to standardize them. Measurements which are indications of the progress of the leading edge of a colony are not used, as they do not give any indication of the size of the colony. It will be noted that all these growth rates are not in a form to be of any practical use to a carbonate sedimentologist. Re-calculation and calibration are required to make these data useful to geologists.

2. Lifespans and turnovers of bryozoans

Smith (1970) clearly noted that without lifespans (or turnovers), growth rates cannot be translated into overall production by a group. If individuals produce 1 g carbonate per year, it matters greatly whether an individual lives for 6 days or 6 months or 6 years. Lifespans of bryozoans, as mentioned above, are quite variable. Lifespans and turnovers are listed in Appendix Table A1.2.

D. CARBONATE PRODUCTION RATES

1. Calculated growth rates

As noted above, there are no published rates of calcification (individual carbonate production rates) available. Thus rates calculated from the literature surveyed in section C will be described.

The growth rate for each species was transformed to a carbonate production rate by using New Zealand measured specimens as a model. Several species of New Zealand bryozoans were obtained from University of Waikato collections. Care was taken to select whole-looking and unencrusted colonies with all organic material removed. Zooids were counted, dimensions measured, and the colonies were weighed. The results were manipulated to produce conversion factors from growth rates to carbonate production rates (Appendix Table A1.3).

These conversion factors were then applied as deemed most appropriate to the growth rates reported in the literature. All the details of calculations are given in Appendix Table A1.4, and summarized in Table 1D.1.

Individual carbonate production rates vary dramatically among the species listed. Lightly calcified bryozoans such as *Bugula* calcify at a rate of up to 5 g $CaCO_3$/y, although only for short periods. More heavily calcified bryozoans (e.g., *Schizoporella unicornis*) may be even greater producers. Most bryozoans, however, appear to produce less than 0.5 g $CaCO_3$/y.

One of the difficulties is quantifying growth rate in colonial organisms is that there is no simple relationship between age and size (Jackson and Winston, 1981). This makes such a calibration as applied above rather limited In addition, growth is strongly influenced by environment and colony size, also affecting the usefulness of the above data.

2. Experimentally determined growth rates

Obviously rates calculated as above are rather questionable. Experimentally determined calcification rates are preferable. Three experiments were carried out to try to study growth in situ. One was a SCUBA photographic study, in which study sites were photographed on a regular basis. Both weather and the difficulty of marking study sites over long periods limited the usefulness of this method. Moreover, annual or

Table 1D.1: Summary of calculated individual bryozoan carbonate production rates from published growth rates (details in Appendix Table A1.4).

Species	Calculated individual production rate (g $CaCO_3$ /y)
Bugula avicularia	0.076
Bugula californica	0.043
Bugula neritina	0.232
Bugula simplex	5.214
Cellarinella margueritae	0.008
Celleporaria fusca	46.332
Cigclisula aviculifera	0.066
Cigclisula turrita	0.006
Cleidochasma porcellanum	0.284
Coleopora sp.	0.075
Conopeum tenuissimum	0.487
Cribrilaria radiata	0.045
Crisulipora occidentalis	0.103
Cryptosula pallasiana	0.984
Cyclicopora longipora	0.834
Disporella fimbriata	0.164
Drepanophora tuberculatum	0.243
Electra bengalensis	0.785
Eurystomella foraminigera	0.041
Fenestrulina sp.	0.026
Flustra foliacea	0.019
Gephyrophora rubra	0.524
Hippoporina indica	4.388
Melicerita obliqua	0.629
Microporella ciliata	0.028
Microporella umbracula	0.210
Parasmittina sp.	0.868
Parellisina curvirostris	0.046
Pentapora foliacea	0.118
Rhynchozoon sp.	0.188
Schizoporella unicornis	11.481
Scrupocellaria scrupea	6.110
Smittipora levinseni	0.629
Steginoporella sp.	0.041
Steginoporella sp. nov.	2.095
Stylopoma spongites	0.374
Trypostega venusta	1.302
Tubulipora pacifica	0.072
Tubulipora sp.	0.043
Valdemunitella valdemunita	3.219
Watersipora arcuata	0.213
Watersipora subtorquata	0.254
Mean	2.117

more short-lived species were not large enough or permanent enough to record regularly.

In another study, plastic containers (used also in a different experiment, for detailed methods see Chapter 8, section B) were anchored just above the sea floor at Cape Rodney in the Hauraki Gulf and collected periodically during a year. It was noticed that the containers were often encrusted by many taxa, including bryozoans (Figure 1D.1). As the exact time of submersion was known, a maximum age was available for these specimens. After being killed in 50% ethanol, they were soaked in dilute bleach to remove organic matter, dried slowly, identified, and whole colonies were weighed. A mean minimum rate of carbonate production for each species was calculated (Appendix Table A1.5).

The largest colony found in the whole experiment was one of *Disporella gordoni*, a heavily-calcified, radially encrusting cyclostome. At 0.58g in 9 mo, the minimum carbonate production rate for that individual is 0.77 g $CaCO_3$/y. This is an order of magnitude higher than the mean carbonate production rate of 0.07 g $CaCO_3$/y. Most species produce carbonate at less than 0.05 g $CaCO_3$/y (Table 1D.2).

There does not seem to be any major difference in ICPR between erect growing species and encrusting ones (Figure 1D.2). There is more variation among encrusting species. With the clear exception of *Hastingsia*, moderately and lightly calcified species tend to produce carbonate more slowly than heavily calcified species (Figure 1D.3). Cyclostomes are generally slower than cheilostomes, but the two highest rates of production are exceptional cyclostomes. There does not appear to be a consistent taxonomic trend (Figure 1D.4).

A third study involved a similar experiment, only the submerged item was the *Rainbow Warrior*, a vessel that was sunk in December, 1987 off the Cavalli Islands for the

Table 1D.2: Summary of individual carbonate production rates calculated from settling experiment.

	Rate of calcification over period of time (g/y)			
Species	3 months	9 months	12 months	Mean
Lichenopora cf. novaezelandiae	0.021	0.003		0.012
Disporella n.sp.	0.037			0.037
Tubulipora anderssoni	0.075		0.010	0.043
Mecynoecia purpurascens	0.090			0.090
Manzonella lepida	0.038			0.038
Galeopsis porcellanicus		0.181	0.092	0.137
Mecynoecia sp.		0.018		0.018
Smittoidea maunganuiensis		0.046	0.033	0.040
Telopora buski		0.015		0.015
Escharoides angela		0.054	0.139	0.097
Disporella gordoni		0.203	0.093	0.148
Caberea zelandica		0.030		0.030
Arachnopusia unicornis		0.121	0.107	0.114
Hastingsia ?irregularis			0.188	0.188
Annectocyma sp.			0.035	0.035
Tubulipora sp.			0.017	0.017
Plagioecia sarniensis			0.001	0.001
Hornera sp.			0.072	0.072
Celleporina sp.			0.112	0.112
Mean	0.052	0.075	0.075	0.065



Figure 1D.1: View of inside surface of sample container showing heavy encrustation by coralline algae, barnacles, and bryozoans. Scale bar is 1 cm.

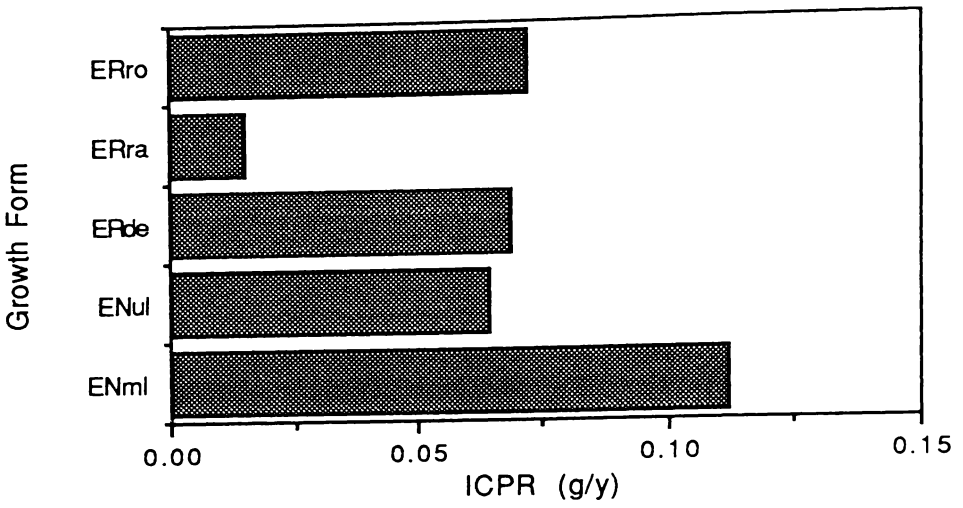


Figure 1D.2: Mean carbonate production by different growth forms of New Zealand bryozoans.

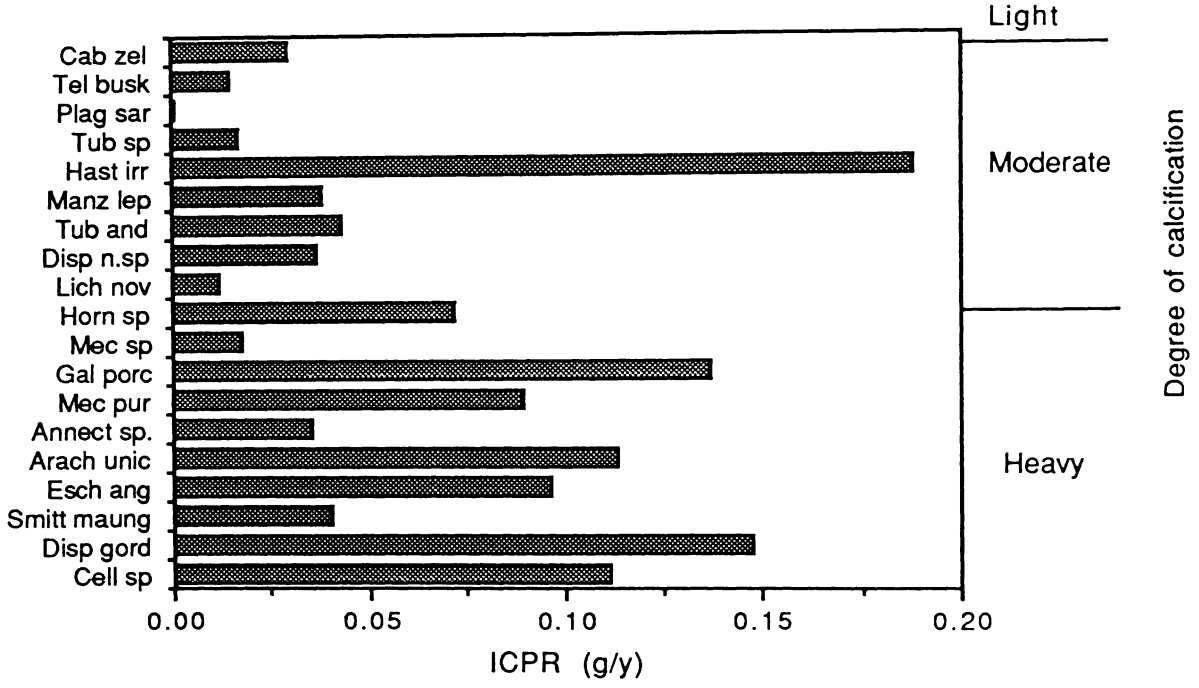


Figure 1D.3: Carbonate production by bryozoans with differing degrees of calcification. Species abbreviations as in Table 1D.2.

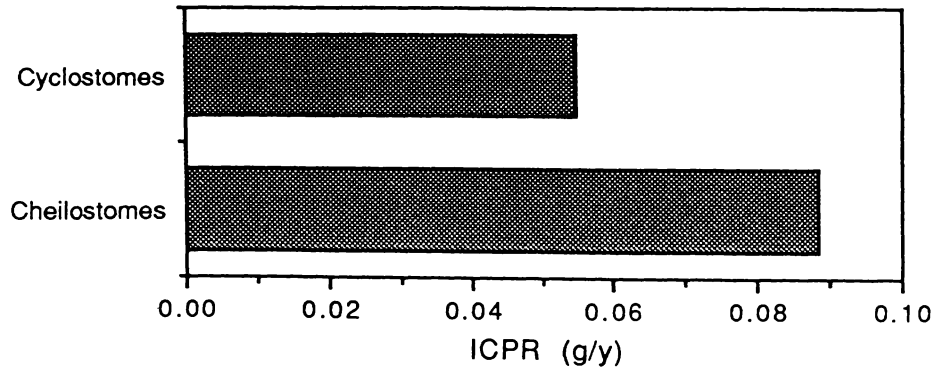


Figure 1D.4: Mean carbonate production rates of the major bryozoan taxa.

purposes of research and recreation. A visit was made almost exactly 4 years after sinking. Large bryozoan colonies live on the wreck. They were measured, identified, and photographed (Figure 1D.5). These provide a longer-term view of colonization and growth rates of some bryozoans.

The largest colonies found on the wreck were of *Celleporaria agglutinans*. A moderate-sized representative was removed and weighed in at 24 g. This would indicate calcification of at least 6 $gCaCO_3/y$ over 4 years. Larger colonies would presumably weigh more. A very large colony of *Hemipustulopora harmeri* was also observed, but as it was the only one, it was left alive.

4. Implications for areal production

In order to translate carbonate production rates into sedimentation rates, the areal distribution of bryozoan colonies is needed. Most ecologists study population density, in colonies per area. Several studies of bryozoans are relevant.

Bryozoans in Block Island Sound, New York, have a mean population density of 2350 colonies/m^2, although it is highly variable. Density depends on substrate availability. The most abundant species (*Cribrilina punctata*) has a maximum density of 9500 colonies/m^2 in late summer. In winter the density decreases to 1500 colonies/m^2 (Abbott, 1973). Diversity thus becomes lower in winter, as annual and rarer species become scarce (see Figure 1C.2A).

In New Zealand, at Leigh, point counts of rocks show that the undersides of boulders are covered with bryozoans. In general there are a few abundant species and many uncommon species; 34 species together make up less than 10% of the total coverage (Ryland, 1975).

In settling experiments, bryozoans may be a major part of the encrusting community. Kay and Keough (1981) found bryozoans covering on average about 10% of cleared

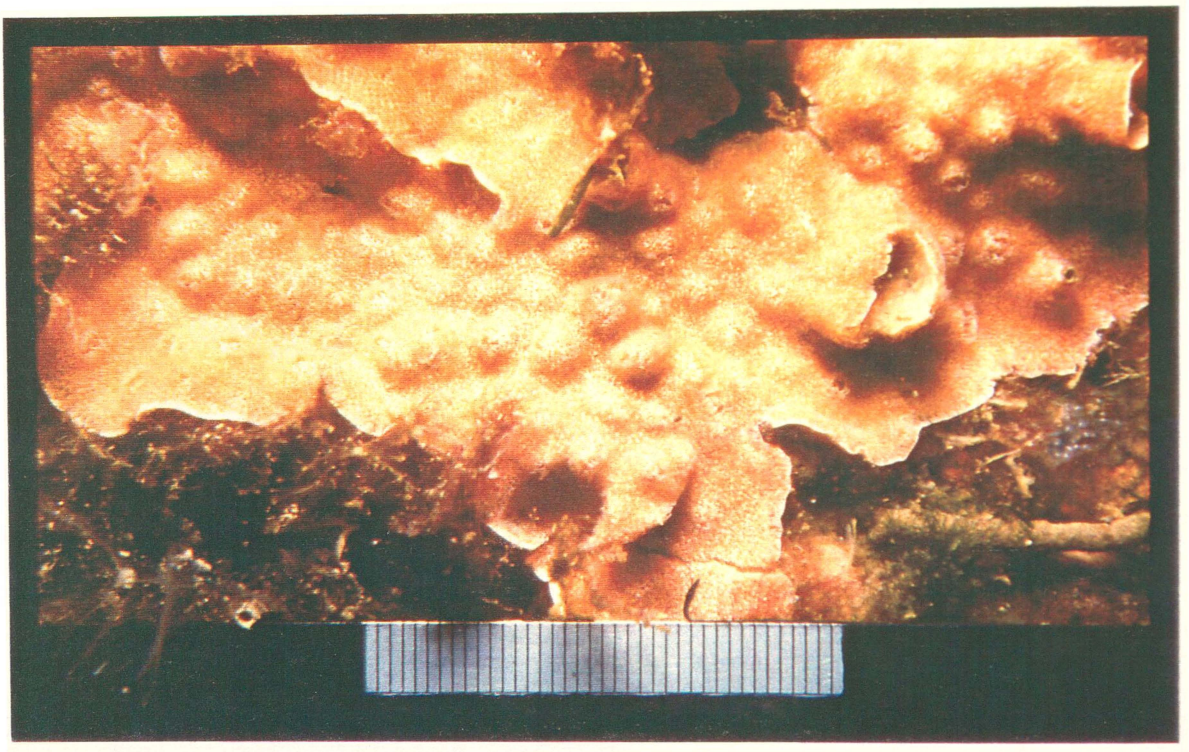


Figure 1D.5: Living colony of the bryozoan *Celleporaria agglutinans* photographed encrusting a wall of the sunken ship *Rainbow Warrior* on 15 December 1990, 4 years after sinking. Scale in mm.

pilings, and 23% of freshly dead bivalves. They were outnumbered by sponges, but still comprised a major portion of the community.

Variability in bryozoan population densities is high. In order to calculate areal production from individual carbonate production rates, population densities in the area in question must be known. Seasonality and available substrates have a strong effect on areal distribution.

The data from the growth rates experiment provide a very direct way to measure areal production. Each plastic sample container had a surface area of 402 cm^2. A total of 4.85 g $CaCO_3$ was removed from five sample containers (at the 12 month collection), thus indicating that bryozoans at Cape Rodney can produce at least 24 g $CaCO_3/m^2$ substrate/y.

5. Carbonate sediment production

Few studies have actually measured carbonate sediment production by bryozoans (Table 1D.3). Pestana (1985) measured carbonate sedimentation by *Sargassum* epibionts, particularly *Membranipora tuberculata*, at 8231 $g/m^2/y$ on a Bermudian beach. Here production depends strongly on transport regime, as the bryozoans live in the open sea, and are washed ashore periodically.

In his carbonate budget for the southern California coast, Smith (1970) derived a figure of approximately 100 to 250 $g/m^2/y$ for all bryozoans. This is out of 400 $g/m^2/y$ for all carbonate producers of the rocky intertidal. In South Australia, bryozoans have been considered to be producing sediment at 0.2 to 2.7 mm/y (Gostin et al., 1988). Bryozoan build-ups or mounds (Bone and Wass, 1990; Bone, 1991) in South Australia have been dated at 760 y BP, thus the largest, at about 25,000 cm^3 in volume, would have been deposited at about 33 cm^3/y.

Table 1D.3: Carbonate sediment production by bryozoans.

Source	Location	Producers	Sedimentation rate
Smith, 1970	California	all bryozoans	100 to 250 g/m²/y
Pestana, 1985	Bermuda	*Membranipora tuberculata* and other epibionts of *Sargussum*	8231 g/m²/y
Gostin et al., 1988	S. Australia	bryozoans sea grass epibionts	0.2-2.7 mm/y 6 m/6000 y
Wass and Bone, 1990	S. Australia	*Membranipora aciculata* in mounds	300 mm high and 400mm in diameter in 750 y
This study	New Zealand	bryozoans	24 g/m²/y

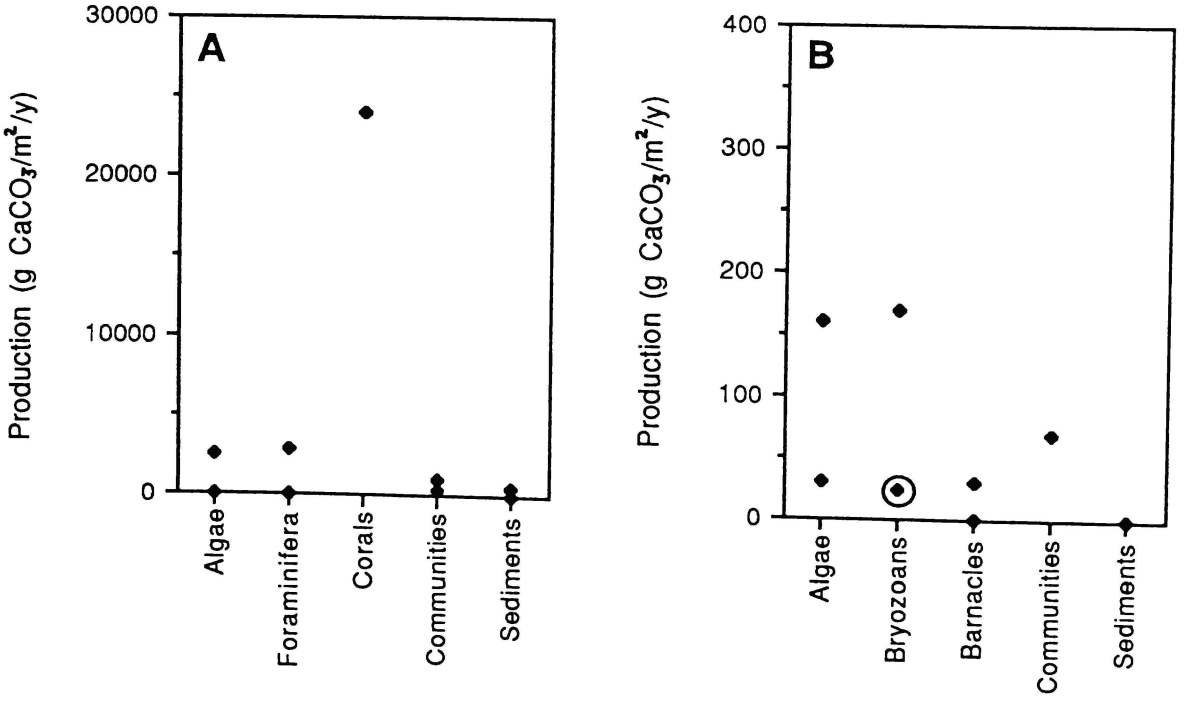


Figure 1D.6: Some production rates for individual species and communities in (A) tropical and (B) temperate settings. Note production axes are different. Circle indicates the results of this study. Data in Appendix Table A1.6.

In the settling experiment at Cape Rodney described above, a conservative value of 24 g $CaCO_3/m^2/y$ was obtained. Although there are very few published data on carbonate production in temperate waters, this study appears to agree with them (about 30 g $CaCO_3/m^2/y$). Tropical rates for many organisms may be two orders of magnitude higher (Figure 1D.6, Appendix Table A1.6).

Six sediment samples were taken by SCUBA divers in a linear transect away from the sunken wreck *Rainbow Warrior*. These were analyzed for bryozoan content, and for bryozoan species present. A comparison with the bryozoans observed on the wreck was made.

Bryozoans on the wreck are generally obvious because many are quite large; they are often particularly common on the underside of surfaces. A visual estimate of coverage by bryozoans made by divers in December 1991 (four years after sinking) at the site was 20%. Many important sediment-producing bryozoans were photographed and identified, including *Celleporaria agglutinans, Hemipustulopora harmeri, Disporella gordoni, Cellaria tenurostris,* and *Galeopsis porcellanicus.*

Sediments, even directly under the wreck, are almost entirely made up of barnacle plates. Bryozoans make up less than 5% of the sediments. The species that are obvious on the wreck are not particularly dominant among the very few bryozoan sediments; *Foveolaria cyclops, Mecynoecia purpurascens*, and *Annectocyma* sp. are equally common. So it appears that the sediment fauna does not reflect the fauna on the wreck. Perhaps four years is not long enough for much sediment to have derived from the wreck.

In general, carbonate sedimentation on temperate marine shelves can be quite slow, on the order of 1 to 2 cm/ky (e.g., Kamp and Nelson, 1988; James and Bone, 1991). Local effects can, however, increase this many times. At Three Kings (northern New Zealand) locally thick (3 m) recent deposits (Nelson, 1982) imply much higher rates (50 cm/ky), and may be a result of local currents redepositing sediment into depressions.

E. DEATH AND DAMAGE

As mentioned above, a single bryozoan individual may die while the colony is quite healthy. In some cases whole areas of the colony may die, while the younger edges of the colony continue to grow and reproduce. Harvell (1984) observed that colonies are seldom killed in a single event. Colony breakage may not result in death, but in generation of a new clonal colony. All of this increases the complexity of studying bryozoans.

Death may be due to physical disturbance, biological predation or overgrowth, "old age," environmental stress, or from chemical pollution. The ecological literature describes many of these causes and gives an indication of the eventual fate of living bryozoans.

Gordon (1977) gave a clear picture of the life cycle of a single individual in *Cryptosula pallasiana*. A polypide (the feeding apparatus and gut) lives about 6 weeks, then regresses to a "brown body", comprising mostly body residues. After some days, a new polypide regenerates. This cycle may occur some 2 or 3 times. In some species the brown body is voided from the new polypide. In others, each brown body formed remains in the zooid, where eventually it becomes too crowded for the polypide to function (Palumbi and Jackson, 1983). Gordon's (1968) observations of *Eurystomella foraminigera* indicate a maximum lifespan for a single zooid of 135 d. Thus for many zooids, "old age" is the cause of death.

Predation is also a major cause of death. Several important predators have been observed, including fish and various invertebrates. Grazers, such as fish and echinoids, may destroy a whole colony, or a major portion of it. Encrusting colonies may only have their edges "pruned" (Best and Winston, 1984), but erect species may be completely destroyed (Vance, 1979). Grazers preferentially destroy erect species; erect branching colonies are subject to tremendous mortality rates due to fish grazing when young (up

to 27% mortality a day), but larger colonies are less affected (Keough, 1984). Echinoids graze on kelp and therefore epibionts are destroyed too (Gordon, 1972). Other less important grazers are chitons and possibly gastropods.

Sponges may increase growth rate in response to grazing by up to 20 times (Ayling, 1981); it is worth exploring whether bryozoans do the same. Certainly encrusting species will survive better than erect species under grazing pressure (Vance, 1979).

Some opisthobranchs (mainly shell-less gastropods, sometimes called sea slugs) and pycnogonids (unusual arthropods called sea spiders, but not in the arachnida) are more specialized single-zooid feeders. Bryozoans make up an important part of their diet (Moore, 1973; Wyer and King, 1973). In some cases predator species are specialized for feeding on a particular species of bryozoan. The predator may puncture the frontal wall of a zooid or wait for the operculum to open before seizing the polypide (Figure 1E.1).

Bryozoans may respond to predation by a change of morphology. *Membranipora membranacea* develops frontal cuticular spines only when grazed. The spines tend to grow on zooids at the edge of the colony, forming a deterrent to opisthobranchs feeding on them. Spine growth stops when the predators are removed (Harvell, 1984). The cost of this defence is high; growth rate decreases by a factor of 6 while spines are being formed (Harvell, 1984).

Other encrusting organisms may overgrow an encrusting bryozoan, causing death of the covered portion. In some bryozoan communities, this sort of competition is more important than predation (Osman, 1977). It is seldom that overgrowth occurs within a species; there seems to be a recognition factor that allows growth to stop in the direction of another colony of the same species. In some species (e.g., *Schizoporella biaperta*) meeting colonies both redirect the direction of growth up, so that their substrates become each other (Osman, 1977). At least one free-living bryozoan has been shown to molt its external layers when overgrown with algae (Winston and Hakansson, 1989).

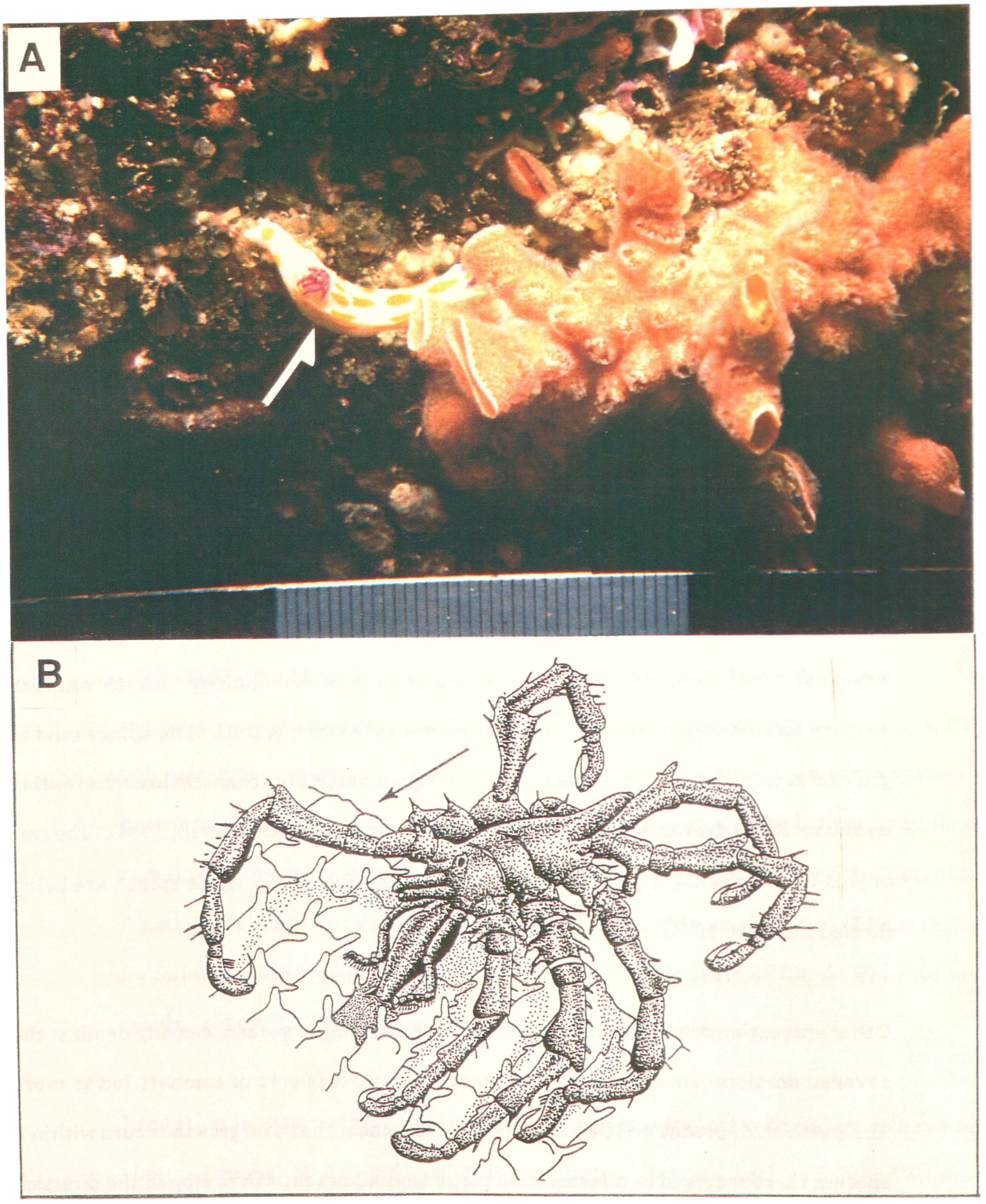


Figure 1E.1: Examples of predators of bryozoans. (A) Opisthobranch *Chromodoris amoena* (arrow) on bryozoan *Celleporaria agglutinans* at Leigh in 20 m water depth. Scale in mm. (B) Diagrammatic representation of pycnogonid *Achelia echinata* feeding on bryozoan zooid (from Wyer and King, 1973).

Benthic species are often quite vulnerable to physical disturbance. Substrates are not always firm; rocks may roll in storm surge, kelp fronds move almost constantly, sand shifts, and even on firm substrates other moving objects may scrape by or crash in. Epibionts have an additional hazard; their substrate may be eaten by herbivores. In a seagrass encrusting species, this is a major source of mortality (Keough, 1986).

Mobile organisms may scrape or dislodge bryozoans incidentally (Keough, 1986). Ophiuroids have been observed to anchor themselves to erect bryozoans, and breakage is sometimes the result (Winston, 1983).

An increasingly important anthropogenic source of physical disturbance is fishing that involves dragging the bottom. Bryozoan mounds have been badly damaged and killed by dragging in Tasman Bay, New Zealand (Bradstock and Gordon, 1983).

The environment around bryozoans is subject to change. A rapid change in temperature or chemistry may kill bryozoans (Keough, 1986), although some appear to be very tolerant of pollutants, as evidenced by their reputation as marine foulers in ports and harbours. Change in food supply would also induce mortality. Figure 1E.2 summarizes the various causes of death and damage in bryozoans.

Rates of death and damage are very poorly known. Pycnogonids have been observed to take an average of 10 min to feed on a zooid. If they feed 50% of the time, this will result in death of 72 zooids/d, or almost 30,000 zooids/y. Since colonies may have thousands of zooids (e.g., *Steginoporella* sp. with 9000 zooids/colony according to Palumbi and Jackson, 1983), this may be about 10 or 20 colonies per year, per individual predator. No information on pycnogonid predation in New Zealand appears to be available.

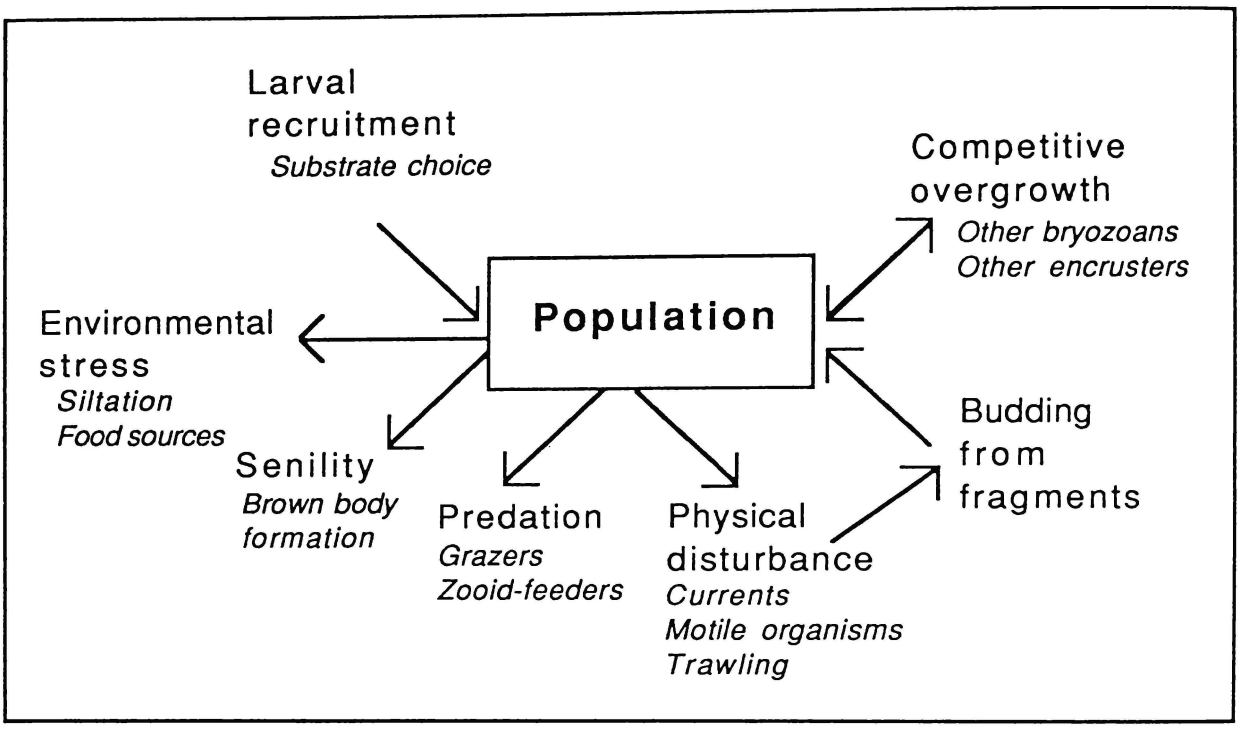


Figure 1E.2: Details of the processes of production and destruction in bryozoan populations.

Opisthobranchs may destroy 1000 zooids in 4 days (Vail and Wass, 1981), resulting in the death of perhaps 50 colonies in a year. They may, however, feed on other benthic species, thus reducing bryozoan mortality.

F. CONCLUSIONS

Calcification by marine bryozoans is extracellular. $CaCO_3$ is laid down by the cuticle, and may be in a variety of crystal forms. Calcification rates in bryozoans are unknown. Growth rates, usually measured by change in colony size over time, are published for a variety of bryozoans, but are not in a form useful to carbonate sedimentologists. Recalculation of these rates in terms of carbonate production indicates that individual bryozoans may produce carbonate as rapidly as 10s of g/y, but that most are limited to less than 3 g $CaCO_3$/y. A mean of 2 g $CaCO_3$/y for individual carbonate production was calculated over a large range of bryozoan species.

A settling experiment from New Zealand waters gives a much lower mean production rate of 0.07 g $CaCO_3$/y. The fastest-growing individual in the study produced carbonate at 0.77 g $CaCO_3$/y. A specimen found on the *Rainbow Warrior* has been calculated to have produced carbonate at 6 g $CaCO_3$/y. Carbonate production by individual bryozoans is usually less than 1 g $CaCO_3$/y, but may in large colonies or over short time periods be rather higher.

Distribution of bryozoans is often very patchy, so a generalized areal rate of production is not useful. The settling experiment at Cape Rodney produced bryozoan carbonate at a rate of at least 24 g $CaCO_3/m^2$/y. Other temperate organisms have been reported to produce carbonate at similar values.

As a sedimentation rate, it is far smaller than other published rates over larger areas and longer periods of time. The *Sargassum* epibionts reported in Bermuda (8231 $g/m^2/y$) and even the Californian bryozoans (100 to 250 $g/m^2/y$) are orders of magnitude higher.

Carbonate is produced by living bryozoans; they go through a variety of processes of death and damage, thus producing sediment. Breakage, predation, senility, and overgrowth are the important processes by which living colonies become sediment. Rates of damage and death are largely unknown.

Initial data from the sunken vessel *Rainbow Warrior* indicate that sedimentation by dead or damaged bryozoans may take some time to register in bottom deposits (more than 4 years). A disucssion of processes affecting bryozoan sediments in New Zealand and a preliminary budget is presented in Chapter 11.

Chapter 2 Skeletal Mineralogy of Bryozoans

"This fortress built by Nature for herself...This precious stone set in the silver sea, which serves it in the office of a wall, or as a moat defensive to a house..."

Wm. Shakespeare, Richard III, 1595

A. INTRODUCTION

1. Mineralogy of Skeletal Carbonates

Carbonate minerals are made up of a metallic cation and the carbonate anion $C0_3^{2-}$, combining to make such compounds as $CaCO_3$ or $MgCO_3$. These minerals are formed in one of two structures. One has six-fold, rhombohedral coordination, the other nine-fold or orthorhombic coordination. The rhombohedral formation is favored by cations with atomic radius less than 1 angstrom such as Mg^{2+}, Fe^{2+}, Mn^{2+}, Zn^{2+}, and Cu^{2+}. In the rhombohedral lattice each oxygen atom is bonded to two cations. The orthorhombic configuration is favored by larger cations like Sr^{2+}, Pb^{2+}, and Ba^{2+}. With these larger cations, the carbonate anion is rotated slightly, so that each oxygen is bonded to three cations. The cation atomic radius determines which lattice structure the cation most readily fits (Deer et al., 1962). The calcium cation has an atomic radius of 0.99 angstrom, and fits either type of structure. Thus, there are two mineral polymorphs of $CaCO_3$, aragonite and calcite (Figure 2A.1).

Calcite is the rhombohedral polymorph of $CaCO_3$. It is moderately susceptible to substitution, especially by Mg^{2+}, Fe^{2+}, and Mn^{2+}. Mg^{2+} is the most common cation to substitute in marine skeletal calcite, which can have up to 18 wt% $MgCO_3$. Calcite with over 4 wt% $MgCO_3$ is usually called Mg-calcite, or high-Mg calcite (Scoffin, 1986; Boggs, 1987). Dolomite, which has 50% of the Ca ions replaced by Mg, is a different mineral, with the Mg and Ca arranged in definite crystal patterns. A partial solid solution occurs between 100% calcite and 100% dolomite, though most skeletal calcites range only from 0 to 14 wt% $MgCO_3$ (Busenberg and Plummer, 1989) (Figure 2A.2).

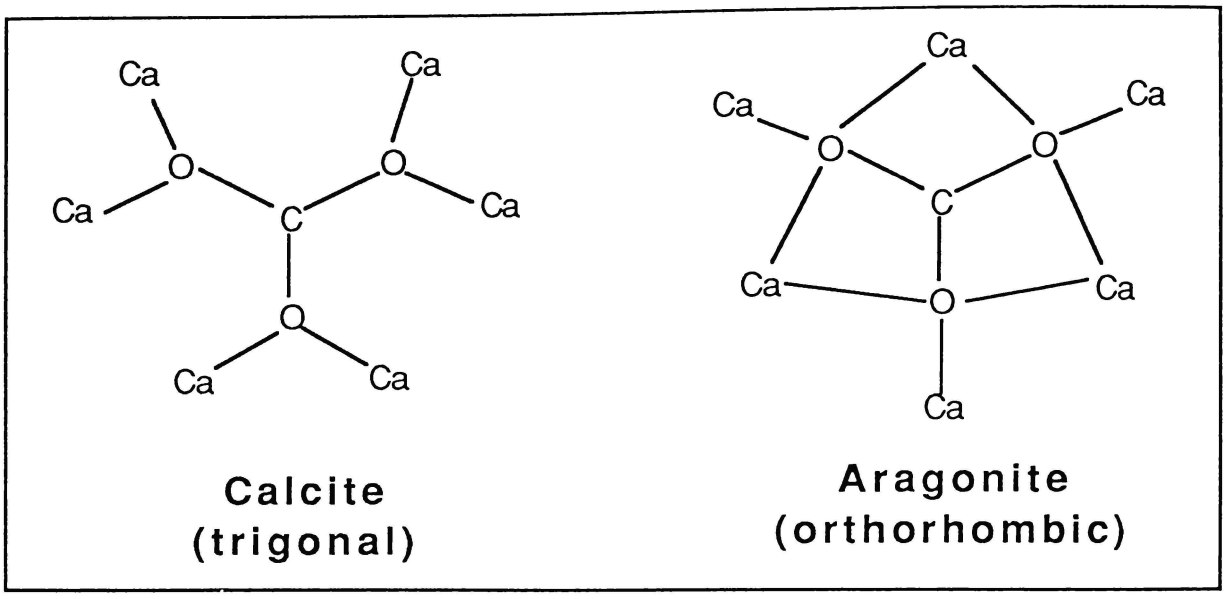


Figure 2A.1: Schematic representations of the atomic structures of calcite and aragonite ($CaCO_3$).

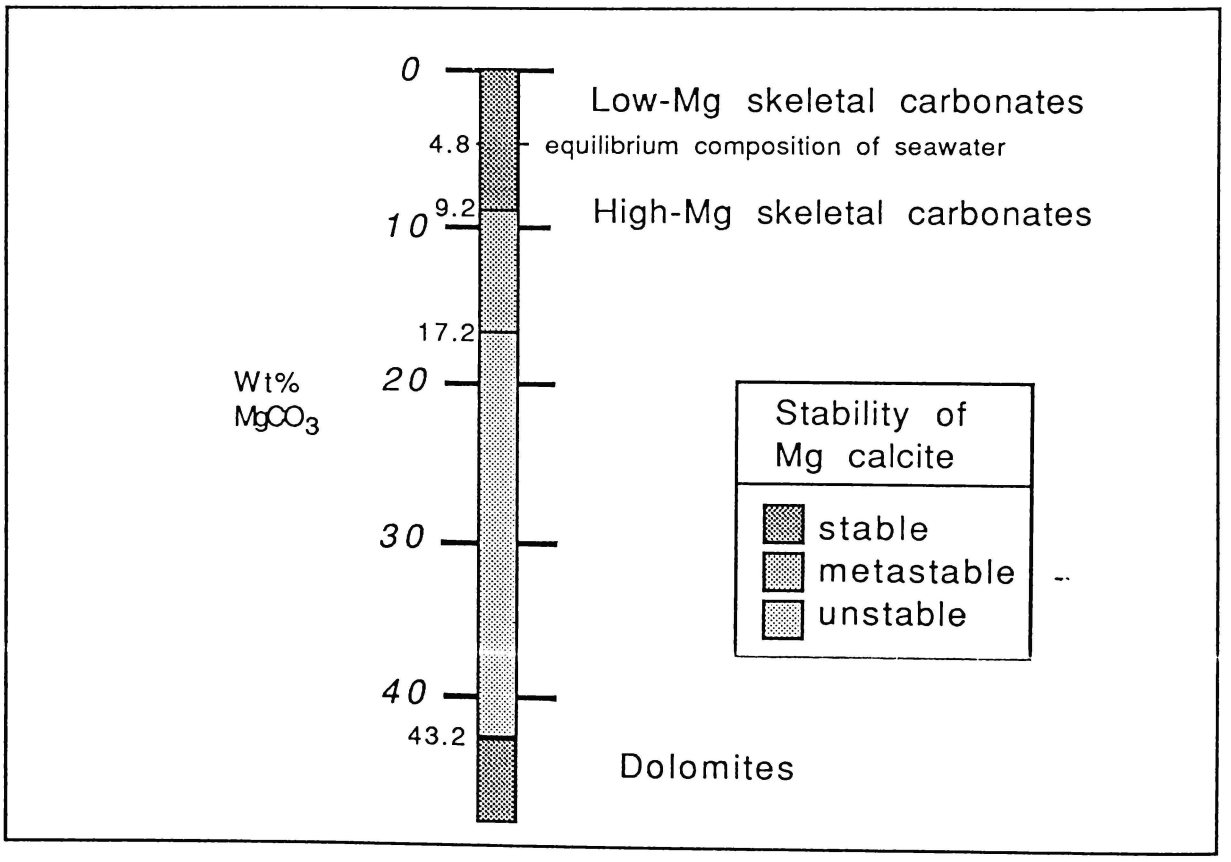


Figure 2A.2: Range of stabilities for magnesium carbonates (after Busenberg and Plummer, 1989).

Aragonite is the orthorhombic polymorph of $CaCO_3$. It is metastable at the Earth's surface, and will dissolve or change with time to calcite. It is usually a high-pressure and high-temperature form of $CaCO_3$, but is found at the Earth's surface because animals and plants are able to precipitate it within their organic micro-environment. Aragonite tends to be fairly pure, but may have some substitution by Sr (up to about 2 wt% $SrCO_3$).

Other forms of $CaCO_3$ also occur, such as vaterite (μ-calcite) (Milliman, 1974). They are seldom formed at the Earth's surface and where they do form they change rapidly to calcite under normal conditions.

The different forms of $CaCO_3$ have different chemical properties which affect their fate as sediment. Solubility is an important factor. In sea water the solubility product (K) of aragonite exceeds that of calcite. Consequently, aragonite is more susceptible to dissolution than pure calcite. Solubility also increases with increasing pressure and therefore with burial depth (Bathurst, 1975). Solubility increases with decreasing temperature as shown in Figure 2A.3 (Li et al., 1969). Other factors such as pH would obviously affect this relationship.

The degree to which ionic substitution occurs in aragonite and calcite also affects their stability. Chave et al. (1962) calculated relative stability using a ratio of solubility products. They found that low-Mg calcite is the most stable at the Earth's surface (Figure 2A.4). Aragonite and higher magnesium calcites are essentially unstable minerals at Earth's surface conditions. The least stable is calcite with >10 wt% $MgCO_3$ (Figure 2A.5). Despite their unstable nature they do persist for a time because of the activation energy required to convert to a more stable polymorph. Nevertheless, ultimately diagenesis may alter or remove them from sediments.

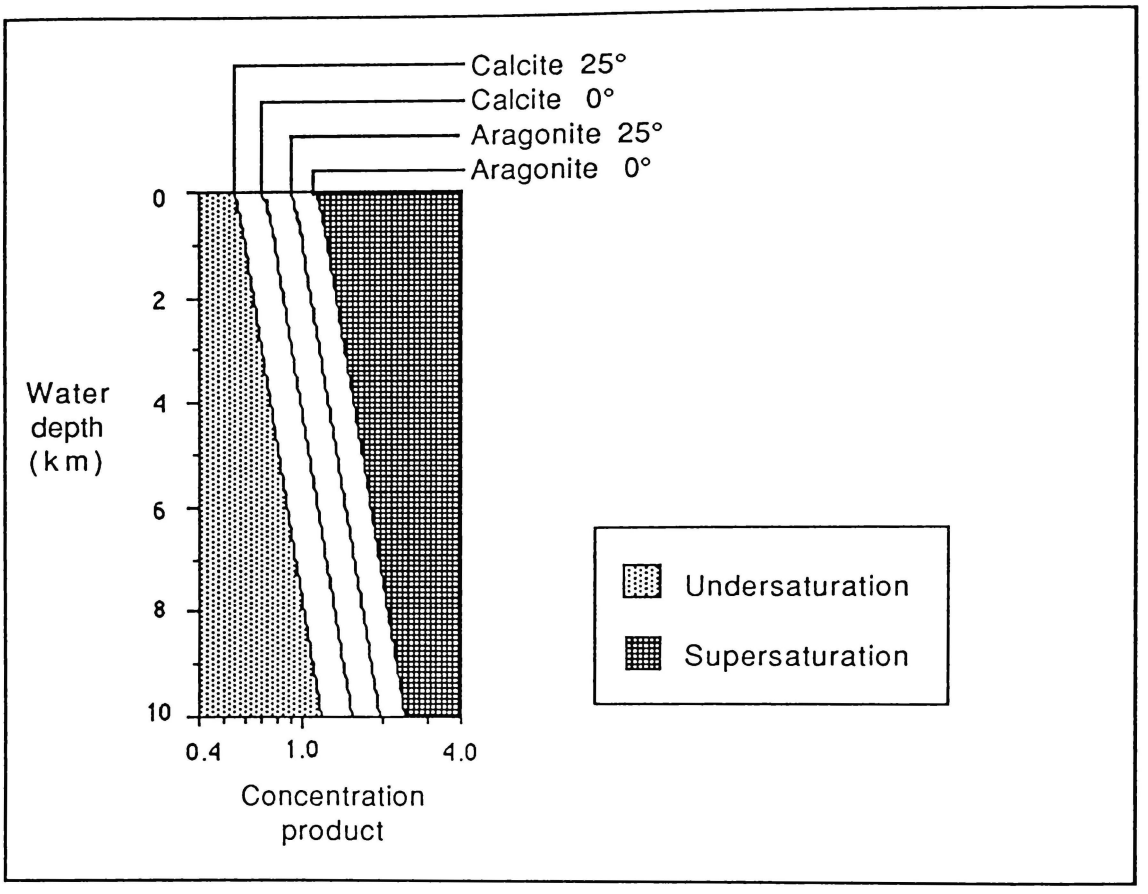


Figure 2A.3: Relationship of concentration of calcium carbonate in sea water to depth. Note that a decrease in temperature increases the solubility at a given depth, and that aragonite dissolves more readily than calcite at any given depth (after Li et al., 1969).

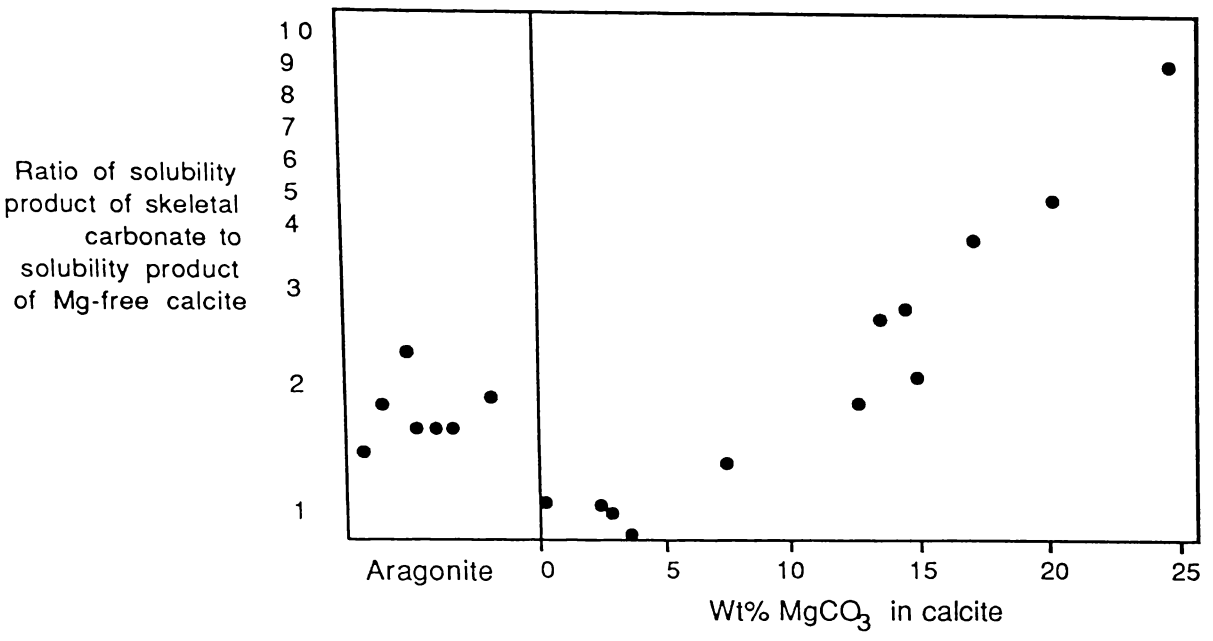


Figure 2A.4: Solubility of skeletal carbonates (after Chave, 1962).

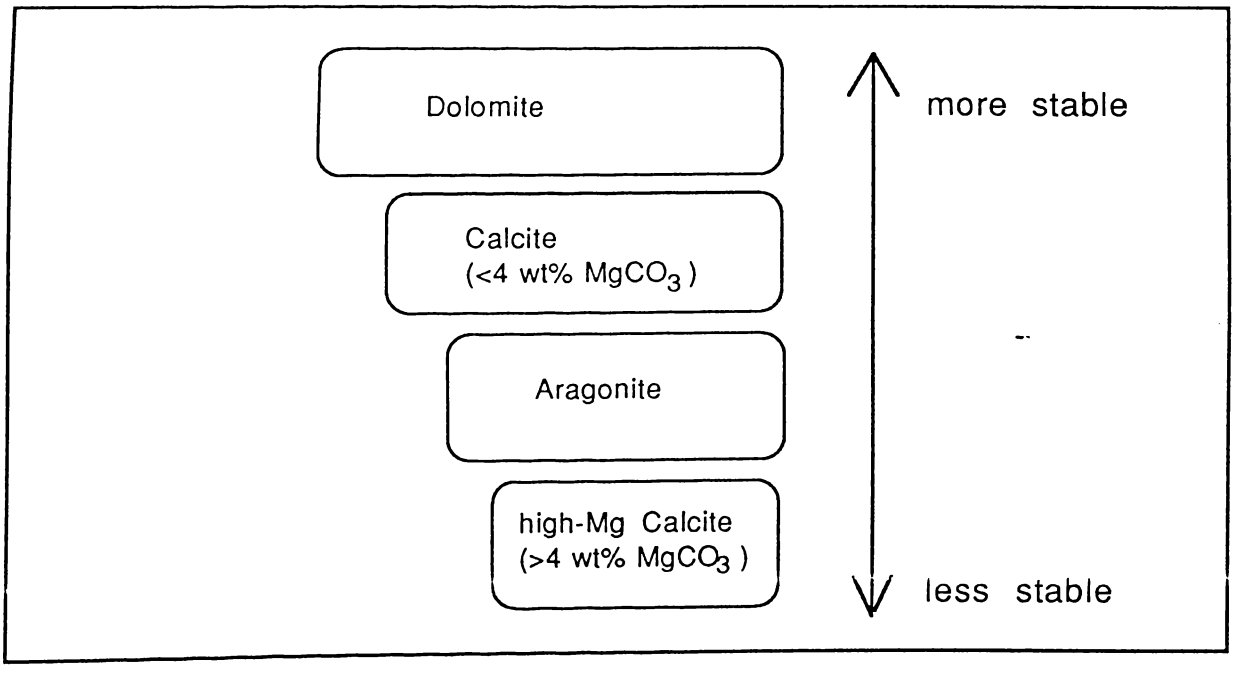


Figure 2A.5: Relative stability of calcium-magnesium carbonates.

There may be an inhibiting effect of the Mg^{2+} ion on the growth of calcite, so that high Mg concentrations in an environment will promote crystallization of aragonite. This has only been shown in vitro. It makes some sense, however, given that high-Mg calcite is an unstable form (Bathurst, 1975).

Some workers have suggested that the presence of Sr should theoretically increase the stability of aragonite. According to Lippman (1973) the solid solution would require 25 mol% $SrCO_3$ to stabilize aragonite. The maximum known content of Sr in natural aragonite is about 4 mol%; skeletal carbonates generally contain less than 1 mol% $SrCO_3$. Therefore, it seems unlikely that Sr content affects the dissolution of natural skeletal aragonites to any major degree.

There is some substitution by Mg in aragonite, as well as in calcite. Molluscs from the Gulf of Aqaba have been shown to have low-Mg aragonite shells (< 0.2 wt% $MgCO_3$), whereas corals from the same area have high-Mg aragonite (>2 wt% $MgCO_3$) (Friedman, 1968). Aragonitic magnesium is seldom found in quantities greater than 2 wt% $MgCO_3$. Chave (1954) found $MgCO_3$ contents from 0.12 to 0.76 wt% in hydrozoan corals. It is not clear what effect magnesium has on aragonite stability.

Aragonite, being metastable at the Earth's surface, should convert to calcite under normal conditions. However, the reaction has a high activation energy (Lippman, 1973), so energy must be added to begin the change. When aragonite is ground for several hours at room temperature it turns to calcite. Without the shear stresses generated by grinding, however, it takes tens of millions of years for dry aragonite to change to calcite at less than 100°C. Temperatures of 400°C are required for rapid dry inversion (Bathurst, 1975). Adding water tends to make the transition easier - at 100°C aragonite in pure fresh water converts to calcite in one day (Lippman, 1973). Because of this metastability of aragonite, modern skeletal carbonate sediments contain more aragonite than do ancient ones.

Different marine organisms precipitate $CaCO_3$ in different parts of the organism and by different organic chemical processes, so that different mineralogies result. With the biological energy added by the organism, and in the presence of certain dissolved organic compounds such as sodium citrate (Kitano and Hood, 1965), metastable and even unstable forms of carbonate can be precipitated. There is considerable variation in skeletal mineralogies. Nevertheless, taxonomic groups can have consistent mineralogies, with the small range perhaps attributable to environmental factors (e.g., Chave, 1954). Skeletal carbonates may in some species be monomineralic, while others may secrete both aragonite and calcite to some degree, often influenced by temperature.

As Figure 2A.6 shows, many taxa have a limited range of possible mineralogies (e.g., barnacle plates are all low-Mg calcite). Bryozoans, it is worth noting, cover a wider mineralogical range than most other taxa.

2. Carbonate Mineralogy of Bryozoans

Bryozoans are a mineralogically varied group of animals. Colonies may secrete $CaCO_3$ as aragonite, calcite (with a range of magnesium concentrations from 0 to 10 wt% $MgCO_3$), or both. Not only is there considerable mineralogical variation throughout the phylum, but the mineralogy within a single species may not be consistent, varying with the environment or the growth form. In addition, fossil bryozoans may be quite different from their modern counterparts, due to evolution, diagenesis, or environmental change. Because of this great diversity of composition, any generalizations made about bryozoan mineralogy must be based on extensive sampling; many different species from different places should be tested.

The available literature is fairly limited; there have been five major studies of bryozoan chemistry/mineralogy. These will be discussed below along with any other relevant data. A summary of results from the literature is given in Appendix Table A2.1.

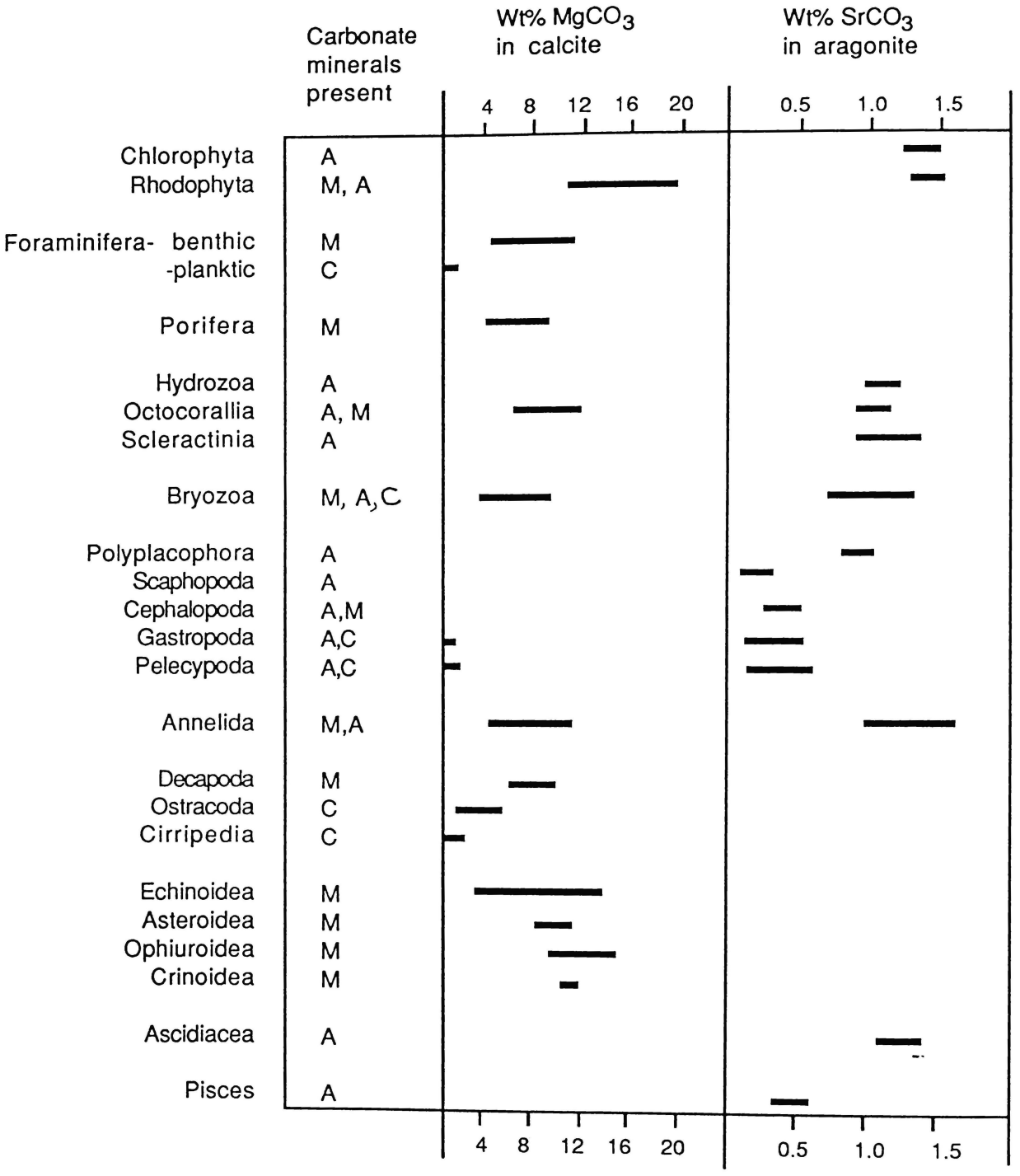


Figure 2A.6: Skeletal carbonate mineralogy of calcifying marine taxa (after Milliman, 1974). Abbreviations: A - aragonite, C - low-Mg calcite, M - high-Mg calcite.

Relatively few studies of the mineralogy of bryozoans have been undertaken, especially in comparison to data available for other carbonate-producing phyla. Some 90 chemical analyses of bryozoans were published prior to 1953, but most of these did not indicate which polymorph of $CaCO_3$ was present, and many were incomplete (particularly in respect to analyzing for Sr) (Schopf and Manheim, 1967). The first complete major element studies of many bryozoans were made by Clarke and Wheeler (1917, 1922). Their work on 13 bryozoans indicated that erect growth forms had higher percentages of $MgCO_3$ than encrusting forms. Their data were recalculated by Schopf and Manheim (1967) to be consistent with other studies. These recalculated data are used here.

Chave (1954) stimulated a number of studies of the geochemistry of marine skeletal carbonates with his summary of skeletal mineralogy. He referred to bryozoans only in passing, noting that magnesium content was generally high, and that data were lacking to make any other observations.

In a study of the bimineralic bryozoan *Schizoporella unicornis* (an ascophoran cheilostome), Lowenstam (1954) was able to correlate increasing ambient water temperature to increasing percentage of aragonite in the skeletal material. This work was done over a fairly limited temperature range (25° to 29°C), involving six specimens taken from areas around Bermuda. Lowenstam (1954) considered this to be significant, as % aragonite in bimineralic skeletons had been shown to be temperature-related in several other sessile organisms, such as the molluscs and serpulids. In addition, some major aragonite producers (codiacean chlorophyta, scleractinian corals) are not found in temperate waters. These two factors should lead to a latitudinal pattern of aragonite being much more common in lower latitudes. Indirect evidence of this trend may be reflected by the depletion of strontium in sea water in the tropics (Odum, 1951), perhaps due to fixing in biogenic aragonite.

Dodd's (1967) summary of Mg and Sr in skeletal carbonates (all phyla) emphasizes the dearth of available mineralogical data for bryozoans. All of his analyses were

summarized from Lowenstam (1954) and include only one species and about 7 data points. From this information Dodd concluded that bryozoan calcites are "fairly high" in Mg and low in Sr. Bryozoan aragonites are low in Mg and "quite high" in Sr compared to aragonitic algae (Dodd, 1967, p. 1320). These data were far too limited to form firm conclusions, and subsequent investigations have shown Dodd's generalizations to be too simple.

Schopf and Manheim (1967) provided the first mineralogical analyses for many different species of bryozoans. Their 13 species included representatives from the cyclostomes (3 spp.) and the cheilostomes (10 spp.). The samples were taken from the northwest Atlantic, particularly near Cape Cod, Massachusetts and in the northern Gulf of Maine, and included some of the much-studied and common Atlantic species such as *Bugula simplex* and *Flustra foliacea*. The compilation and recalculation of mineralogical data from the literature (primarily Clarke and Wheeler, 1917, 1922), plus the new analyses done by Schopf and Manheim on major element chemistry and mineralogy, led to them making several general statements:

1. The association of higher Mg content with erect colonial growth forms reported by Clarke and Wheeler (1917) was not borne out by their investigations (p. 1201).

2. The relationship of Mg and Sr content to $CaCO_3$ polymorph was explored and confirmed. Aragonitic forms contain very much less Mg and more Sr than calcitic forms. Aragonitic forms account for about 20% of living bryozoan species.

3. Cyclostomes with calcitic skeletons have Mg concentrations that are lower than calcitic cheilostomes (p. 1216). Cyclostomes tested have a lower mean Mg content than calcitic cheilostomes. (It should be noted that only 3 species of cyclostome were tested, so this statement requires confirmation by additional research.)

4. Higher concentrations of Mg were found in calcitic species making up an assemblage from lower latitudes (i.e., higher water temperatures). This is different from Lowenstam's (1954) conclusion which referred to variation within a single species growing under different temperatures. Schopf and Manheim (1967) considered groups of species that were typical of warmer waters vs. assemblages from colder waters.

5. Sr concentrations in bryozoans are higher than those predicted by chemical equilibria with sea water. In bryozoan calcite Schopf and Manheim (1967) found that Sr content varied between 0.28 and 0.62 wt% $SrCO_3$. The equilibrium condition would predict 0.19 at 0°C, decreasing with increasing temperature. There is some evidence that the increased concentration of Sr is due to the effect of the organic matrix in mineralization (Kitano and Hood, 1965).

6. Salinity and depth may influence the mineralogy of bryozoans.

7. Bryozoans concentrate Fe, Mg, Ca, Ba, Sr, P^4, and P^5 to varying degrees relative to their concentration in sea water. The most concentrated are Fe, Ba, and both forms of P. This may be of interest in terms of records of pollution and/or radioactivity.

Even following this analysis, with its many conclusions and interesting data, less than 1% of living bryozoan species had been studied. For this reason, the conclusions should be considered provisional, to be confirmed by additional study.

Schopf and Manheim determined the major element composition of all 13 bryozoans but only checked the mineralogy (that is, which polymorph was present) of a few specimens using x-ray diffraction (XRD). Rucker's (1968) preliminary study of 61 bryozoans made no mention of Mg content, but was later expanded by Rucker and Carver (1969), who used XRD to study the mineralogy of 61 species of cheilostome bryozoans. These were divided fairly evenly between anascan cheilostomes (32 spp.) and ascophoran cheilostomes (28 spp.), and one acanthostegan cheilostome (cribriomorph).

Surprisingly, the collection areas of the tested specimens were not indicated, but they appear to have come from both Atlantic and Pacific Northern Hemisphere collections. This much larger data set allowed Rucker and Carver to make some conclusions about cheilostomes as a group, and even about the suborders.

1. Anascans are likely to be calcitic; 25 of 32 species were monomineralic for calcite. The non-calcitic anascans were mainly discoidal free-living forms. These were either aragonitic or of mixed mineralogy. Anascan calcite was generally 4-8% $MgCO_3$, except for one instance of 10-13% $MgCO_3$. (It is not clear whether Rucker and Carver measured wt% or mol% $MgCO_3$; since they used such large ranges their data are rather limited in usefulness.) No difference between encrusting and erect anascans was reported.

2. Many ascophoran species are of mixed mineralogy, although there is considerable variation within species. Mixed mineralogies tend to be mainly calcite with a secondary thickening of the frontal wall by aragonite. As a result, the degree of aragonite precipitation may be an indication of age. Some apparently monomineralic ascophorans may just be too young to have begun secondary mineralization.

3. *Schizoporella unicornis* from the coasts of North America appeared to confirm Lowenstam's (1954) temperature correlation with % aragonite. The data were not published.

Since then, several microprobe studies (e.g., Cheetham et al., 1969; Schopf and Allan, 1970) have determined that bimineralic bryozoans have two distinct layers, usually on the frontal wall, and that the aragonitic layers are due to secondary calcification. These layers may be so discrete that they separate after the death of the organism (Ryland, 1970).

Ryland (1970) pointed out that secondary calcification in ascophoran bryozoans only occurs in forms in which the primary skeletal layer is perforated with "pseudopores." Initially the surface layer of cells (epithelium) precipitates calcite into the primary skeletal layer. As the bryozoan ages a second epithelium emerges through the pseudopores and precipitates aragonite on top of the calcite. This explains how both minerals can be precipitated; they are precipitated by different tissues.

Rucker and Carver (1969) made only a single attempt to correlate mineralogy with latitude/water temperature, and did not attempt to correlate mineralogy with depth, or salinity. They also did not study any cyclostome bryozoans. As a result, although they added a great deal of information about cheilostome mineralogy, and especially phylogenetic variation, many of Schopf and Manheim's (1967) conclusions remained untested.

Poluzzi and Sartori (1973, 1974) noted that no studies had included Mediterranean bryozoans. In order to rectify this omission and to provide more data, they studied 94 species of Mediterranean bryozoans (collected live). Their 16 cyclostomes and 78 cheilostomes were from the Adriatic Sea to the Strait of Sicily, a temperate area covering latitudes 36° to 46°N. From their XRD analyses, they reached the following conclusions:

1. The Mg content in calcite shows some ontological variation, that is, the amount of $MgCO_3$ in calcitic bryozoans may decrease from the older parts of the organism to the younger.

2. Increasing temperature leads to increases in Mg content and aragonite percent within species.

3. Different species within the same genus that resemble each other closely may have very different mineralogies. In one case Poluzzi and Sartori (1973) even suggested using mineralogy as a diagnostic feature for identification.

4. The phylogenetic groups show distinct mineralogical characters. Cyclostomes are wholly calcitic, with Mg content ranging from low to high. The mean Mg content is 4 wt% $MgCO_3$, with modes at 2 and 6. Cheilostomes are more varied. Anascans tend to be monomineralic, possibly because they may have no frontal-shield structure on which to precipitate a secondary mineral. Ascophorans are more likely to be of mixed mineralogy. Cheilostomes tend to have high-Mg calcite, with a mean and a mode of 7 wt% $MgCO_3$. It appears that with increasingly complex structure and advanced taxonomic position (i.e., from cyclostomes to anascan cheilostomes to ascophoran cheilostomes) there is an increase in Mg content, a contraction of the range of Mg contents, and a general increase in aragonite content.

5. Growth form may be correlated with mineralogy. In cheilostomes, encrusting forms show a wide range of mineralogies, but are only aragonitic if the basal wall is heavily calcified. Erect rigid forms are mainly monomineralic, typically of calcite. Erect flexible forms are almost always calcitic, with the exception of the bimineralic *Margaretta cereoides*. They did not test any free-living forms, but noted that they are often found to be aragonitic or bimineralic. In anascan cheilostomes the erect flexible forms tend to be calcitic and the encrusting forms calcitic or of mixed mineralogy.

6. No major difference in mineralogy was noted between fresh specimens and sub-fossil specimens of the same organism (Poluzzi and Sartori, 1973).

In his sizeable collection of data on the mineralogy of carbonate sediment producers generally, Milliman (1974) summarized the above studies, adding his own observations. One of these observations relates to the correlation of water temperature and degree of aragonite calcification. He used data on *Schizoporella unicornis* from Schopf and

Manheim (1967), Rucker and Carver (1969), and his own unpublished work. *S. unicornis* colonies from Woods Hole, Massachusetts (temperate) are 50-60% aragonite, from Bermuda (subtropical) are 50-70% aragonite, and from southern Florida (tropical) are >80% aragonite. This may be due to thickening of the superficial aragonite layer.

Sandberg (1977) summarized the available data on the mineralogy of bryozoans, particularly with reference to the fossil record. He stated that cyclostomes are calcitic, with magnesium contents ranging from 1 to 8 wt% $MgCO_3$. This fairly wide range may explain the considerable textural variation in fossil cyclostomes and other stenolaemates, and the high degree of fossil preservation in cyclostomes, as low-Mg calcite is the most stable form of $CaCO_3$.

Cheilostome calcite generally has more Mg, from 4 to 10 wt% $MgCO_3$ with a mean of 7%. Aragonitic cheilostomes have a low magnesium content and a Sr:Ca ratio close to that of sea water (about 1:100). In bimineralic cheilostomes, aragonite forms either frontal wall thickenings or wedges between side walls and the base. Sandberg (1977) states that in some fossil bryozoans one can detect such a wedge, but the material has dissolved away. This reflects the lower stability of aragonite relative to calcite (Sandberg, 1977).

The above summaries (Milliman, 1974; Ryland, 1970; Sandberg, 1977) were almost entirely based on Northern Hemisphere bryozoans. The only Southern Hemisphere bryozoans analyzed up to that time were two species from "Australia" by Clarke and Wheeler (1917). This discrepancy is most unfortunate, as bryozoans make up a very important part of the marine fauna and are major sediment producers in parts of the Southern Hemisphere (e.g., northern and southern New Zealand shelf (Nelson et al., 1988a, b), southern Australian shelf, including Tasmania (Wass et al.,1970)). There is a major lack of mineralogical data for these organisms.

Nelson et al. (1988b) reported on some mineralogical work on bryozoans from New Zealand (data listed in Keane, 1986). The 18 species studied (2 cyclostomes, 16 cheilostomes) were taken from the Three Kings Platform, north of New Zealand, and their XRD analysis gives additional information:

1. The cyclostomes tested secrete very low-Mg calcite. This is further confirmation of a trend already noted in the Northern Hemisphere. Cheilostome calcites vary from 4.5 to 9.5 wt% $MgCO_3$, whereas cyclostomes range from 1.0 to 2.8 wt% $MgCO_3$.

2. Anascan cheilostomes tested are of monomineralic calcite, whereas some of the ascophorans are bimineralic. The only all-aragonite bryozoan tested was a free-living form.

4. The data do not seem to support any mineralogical trend with growth form. Encrusting species are not noticeably different from erect ones.

This Section, then, is a brief review of the global literature on bryozoan skeletal mineralogy. A summary of the major conclusions reached is given in Table 2A.1.

There are about 4,000 living species of bryozoan in the world today (Ryland, 1970). Of these, the studies mentioned in this section have investigated the mineralogies of only 124 species. This is about 3% of living species. The cheilostomes have been much better covered than the cyclostomes. Of the 600-odd genera of cheilostomes, one or more representatives of 73 genera have been tested (12%); of the 250 genera of cyclostomes, representatives of 12 have been studied (5%).

Considering the degree of variation and the number of sources of variation, the coverage of the bryozoan phylum has not been adequate to justify the often sweeping statements that have sometimes been made.

Table 2A.1: Summary of major conclusions reached in the published literature on bryozoan mineralogy.

	Clarke and Wheeler 1917, 1922	Lowenstam 1954	Schopf and Manheim 1967	Rucker and Carver 1969	Poluzzi and Sartori 1973, 1974	Nelson et al. 1988
Species studied	13	1	13	61	94	18
Variation within colonies					Mg decreases in younger parts	
Variation among populations		more A with increased T	more Mg in high latitudes; salinity/depth may be important	more A with increased T	increasing Mg and increasing A with increasing T	
Variation among species					can diagnose species within genus by mineralogy	
Variation among higher taxa			cy have less Mg than ch	anas: med-Mg C asco: Bi	cy: low-Mg C anas: Mo asco: Bi, high-Mg C	cy: low Mg C anas: C asco: Bi/C
Variation among growth forms	more Mg in erect than in encrusting		cannot confirm Clarke and Wheeler observation		erect usually C freeliving A/Bi enrusting variable	no trend
Variation after diagenesis					no major difference between subfossils and fresh specimens	

Abbreviations used: A-aragonite; anas-anascans; asco-ascophorans; Bi-bimineralic; C-calcite; ch-cheilostomes; cy-cyclostomes; Mo-monomineralic; T-temperature.

3. Methodology Used in Determining Mineralogy

Information about mineralogy has kept pace with technology. Clarke and Wheeler (1917, 1922) did all their work by painstaking staining, titration, and multi-step preparation. All early work was "chemical," that is it involved chemical techniques such as staining, igniting, and titrating. The early workers were hampered by not having a good reliable method for distinguishing aragonite from calcite. For this reason, we have more (especially early) information about cations (%Mg, for example) than about $CaCO_3$ mineralogy. Schopf and Manheim (1967) used spectrochemical analysis, and Rucker and Carver (1969) reported a reliable staining method for differentiating aragonite and calcite. With these exceptions, the majority of the data available on bryozoan mineralogy are based on x-ray diffraction (to be described in detail below in Section B.2). The sample preparation and cleaning methods used in the major works on the mineralogy of bryozoans are summarized in Table 2A.2.

The early research on magnesium content of skeletal material referred to magnesium content in weight percent (wt%) $MgCO_3$ (Chave, 1952). Rucker and Carver (1969) also used wt% $MgCO_3$; they were using Chave's method. Researchers using traditional chemical analysis (e.g., Schopf and Manheim, 1967) expressed magnesium concentration in different units: wt% Mg, or wt% MgO. Poluzzi and Sartori (1973) used magnesium concentrations of mol% $MgCO_3$, as others have also done. Strontium is even more complicated; Dodd (1967) used an atomic ratio of Sr:Ca. Wt% $SrCO_3$ has been used, and Milliman (1974) did all his summaries in wt% Sr, whereas Schopf and Manheim (1967) did theirs in wt% SrO.

It is imperative to distinguish between these and to be able to convert from one to another. Otherwise, comparison between work done by different people becomes complicated and may introduce error. Below are the methods for converting between these units, and the formulae needed, including graphic relationships.

Table 2A.2: Sample preparation methods used in published XRD studies of bryozoan mineralogy.

	Lowenstam 1954	Schopf and Manheim 1967	Rucker and Carver 1969	Poluzzi and Sartori 1974
specimen choice	entire skeleton	100 mg same species	as available	one colony per sample
cleaning technique	brushed bleached	encrusters removed bleached	hand picked	hand picked
grinding/ size of powder	ground to <100 microns		crushed on slide with NaCl	powdered with CaF_2
mounting	slurry on slide powder mount		glued to slide	powder mount

A weight percent (number of grams of material in 100 grams of sample) can be converted into a mole percent (or mol% or molar %) (number of moles of material in 100 moles of sample) using the molecular weight of the compounds in question, as follows:

$$\text{mol\% X} = \frac{(100)(\text{wt\% of X})/(\text{mol wt of X})}{(\text{wt\% of X})/(\text{mol wt of X}) + (\text{wt\% of non-X})/(\text{mol wt of non-X})}$$

The atomic and molecular weights of the common carbonate ions and compounds are:

ATOMIC WEIGHTS	MOLECULAR WEIGHTS
$Ca^{2+} = 40.1$	$CaCO_3 = 100.1$
$Mg^{2+} = 24.3$	$MgCO_3 = 84.3$
$Sr^{2+} = 87.6$	$SrCO_3 = 147.6$
$C^{+} = 12.0$	
$O^{-} = 16.0$	

Using the molecular weight of $MgCO_3$, conversions between wt% and mol% are as listed in Table 2A.3.

This assumes that the non-magnesium calcite is entirely calcium carbonate. If there is substitution by, for example, iron, this is an incorrect formula. Nevertheless, in most biogenic carbonates there is sufficiently little non-calcium carbonate to make this a fair assumption.

Some data are given in the form of wt% Mg, and if all the Mg in the sample is in the form of $MgCO_3$, one can convert that to wt% $MgCO_3$. If, as may be true in some red algae (Milliman, 1974), some of the Mg is in another form (e.g., brucite) then this conversion is inaccurate. In 100% $MgCO_3$, there are 24.3 g Mg to the total of 84.3 g. Therefore any percentage of Mg will be a percentage of that ratio, thus:

$$\text{wt\%}MgCO_3 = \frac{(\text{wt\% Mg})(\text{mol wt of } MgCO_3)}{(\text{atomic wt of Mg})(100)}$$

Table 2A.3: Formulae for conversion between different units of Mg content in carbonate.

Mol% to wt% of carbonate mineral (if the rest of the compound is $CaCO_3$)
mol% $MgCO_3$ = 10010/(15.8 + 8430/wt% $MgCO_3$)
wt% $MgCO_3$ = 8430/(10010/(mol% $MgCO_3$ - 15.8))
Wt% cation to wt% carbonate mineral (if all the cation present is in the carbonate mineral)
wt% Mg = 0.288 wt% $MgCO_3$
wt% $MgCO_3$ = wt% Mg/0.288
Wt% oxide to wt% carbonate mineral (if all the oxide present is in the carbonate mineral)
wt% MgO = 0.478 wt% $MgCO_3$
wt% $MgCO_3$ = wt% MgO/0.478

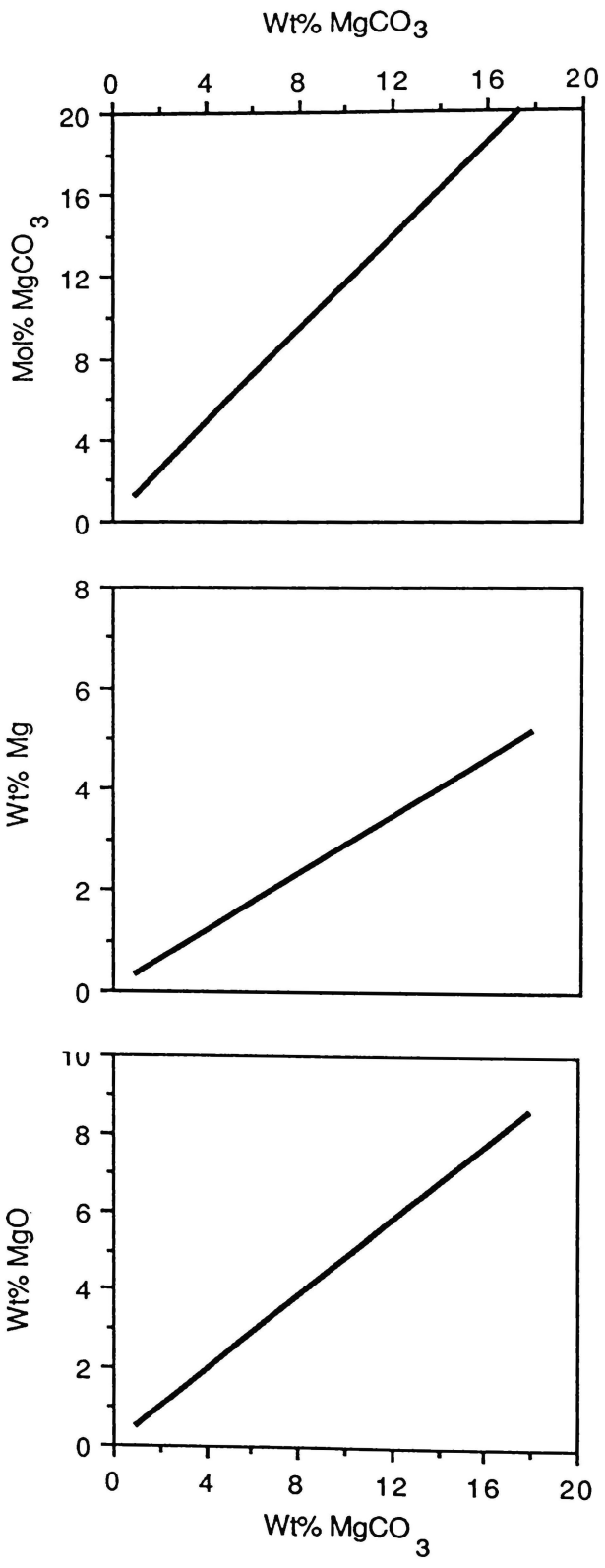


Figure 2A.7: Graphs for conversion of different units of concentration of Mg in calcite.

Similarly, if all the magnesium oxide in a sample is in the form of $MgCO_3$, then one can also convert wt% MgO to wt% $MgCO_3$.

Table 2A.3 lists all the necessary formulae for making conversions as above using Mg. Figure 2A.7 gives graphs to make conversions easier. Sr and Ca can be calculated by analogy.

Other units that have been used (ppm, molar ratios) are less common and are not as easily converted. Dodd's (1967) atomic ratio (number of Sr atoms for every 1000 Ca atoms) seems not to have become popular among bryozoologists. Neither has the distribution coefficient (molar ratio of Mg to Ca in skeleton relative to molar ratio in sea water) come into use.

As far as possible in this work data in the literature have been converted to wt% $MgCO_3$. This is a reasonable standard, as Chave (1962) used wt% $MgCO_3$ in his initial work, and one avoids compounding errors by not converting it.

B. CARBONATE MINERALOGY OF NEW ZEALAND BRYOZOANS

1. Purpose

However preliminary and limited previous studies of bryozoan mineralogy may have been, they have raised a number of important ideas and questions. It is clear there is a wide range of carbonate mineralogies within the bryozoans, and that a number of different factors are responsible for this.

Variation within colonies

To what extent does mineralogy vary over the course of a colony's development? Some evidence suggests that older parts of a colony may have different mineralogy than younger parts. How can this be, if a colony is essentially a collection of replicate units?

Is this due to a change in the organism's interaction with sea water, or to an actual, perhaps seasonal, change in sea water?

Variation within populations

How much variation is there between colonies of the same species in the same environment? This is the background "noise" against which all other variation is measured, but it remains unquantified. A very few species have had multiple colonies analyzed from the same environment (e.g., *Cryptosula pallasiana* by Rucker and Carver, 1969). Interpreting these sorts of data is clearly of great importance in determining the significance of other sources of variation.

Variation among populations

It has been shown that some bryozoans show a relationship between mineralogy and latitude. Can one say that this is a response to temperature? Other factors (depth, light, salinity, turbulence, turbidity, and food quality and abundance) may have effects. What are they? How "good" is the alleged temperature correlation with bryozoan mineralogy? Can one describe it as an environmental response? Which bryozoans show this relationship and do they have anything in common? Are there regional differences between New Zealand bryozoans and those from other areas (Atlantic Ocean, Northern Hemisphere)? Are temperate populations different in mineralogy from tropical ones?

Variation among species

Just how different are different species? What are the outer limits of the mineralogy of bryozoans? Do bryozoans tend to fall into obvious mineralogical groups?

Variation among higher taxa

Is there any consistency of mineralogy within genera? How does mineralogy vary with wider systematic position? At what taxonomic level are mineralogical generalizations true? It appears that cyclostomes are generally low-Mg calcite - is this always so? Is

there some chemical/organic reason for this? Can one make similar statements about anascans and/or ascophorans? It appears that cyclostome calcite is lower in Mg than cheilostome calcite. Do further tests confirm this? Do the phylogenetic trends go to the level of family? Is a bimineralic skeleton the most advanced? Why should it be?

Variation among growth forms

Bryozoans may grow into a variety of forms, usually in response to their environment. What influence does growth form have on mineralogy? Is it true that erect forms differ from encrusting forms? Do free-living forms have some reason for being mainly aragonitic? What might this be?

Variation after death

To what extent are bryozoan mineralogies changed after the death of the organism? Are aragonitic and high-Mg calcite bryozoans more susceptible to dissolution and alteration? Is there some differential survival into sediments? What diagenetic effects occur with time in the sediments?

These questions cannot possibly all be answered definitively by one study. What they indicate is that further data are urgently needed on the mineralogy of bryozoans from all over the world and from many different environments. Thoughtful and statistically careful analyses are needed to determine significant correlations. Care is needed, especially about making generalizations based on data that are limited.

The answers to these questions have implications far beyond bryozoology. The geochemistry of carbonate sediments is highly dependent upon the geochemistry of the sedimentary components. The understanding of diagenesis and the accuracy of interpretation of ancient environments will be increased by answering such questions. Bryozoans are important sediment components, particularly in temperate carbonates; understanding of their mineralogy will lead to an increased understanding of temperate carbonate processes.

The purpose of this part of the study, then, is to analyze the mineralogy of the New Zealand bryozoans, which are important skeletal sediment producers on parts of the New Zealand shelf. Using many samples from a wide range of environments, some of the questions listed above may be answered in regard to New Zealand species. In addition, a comparison of New Zealand data to world-wide published data will be possible.

2. Materials and Methods

Bryozoan colonies or recognizable fragments thereof were collected from the gravel fraction of shelf sediment samples from around New Zealand. Some 48 shelf sediment samples were used. These samples have a considerable range of latitude, longitude, and depth (see Figures 2B.1 and 2B.2, Table 2B.1, Appendix Table A2.2).

In some instances the sample coverage was augmented by including specimens collected while living and killed in alcohol. Some samples were cleaned ultrasonically and some were soaked in dilute bleach to remove organic matter. Neither procedure appeared to make any difference to the results. Many sediment samples and some living specimens were provided by the University of Waikato archives and the New Zealand Oceanographic Institute (NZOI) archives. Others were gathered by the author in the course of this study.

Bryozoans removed from the sediments were identified by the author using the three very useful volumes by Gordon (1984, 1986, 1989). Identification of difficult or rare specimens was undertaken by D.P.Gordon of NZOI. In the case of many cyclostomes, species descriptions are not available, as the whole group is rather poorly understood. In these cases, similar specimens were grouped together and named according to their growth form (i.e., idmidroneiforms). Some averaging of mineralogies may take place as a result.

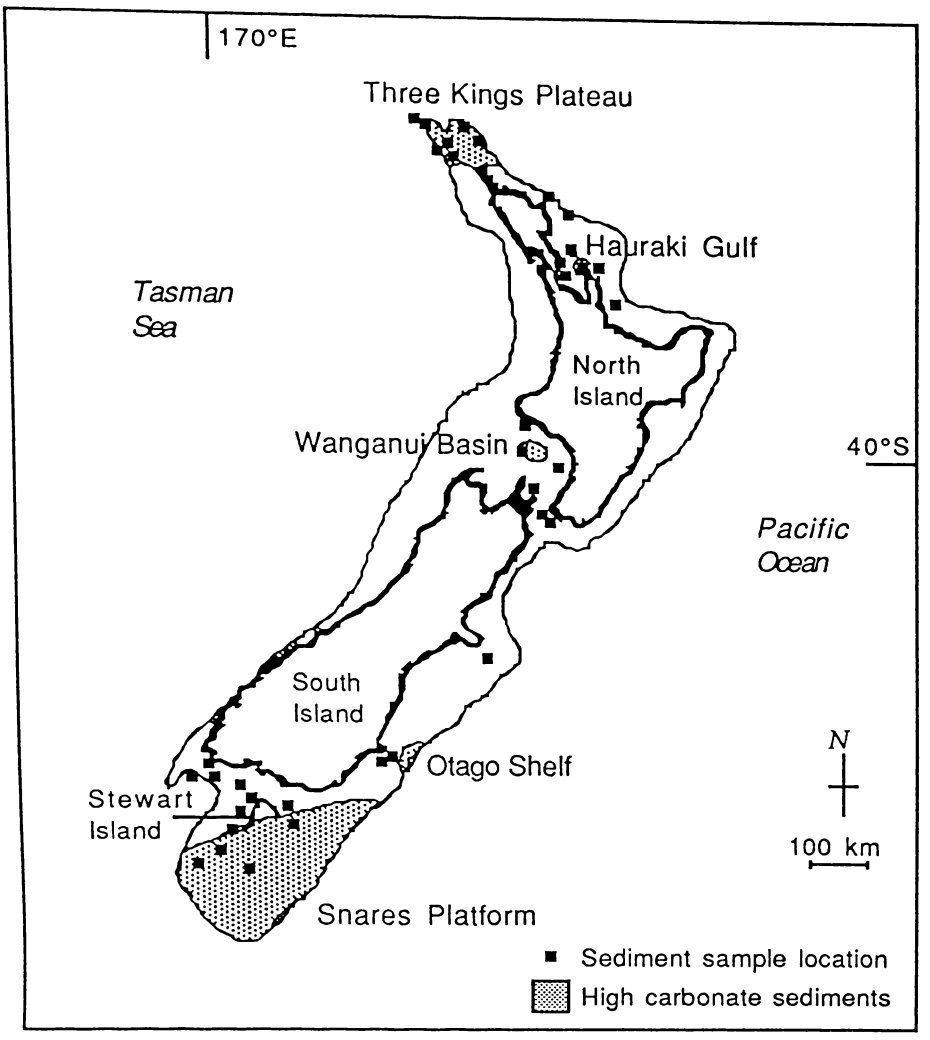


Figure 2B.1: Mineralogical sample locations on New Zealand shelf, excluding 1 sample from Norfolk Ridge (to the northwest) and 3 samples from the Subantarctic Islands (southeast).

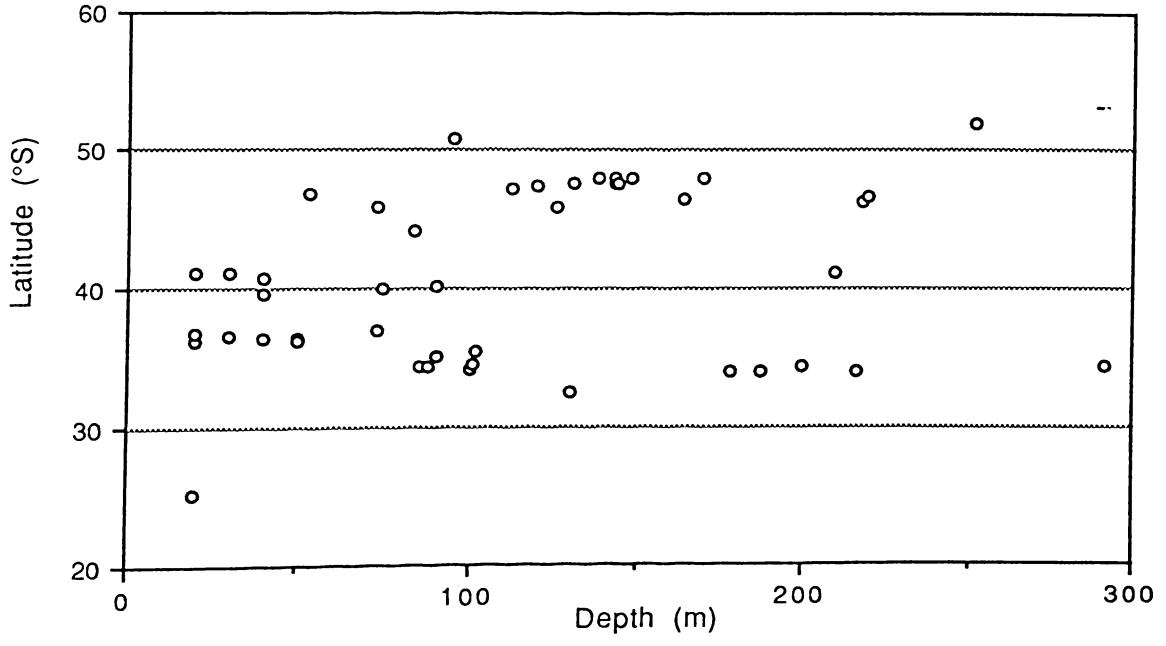


Figure 2B.2: Depths and latitudes of sample locations, showing good coverage of the New Zealand shelf.

Table 2B.1: Sample locations from which New Zealand bryozoans have been collected for determination of carbonate mineralogy.

Sample	Latitude (°S)	Longitude (°E)	Depth (m)	No. specimens	Source
DPG1	25.17	167.17	20	1	DPG
E842	33.90	172.28	187	1	NZOI
E849	33.92	171.53	216	4	NZOI
P558	33.98	171.72	178	18	CSN
P507	34.15	172.75	100	14	CSN
P458	34.23	171.94	200	11	CSN
P454	34.25	172.16	292	18	CSN
P489	34.30	172.68	88	10	CSN
P492	34.36	172.61	85	15	CSN
P448	34.39	172.47	101	35	CSN
RW	34.98	173.94	90	8	AMS
E559	35.45	174.75	102	1	NZOI
LF	36.27	174.80	20	6	AMS
LS	36.27	174.80	20	6	AMS
L**	36.28	174.67	50	20	AMS
C**	36.45	175.30	50	28	AMS
K**	36.45	174.92	40	14	AMS
O F1	36.72	175.83	20	3	AMS
E644	37.01	176.08	73	3	NZOI
C176	39.67	173.95	40	3	NZOI
P609	40.01	174.08	75	11	UW
P614	40.17	174.58	90	16	UW
A441	41.13	174.65	210	4	NZOI
DPG2	41.17	174.67	20	1	DPG
DPG3	41.13	174.50	30	1	DPG
DPG4	40.80	174.17	40	1	DPG
D114	44.20	173.30	84	9	NZOI
B567	46.00	170.92	126	3	NZOI
B568	46.00	170.72	73	2	NZOI
E817	46.23	166.48	218	1	NZOI
B488	46.48	166.24	164	6	NZOI
E820	46.58	165.97	220	4	NZOI
E833	46.95	168.15	53	1	NZOI
B574	47.33	168.22	113	1	NZOI
D044	47.50	168.01	120	11	UW
E028	47.66	167.92	143	7	UW
E027	47.67	167.65	131	12	UW
E026	47.68	167.40	144	7	UW
B581	48.00	168.10	138	6	UW
G009	48.00	166.59	170	12	UW
G007	48.02	167.62	148	7	UW
D104	50.82	166.26	95	4	NZOI
D038	51.97	165.47	252	5	NZOI
DPG5	49.75	179.00		1	DPG

NOTES: Sample numbers are those given by the source of the sample. Latitude and longitude have been converted to decimals. Sources are: AMS - collected by the author; CSN - Dr. C.S. Nelson; DPG - Dr. D.P. Gordon; NZOI - New Zealand Oceanographic Institute, Wellington; UW - University of Waikato, Hamilton. ** indicates a range of sample numbers from one area.

Standard semi-quantitative x-ray diffraction (XRD) techniques were used (e.g., Hume and Nelson, 1982; see Appendix Table AI.3). The specimens and a very small amount of an internal standard, halite, were ground to less than 200 μm and the resulting material back-filled into a powder mount. The flat surface was exposed to x-rays and the resulting emissions were quantified on a standard trace. The printer was set to a very slow chart speed (50 mm/°2θ), and was set to recover data from the range of the major carbonate and halite peaks (25.5 to 32.5 °2θ). Appendix Table AI.3 gives details.

Each trace was graphically examined to determine the exact location of the calcite peak in relation to the standard halite peak. If aragonite was present, the heights of both aragonite peaks and the calcite peak were measured. Figure 2B.3 shows typical traces.

It is clear from various other workers' experience (e.g., Milliman, 1974; Hume and Nelson, 1982) that a systematic relationship exists between the dimensions of the aragonite and calcite peaks and their relative percentages. It does appear, however, that this varies from machine to machine, with different machine settings, and probably from operator to operator. As a result, a set of standards composed of biogenic aragonite (bivalve) and calcite (bryozoan) in various ratios was analyzed using a standard XRD procedure and the results were used to produce an equation relating the two. Various combinations of peak heights and peak areas were examined to find the best predictor. A ratio of the sums of peak heights was found to produce the best relationship (Figure 2B.4).

The exact position of the calcite peak relative to the internal halite calibration peak has been shown to indicate the amount of substitution by Mg of Ca in the calcite present (Chave, 1952). Wt% $MgCO_3$ can be determined from this position using Figure 2B.5.

3. Results

The 48 species from 48 sample locations on the New Zealand shelf provide a great deal of information in a rather cumbersome form (see Appendix Tables A2.2, A2.3). These

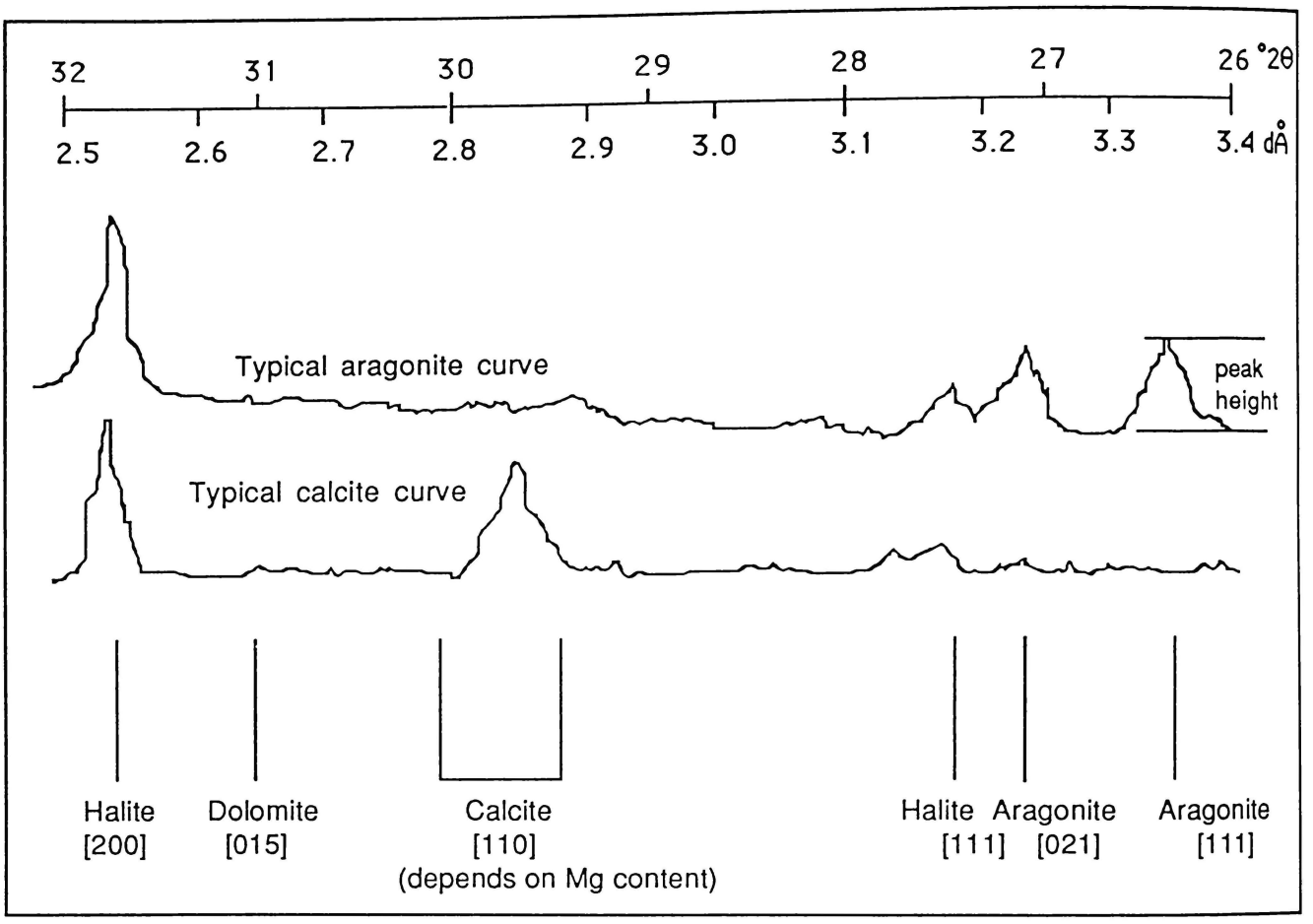


Figure 2B.3: Interpretation of XRD traces, showing the locations of carbonate mineral peaks in relation to the internal standard, halite. Miller indices are given in brackets.

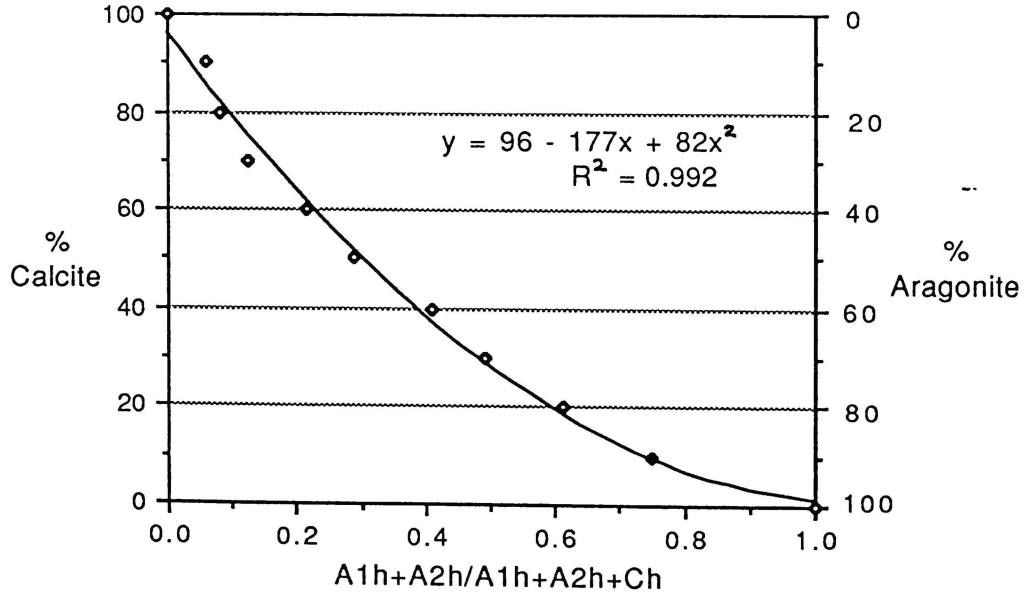


Figure 2B.4: Calibration curve for quantifying the aragonite and calcite content of samples using XRD. Based on a series of standardized mixtures of biogenic calcite and aragonite.

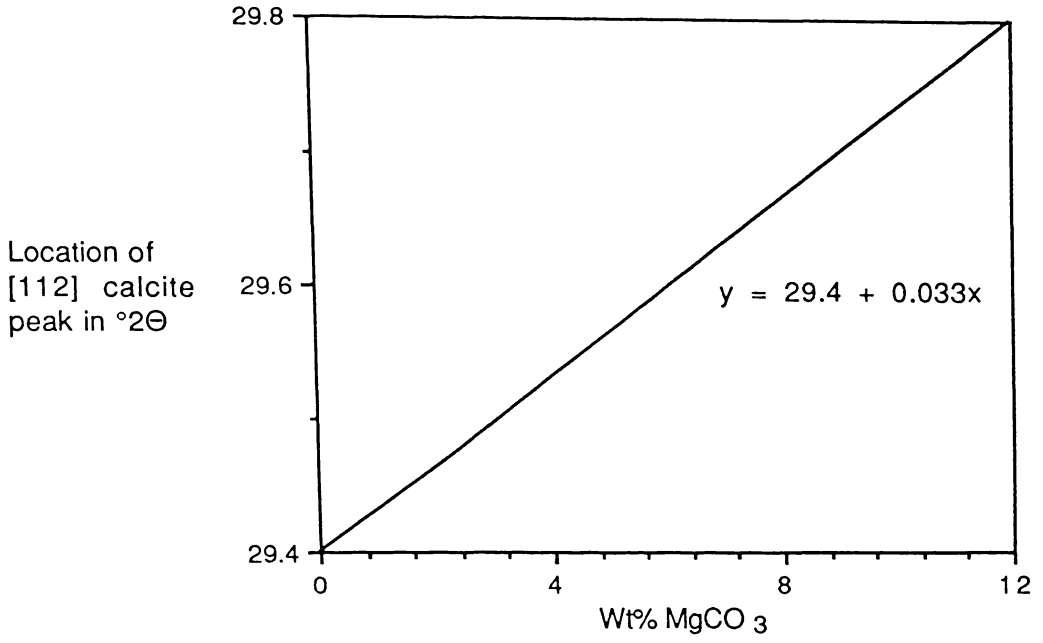


Figure 2B.5: Relationship between calcite peak position and Mg content in biogenic calcites (after Chave, 1952).

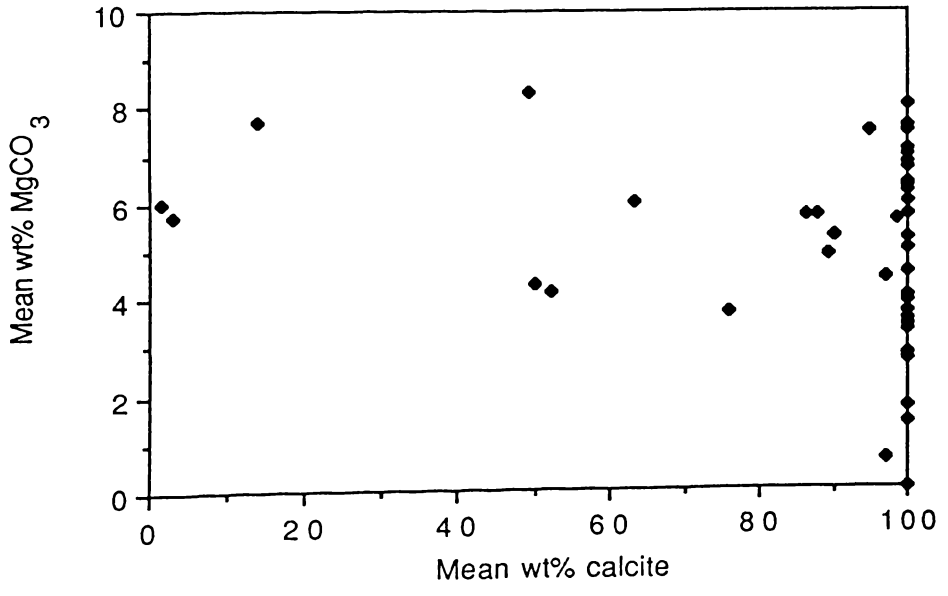


Figure 2B.6: Mean carbonate mineralogy of 48 New Zealand bryozoan species.

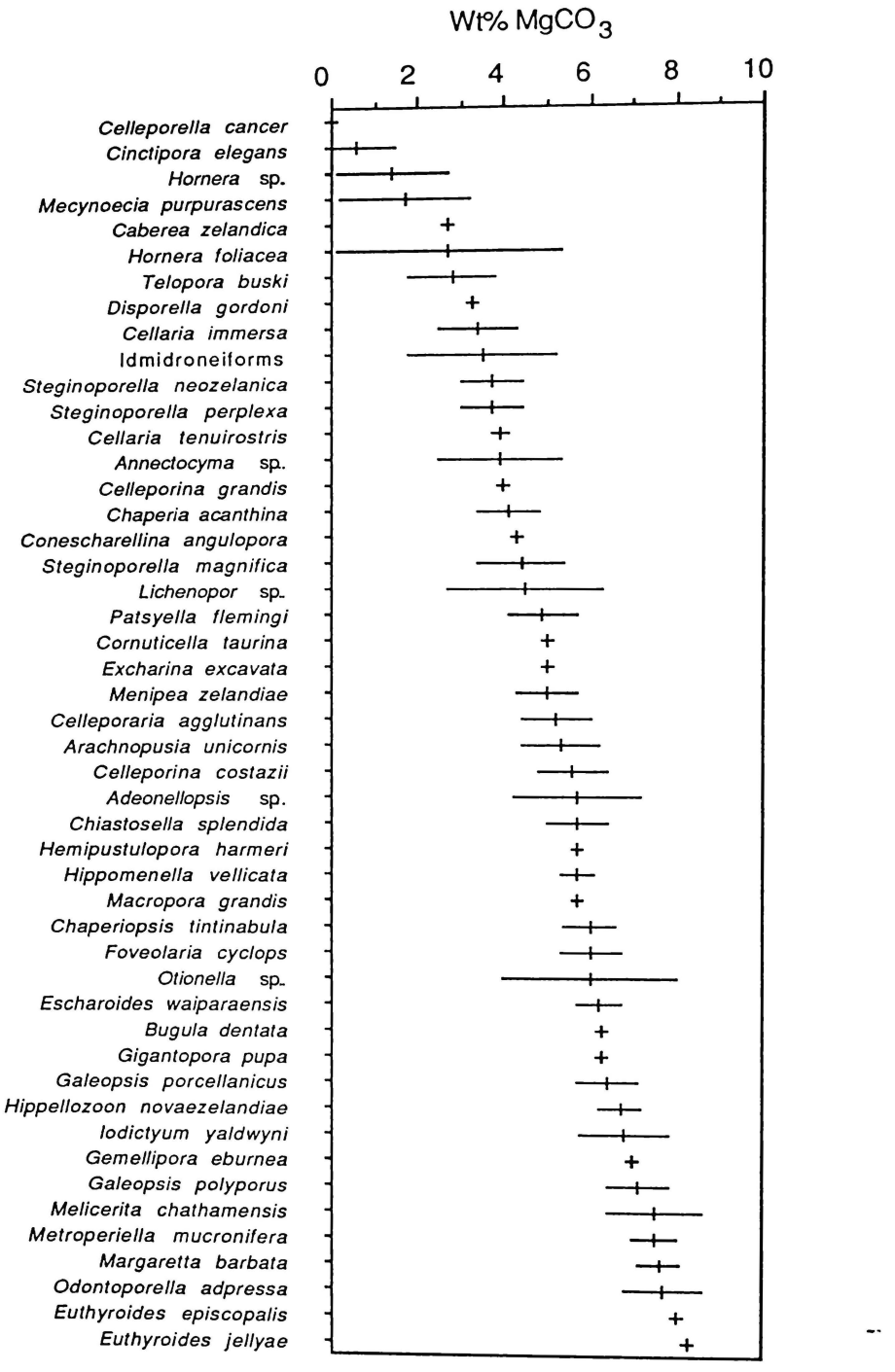


Figure 2B.7: Mean Mg content in calcite for 48 species of New Zealand bryozoans. Standard deviations (bars) given when more than one sample was taken. Data in Appendix Table A2.4.

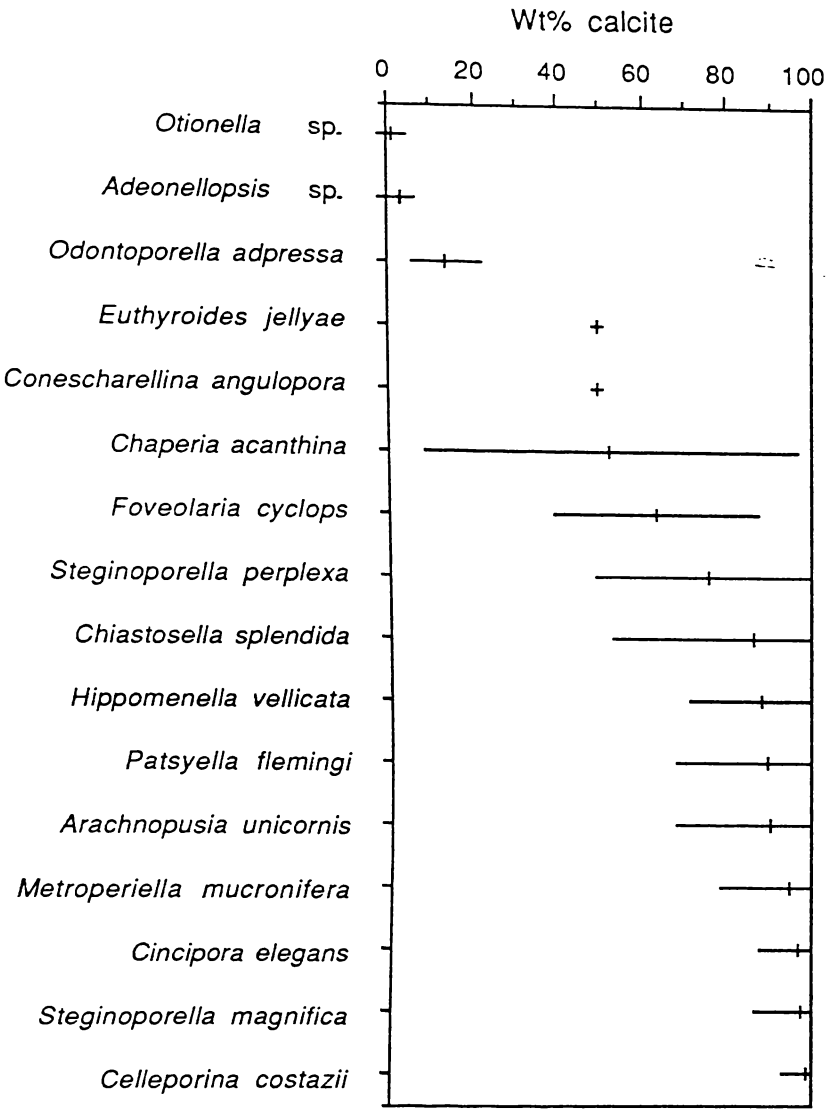


Figure 2B.8: Mean calcite content in carbonate for 14 bimineral species of New Zealand bryozoans. Standard deviations (bars) given when more than one sample was taken. Data in Appendix Table A2.4.

data can however be usefully simplified to aid analysis. Means, ranges, and standard deviations for all species are shown in Figures 2B.6 to 2B.8 and Appendix Table A2.4.

It will be noted that no single simple category will describe bryozoans as a whole. Although many carbonate sedimentologists have stated that bryozoans are mainly formed from high-Mg calcite (e.g., Milliman, 1974), in fact it is clear that nearly every possible mineralogy is found in bryozoans. They range from aragonite to calcite and from very low Mg content to relatively high. In addition, New Zealand bryozoans do not appear to show the bimodal distribution of $MgCO_3$ shown by other taxa and described by Bøggild (1930). There is no apparent grouping of high-Mg versus low-Mg calcites (Figure 2B.9). Nevertheless, none of the New Zealand bryozoans studied shows the extremely high Mg content of some skeletal carbonates, such as in the coralline algae. Most may be characterized as having moderately high (5-8 wt% $MgCO_3$) Mg contents.

In discussing different possible sources of variation in bryozoan mineralogy different parts of the large database will be useful. Therefore pertinent results will be tabulated in each section of the discussion and listed in the Appendix.

4. Discussion

Variation within colonies

In *Steginoporella neozelanica* the branches grow out from a base, such that the tip of the branch is the youngest part of the living colony (Figure 2B.10). Fresh *S. neozelanica* were chosen to be studied as they are not likely to be complicated by diagenetic factors. Samples were collected from subtidal areas off the northeastern North Island (Figure 2B.11). Each specimen was disarticulated, and 4 branches of approximately the same length were selected. These were cleaned and prepared as described above, but before grinding, each branch was cut into 3 segments. Cuts were made 1 cm from the tip of the branch and 1 cm from the base of the branch (Figure 2B.12). The bases from the 4 branches from a single individual were combined and powdered, as were the 4 tips and the 4 middles.

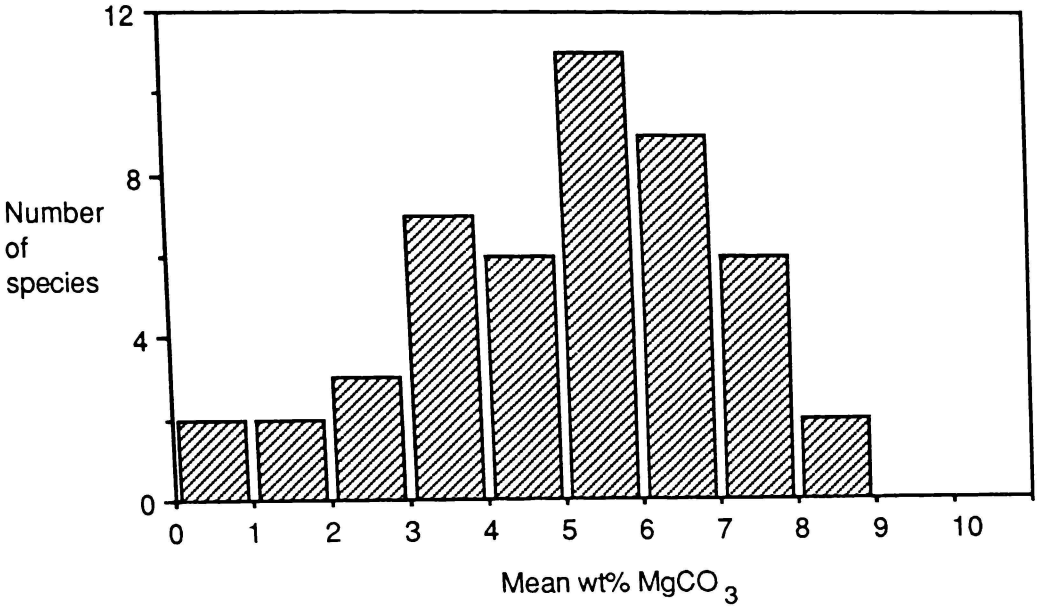


Figure 2B.9: Distribution of mean wt% $MgCO_3$ in calcite for 48 species of New Zealand bryozoans.



Figure 2B.10: Growth habit of *Steginoporella neozelanica*. Scale bar is 10 mm long (for details of underwater photography, see Appendix Table AI.3).

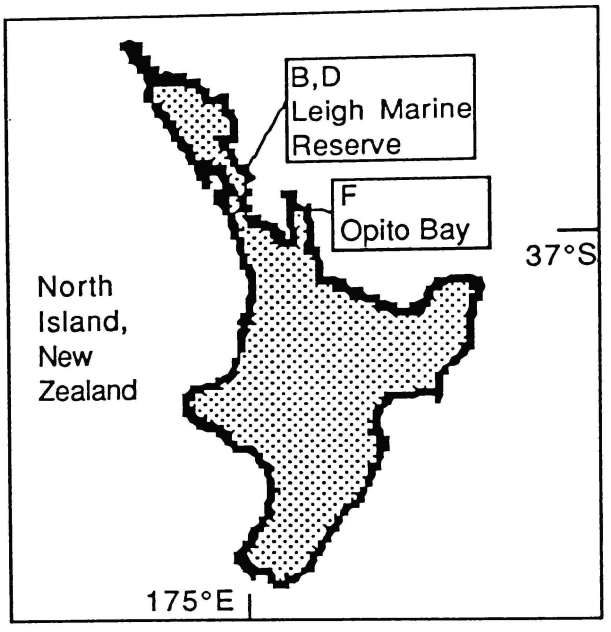


Figure 2B.11: Sample locations for age study.

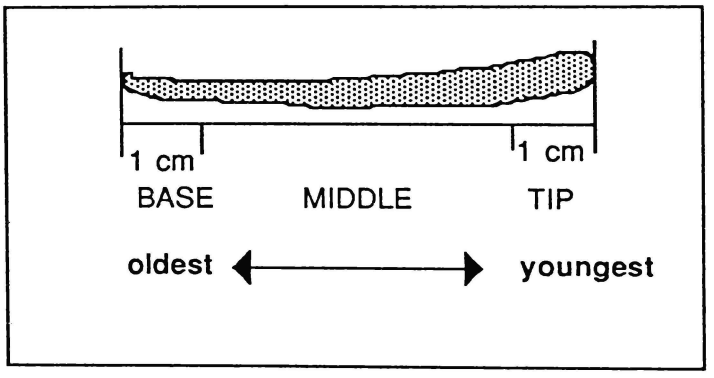


Figure 2B.12: Partitioning branch of *Steginoporella neozelanica* for analysis.

All samples were 100% calcite, consistent with other measurements of this species (see Appendix Table A2.3). Magnesium content of the different parts of the branches varied somewhat, within a range of 2.4 wt% $MgCO_3$. It appears that there is a trend for the Mg content to decrease with distance from the base, that is, for older zooids to show a higher Mg content (Figure 2B.13, Appendix Table A2.5).

There are very few published data on this type of localized variation in mineralogy within individuals. Some studies have shown that aragonite increases with age. For example, Rucker and Carver (1969) found that eight specimens of *Cryptosula pallasiana* were wholly calcitic whereas the ninth, much more heavily calcified and therefore perhaps older, was only 50% calcite. Staining confirmed that the aragonite was accreted in a superficial layer on the outer frontal wall. If such accretion were limited to mature zooids, as suggested by Poluzzi and Sartori (1974), this would result in an age-related increase in aragonite content. Cheetham et al. (1969) found a similar situation with *Metrarabdotos unguiculatum*, in which aragonite was found only on the frontal wall as ornamentation in heavily calcified zooids. Young zooids near the growing edge of this colony showed little or no aragonite.

Essentially, then, calcitic skeletal material is laid down until the zooid reaches a certain stage of development, at which time the aragonitic material is secreted (Cheetham et al., 1969). Other shell-producing invertebrates, and particularly molluscs, show a "secretory development" in phases such that shell layers of different structures and chemical natures occur in one shell (Mutvei, 1964, cited in Cheetham et al., 1969). The practical result of this is that a bimineralic bryozoan skeleton may reflect the age of the organism.

Poluzzi and Sartori (1974) tested basal, older parts and lateral, or distal, younger parts of the same organism for four species (Appendix Table A2.3 and Figure 2B.14). In all cases the older parts of the colony have a higher Mg content. This is also true of the *Steginoporella neozelanica* tested (Figure 2B.13). Saundray and Bouffandreau (1958, in

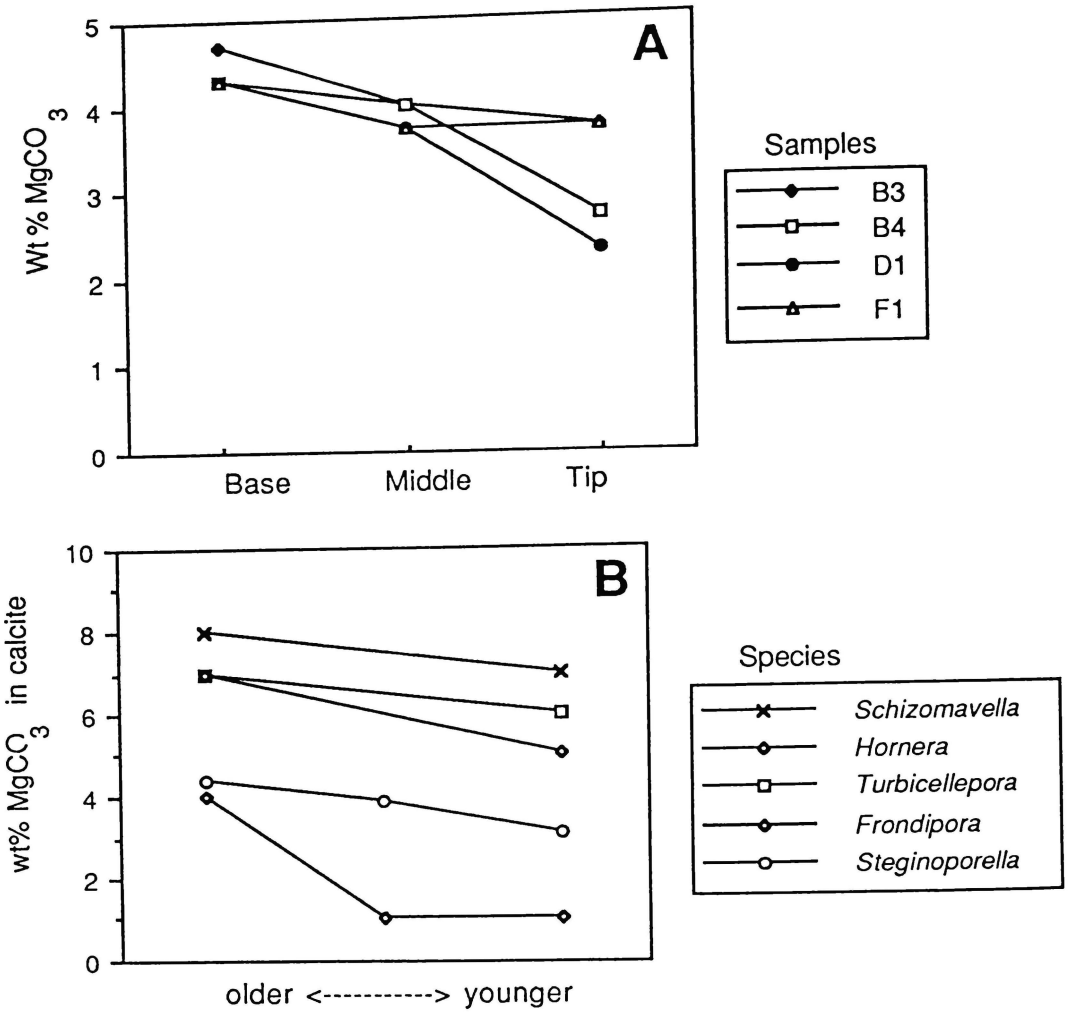


Figure 2B.13: Within-colony variation in mineralogy. (A) Change in Mg content with variation from base in *Steginoporella neozelanica.* (B) Data from Poluzzi and Sartori (1974) and the mean from this study.



Figure 2B.14: Mg content of branches from two colonies of *Steginoporella neozelanica.* Both colonies from Leigh, location B. Colony B1 - 8 branches, colony B2 - 10 branches.

Poluzzi and Sartori, 1974) found the older axial areas of *Bugula turbinata* to be 2.5 times richer in Mg than the presumably younger branches.

There are still fairly few data available, but all nine measurements of six species show the same trend of increasing Mg content with age. The reasons for this trend, sketchy as it is, are not clearly explained. Two ideas are advanced here, an environmental response and a diagenetic response.

It is possible that the older parts of a colony actually precipitate a different calcite than the younger parts, perhaps due to different conditions at the time of precipitation. For example, if the base of the branch was precipitated in summer and the tip was not precipitated until winter, then a gradual decrease in temperature might lead to a decrease in Mg content (e.g., Chave, 1954). One would need to know the seasonal growth of the colony or a branch to be able to test this theory.

It is also possible that the organism has always precipitated calcite of a uniform Mg content, but that the older parts have had longer to equilibrate with sea water. According to Busenberg and Plummer (1989), the equilibrium concentration of Mg in average sea water is about 5 wt% $MgCO_3$. Thus, lower-Mg calcites could be equilibrating upward, and the older parts of the organism would have had longer to do so and would therefore have higher Mg contents. If this is the case it calls into question the common assertion that low-Mg calcite is the most stable form of $CaCO_3$.

Variation within populations

The degree to which different colonies vary in mineralogy under the same environmental conditions is of great importance. It is this intra-population variation that is the "background noise" of any other variation to be discussed. If this variation is sufficiently high, then variation between species may not be determinable.

In the case of the multiple-branched colony *Steginoporella neozelanica*, the question arises first about different branches attached to the same base. Clearly these share the same environment and the same micro-environmental conditions and they may be of approximately the same age. One would expect them to have very similar mineralogies, as other factors appear equal.

Single individuals of *S. neozelanica* were disarticulated and branches were cleaned and powdered for XRD. Large branches produced enough powder to be analyzed individually, but smaller branches had to be combined in order to be analyzed. Two individuals were studied, both collected by hand from offshore at Leigh in 8 m of water (site B in Figure 2B.11).

The results (Appendix Table A2.6, Figure 2B.14) show no variation in terms of calcite/aragonite ratio. All branches were 100% calcite. The Mg content shows some little variation, small enough and non-systematic enough to be explained by experimental error. This error is about 0.5 wt% $MgCO_3$.

The branches of a single individual show little variation; it is therefore possible to investigate the variation in different colonies of the same species from the same location. Branches of the same length were selected from different colonies of *S. neozelanica* at the same location. These samples were collected by hand using SCUBA, within a 1 m^2 area at 8-10 m water depth (sites B and D in Figure 2B.11). Living samples were used to render environmental differences as small as possible.

The data again show no variation in the calcite/aragonite ratio. Mg content varies somewhat more (Appendix Table A2.7) between colonies than was found within a colony. This may be due to micro-environmental differences or age differences. The data nevertheless cover a very limited range of the possible mineralogies shown by New Zealand bryozoans (Figure 2B.15).

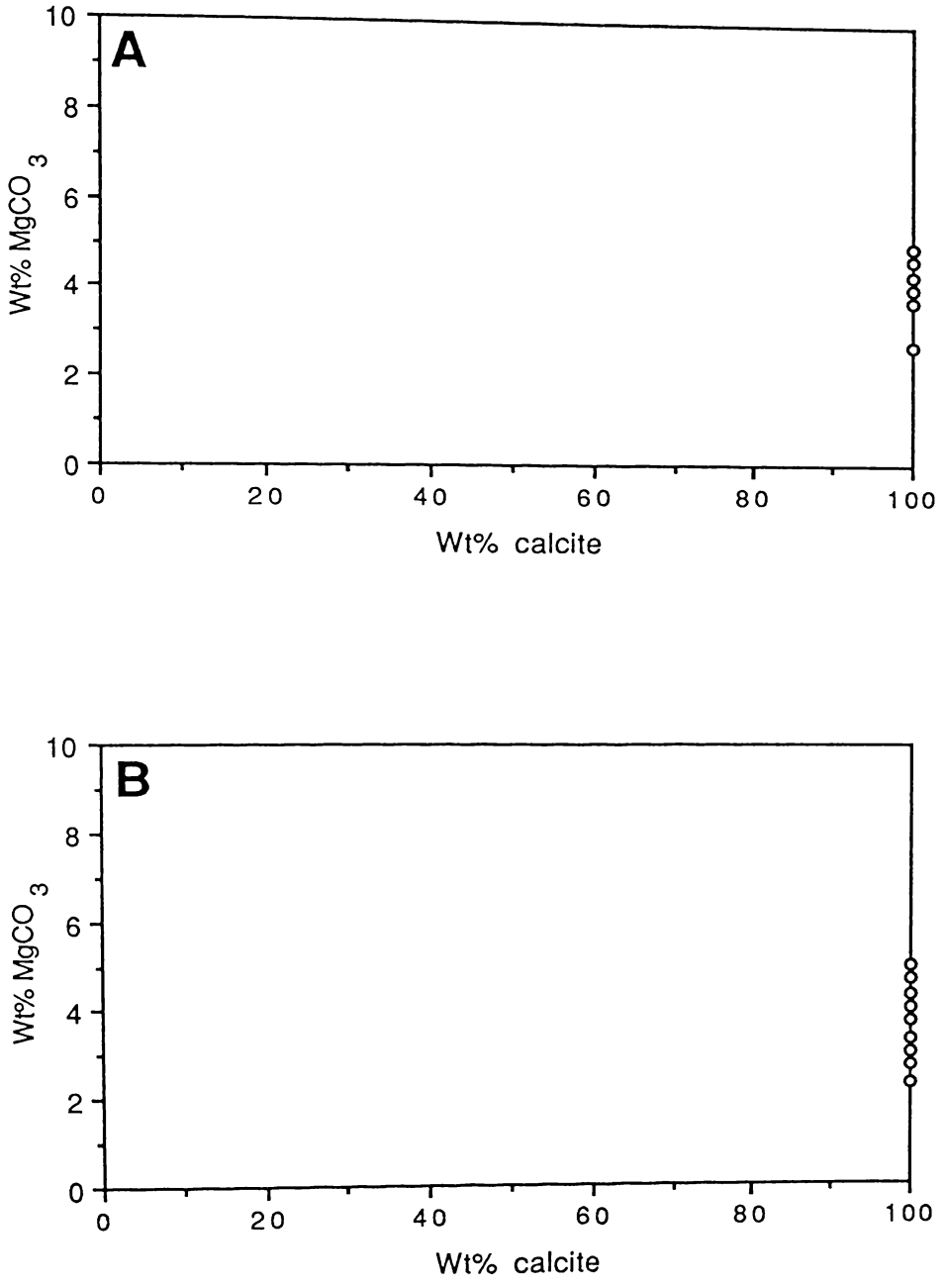


Figure 2B.15: Mineralogy of different colonies of *Steginoporella neozelanica*. (A) 11 colonies from Leigh B. (B) 21 colonies from Leigh D.

Several sediment samples (see Table 2B.1 for locations) contained sufficient quantities of some species to allow for replicate tests. These are summarized in Appendix Table A2.8 and Figure 2B.16. Although these colonies may have grown in different conditions and may have different transport and diagenetic histories, their overall environment (latitude, depth) was probably much the same.

The results show mainly that there is variation in degree of variation! One all-calcite species (*Cinctipora elegans*) shows almost no variability in Mg content, whereas others show rather more. The only bimineralic species tested (*Adeonellopsis* sp.) shows a wide range in both Mg content and in calcite-aragonite ratio.

It seems quite clear that no variability occurs in the calcite-aragonite ratio within *S. neozelanica*. Many calcite species show this absolute lack of aragonite (see Appendix and Section 4c). In contrast, bimineralic species and aragonite species show much more variation in the calcite-aragonite ratio. An example given here, *Adeonellopsis* sp., shows no variability (all aragonite) in one location and some in another. The calcite percentage shows a fair degree of variation (s=3.3) in location G007. A conservative estimate of error in bimineralic species might be 5% calcite.

Within-population variability must also be examined in terms of Mg content. As might be expected, Mg content within a colony shows less variation (mean s = 0.15) than that between colonies (mean s = 0.18), and the range of Mg contents is larger. Similarly, colonies from the same region but not the exact location generally show more variation again (mean s = 0.49), although the ranges vary considerably (Table 2B.2). Bimineralic species were not included as the results of Mg content analysis on very small amounts of calcite are somewhat suspect. As aragonite colonies have no calcite, they must be disregarded.

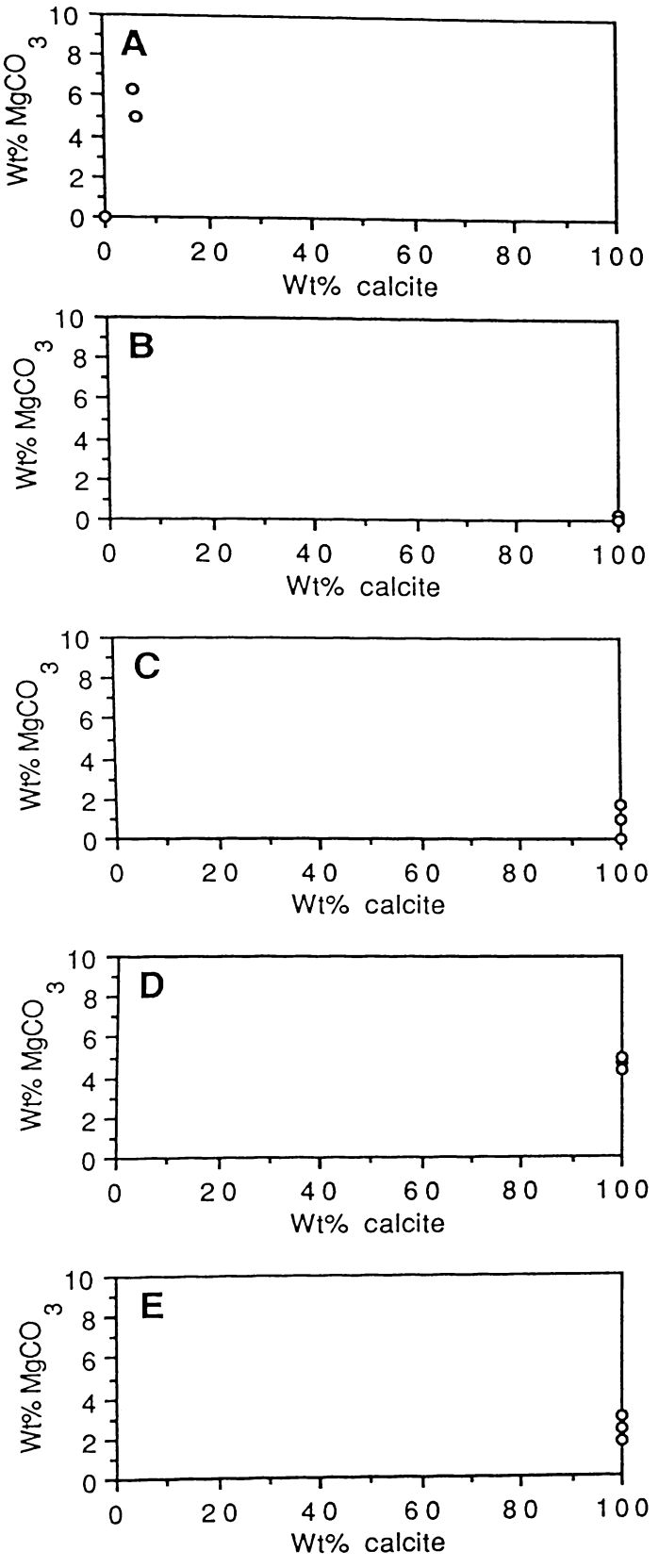


Figure 2B.16: Mineralogy of five bryozoan populations, with colonies chosen from the same sediment sample.

(A) *Adeonellopsis* sp.	G7	Snares	3 samples
(B) *Cinctipora elegans*	D114	Canterbury	7 samples
(C) *Hornera* sp.	G9	Snares	3 samples
(D) *Steginoporella magnifica*	P448	Three Kings	3 samples
(E) *Telopora buski*	P448	Three Kings	3 samples

Table 2B.2: Simple statistics describing variability of Mg content (wt% $MgCO_3$) within bryozoan species.

Species	Location	Sample	No. of spls. (n)	Mean ($\bar{x}$)	Range	Variance (s^2)	Standard deviation (s)
Different branches, same colony							
Steginoporella neozelanica	Leigh	B1	7	3.43	1.00	0.14	0.37
Steginoporella neozelanica	Leigh	B2	9	3.69	1.30	0.21	0.46
Different colonies, same location							
Steginoporella neozelanica	Leigh	B	11	4.05	2.30	0.46	0.68
Steginoporella neozelanica	Leigh	D	21	3.58	2.70	0.49	0.70
Different colonies, same region							
Cincipora elegans	Canterbury	D114	7	0.04	0.30	0.01	0.10
Hornera sp.	Snares	G9	7	0.04	1.70	0.72	0.85
Steginoporella magnifica	Three Kings	P448	3	4.67	0.70	0.12	0.35
Telopora buski	Three Kings	P448	3	2.33	1.30	0.42	0.65

The largest degree of variation within species in Mg content is s=0.85. This suggests that any single measurement of Mg content in a colony is a fairly accurate estimate of the mean Mg content of colonies in that area, probably accurate to 1.0 wt% $MgCO_3$.

Given this degree of variation within populations (5% calcite and 1 wt% $MgCO_3$), it is now possible to determine other sources of larger variations in mineralogy.

Variation among populations

Within species one might reasonably expect some variation in mineralogy in response to environmental conditions. Some of the factors that might influence bryozoan growth and therefore presumably skeletal development include: substrate, nutrients, temperature, turbulence, and turbidity (Jebram, 1977). Of these, the only one discussed in the literature is temperature.

Temperature has been correlated with both calcite-aragonite ratio and with Mg content of calcite. Aragonite has been associated with higher temperatures and calcite with lower temperatures (Lowenstam, 1954). In addition, the aragonite content has been shown to increase within a single bimineralic species as mean surface temperature increases (Lowenstam, 1954). In fact, Lowenstam (1954) suggested that enough temperature-related variation occurs within species to require the use of a special term incorporating temperature and mineralogy!

Lowenstam's data cannot be seen as more than an indication of a possible trend. His six data points, all from Bermuda, covered only a very small range of temperatures (25.5°C to 29°C). The single species studied, *Schizoporella unicornis*, is a common Northern Hemisphere species, but can the results obtained from one species necessarily be applied to others? Using the same species, Rucker and Carver (1969) studied 13 specimens from both coasts of North America, and described a similar trend of increasing aragonite with increasing temperature. Unfortunately they did not report

their data in sufficient detail for it to be used by others. Milliman (1974) added three more data points to the *S. unicornis* story that appeared to confirm this trend.

Chave (1954) found that in many carbonate-producing taxa (e.g., foraminifera, corals, echinoids, barnacles) the Mg content is positively correlated with mean annual water temperature. Bryozoans were not discussed in any detail due to a lack of data.

There are thus some indications that water temperature may be correlated with skeletal mineralogy. A more extensive and deliberate survey of the bryozoans is required. New Zealand is well-suited for this sort of survey, as the shelf covers about 20° of latitude (33°-53°S). As the subantarctic islands and the South Pacific islands are also available for sampling, the range is significant.

Ten common and fairly large bryozoans of a variety of mineralogies were selected for this survey. Three are bimineralic, five are low-Mg calcite, and two are higher-Mg calcite (Table 2B.3, Figure 2B.17). Four are cyclostomes, three are cheilostome anascans, and three are cheilostome ascophorans. Each is found in samples covering a wide geographic range, and each is sufficiently large so that collecting a sample is not difficult. Results are described below and listed in Appendix Table A2.9.

There are three bimineralic species in this study. *Otionella* sp. and *Adeonellopsis* sp. are comprised mainly of aragonite (<6% calcite), while *Foveolaria cyclops* has around 60% calcite (although the range is from 35 to 100% calcite). Figure 2B.18 shows that no obvious correlation of calcite-aragonite ratio and latitude (and therefore temperature) occurs. The data cover a large range of latitudes, and there is some variability. Latitude, however, does not explain it. Even when plotted in more detail (Figure 2B.19) with all the monomineralic specimens omitted, only the weakest of trends emerges -- and it is opposite to the one predicted by Lowenstam (1954)! A similar lack of correlation has been found in bimineral serpulid worms (Bornhold and Milliman, 1973).

Table 2B.3: Mineralogy of bryozoan species used in study of among-population variation.

Species	Number specimens tested	Mineralogy	Mean wt% calcite	Mean wt% $MgCO_3$
Adeonellopsis sp.	29	aragonite and bimineral	3.1	5.7
Cellaria immersa	22	calcite	100.0	3.4
Celleporina costazii	14	calcite	100.0	5.6
Cinctipora elegans	19	calcite	100.0	0.6
Foveolaria cyclops	21	bimineral	63.3	6.0
Galeopsis porcellanicus	24	calcite	100.0	6.4
Hornera sp.	19	calcite	100.0	1.4
Mecynoecia purpurascens	14	calcite	100.0	1.7
Otionella sp.	13	aragonite and bimineral	1.6	6.0
Telopora buski	24	calcite	100.0	2.8

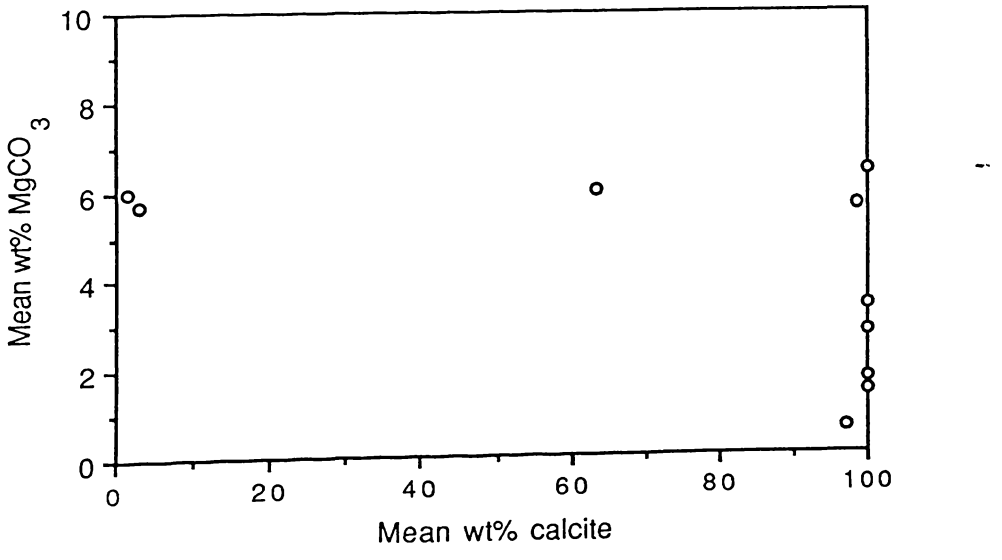


Figure 2B.17: Mineralogies of bryozoans used in study of environmental variation. Ten species cover the range of New Zealand bryozoan mineralogies.

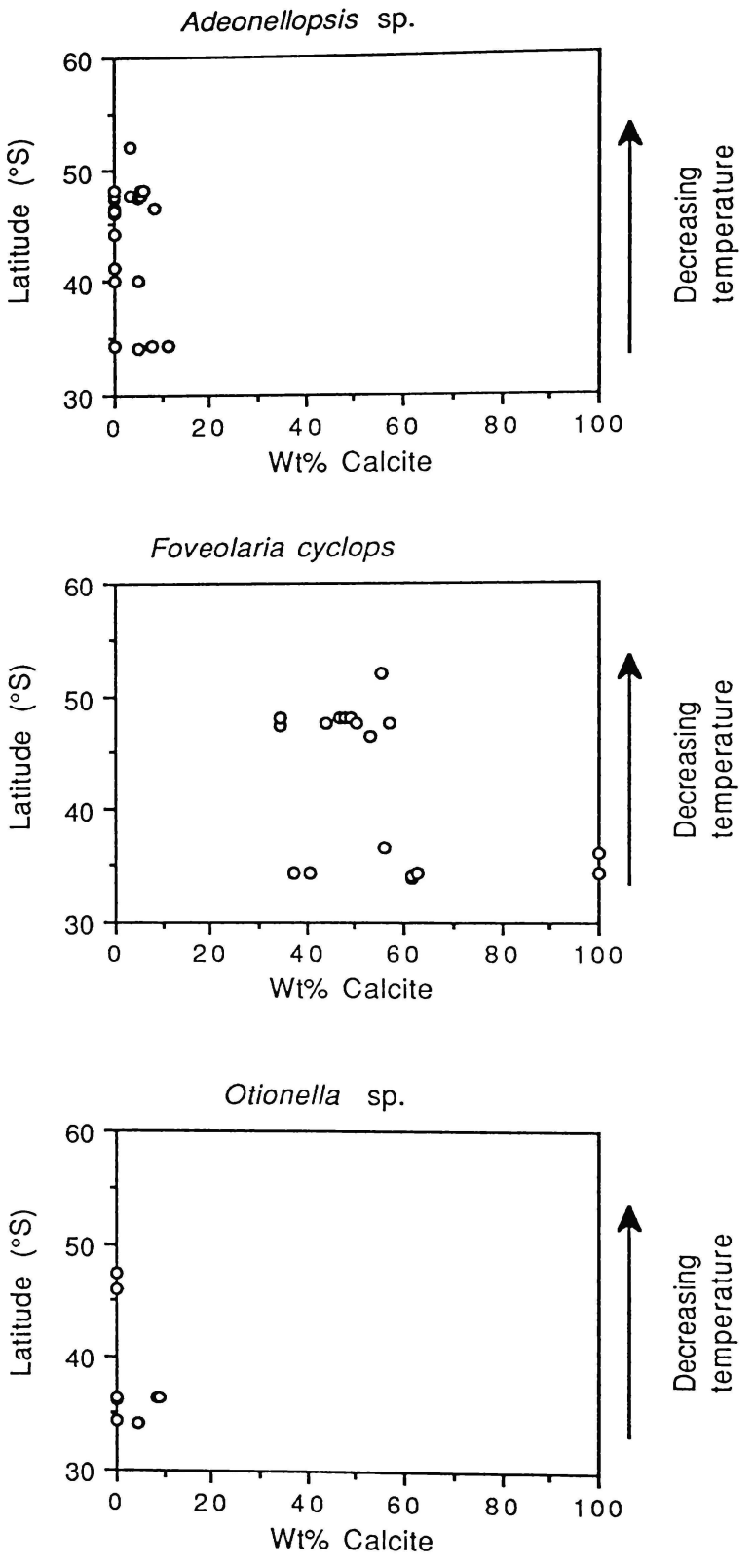


Figure 2B.18: Calcite content of three species of bimineralic bryozoans, showing variation with latitude.

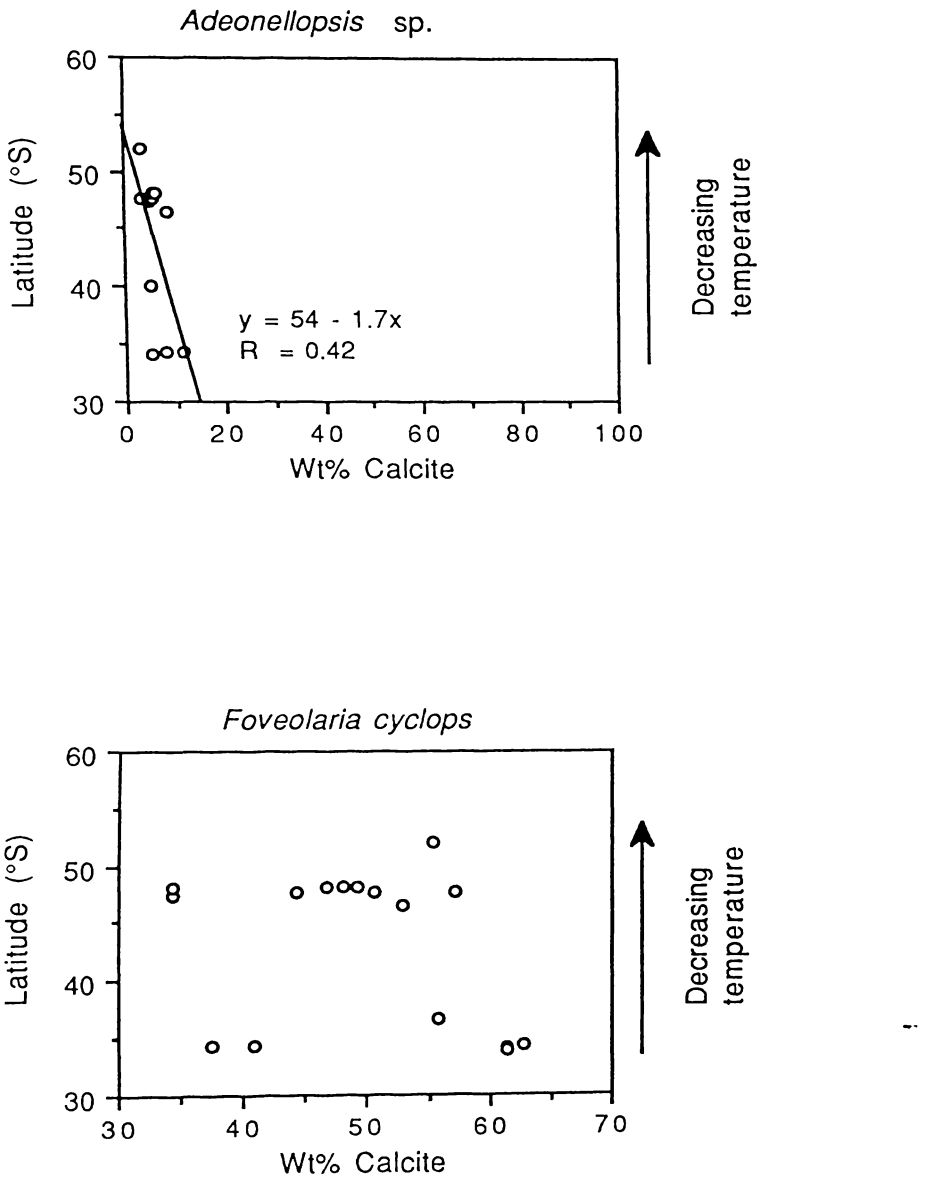


Figure 2B.19: Calcite content of bimineralic specimens of two of the species shown in Figure 2B.18, showing variation with latitude.

In these same three bimineralic samples, when the Mg content in the calcite is compared to latitude, again no clear trend emerges (Figure 2B.20). It may be that the aragonite content confuses the issue. However, the all-calcite species give not much more information (Figures 2B.21 and 2B.22). In some cases there may be weak trends (for example *Mecynoecia purpurascens*) but there is little in the way of an obviously consistent relationship between latitude and mineralogy, such as that found in calcite serpulid worm tubes (Bornhold and Milliman, 1973).

Chave (1954) noted that the slopes of the lines indicating the relationship of temperature to Mg content for different taxa varied systematically, such that more phylogenetically advanced taxa (such as barnacles) had a higher slope than those less advanced (such as sponges). In the bryozoans, ascophoran cheilostomes are considered to be more advanced than anascan cheilostomes, and both are more advanced than cyclostomes (Ryland, 1970). However, as no systematic trends have been found in New Zealand bryozoans, Chave's phylogenetic conclusion cannot be confirmed.

It appears that the ten New Zealand bryozoans analyzed do not show any mineralogical pattern that correlates with temperature as approximated by latitude. This is the first study in which many specimens of the same species across a wide range of latitudes have been analyzed. It is possible that the small sample sizes of Lowenstam (1954) and Milliman (1974) created trends that are not real. It is also possible that the species chosen for study in New Zealand simply do not reflect their environment as clearly as *S. unicornis* does.

Nevertheless, specimens from different locations show more variation in mineralogy than can be accounted for by individual variation (as discussed above). Some environmental response appears to be operating. An analogous attempt to correlate mineralogy with depth shows a similar lack of any simple trend (Figure 2B.23). Whatever possible environmental source of variation in mineralogy is operating at different sample locations, it is a complex one.

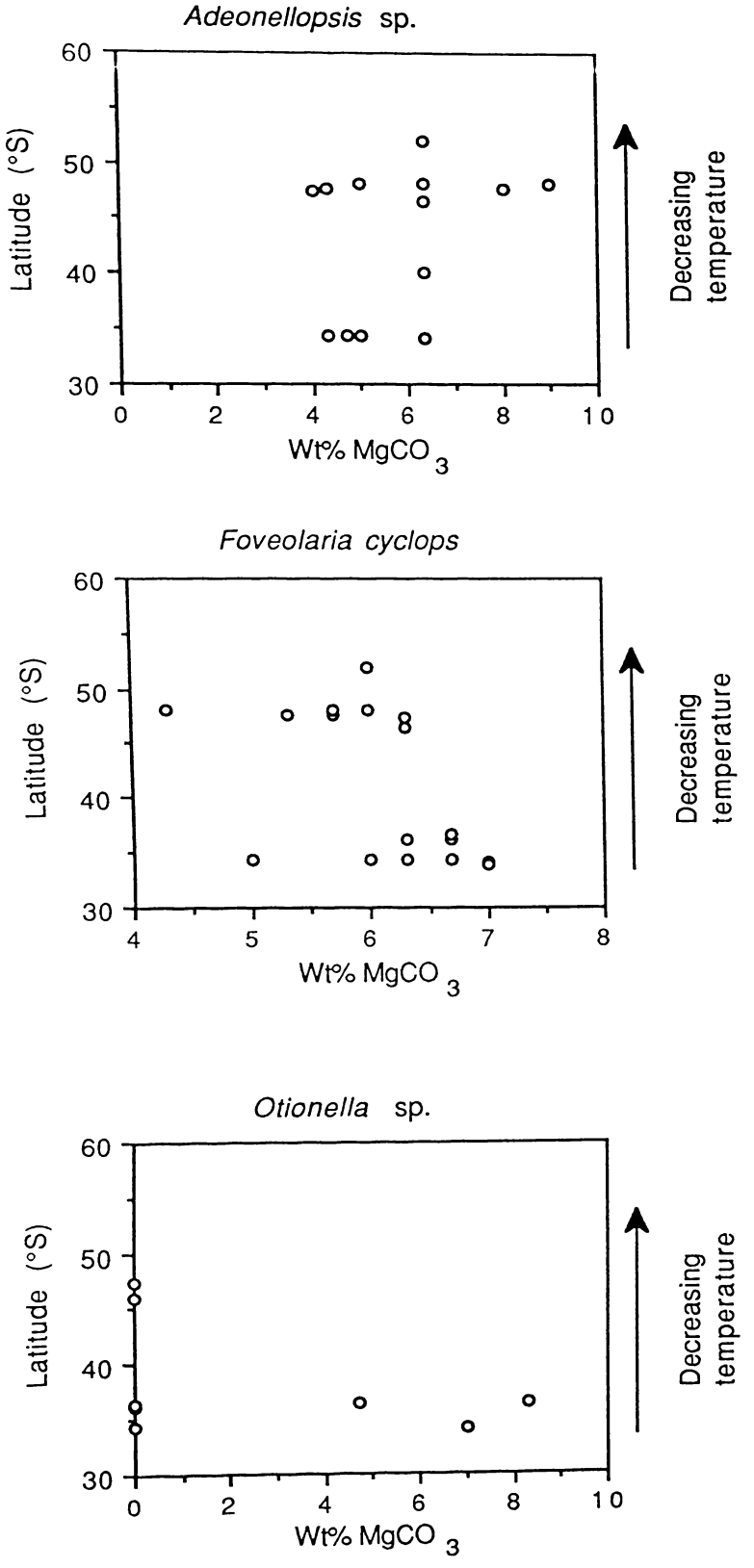


Figure 2B.20: Mg content in calcite of three bimineralic bryozoans, showing variation with latitude.

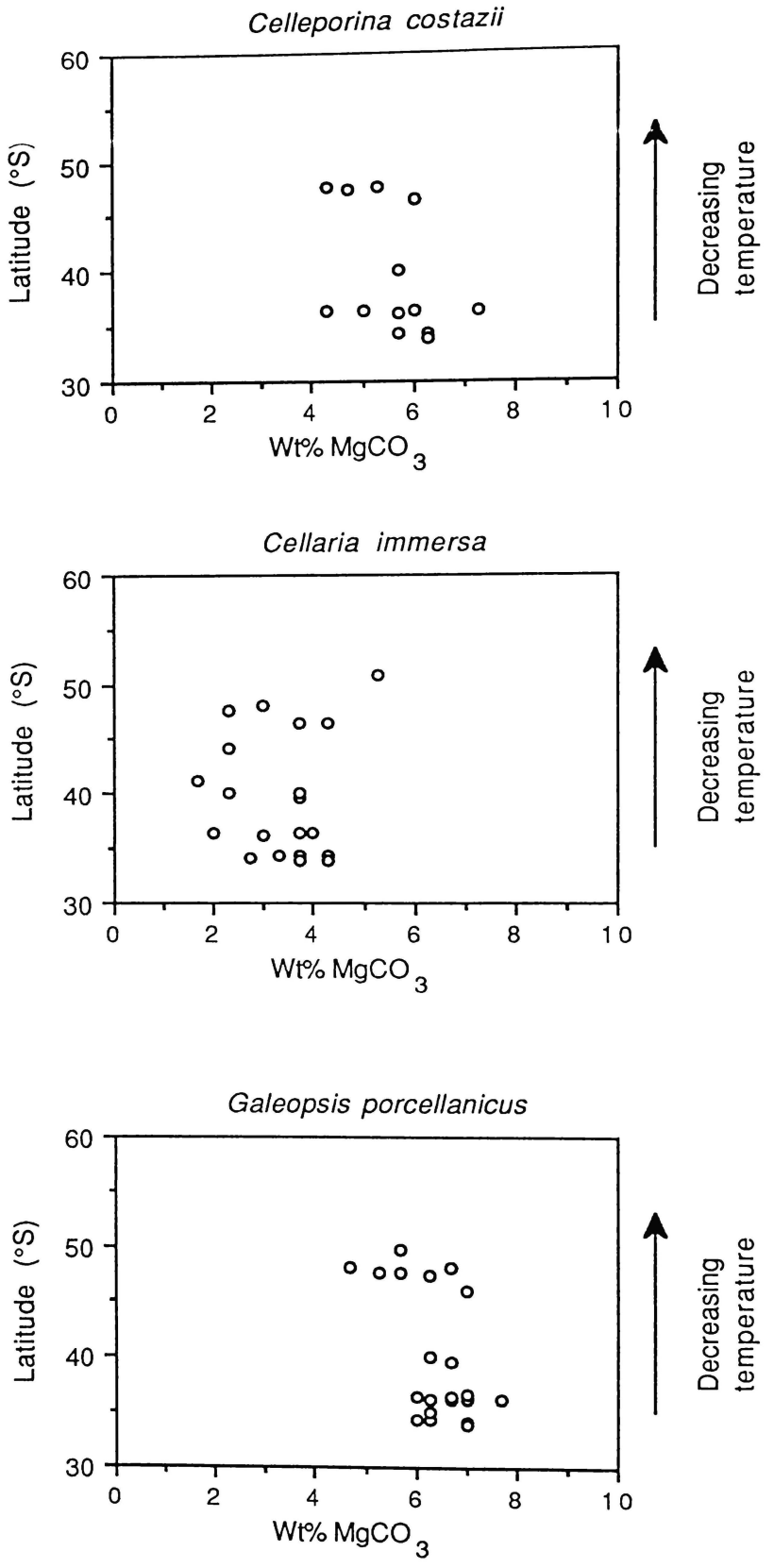


Figure 2B.21: Mg content of three calcitic cheilostome bryozoans, showing variation with latitude.

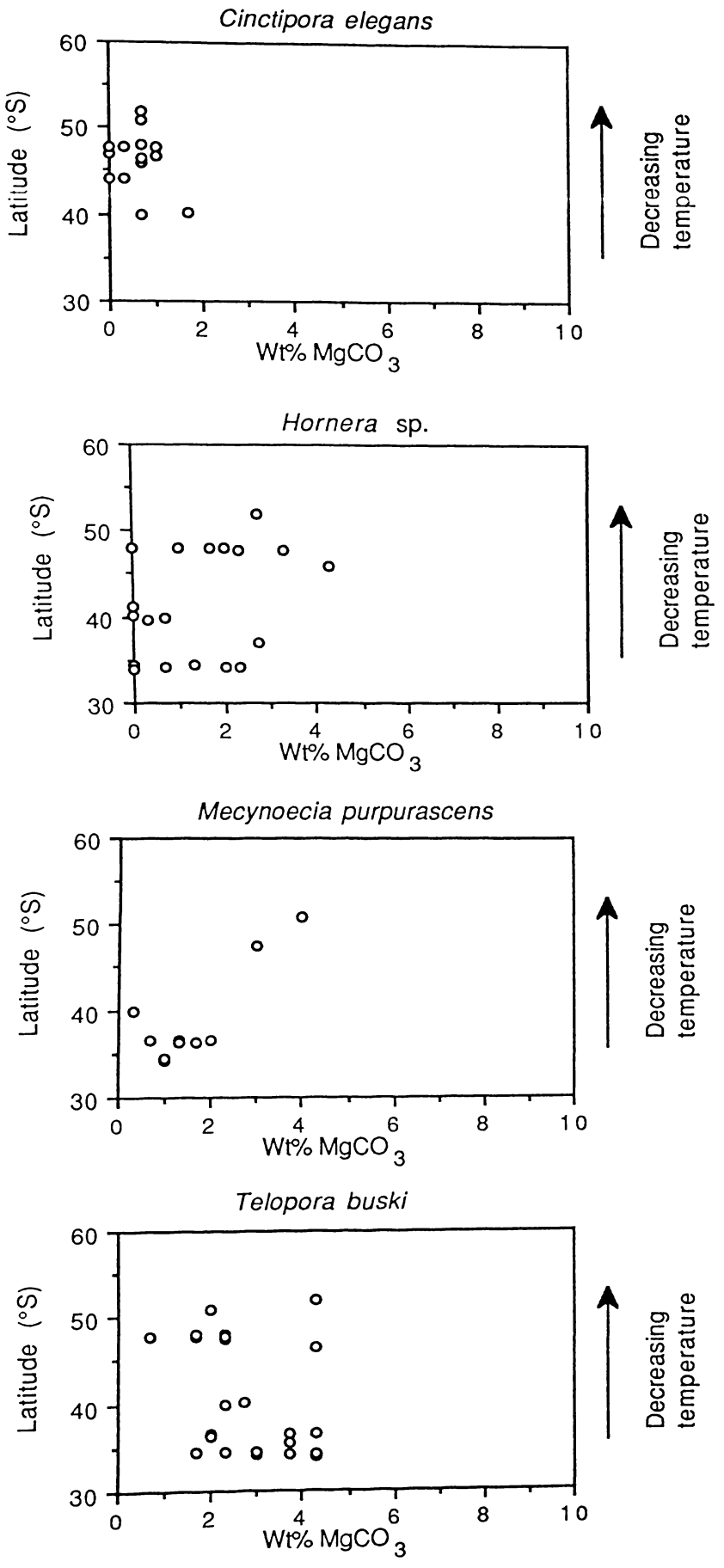
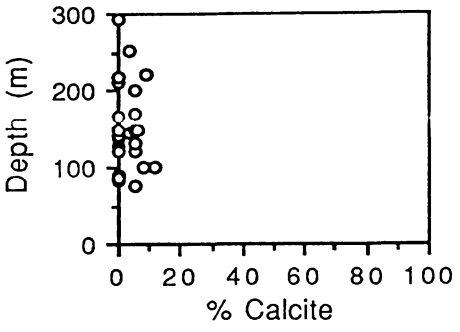
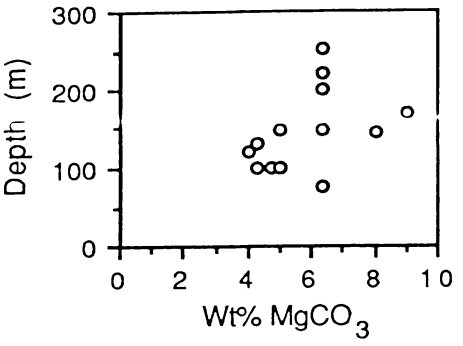


Figure 2B.22: Mg content of four calcitic cyclostome bryozoans, showing variation with latitude.

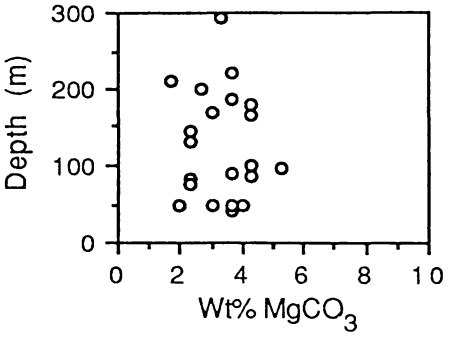
Adeonellopsis sp.



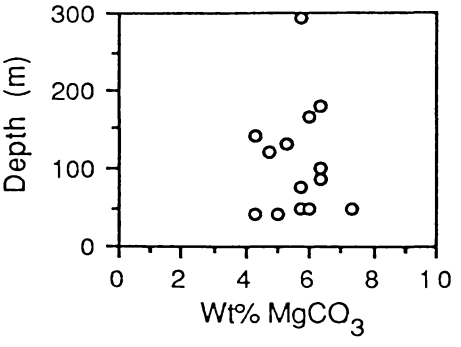
Adeonellopsis sp.



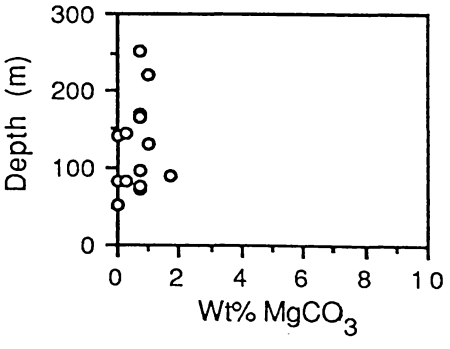
Cellaria immersa



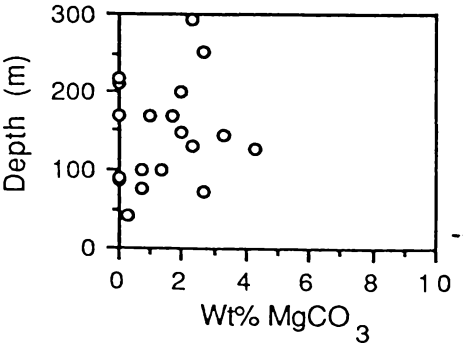
Celleporina costazii



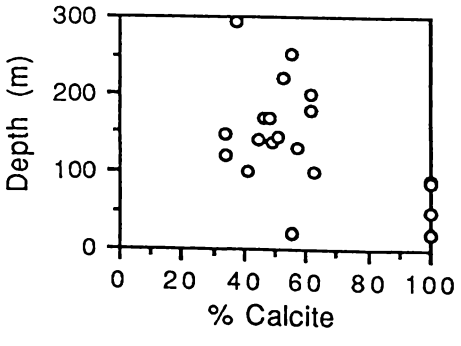
Cinctipora elegans



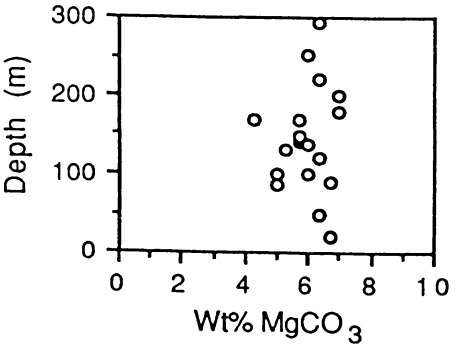
Hornera sp.



Foveolaria cyclops



Foveolaria cyclops



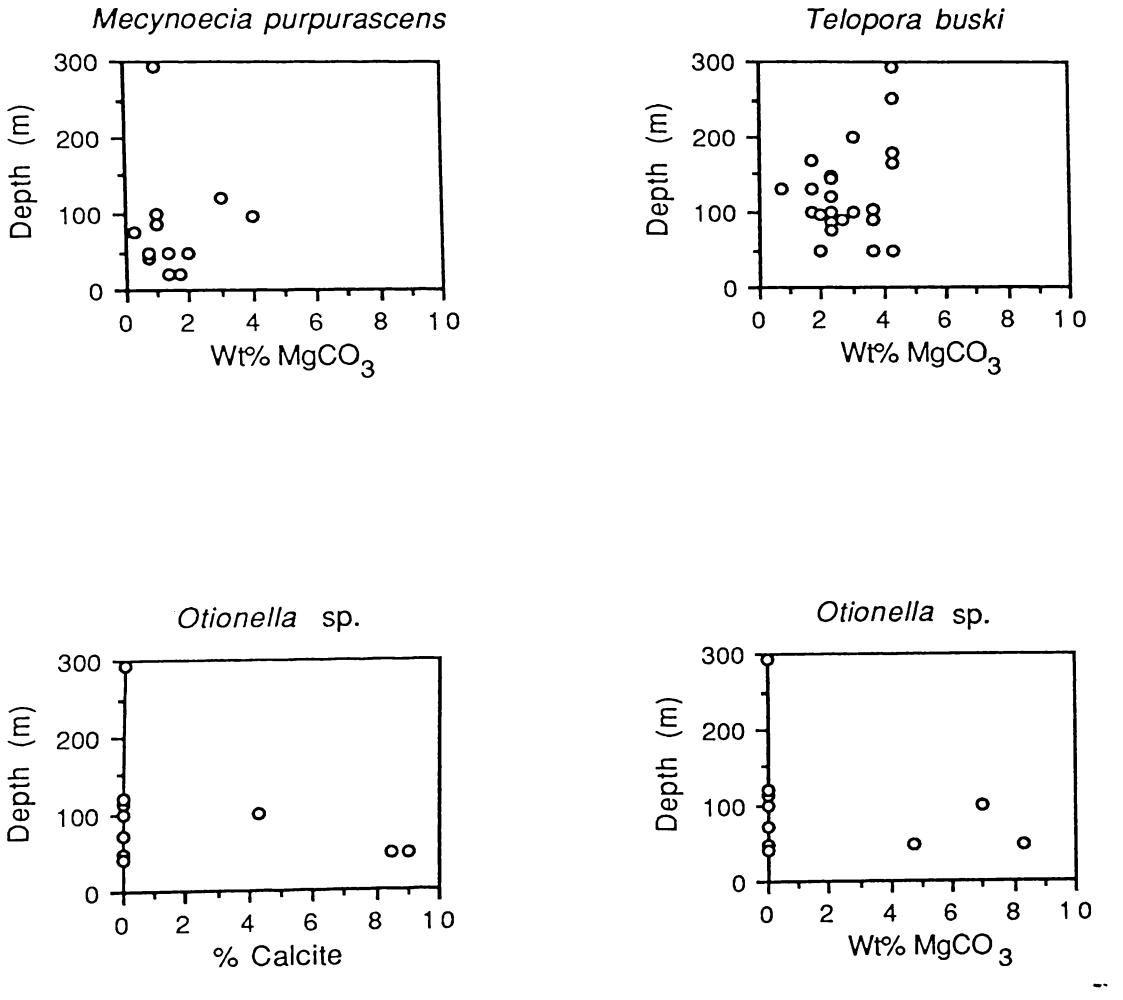


Figure 2B.23: Relationship of mineralogy (calcite and Mg content) to water depth for each of ten bryozoans.

Variation among species

As noted above, the 48 species of New Zealand bryozoans for which mineralogies have been determined cover a large range (Figure 2B.24). Generally, however, an individual species does not cover the whole range of possibilities, but the data tend to converge. It is therefore possible to determine different classifications of mineralogy into which several species may fall.

The data appear to consist of categories or classifications (Figure 2B.25) described in detail below. Each classification has been given an abbreviation for ease of reference.

Low-Mg calcite (lo C) -- almost all specimens are 100% calcite, with low to very low Mg content (0-3 wt% $MgCO_3$).

Moderate-Mg calcite (mod C) -- almost all specimens are 100% calcite, with moderate to higher Mg content (3-5 wt% $MgCO_3$).

High-Mg calcite (hi C) -- almost all specimens are 100% calcite, with high Mg content (5-9 wt% $MgCO_3$).

Bimineralic or Calcite (B/C) -- some specimens are all calcite, but an appreciable number are bimineralic. Bimineralic specimens are seldom less than 50% calcite. Mg content is mainly in the moderate range (3-6 wt% $MgCO_3$).

Bimineralic or Aragonite (B/A) -- some specimens are all aragonite, but an appreciable number are bimineralic. Bimineralic specimens are seldom more than 10% calcite. Mg content is moderate to high (5-8 wt% $MgCO_3$).

The relationship of the various New Zealand bryozoans to this mineralogical classification is shown in Table 2B.4.

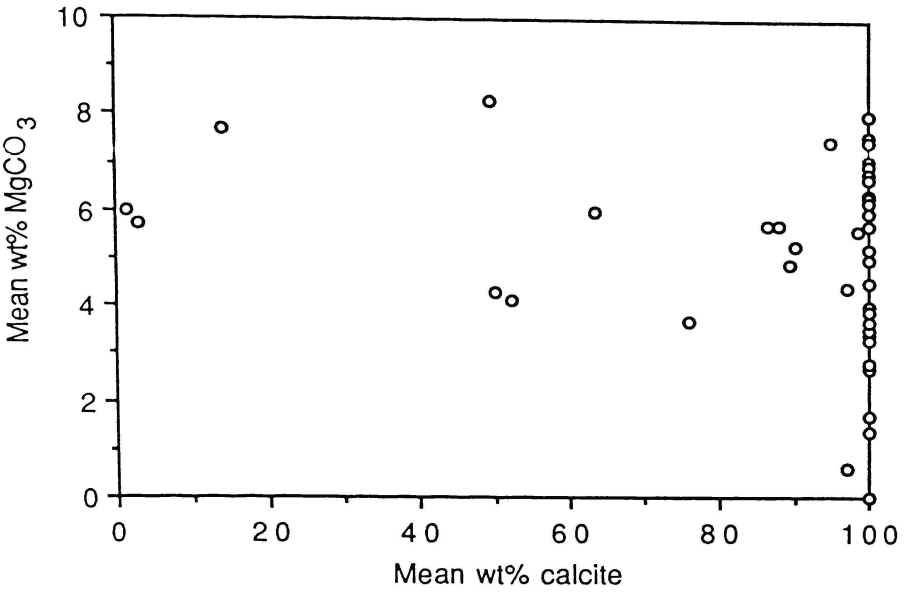


Figure 2B.24: Mean mineralogies of 48 species of New Zealand bryozoans.

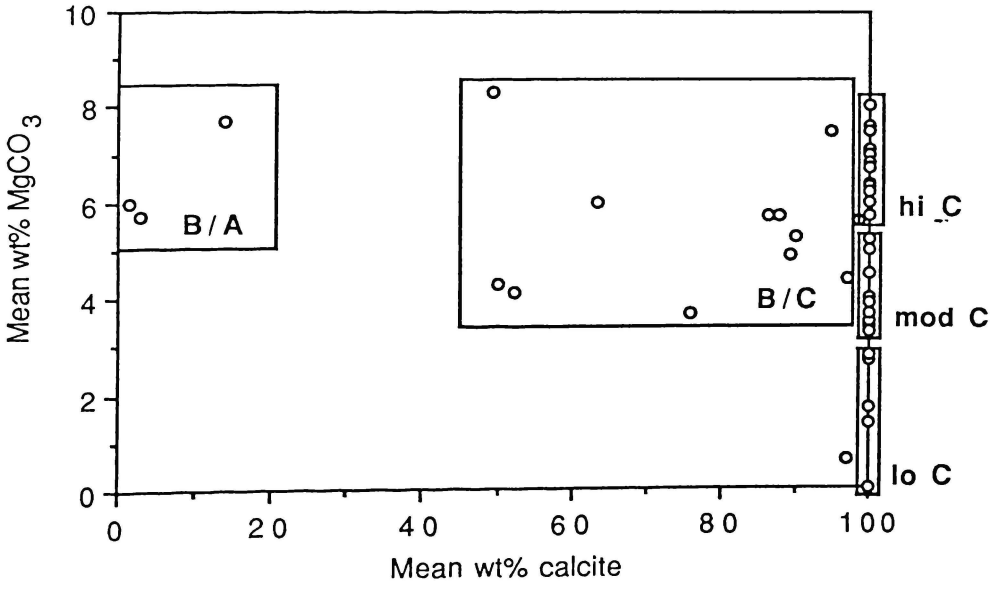


Figure 2B.25: Five classifications of carbonate mineralogy of New Zealand bryozoans.

Table 2B.4: Mineralogical classifications of New Zealand bryozoans.

lo C	mod C	hi C	B/C	B/A
Calcite	Calcite	Calcite	50-100% calcite	0-10% calcite
0 to 3 wt% $MgCO_3$	3 to 5 wt% $MgCO_3$	5 to 9 wt% $MgCO_3$	3 to 6 % $MgCO_3$	5 to 7 wt% $MgCO_3$
Caberea zelandica	*Celleporaria agglutinans*	*Bugula dentata*	*Arachnopusia unicornis*	*Adeonellopsis sp.*
Cellaria immersa	*Celleporina costazii*	*Euthyroides episcopalis*	*Chaperia acanthina*	*Odontoporella adpressa*
Cellaria tenuirostris	*Chaperiopsis tintinabula*	*Euthyroides jellyae*	*Conescharellina angulopora*	*Otionella squamosa*
Celleporella cancer	*Chiastosella splendida*	*Galeopsis polyporus*	*Foveolaria (O.) cyclops*	
Celleporina grandis	*Cornuticella taurina*	*Galeopsis porcellanicus*	*Patsyella flemingi*	
Cinctipora elegans	*Escharina waiparaensis*	*Gemellipora eburnea*		
Annectocyma sp.	*Escharoides excavata*	*Gigantopora pupa*		
Disporella gordoni	*Hemipustulopora harmeri*	*Hippellozoon novaezelandiae*		
Hornera foliacea	*Hippomenella vellicata*	*Iodictyum yaldwyni*		
Hornera sp.	*Lichenopora sp.*	*Margaretta barbata*		
Idmidroneiforms	*Macropora grandis*	*Melicerita chathamensis*		
Mecynoecia purpurascens	*Menipea zelandica*	*Metroperiella mucronifera*		
Telopora buski	*Steginoporella magnifica*			
	Steginoporella neozelanica			
	Steginoporella perplexa			

Data culled from the world-wide bryozoan mineralogy literature shows a similar range of possible mineralogies, although the bimineral specimens cover a wider range of possible calcite/aragonite ratios (Figure 2B.26) and the upper limit of Mg content is higher than in New Zealand. The calcitic species fall into the traditional high-Mg calcite and low-Mg calcite categories, with the boundary around 4 wt% $MgCO_3$. New Zealand bryozoans, in contrast, show three separate groups. Both moderate- and high-Mg calcites as shown in Figure 2B.25 are usually described as high-Mg calcite.

It is of interest that there appear to be two different types of bimineralic mineralogy (listed as B/A and B/C above and shown clearly in Figure 2B.8). These two different types of bimineralism are quite different in character, and can be explained by quite different mechanisms.

Species listed as B/A show the sort of mineralogy one would expect from a metastable mineral like aragonite. In most individuals taken from recent sediments the aragonite is largely intact, but a few older specimens show a small degree of (perhaps surficial) conversion to calcite. This is a diagenetic type of bimineralism.

Species described in the B/C group, on the other hand, show a biological bimineralism. It is apparent on visual observation that there are two distinct zones of precipitation of two types of skeletal material (Figure 2B.27). The main structure of the skeleton is calcite and granular, whereas the "drop-shaped" secondary aragonite that appears affixed to the frontal wall is vitreous in texture. Others (Rucker, 1968; Cheetham et al., 1969; Hayward and Ryland, 1979) have described a basic skeleton of calcite with secondary deposits of aragonite on the frontal wall. These secondary deposits are described as quite discrete and are "fairly easily" stripped off the organism after death (Ryland, 1970).

Thus one might expect specimens that are nearly fresh to include some percentage of aragonite, whereas specimens that have been subject to abrasion would be only calcite,

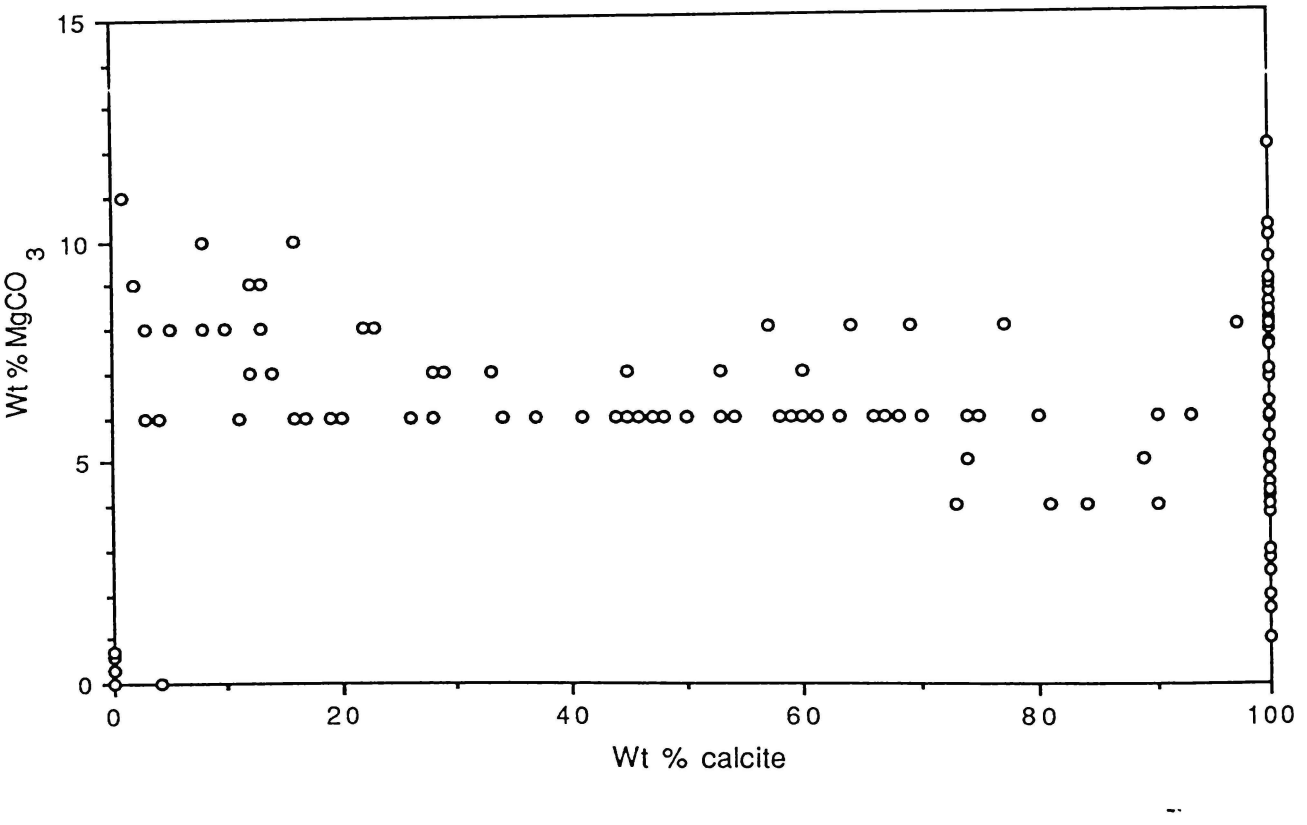


Figure 2B.26: Mineralogy of bryozoans as reported in the world-wide literature (data in Appendix Table A2.1).

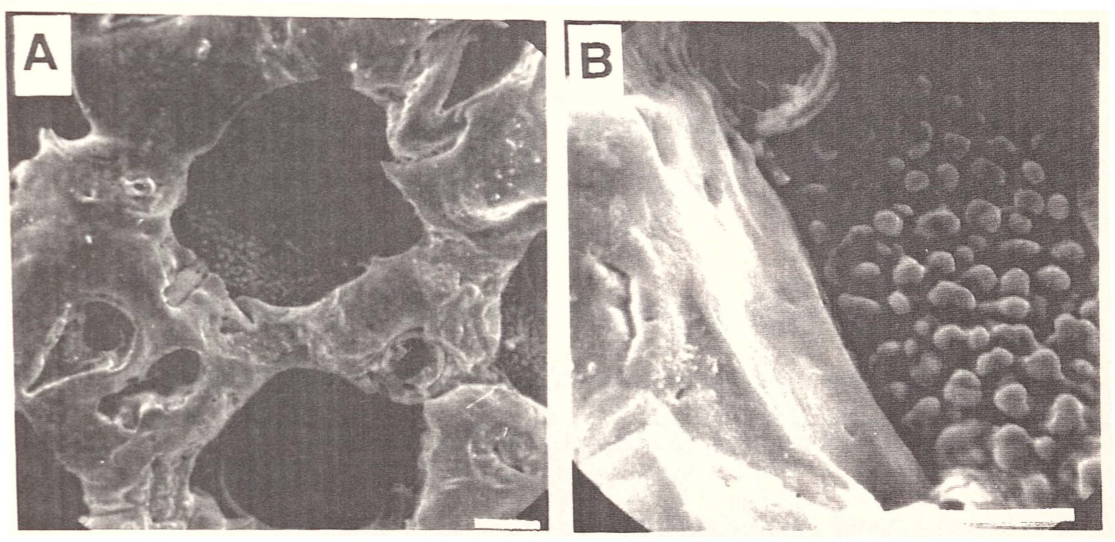


Figure 2B.27: Discrete layers of calcification in *Foveolaria cyclops*. SEM micrographs of (A) two zooids and (B) contact between smooth aragonite and granular calcite. Scale bar equals 0.1 mm.

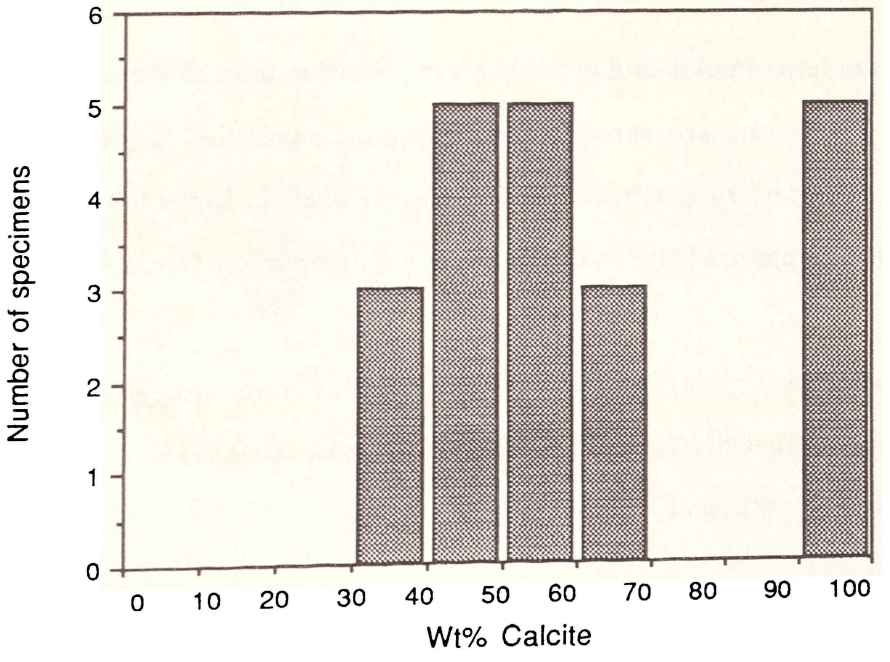


Figure 2B.28: Bimodal variation in calcite content of *Foveolaria cyclops*.

as the aragonite would have dropped off. After long periods of time the aragonite that did adhere may alter to calcite, although the bilaminar structure remains (Sandberg, 1975). Over time, then, one would expect such colonies to lose aragonite. This is consistent with the mineralogy of different specimens of *Foveolaria cyclops*, which exhibits a bimodal distribution with some specimens varying between 30 to 60% calcite and others comprising wholly calcite (Figure 2B.28).

Thus bryozoan sediment grains that are bimineralic may be due to biological or diagenetic causes. These two types of bimineralism are quite different and justify the two different mineralogical classes defined (Figure 2B.29).

Variation among higher taxa

Within the three classes of Bryozoa, only two contain calcifying organisms, the Gymnolaemata and the Stenolaemata. In the Stenolaemata, the order Cyclostomata contains the only non-fossil species. The systematic positions of New Zealand cyclostomes are poorly understood. In the Gymnolaemata, the order Cheilostomata contains several suborders of marine calcareous bryozoans, encompassing the anascan and the ascophoran grades of organization (Figure 2B.30).

Cyclostomes are less complex and possibly more primitive than cheilostomes. In the cheilostomes, ascophorans are more advanced than anascans in that they have a frontal shield that may be perforate, spinose, or otherwise decorated. In the following figures and tables these groups are listed in taxonomic order, according to Gordon (1986, 1989).

48 common sediment-forming bryozoans were analyzed for mineralogy from all these taxa. The results (Appendix Table A2.10) were grouped by taxon, as were data from the world-wide literature (Appendix Table A2.1).

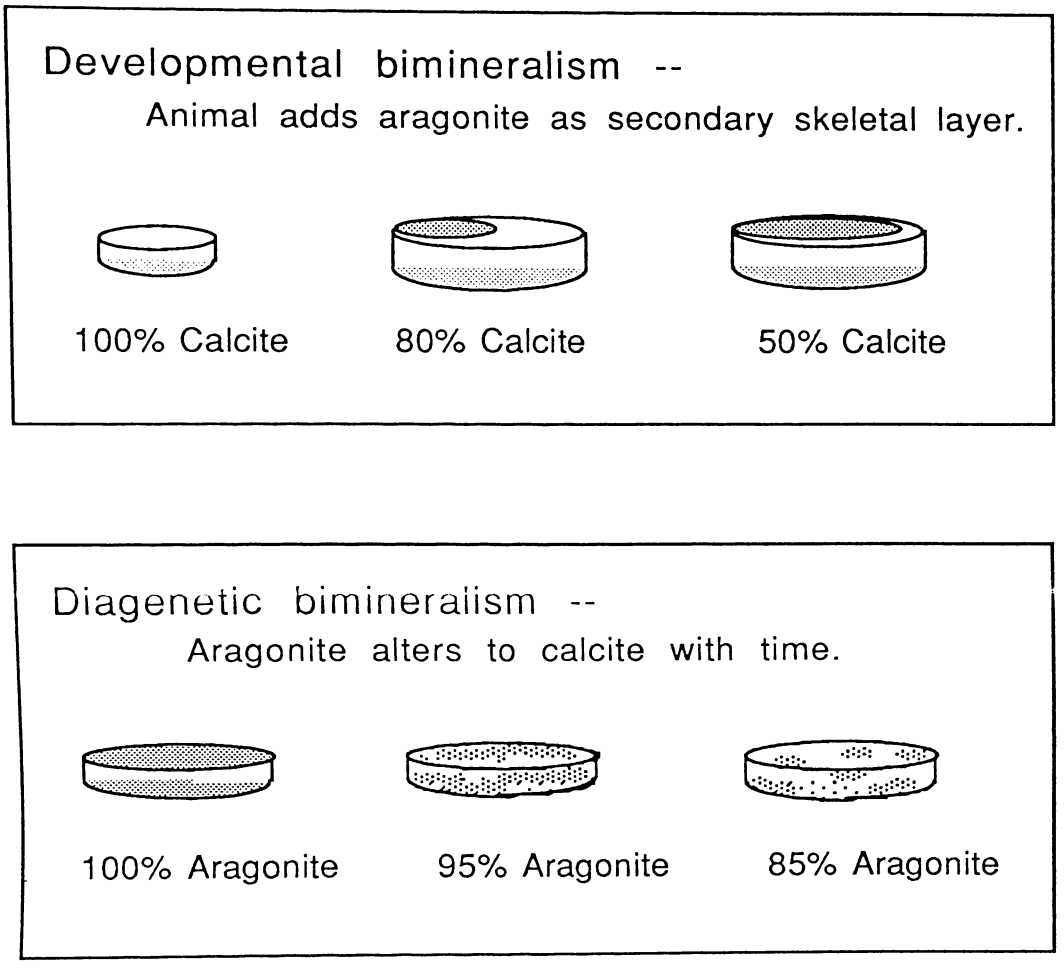


Figure 2B.29: Two different mechanisms for formation of bimineral bryozoan skeletons.

PHYLUM	CLASS	ORDER	SUBORDER	SUPERFAMILY or INFRAORDER
Bryozoa	Phylactolaemata FRESHWATER			
	Stenolaemata	Cyclostomida	Tubuliporina	Tubuliporoidea
			Articulina	Crisioidea
			Cancellina	Horneroidea
			Rectangulina	Lichenoporoidea
		Cystoporida EXTINCT		
		Trepostomida EXTINCT		
		Cryptostomida EXTINCT		
	Gymnolaemata	Ctenostomida NOT CALCIFIED	Malacostegina	Membraniporoidea
			Scrupariina	Scruparoidea
		Cheilostomida	Neocheilostomina ("Anascans")	Calloporoidea
				Buguloidea
				Microporoidea
				Cellarioidea
			Ascophorina ("Ascophorans")	Cribriomorpha
				Hippothoomorpha
				Umbonulomorpha
				Lepraliomorpha

Figure 2B.30: Higher systematics of bryozoans. Non-marine and uncalcified groups shaded. See Appendix Table AI.1 for details.

New Zealand cyclostomes are quite tightly grouped in low to moderate levels of Mg in calcite. Only one specimen of the 103 tested was partly aragonite. The world-wide literature gives a wider range of Mg content for cyclostomes, but confirms that they are monomineralic calcite.

Cheilostomes are quite different, having higher Mg content and much more variation in calcite/aragonite ratio (Figure 2B.31 and Table 2B.5). Anascans have overall lower Mg calcite than ascophorans, and there appears to be very little difference in calcite-aragonite ratios between anascans and ascophorans. World-wide data on anascans and ascophorans show far more ascophorans are bimineralic, but that they cover similarly wide ranges of mineralogy (Figure 2B.31).

These data were classified according to the 5-class scheme described in Table 2B.4, shown in Figure 2B.32. World-wide, cyclostomes have a wider range of mineralogies than in New Zealand. Anascans world-wide have fewer species composed of low-Mg calcite than in New Zealand, and more are high-Mg calcite, proportionally. The total proportion of bimineral species is similar, but more are B/A in New Zealand, whereas more are B/C in the larger set of data. Far more ascophorans are bimineralic in the world-wide literature than in New Zealand, but the proportion of types of bimineralism is similar.

The New Zealand results shed light on some of the conclusions reached by Poluzzi and Sartori (1974). With increasing complexity and advanced evolutionary position, a slight tendency to high-Mg calcite is evident in the major taxa. The lower taxa of cheilostomes (infraorders and superfamilies) show no obvious pattern in mineralogy with phylogenetic advancement (Figure 2B.33). A reported smaller range of variation in more advanced taxa is also not evident in New Zealand samples. Another idea put forth in several papers (e.g., Poluzzi and Sartori, 1973; Rucker and Carver, 1969) was that bimineralic skeletons were limited to ascophoran cheilostomes. This is not borne out by this study.

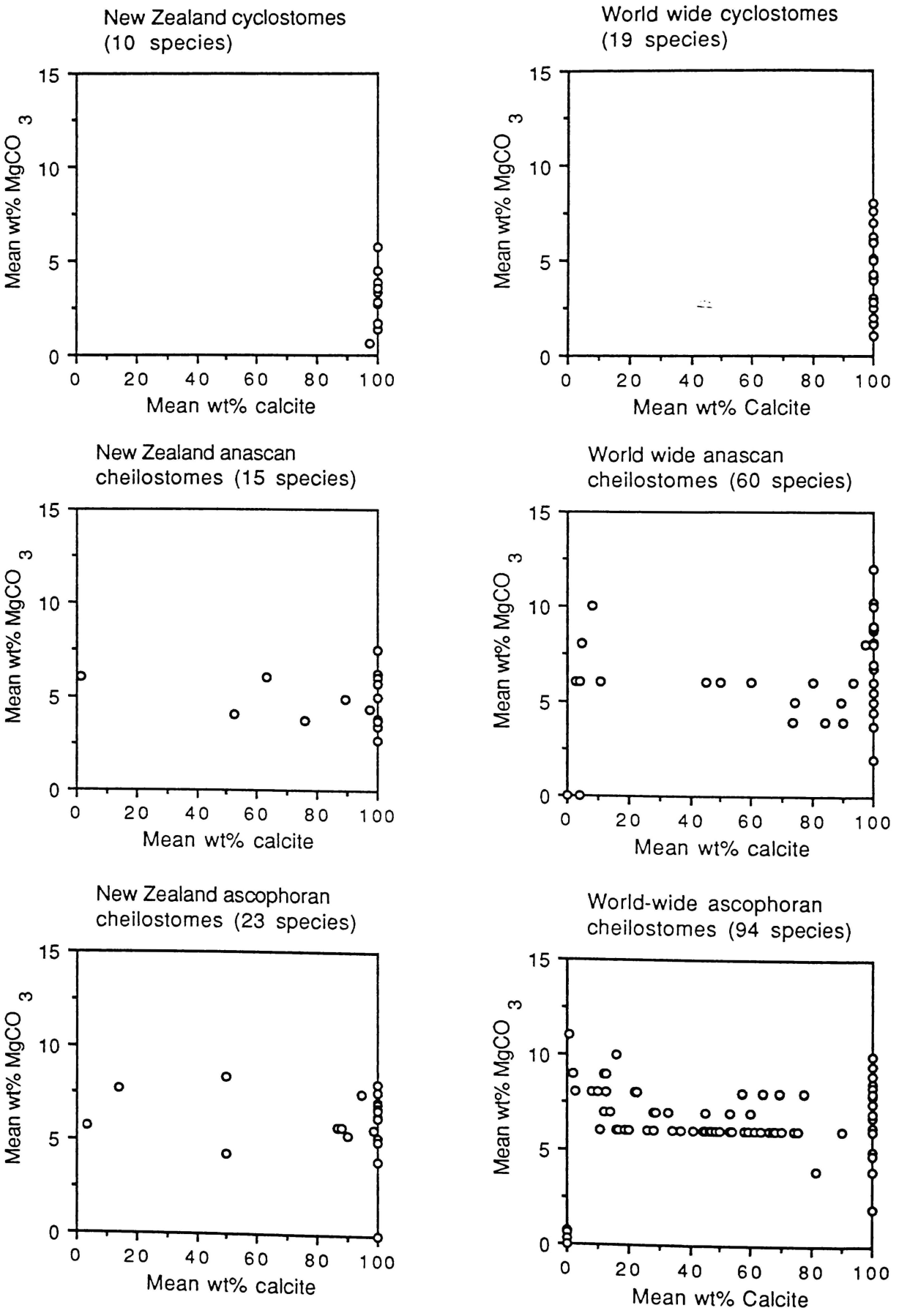


Figure 2B.31: Mineralogy of the major bryozoan taxa, from New Zealand and the world-wide literature.

Table 2B.5: Mean mineralogy of higher taxa of New Zealand bryozoans.

Taxon	Number samples	Number species	Mean wt% calcite	Mean wt% $MgCO_3$
Cyclostomata		10	100	3.0
Cheilostomata		38	86	5.5
ANASCA		15	85	4.9
ASCOPHORA		23	86	6.0
Within ANASCA				
Calloporoidea	34	4	68	5.6
Buguloidea	6	3	100	4.5
Microporoidea	51	5	69	4.6
Cellaroidea	29	3	100	3.7
Within ASCOPHORA				
Cribriomorpha	2	2	75	8.2
Hippothoomorpha	2	2	100	3.5
Umbonulomorpha	50	5	40	5.5
Lepraliomorpha	104	14	96	6.4

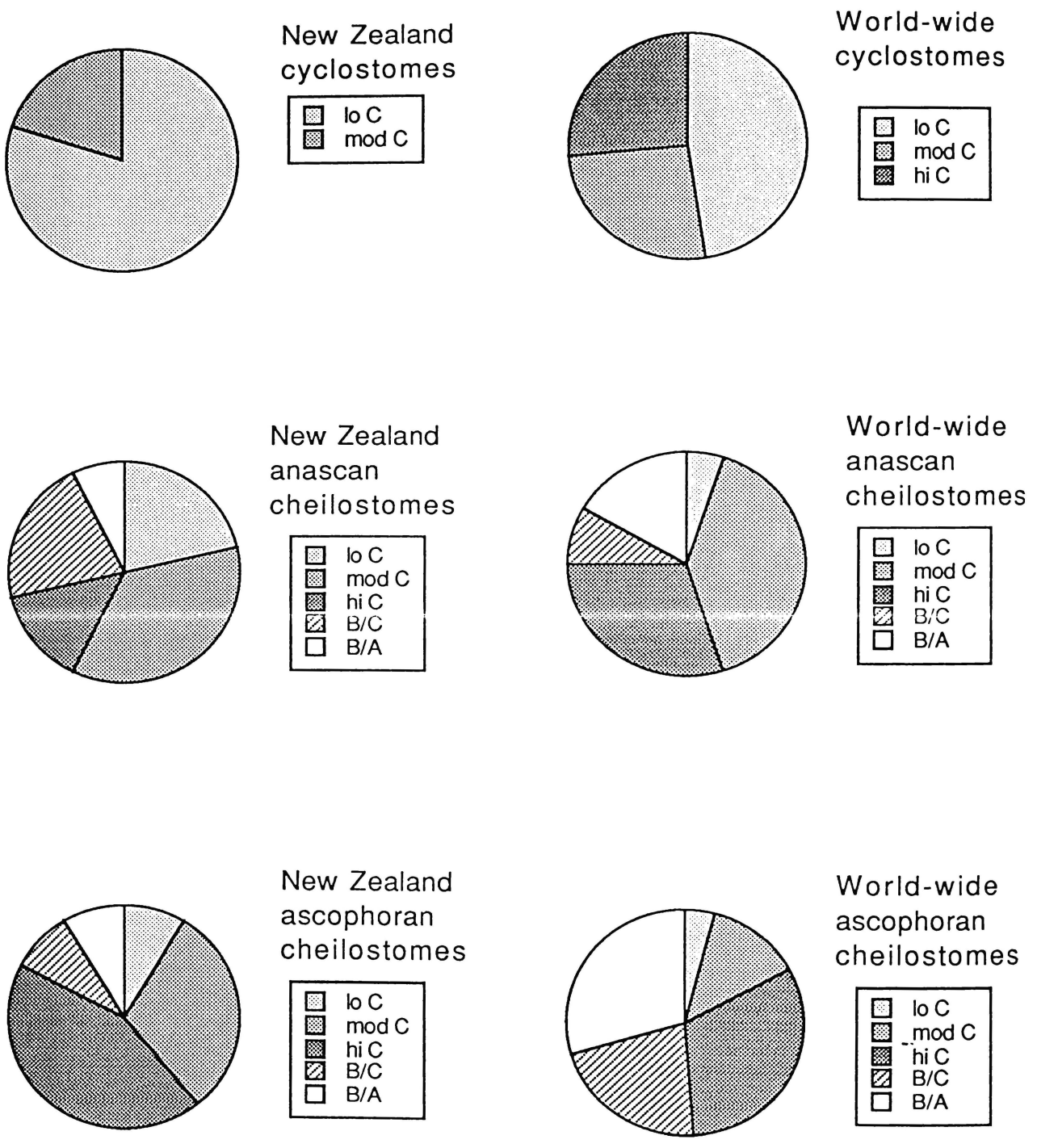


Figure 2B.32: Percentage of species found in mineralogical classes (defined in Figure 2B.25) in each of the major bryozoan taxa, from New Zealand and the world-wide literature.

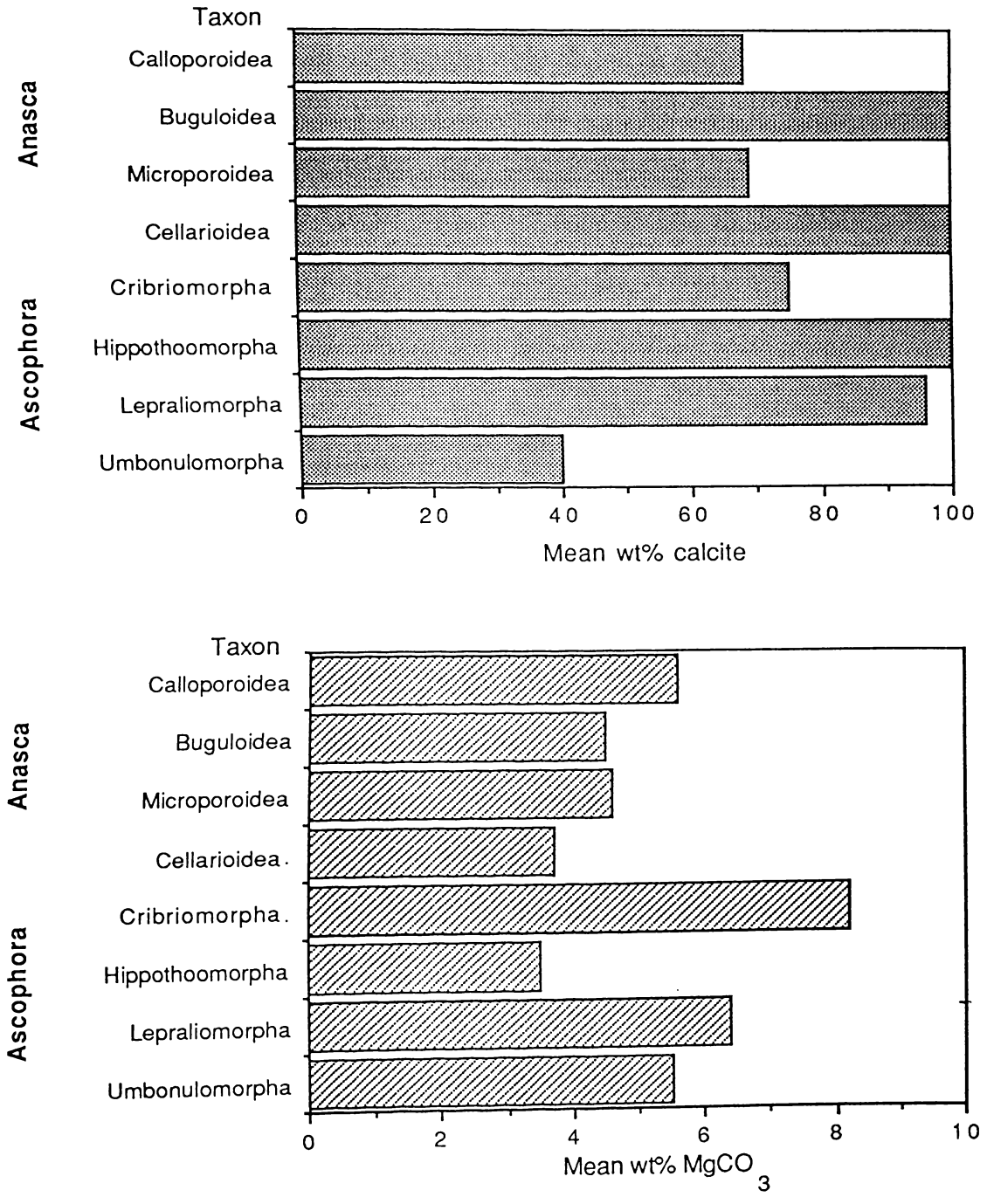


Figure 2B.33: Mineralogy of the lower bryozoan taxa (superfamilies and infraorders) of the cheilostomes. (A) Calcite and (B) Mg content.

Hayward and Ryland (1979) refer to cheilostome species as being 50% calcite, 10% aragonite and 40% mixed. By "mixed" they appear to mean the biological type of bimineralic skeleton. In contrast, this study's test of New Zealand bryozoans shows that no species is always entirely aragonite, and that the majority of cheilostomes are wholly calcitic.

Variation among growth forms

Individual bryozoans combine to form an astonishing variety of colonial growth forms. These forms may be encrusting or erect, rigid or articulated, attached or free-living. The classification scheme of Nelson et al. (1988b), developed for geological use, is used here as it requires no knowledge of soft-part morphology and can be used across taxa.

The most common growth forms are listed in Table 2B.6. Mineralogical data from 48 species (511 specimens) were collected and analyzed according to growth form (Appendix Table A2.11, Figure 2B.34).

Several growth forms show only calcite in all specimens: ERde, ERfe, ERma, and ERra. Forms ENml and EF (including EFar and EFrt) show all but one specimen as calcite. FL (including FLrt and FLmo) is mainly bimineral/aragonite. ENul, ERfo, and ERro show the most variation within growth form.

Most growth forms average out to moderate- or low-Mg calcite. ENml and ERfo cover the smallest range of Mg content. It is interesting that in ERfe, the bimodal distribution of Mg content is directly related to the fact that some are cyclostomes (low-Mg) and some are cheilostomes (high-Mg). This is also seen, somewhat less clearly, in the ERde and ERro Mg contents.

There is a high degree of variability shown within growth forms. This variation is probably related to other factors (particularly phylogenetic variation) and not to any particular relationship between growth form and mineralogy.

Table 2B.6: Common colonial growth forms among New Zealand bryozoans (presented in more detail in Figure IB.2 and IB.3).

Life Habit	Zooid arrangement	Abbrev.	New Zealand example
ENCRUSTING	unilaminar	ENul	*Chaperia acanthina*
	multilaminar	ENml	*Celleporaria agglutinans*
ERECT	articulated	EFar	*Cellaria immersa*
FLEXIBLE	rooted	EFrt	*Steginoporella neozelanica*
	delicate branching	ERde	*Galeopsis porcellanicus*
	robust branching	ERro	*Adeonellopsis sp.*
ERECT	foliose	ERfo	*Arachnopusia unicornis*
RIGID	fenestrate	ERfe	*Hippellozoon novaezelandiae*
	radiate	ERra	*Telopora buski*
FREE-LIVING	motile	FLmo	*Otionella squamosa*

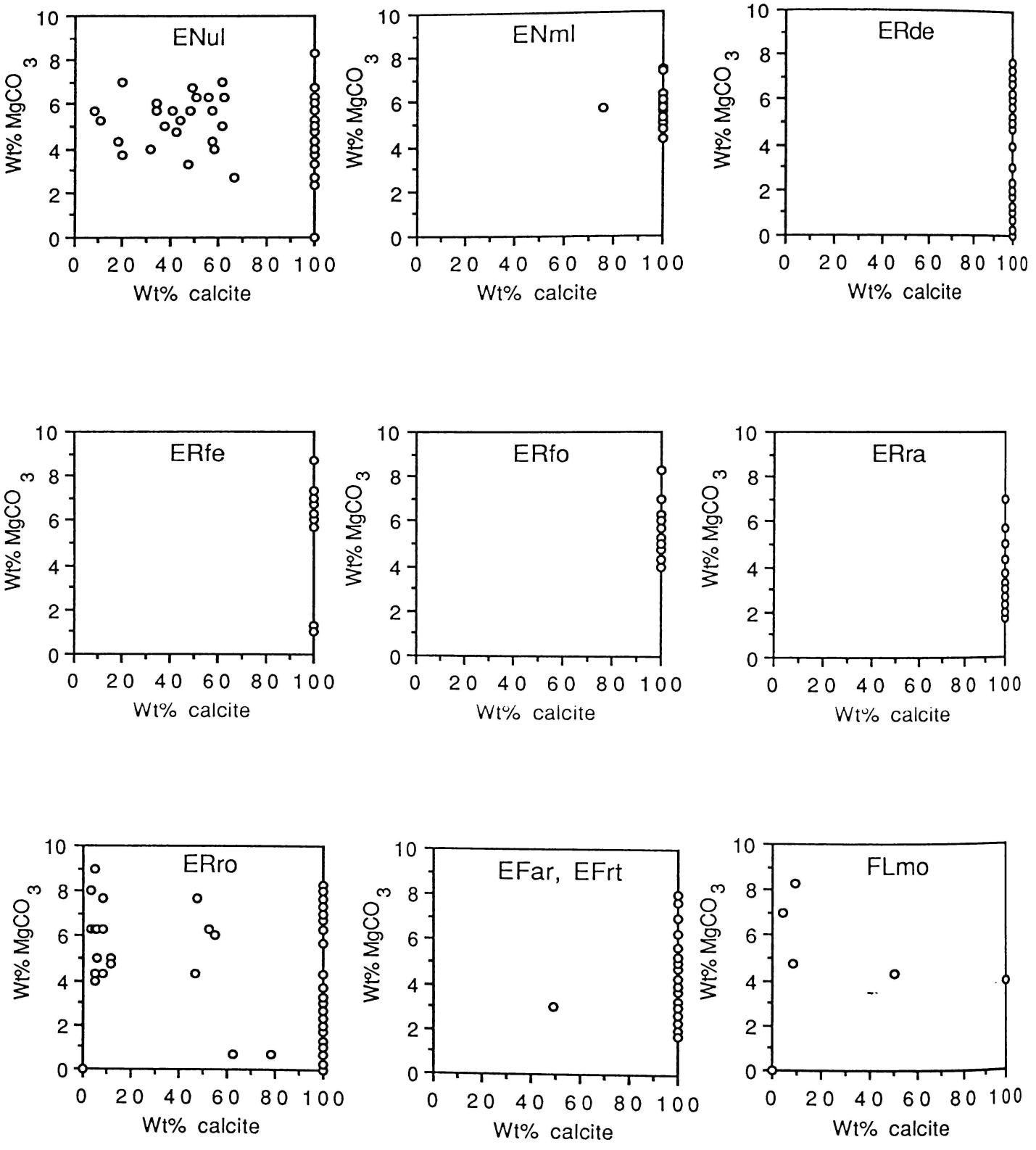


Figure 2B.34: Mineralogy of nine major colonial growth forms (defined in Table 2B.6) of New Zealand bryozoans.

One common sediment-forming species, *Foveolaria cyclops*, grows in both an erect rigid robust branching form and a unilaminar encrusting form. Contrasting the mineralogies of these shows no significant difference (Appendix Table A2.12, Figure 2B.35).

These data support Schopf and Manheim (1967) in rejecting the 1922 conclusion of Clarke and Wheeler that erect forms show more Mg than encrusting ones. In fact, *F. cyclops* shows the opposite pattern, if any. New Zealand bryozoans seem mainly to follow the Mediterranean pattern observed by Poluzzi and Sartori (1974), namely that erect forms are usually all calcite. All the erect rigid forms, excepting ERro, are mainly calcite. Their observation that free-living forms are usually bimineralic or aragonite is also borne out by the New Zealand data. Another point, that encrusting colonies vary significantly in mineralogy, is only true of the unilaminar encrusters. Multilaminar colonies have a fairly consistent mineralogy.

Diagenetic Variation

It seems likely that age of sediment, or residence time, would affect the mineralogy of skeletal components. Some specimens in this study were collected live while others came from sediment samples. These sediments are in a variety of conditions, ranging from fairly fresh-looking (clean, undamaged grains with sharp edges) to quite degraded (stained grains, often broken and with dulled edges). Sediments were classified according to these criteria, and specimens were identified as being collected live, from a fresh-looking sediment, or from a degraded-looking sediment.

Four common species which were collected both live and from sediments were considered. Sample locations were classified as to state of sample (i.e., freshness) and comparisons made (Appendix Tables A2.13 and 14). Means were calculated within each classification of sample state (Table 2B.7, Figures 2B.36 and 2B.37).

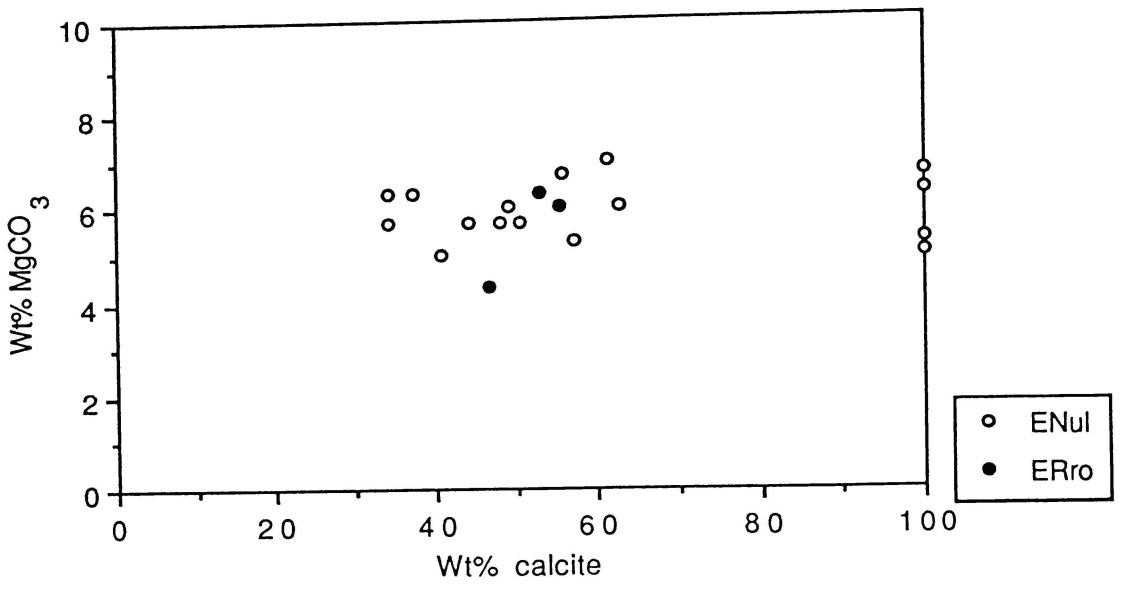


Figure 2B.35: Mineralogy of the two different growth forms of the New Zealand bryozoan *Foveolaria cyclops*.

Table 2B.7: Mean mineralogies of common New Zealand bryozoans in different states of preservation.

	Mecynoecia purpurascens Wt% $MgCO_3$	*Steginoporella neozelanica* Wt% $MgCO_3$	*Galeopsis porcellanicus* Wt% $MgCO_3$	*Foveolaria cyclops* Wt% $MgCO_3$	Wt% calcite
LIVING	1.3	3.5	6.8	6.7	54.7
FRESH SEDIMENT	1.4	4.3	6.5	6.1	52.6
DEGRADED SEDIMENT	2.4	3.7	6.1	5.7	45.5

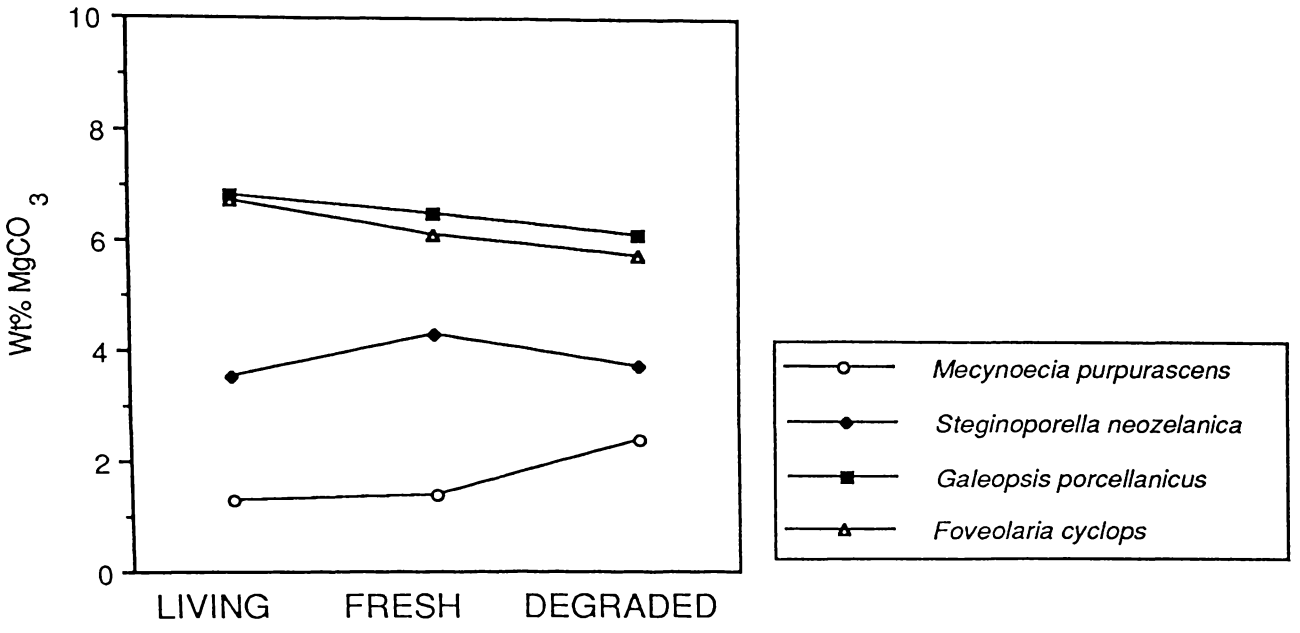


Figure 2B.36: Mean Mg content of common New Zealand bryozoans according to preservation state.



Figure 2B.37: Mean calcite content according to preservation state of *Foveolaria cyclops*.

Although there is some variation, there is no systematic pattern involved, and there are no large variations from the mean that cannot be explained by other sources of variation.

It does not appear that diagenetic state, at least in surface samples, has any significant effect on mineralogy. This confirms Poluzzi and Sartori's (1974) finding that subfossil colonies were not different in mineralogy than fresh ones of the same species.

5. Conclusions

The data presented on the mineralogy of New Zealand bryozoans have provided several useful checks on conclusions reached in the past, as well as indicating some interesting new ideas.

Variation within colonies has been shown to occur, but only to a small degree. There may be age-related differences in Mg content within calcitic colonies or there may be seasonal differences among different parts of the same colony. This is on the order of 0.5 wt% $MgCO_3$.

Within populations, individual colonies may vary up to about 1.0 wt% $MgCO_3$ and 5 wt% calcite. This is a fair amount of variation and must be kept in mind when assessing small differences between other groups.

The literature reports some systematic variation among populations found at different latitudes. No species studied in detail in New Zealand samples (from 33° to 49°S) shows much of a trend in either Mg content or calcite/aragonite ratio. Nevertheless, quite a bit of variation within species did occur, more than might be expected from individual variation.

The 48 species tested fall into five different categories: low-Mg calcite (<3 wt% $MgCO_3$), moderate-Mg calcite (3-5 wt% $MgCO_3$), high-Mg calcite (>5 wt% $MgCO_3$), bimineralic/calcite, and bimineralic/aragonite. The two bimineralic groups probably have quite different origins. The mostly aragonitic species appear to be diagenetically bimineralic, whereas the mainly calcitic species are developmentally bimineralic. The diagenetic state of the material studied does not, however, appear to have a systematic effect on mineralogy.

There are clear mineralogical signatures to the major taxa. Cyclostomes are overwhelmingly low- to moderate-Mg calcite. Cheilostomes show far more variation. Anascans have overall lower Mg content than ascophorans. Both groups show considerable variation in calcite/aragonite ratio. Increasing Mg content with increasing taxonomic complexity, as reported in the literature, is confirmed by New Zealand species.

Colonial growth forms have less clear mineralogical attributes. Erect forms tend to be mainly calcite and encrusting ones show more variation. Free-living forms are usually bimineralic or aragonite.

The mineralogy of a single colony may be characterized as a product of its age, the season, its location, its systematic position, and to a lesser extent its growth form. Table 2B.8 summarizes the levels of variation found in this study.

Table 2B.8: Variability of mineralogy in New Zealand bryozoans with different degrees of spatial variation.

	Different ages, same branches	Different branches, same colony	Different colonies, same location	Different colonies, same sed. sample	Colonies from different locations
Standard deviation (s) wt % $MgCO_3$	0.6	0.4	0.7	0.9	0.7
Standard deviation wt% calcite in bimineral species				3.5	17.7

Chapter 3 Geochemistry of Bryozoans

"...self-made from elements least visible..."

Elizabeth Bishop, The Imaginary Iceberg, 1946

A. INTRODUCTION

Calcite and aragonite are most unlikely to be pure $CaCO_3$, particularly when they have precipitated from the complex chemical environment of sea water. Co-precipitation of other elements from sea water is common within such carbonate minerals. Cations (anions are less well-studied) may substitute for Ca in the crystal lattice, or they may be incorporated into the organic material, or they may adsorb onto the surface of the minerals. In sufficient concentrations, these elemental "impurities" may change the characteristics of the carbonate minerals.

The major co-precipitate in calcite is Mg. When Mg makes up 50% of the cations in the lattice, the mineral is dolomite. There is also a fairly high degree of substitution (up to 30%) in calcite, in which case the mineral is called magnesium (or magnesian) calcite. For this reason, Mg content has also been considered in Chapter 2, in the context of skeletal mineralogy. The discussion of Mg in this chapter will focus more on interactions with other ions and environmental variation.

Major (e.g., Ca, Mg), minor (e.g., Sr), and trace (e.g., Mn) element co-precipitates have been studied in a variety of carbonates, including inorganic precipitates (e.g., Kinsman, 1969; Folk, 1974), individual organisms (e.g., Pilkey and Harris, 1966; Gordon et al., 1970), sediments (e.g., Rao and Green, 1983; Rao, 1986), and limestones (e.g., Rao, 1981b). They have mainly (paleo)environmental and diagenetic applications.

It is simple enough to postulate that $CaCO_3$ precipitated inorganically from sea water will follow chemical "rules," and that temperature, pressure, and sea-water chemistry may be inferred from the geochemical "signature" of the mineral. Indeed, a study of inorganic cements reveals just such a useful correlation (Folk, 1974). In older

sediments and in limestones, diagenesis may affect the geochemical composition of the carbonate, adding increasing complexity to interpretation.

It is much more problematic when the $CaCO_3$ is precipitated by living organisms. Vital effects, that is, preferences of organisms for or against certain ions, will strongly bias the record. An example is the amount of Sr in aragonite. Generally, Sr is the most abundant co-precipitate in skeletal aragonite, at about 0.8 to 1 wt% $SrCO_3$ (Dodd, 1967). This is the same range as predicted for Sr substituting in inorganic $CaCO_3$. Ooids, aragonite muds, and corals are among the grains tested that fall into that range. Many molluscs, however, secrete aragonite shells with lower Sr concentrations, between 0.1 and 0.4 wt% $SrCO_3$. Their "aversion" to Sr leads to a preferential exclusion of $SrCO_3$ substitution (Morse and Mackenzie, 1990). Interpretation of the Sr content of sediments containing both molluscs and corals would consequently be complicated.

Vital effects, or biological fractionation, have the potential to be extremely disruptive in interpretation of data. They may vary among taxa, among organisms, and even within an individual (as it ages, for example). Some effects may be seasonal, as growth rate and saturation of sea water have been shown to influence co-precipitation in some organisms (e.g., Moberly, 1968). On the other hand, vital effects can also be useful. Organisms are subject to forces not felt by inorganic systems (e.g., food supply, turbidity), and if vital effects could be separated from physico-chemical effects (e.g., ambient sea water, temperature), there could be much information revealed by carbonate geochemistry. There may be fewer vital effects in less complex organisms which have simpler biomineralization mechanisms (Morse and Mackenzie, 1990).

Despite the difficulties, geochemistry is used mainly in chemical interpretations: temperature (e.g., Cronblad and Malmgren, 1981) and salinity (e.g., Rucker and Valentine, 1961) of ambient sea water at the time of precipitation have been investigated, also age as indicated by diagenetic state. To a lesser extent, the effect of depth has been studied - this is more direct but less informative as depth contains a

variety of effects (temperature, salinity, pressure, and light). Most of these investigations assume that the geochemical signature of skeletons reflects the environment of precipitation. As discussed above, this seems at best an oversimplification. Nevertheless, "it is among the best approaches we have" for paleoenvironmental interpretation (Morse and Mackenzie, 1990, p. 201).

Stable isotopes are another useful tool. Found in sea water at known proportions under known conditions, the ratios in carbonate (signified by δ) are related to a known standard. In the case of oxygen ($\delta^{18}O$) and carbon ($\delta^{13}C$) isotopes, the common standard is a Cretaceous belemnite known as PDB, and results are reported in mg/g (ppt) difference from PDB. Some organisms appear to incorporate carbon and oxygen in skeletal carbonate ($CaCO_3$) in much the same proportions as are present in the ambient sea water. Their carbonate is at or near isotopic equilibrium with the seawater. Many skeletal carbonates have been studied with regard to stable isotopes. As with co-precipitates, some organisms exert vital effects. For example, according to Weber and Raup (1966), echinoderms do not secrete skeletons in isotopic equilibrium with ambient sea water. Foraminifera (e.g., Emiliani, 1970) and molluscs (e.g., Lloyd, 1964) are two groups that commonly precipitate $CaCO_3$ close to isotopic equilibrium, and have therefore been used for interpretation of isotopic variation. Stable isotopes have been used in deep-sea cores and climate change studies, and in temperature and salinity predictions (e.g., Kennett, 1982).

Skeletal geochemistry of bryozoans was first addressed by Clarke and Wheeler (1917). Small-scale tests of individuals had been done before then, but species were not always clearly identified, and many ions were ignored. Clarke and Wheeler really began the study of invertebrate skeletal geochemistry generally in their two extensive papers (1917, 1922). They reported on 13 species of bryozoans. Other studies followed (e.g., Saundray and Bouffandreau, 1958) and were summarized by Schopf and Manheim (1967), who added 28 analyses of their own. The data were reported in various units (wt% MgO, mol% $MgCO_3$, ppm Mg), making comparisons difficult; they have all been

Table 3A.1: Some published data on co-precipitates in bryozoans (Clarke and Wheeler, 1922; Thomsen ai Chow, 1955; Saundray and Bouffandreau, 1958; Schopf and Manheim, 1967; and Land and Hoops, 1973).
Ch - Cheilostome; Cy - Cyclostome.

Source	Species	Taxon	Location	Co-precipitates in µg/g			
				Ca	Mg	Sr	Fe
C&W 22	*Schizoporella unicornis*	Ch	Vineyard Sound, Massachusetts	385989	1808		
C&W 22	*Schizoporella unicornis*	Ch	Johns Pass, Florida	365975	13014		
C&W 22	*Microporella grisea*	Ch	Australia	389563	3193		
C&W 22	*Cellepora incrassata*	Ch	Grand Banks	372408	17413		
C&W 22	*Flustra membranacea truncata*	Ch	St. Paul Is, Alaska	339528	19100		
C&W 22	*Cryptosula pallasiana*	Ch	Gloucester, Massachusetts	355253	16147		
C&W 22	*Lepralia rosterigera*	Ch	Cedar Keys, Florida	381701	7953		
C&W 22	*Holoporella albirostris*	Ch	Cedar Rapids, Florida	383130	7351		
C&W 22	*Frondipora verrucosa*	Cy	Near Naples	358112	422		
C&W 22	*Catenicella margaritacea*	Ch	Australia	353824	25607		
C&W 22	*Bugula turrita*	Ch	Georges Bank, Massachusetts	260185	27414		
C&W 22	*Bugula neritina*	Ch	Florida	247319	27233		
T&C 55	*Crisia sp.*	Cy		378841		3044	
T&C 55	*Idmonea sp.*	Cy		385989		3298	
T&C 55	*Bugula californica*	Ch		283774		1945	
T&C 55	*Hippodiplosia insculpta*	Ch		341672		2875	
T&C 55	*Phidolopora pacifica*	Ch		360257		2368	
S&B 58	*Bugula turbinata (branches)*	Ch		246604	13255		
S&B 58	*Bugula turbinata (axis)*	Ch		254467	33138		
S&B 58	*Bugula sp.*	Ch		243745	7833		
S&B 58	*Cellepora pumicosa*	Ch		247319	7351		
S&B 58	*Flustra foliacea*	Ch		235882	25908		
S&B 58	*Membranipora membranacea*	Ch		240886	16388		
S&M 67	*Eschara foliacea*	Ch	Bay of Naples	384560	7772		
S&M 67	*Lepralia sp.*	Ch	Bay of Naples	365260	14460		
S&M 67	*Eschara cervicornis*	Ch		250893	14822		

Source	Species	Taxon	Location	Co-precipitates in µg/g			
				Ca	Mg	Sr	Fe
S&M 67	*Crisia eburnea*	Cy	Martha's Vineyard, Massachusett	346676	13858	2368	35
S&M 67	*Idmonea atlantica*	Cy	Grand Manan Island, Nova Scotia	350964	12050	3382	245
S&M 67	*Tubulipora liliacea*	Cy	Vineyard Sound, Massachusetts	372408	10845	2959	315
S&M 67	*Tubulipora liliacea*	Cy	Vineyard Sound, Massachusetts	329520	10845	2537	735
S&M 67	*Bugula simplex*	Ch	Woods Hole, Massachusetts	290922	24100	2706	840
S&M 67	*Bugula simplex*	Ch	Woods Hole, Massachusetts	336668	23498	1522	2973
S&M 67	*Bugula simplex*	Ch	Woods Hole, Massachusetts	322373	22895	2114	3358
S&M 67	*Bugula simplex*	Ch	Woods Hole, Massachusetts	340957	23498	2452	1364
S&M 67	*Bugula turrita*	Ch	Woods Hole, Massachusetts	288062	22895	2621	2274
S&M 67	*Cryptosula pallasiana*	Ch	Falmouth, Massachusetts	325947	17473	3044	1504
S&M 67	*Cryptosula pallasiana*	Ch	Falmouth, Massachusetts	298784	19280	3805	1049
S&M 67	*Cryptosula pallasiana*	Ch	Falmouth, Massachusetts	289492	19280	4397	1469
S&M 67	*Cryptosula pallasiana*	Ch	Falmouth, Massachusetts	334524	16268	3720	944
S&M 67	*Cryptosula pallasiana*	Ch	Falmouth, Massachusetts	337383	19280	2368	1049
S&M 67	*Eucratea lorica*	Ch	Crowe Neck, Maine	262330	21690	1437	8395
S&M 67	*Eucratea lorica*	Ch	Nantucket, Massachusetts	319513	20485	2452	1819
S&M 67	*Flustra foliacea*	Ch	St. Johns, New Brunswick	348820	18678	2198	1504
S&M 67	*Membranipora lacroixi*	Ch	Falmouth, Massachusetts	333094	22293	2114	1119
S&M 67	*Membranipora lacroixi*	Ch	Falmouth, Massachusetts	327376	29523	2452	525
S&M 67	*Parasmittina nitida*	Ch	Vineyard Sound, Massachusetts	383845	1627	8963	455
S&M 67	*Parasmittina nitida*	Ch	Vineyard Sound, Massachusetts	384560	1988	8456	560
S&M 67	*Parasmittina nitida*	Ch	Vineyard Sound, Massachusetts	373838	844	7948	455
S&M 67	*Porella smitti*	Ch	Yarmouth, Nova Scotia	356683	22293	2621	175
S&M 67	*Rhamphostomella bilaminata*	Ch	Cape Cod Bay, Massachusetts	356683	13858	2790	455
S&M 67	*Schizoporella unicornis*	Ch	Vineyard Sound, Massachusetts	357398	13858	6342	910
S&M 67	*Schizoporella unicornis*	Ch	Vineyard Sound, Massachusetts	373123	9640	4904	245
S&M 67	*Schizoporella unicornis*	Ch	Vineyard Sound, Massachusetts	371693	10243	4989	280
S&M 67	*Schizoporella unicornis*	Ch	Cape May, New Jersey	366690	10845	4735	525
L&H 73	*Membranipora sp.*	Ch	So. California		9216	2820	
L&H 73	*Retepora pacifica*	Ch	So. California		25344	2900	
MEAN				331360	15609	3476	1271

converted to μg/g (=ppm) in Table 3A.1. Following Schopf and Manheim (1967), attention turned to mineralogy with the development of X-ray diffractometry, and very few geochemical tests of bryozoans have been reported since then.

Some stable isotope values for bryozoans have been reported, mainly from the northern hemisphere (Table 3A.2). Forester et al. (1973) concluded that bryozoans secrete carbonate in isotopic equilibrium with sea water. Almost all the data available on stable isotopes of bryozoans from the southern hemisphere are from Tasmania (e.g., Rao, 1981b; Rao and Green, 1983, Rao and Nelson, 1992).

This study, then, has been designed to determine the geochemistry and stable isotopes of the skeletons of some important sediment-forming bryozoans from New Zealand. A comparison with Australian examples will be made, and possible correlations of bryozoan geochemistry with environment will be considered.

B. METHODS

Specimens of 27 species of sediment-forming bryozoans from 30 different carbonate sediment samples were selected for analysis. Fresh-looking, unencrusted specimens were selected whenever possible. Sediment sample locations ranged in latitude from 32 to 52°S, and in depth from 10 to 292 m, mainly from the New Zealand shelf (for sample details see Appendix Table A2.2). Appendix Table A3.1 shows the coverage of the shelf for each species. Each geochemical analysis is of a single species from a single location.

Specimens were washed in distilled water, dried, and ground to a fine powder. One g of powder was dissolved in 50 ml 1M HCl, filtered, and the insoluble residue washed away. Diluted to 1/100, the samples were analyzed using atomic absorption spectrophotometry (Robinson, 1980). Major elements Ca and Mg, minor elements Sr and Fe, and trace element Mn were measured. Results were converted using calibrated

Table 3A.2: Some published data on stable isotopes in bryozoans (Forester et al., 1973; Bone and Wass, 1990; Rao and Nelson, 1992).

Source	Species	Taxon	Location	Isotopes in mg/g PDB $\delta^{13}C$	$\delta^{18}O$
FSA 73	*Adeonella gibbera*	Ch	Philippines	1.55	-1.29
FSA 73	*Adeonella gibbera*	Ch	Philippines	1.33	-1.16
FSA 73	*Celleporina surcularis*	Ch	N.E. Canada	1.02	2.36
FSA 73	*Celleporina? sp.*	Ch	Japan	0.33	2.70
FSA 73	*Conescharellina grandiporosa*	Ch	Philippines	1.36	-1.44
FSA 73	*Crisia sp.*	Cy	Japan	0.16	0.58
FSA 73	*Cupuladria sp.*	Ch	Philippines	2.74	1.10
FSA 73	*Cystisella saccata*	Ch	Nova Scotia	1.69	2.72
FSA 73	*Cystisella saccata*	Ch	off Labrador	1.81	3.05
FSA 73	*Holoporella sp.*	Ch	Brazil	2.70	-0.56
FSA 73	*Idmonea sp.*	Cy	Japan	0.71	0.54
FSA 73	*Micropora sp.*	Ch	Alaska	1.39	1.73
FSA 73	*Micropora sp.*	Ch	Alaska	0.38	1.65
FSA 73	*Myriozoum coarctatum*	Ch	Alaska	1.18	1.96
FSA 73	*Myriozoum subgracile*	Ch	Nova Scotia	1.45	2.77
FSA 73	*Porella compressa*	Ch	Nova Scotia	1.44	2.53
FSA 73	*Porella compressa*	Ch	off Alaska	1.29	3.08
FSA 73	*Triphyllozoon sp.*	Ch	Philippines	1.18	-1.54
FSA 73	*Tryphyllozoon sp.*	Ch	Japan	1.30	1.01
FSA 73	*Veleroa? sp.*	Ch	Vancouver	2.86	2.73
B&W 90	*Membranipora aciculata*	Ch	Australia	0.11	2.56
B&W 90	*Membranipora membranacea*	Ch	Australia	-1.16	0.03
B&W 90	*Celleporaria cristata*	Ch	Australia	0.15	0.27
B&W 90	*Petralia undata*	Ch	Australia	1.81	0.50
R&N 92	*Hornera sp.*	Cy	New Zealand	1.81	1.08
R&N 92	*Mecynoecia purpurascens*	Cy	New Zealand	-0.34	0.05
R&N 92	*Telopora buski*	Cy	New Zealand	1.72	1.61
R&N 92	*Cellaria immersa*	Ch	New Zealand	1.59	1.00
R&N 92	*Foveolaria cyclops*	Ch	New Zealand	1.69	2.94
R&N 92	*Otionella squamosa*	Ch	New Zealand	2.65	1.33
R&N 92	*Steginoporella magnifica*	Ch	New Zealand	0.39	0.44
R&N 92	*Steginoporella neozelanica*	Ch	New Zealand	-2.92	-0.73
R&N 92	*Steginoporella neozelanica*	Ch	New Zealand	-0.26	2.54
R&N 92	*Steginoporella perplexa*	Ch	New Zealand	-0.74	0.39
R&N 92	*Adeonellopsis sp.*	Ch	New Zealand	2.74	1.78
R&N 92	*Arachonpusia unicornis*	Ch	New Zealand	0.28	0.06
R&N 92	*Celleporina costazii*	Ch	New Zealand	1.43	1.15
R&N 92	*Chiastosella splendida*	Ch	New Zealand	1.07	0.56
R&N 92	*Galeopsis polyporus*	Ch	New Zealand	1.15	1.03
R&N 92	*Galeopsis porcellanicus*	Ch	New Zealand	1.07	0.37
R&N 92	*Galeopsis porcellanicus*	Ch	New Zealand	1.90	1.00
R&N 92	*Hippellozoon novaezelandiae*	Ch	New Zealand	1.79	1.27
R&N 92	*Hippomenella vellicata*	Ch	New Zealand	2.06	1.17
R&N 92	*Iodictyum yaldwyni*	Ch	New Zealand	2.03	0.64
R&N 92	*Metroperiella mucronifera*	Ch	New Zealand	2.06	1.40
MEAN				1.15	1.09

Note: Ch - Cheilostome; Cy - Cyclostome.

standards to μg/g. Experimental error for most analyses is about 3%; it may be higher in very low concentrations (Dr. C.H. Hendy, pers. comm.).

For isotope analysis, small samples of powdered specimens were roasted at 400°C to remove organic contaminants, crushed, and reacted completely with 100% orthophosphoric acid at 50°C. Stable isotope ratios of the resulting CO_2 gas (reported as $\delta^{13}C$ and $\delta^{18}O$, mg/g (ppt) deviations from the PDB standard) were determined using a VG Micromass 602E mass spectrometer, after the method of Shackleton (1965). The standard used was NBS-19, but these data have been converted to PDB for ease of comparison with other results. Analytical precision for isotopic analyses is better than 0.01% (Cuthbertson, 1988).

C. RESULTS

Results are given in Appendix Tables A3.2 and A3.3. Overall means are given in Figure 3C.1. Species means for the elements analyzed by AA are plotted in Figure 3C.2. Isotope data are plotted in Figure 3C.3.

As Mg content was measured both by XRD (as reported in Appendix Table A2.2) and by atomic absorption (AA), a comparison of the methodologies is possible. Although the identical samples were not used, the same species from the same location was often tested by both methods. Appendix Table A3.4 gives the data for comparison. It is clear that Mg content as measured by AA is consistently higher (by 2-3 wt% $MgCO_3$) than that determined from XRD, whether one compares individual samples or species means (Figure 3C.4). The slope of the line is very nearly one, so the difference seems to be a simple off-setting. Calibration and the relationship between the two techniques requires further more detailed investigation, beyond the scope of this study.

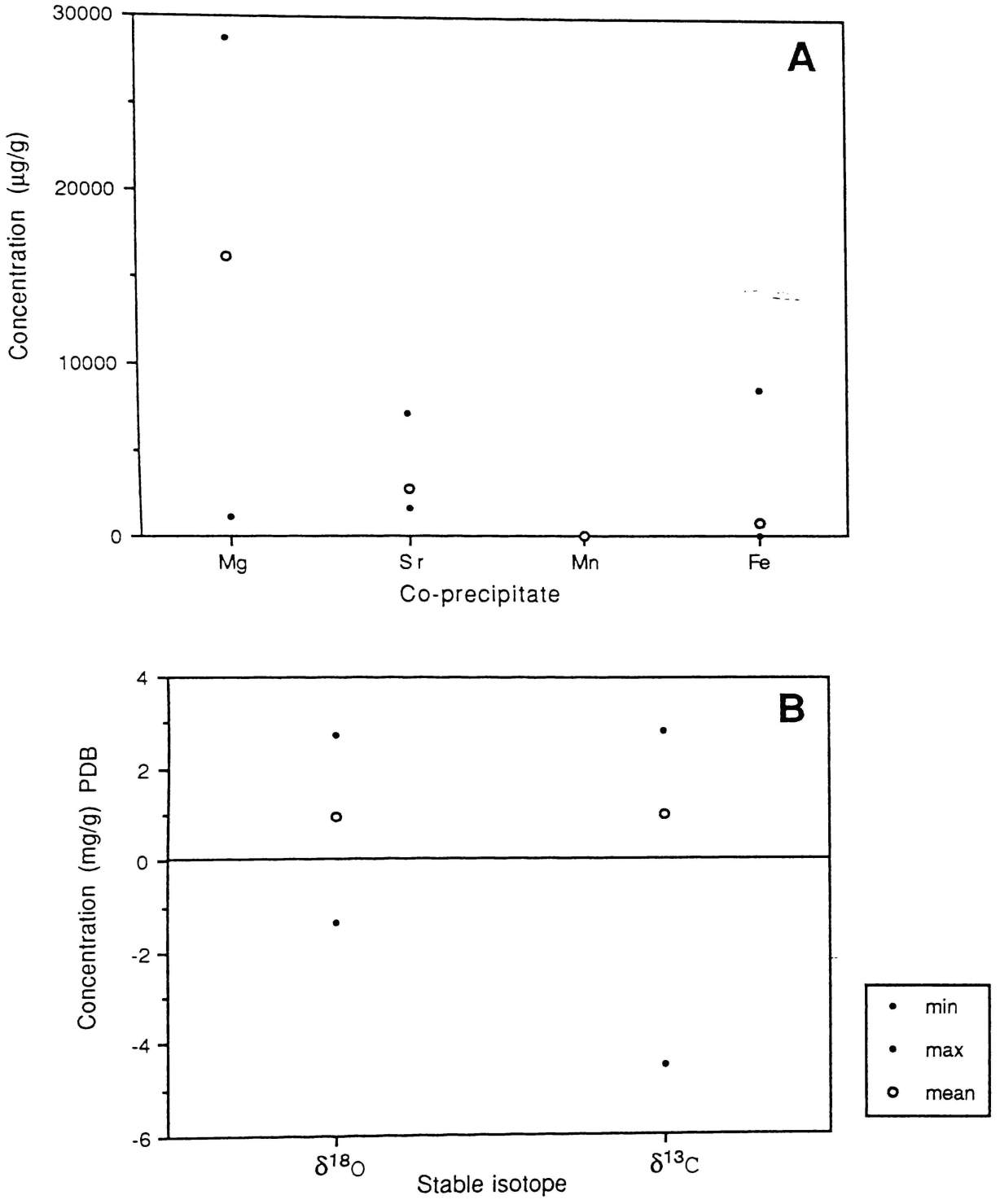


Figure 3C.1: Summary geochemical data for studied New Zealand bryozoans. Mean (circle) and range (line) for (A) co-precipitates and (B) stable isotopes.

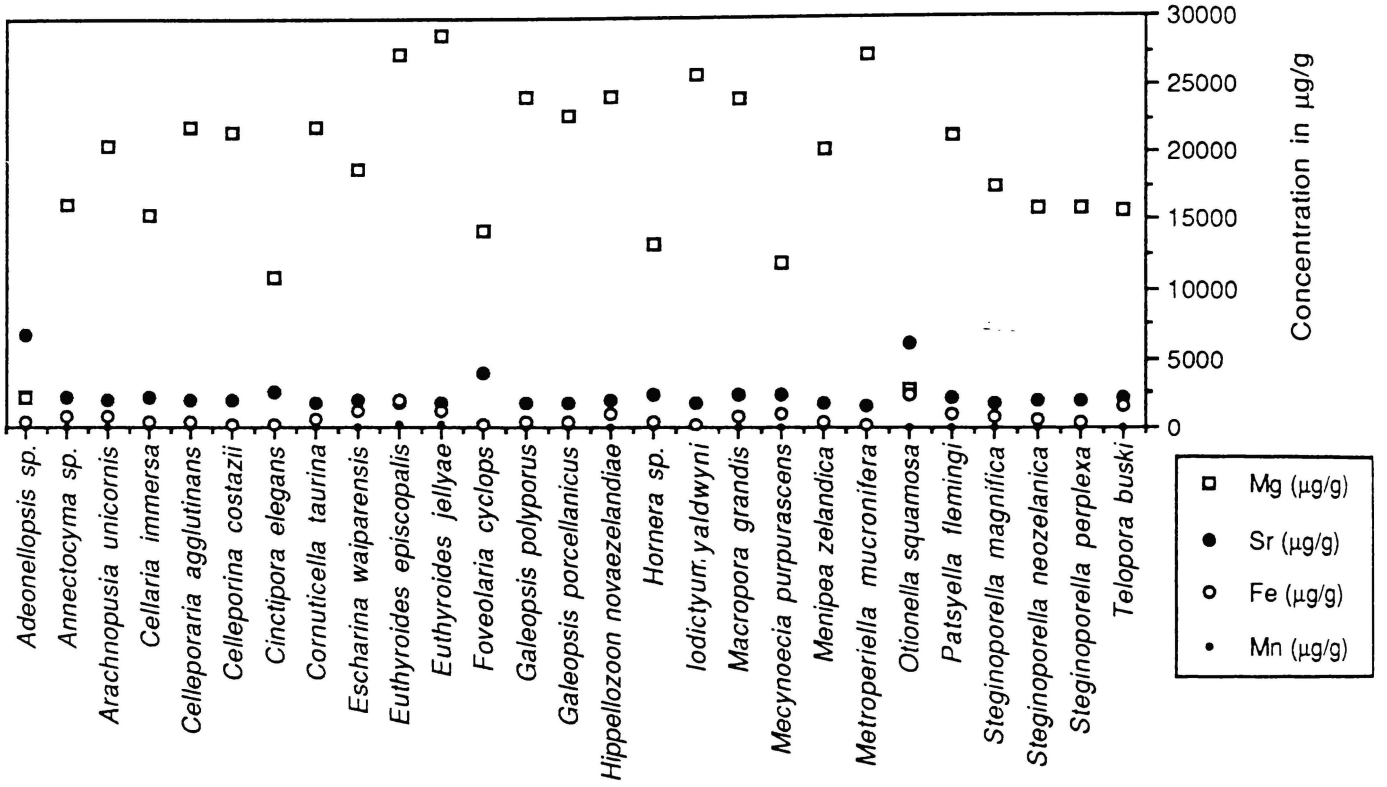


Figure 3C.2: Mean concentration of co-precipitates for 27 species of New Zealand bryozoans.

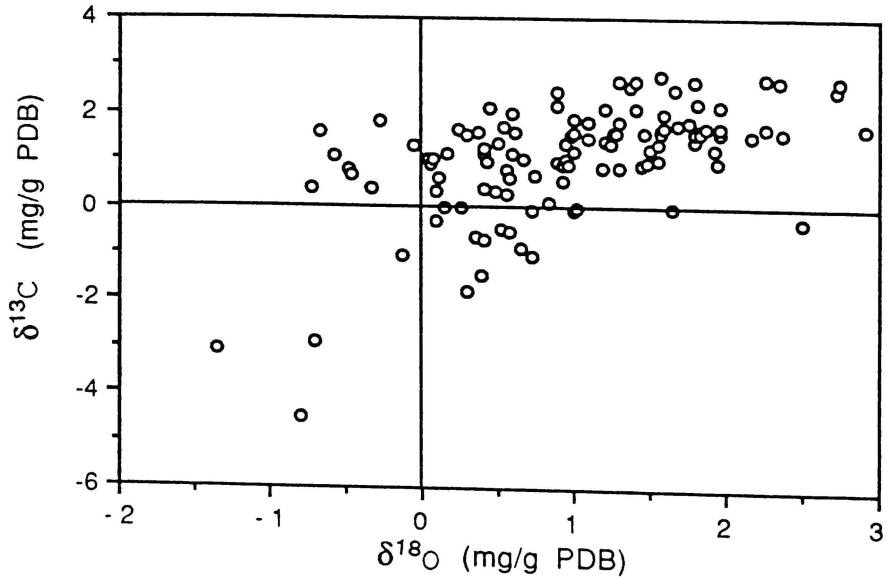


Figure 3C.3: Stable isotope results for New Zealand bryozoans.

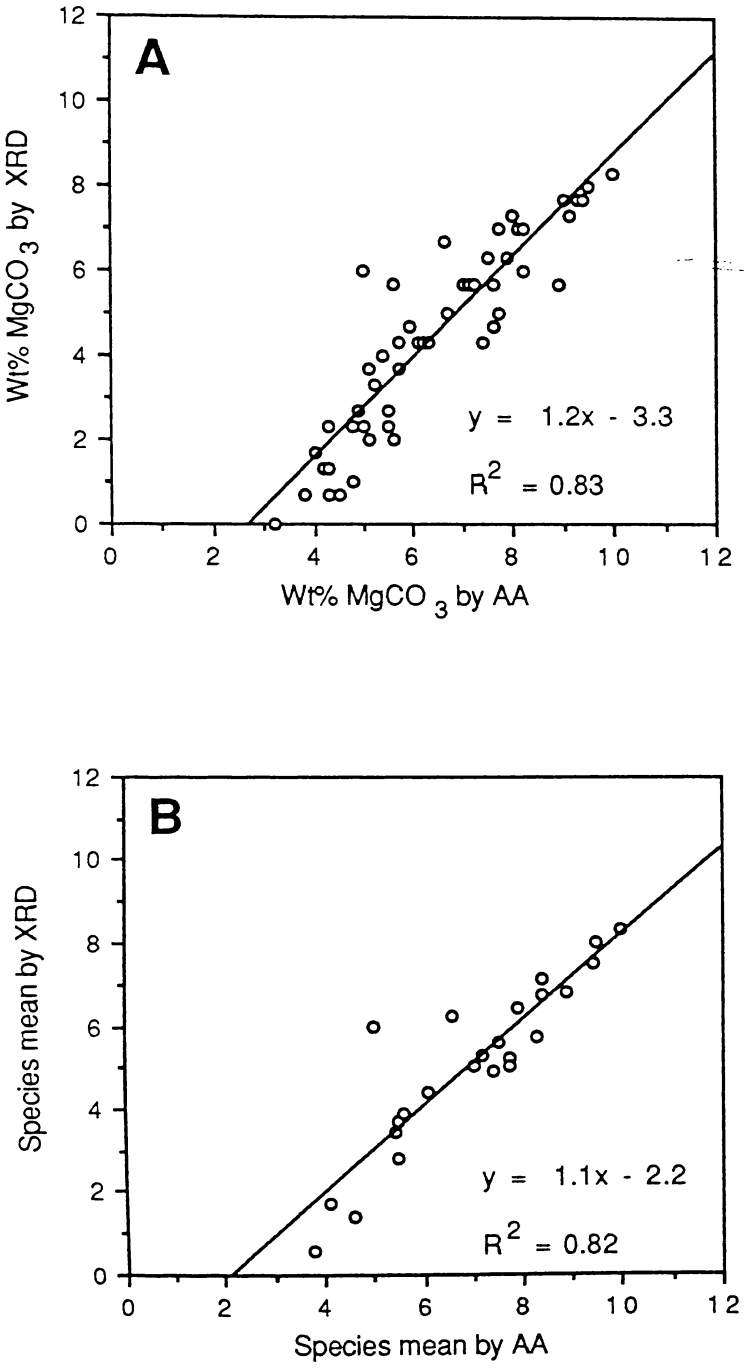


Figure 3C.4: Comparison of Mg content as measured by atomic absorption (AA) and x-ray diffraction (XRD). (A) Same species from the same sample. (B) Mean of species from all samples.

1. Co-precipitates in bryozoan skeletons

Magnesium

Magnesium is the most important substitute for Ca in the calcite lattice. In aragonitic corals it has been shown that 75% of the Mg present is in the aragonite lattice; the remainder is adsorbed onto the mineral surfaces or in organic material (Amiel et al., 1973). As Rao and Green (1983) points out, if Mg is mainly substituting for Ca in the mineral lattice, there should be some inverse relationship between Mg and Ca, and indeed his data show this trend. This is not the case, however, for the New Zealand bryozoans (Figure 3D.1). This may indicate that Mg is also incorporated into bryozoan carbonate interstitially or superficially, as noted by Dodd (1967) in other taxa.

Magnesium content has been shown to be strongly correlated with mineralogy, so much so that Mg content was used as a mineralogical indicator before the development of XRD technology (e.g., Schopf and Allan, 1970). In New Zealand bryozoan calcite, Mg varies from about 10,000 to 40,000 µg/g (1 to 4 wt% Mg or 2 to 10 wt% $MgCO_3$). In bryozoan aragonites it is much lower, only 2000 to 4000 µg/g (Figure 3D.2). These ranges are similar to observations made elsewhere (Figure 3D.3).

There is considerable uncertainty about the use of Mg in predicting paleotemperatures. Inorganic calcites show a strong positive correlation with temperature of precipitation (Morse and Mackenzie, 1990), as do some taxa of marine invertebrates (Chave, 1954). It has been suggested that the increase of Mg in higher temperatures results from faster colonial growth rates (Morse and Mackenzie, 1990). There has even been published a linear scale from which temperature may be predicted from Mg content (Fuchtbauer and Hardie, 1976). Rucker and Valentine (1961), however, found no indication of a temperature control on Mg content in Atlantic oysters.

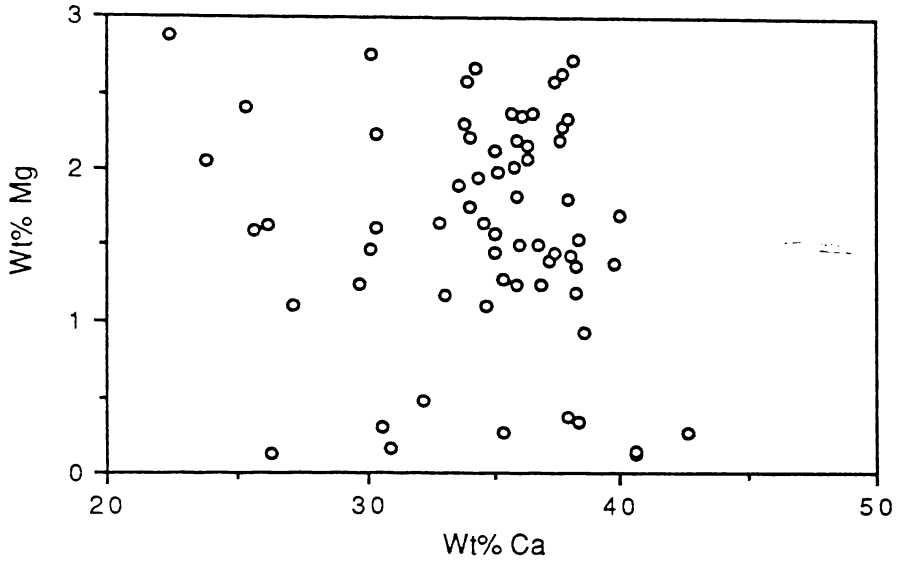


Figure 3D.1: Mg content relative to Ca content in New Zealand bryozoans. Data do not show the strong positive correlation evident in Rao's (1986) analyses, suggesting that not all the Mg is present in substitution for Ca.

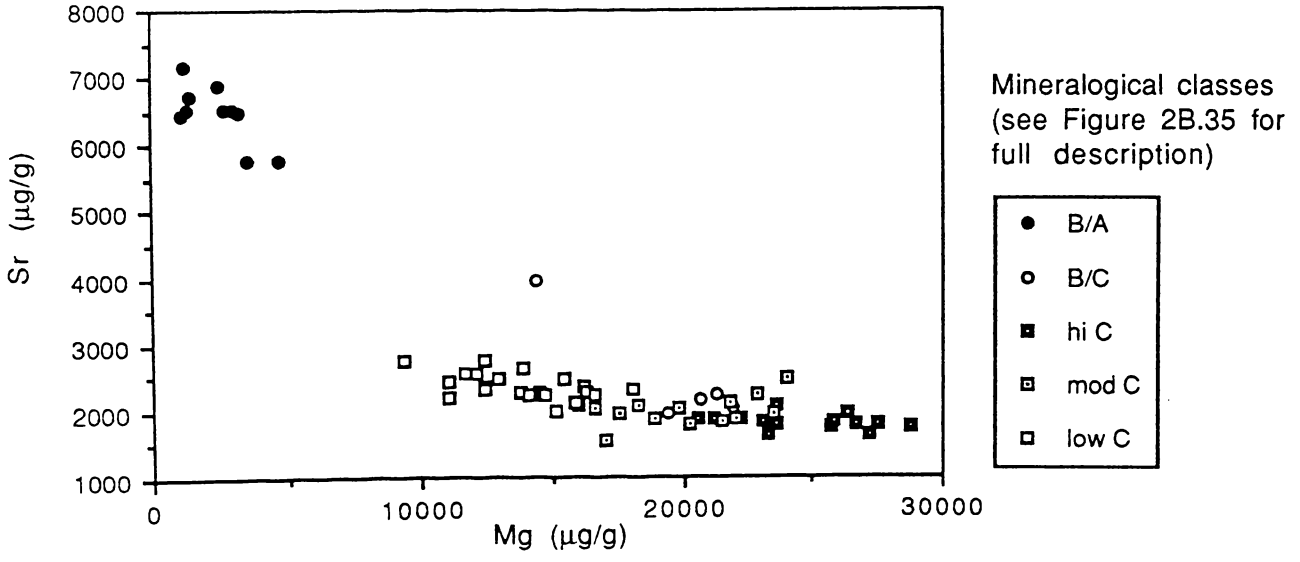


Figure 3D.2: Sr content relative to Mg content in New Zealand bryozoans, with mineralogical classes indicated. Aragonites are clearly separate from calcites.

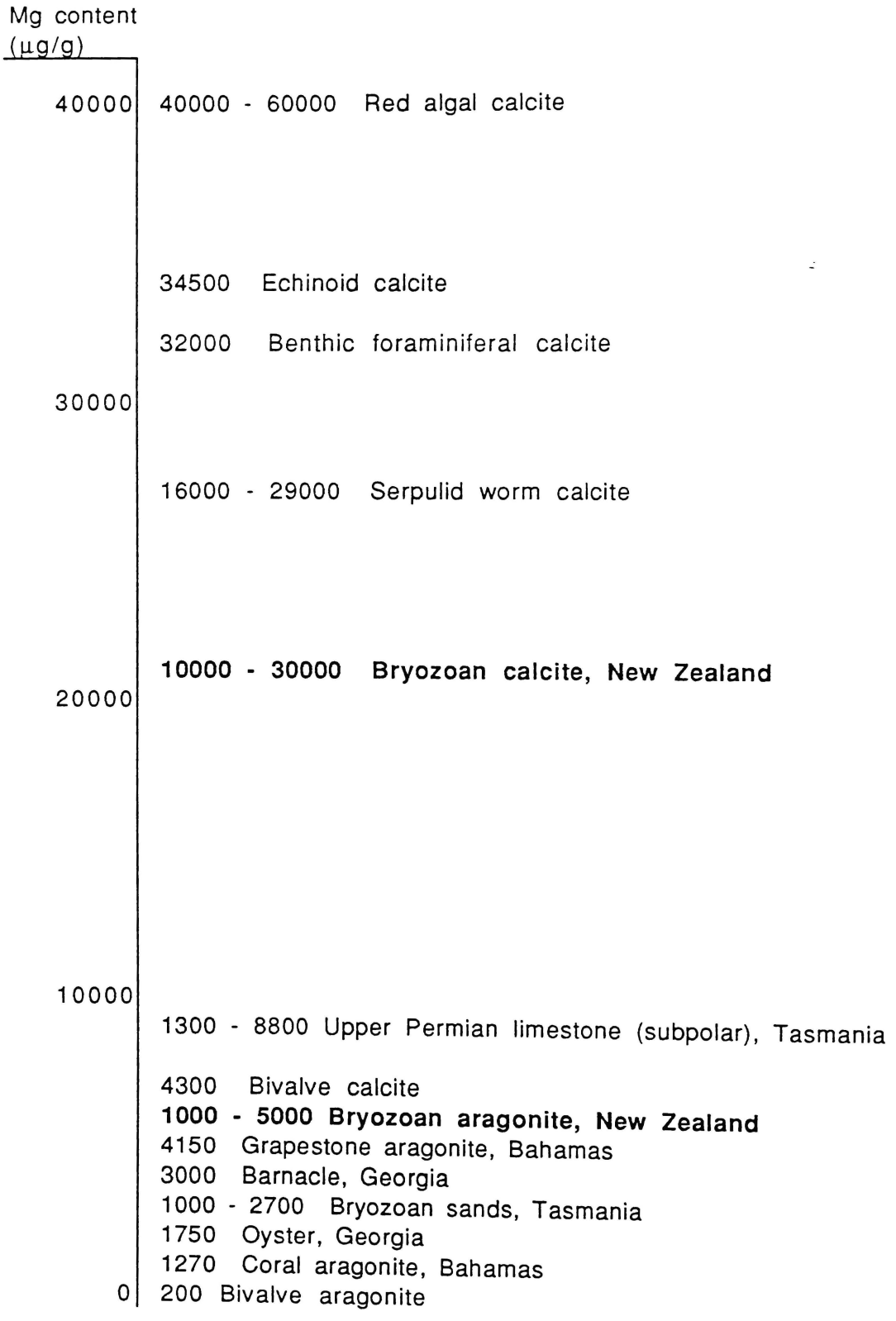


Figure 3D.3: Some published data on the geochemistry of Mg in carbonate components. This study shown in bold. (Compiled from Pilkey and Harris, 1966; Kinsman, 1969; Land and Hoops, 1973; Milliman, 1974; Rao and Naqvi, 1977; Cronblad and Malmgren, 1981; Rao, 1981b; 1990).

When the New Zealand bryozoan Mg data are plotted against two likely indicators of temperature, latitude and depth, no patterns emerge (Figure 3D.4). There appears to be no clear relationship of Mg to temperature, at least as indicated by depth and latitude, in New Zealand bryozoans. This agrees with the similar lack of correlation of latitude with mineralogy (see Figures 2B.18 to 2B.22).

Another possible correlation with Mg content is that of phylogenetic variation. In many taxa, more advanced members show less Mg in calcite than more primitive members (Chave, 1954). Chave also showed that more advanced taxa followed the same pattern (see also Dodd, 1967). Neither Chave nor Dodd had much data on the bryozoans, as they emphasized.

The New Zealand bryozoans show a surprising trend in Mg content related to phylogenetic position (Figure 3D.5A). The most primitive taxon, Cyclostomata, clearly has the least Mg. Within the Cheilostomata, the Anasca (less complex) have less than the Ascophora. Thus there is a trend of increasing Mg with increasing advancement, exactly the opposite of Chave's observations! This relationship appears to be limited to the calcite bryozoans; aragonite specimens show no similar trend (Figure 3D.5B).

Magnesium in carbonate skeletons and sediments has been shown to be related to salinity (Folk, 1974), facies (Renard, 1984), and degree of diagenesis (Brand and Morrison, 1987). As all the samples used in this study are fully marine and fairly recent, there is likely to be little variation of Mg due to these properties.

Strontium

In skeletal aragonite, Sr is the major ion substituting in the lattice for Ca, at least in corals (Amiel et al., 1973). One might expect Ca and Sr contents to vary inversely if simple lattice substitution is taking place. In the few aragonitic bryozoans tested, this does not seem to be the case, nor is Sr related to Ca in bryozoan calcites (Figure 3D.6).

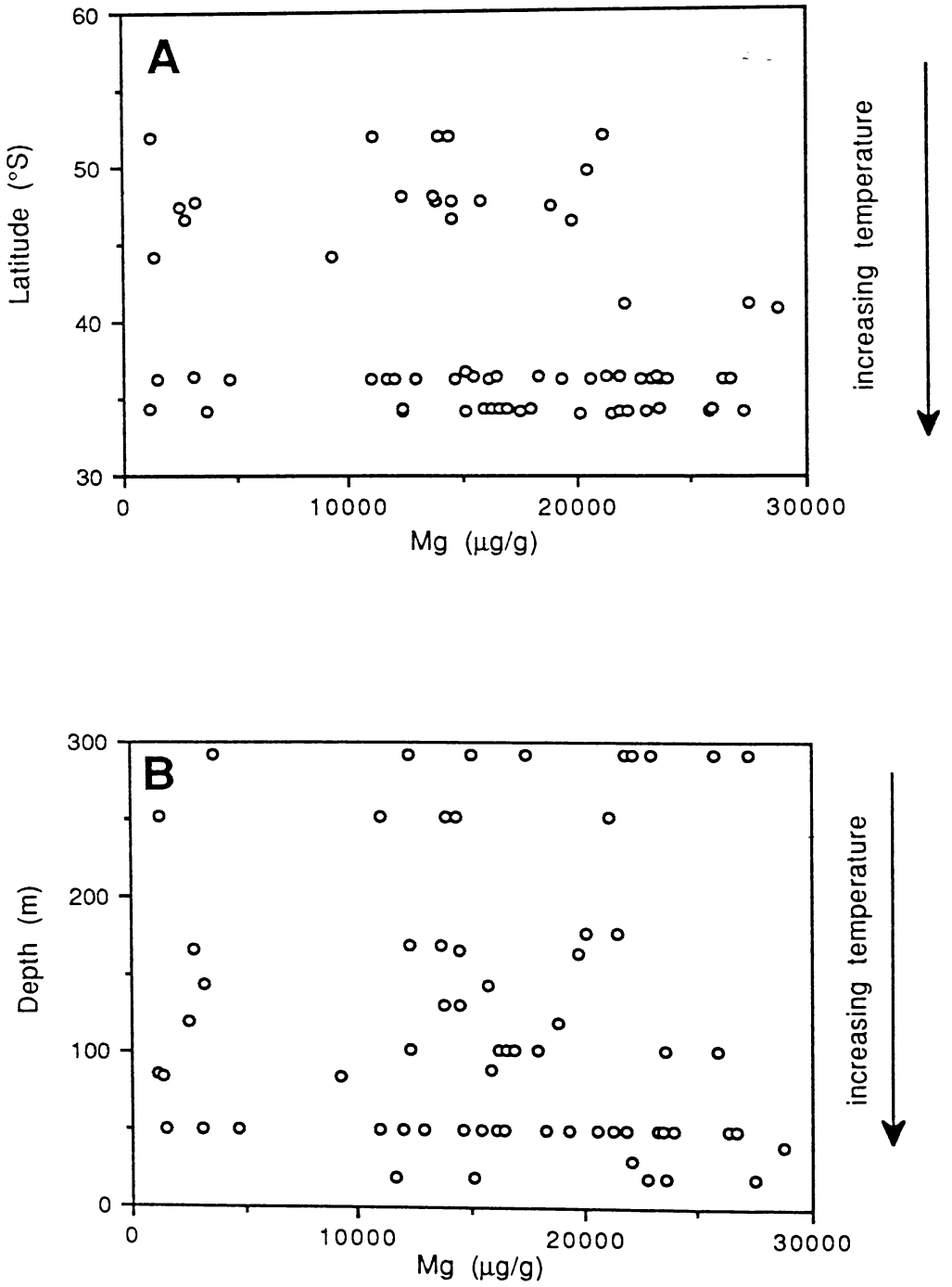


Figure 3D.4: Latitude (A) and depth (B) in relation to Mg content of New Zealand bryozoans.

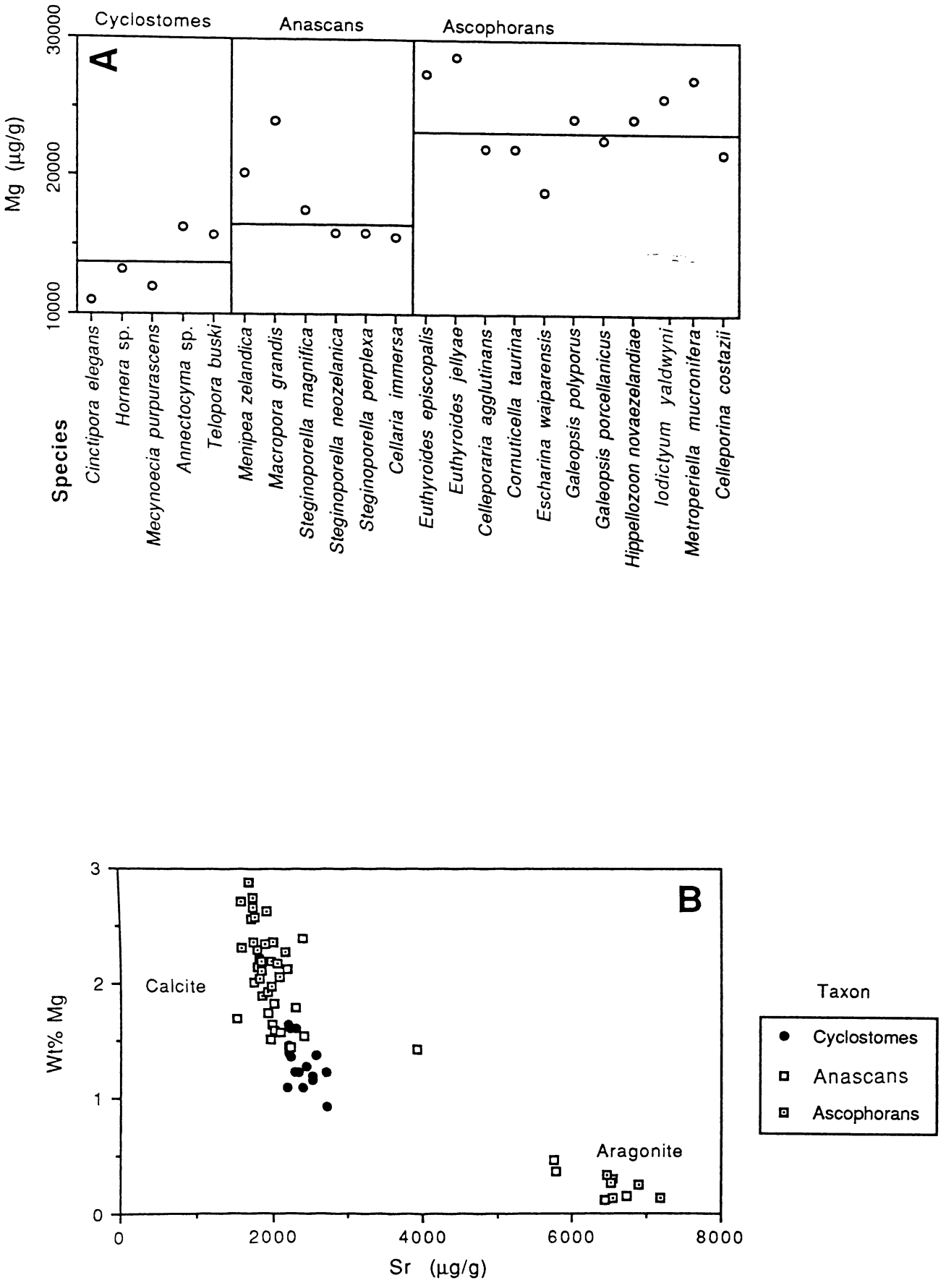


Figure 3D.5: Relationship of taxonomic position to Mg content. (A) Means of calcitic species, in approximate phylogenetic order. (B) Relationship of Mg to Sr within taxa.

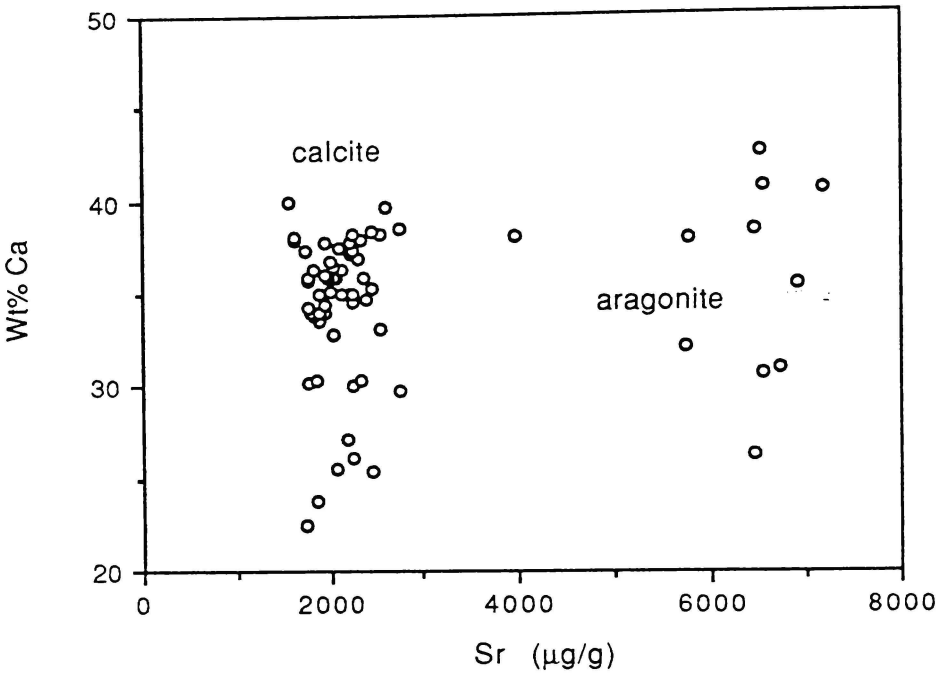


Figure 3D.6: Sr content relative to Ca in New Zealand bryozoans.

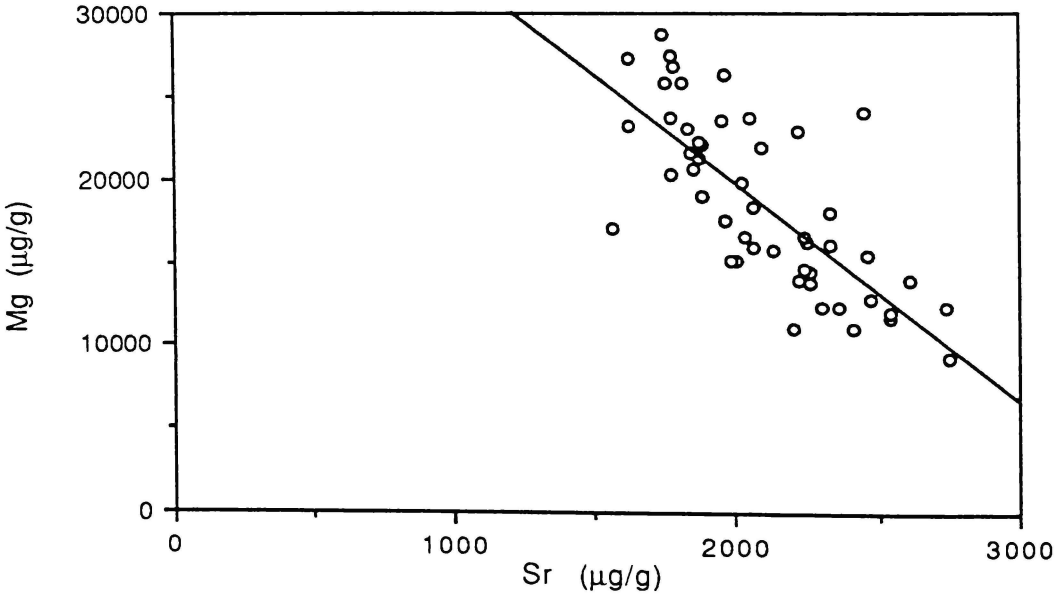


Figure 3D.7: Sr content relative to Mg in wholly calcitic New Zealand bryozoans.

New Zealand bryozoans do not show an increase in Sr with increasing Mg, as suggested by Dodd (1967), in fact the reverse is true (Figure 3D.7).

As with Mg, Sr content is mineralogically controlled. Most skeletal aragonites have Sr contents similar to inorganically precipitated aragonite (8000 to 9000 μg/g), such as corals and codiacean algae. Many molluscs are exceptions to this, selectively avoiding Sr in aragonite (Morse and Mackenzie, 1990). Calcites, however, are far lower in Sr (Figure 3D.8), around 1000 μg/g, although certain taxa may have rather high Sr calcite (e.g., some arthropods). Similarly, inorganic calcite is generally about 1200 μg/g (Morse and Mackenzie, 1990). This gap in Sr content between calcite and aragonite has been used to indicate aragonite shells that have undergone diagenetic alteration to calcite, but retain (due to element partitioning) the diagnostic high Sr content (e.g., Rao, 1981b).

The New Zealand bryozoans certainly show a mineralogical trend in Sr (see Figure 3D.2). Bryozoan aragonites are much higher in Sr than bryozoan calcites. They are not, however, as high as corals or inorganically precipitated aragonites, nor are they as high as some values for aragonitic bryozoans reported in the literature (e.g., Lowenstam, 1963). This may be due to the bimineral character of the species tested. Bryozoan calcites cover a rather wide range from 1000 to 3000 μg/g. This widening of the range is consistent with the inclusion of bimineral specimens. It probably also explains Rao's (1986) rather high figure of 3200 μg/g Sr for "pure bryozoa" (Figure 3D.8); it is probably a mixture of aragonite, calcite, and bimineral species.

Some environmental correlations with Sr have been postulated. Sr content may be higher in hypersaline or deep-sea environments than in littoral to shallow bathyal ones (Veizer and Demovic, 1974). Sr content has been seen to parallel $\delta^{18}O$ variations as a paleoclimatic indicator in deep-sea cores (Cronblad and Malmgren, 1981). No correlation between $\delta^{18}O$ and Sr content appears in the New Zealand bryozoans.

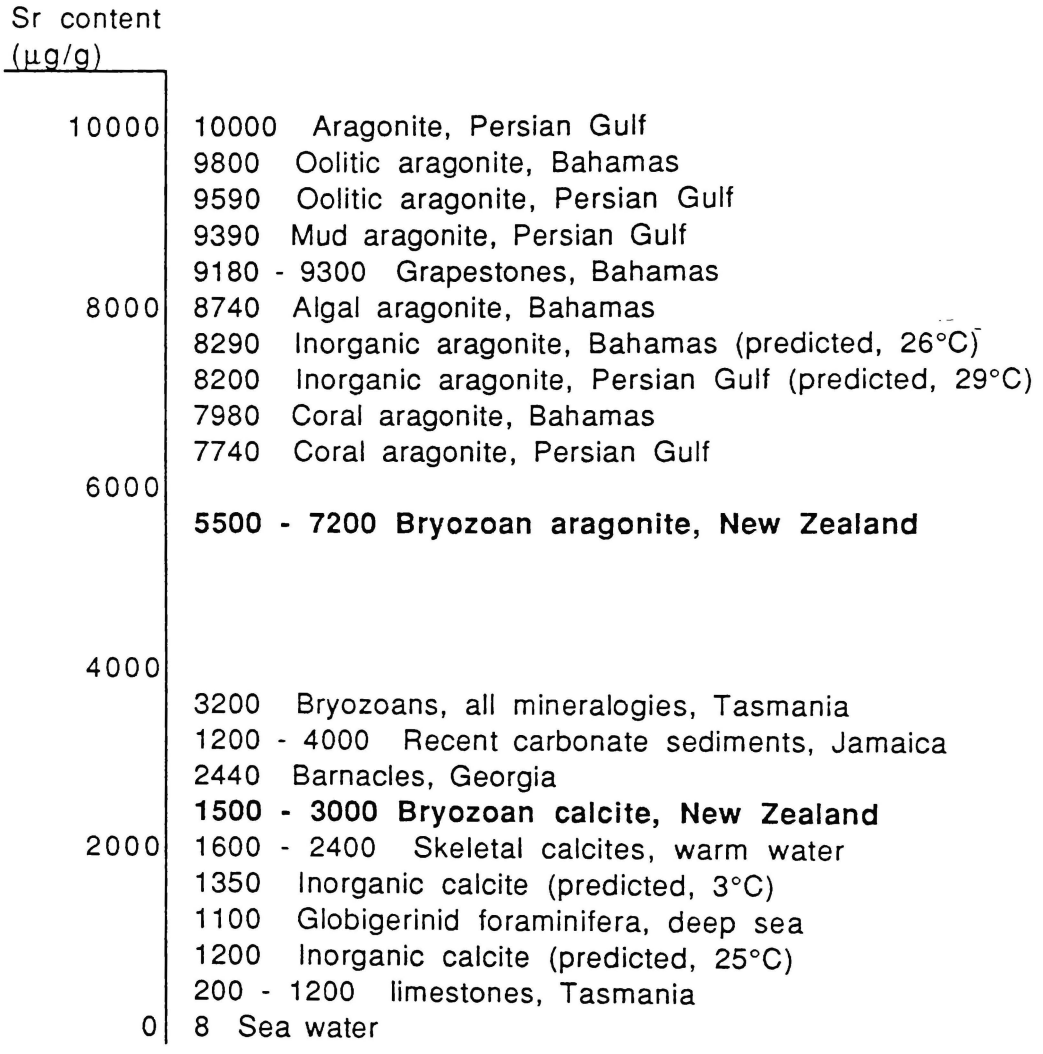


Figure 3D.8: Some published data on the geochemistry of Sr in carbonate components. This study shown in bold. (Compiled from Pilkey and Harris, 1966; Kinsman, 1969; Land and Hoops, 1973; Rao and Naqvi, 1977; Cronblad and Malmgren, 1981; and Rao, 1981b, 1986).

Rucker and Valentine (1961) found no correlation between Sr and temperature or salinity.

Manganese

Manganese may be found substituting for Ca in lattice sites, or adsorbed onto mineral surfaces (Gordon et al., 1970). In New Zealand bryozoans, both mechanisms may be operating, as Mn does not vary inversely with Ca (Figure 3D.9).

Mn content may reflect the geochemistry and mineralogy of the carbonate in which it is found. Thompson (1972) found a clear mineralogical difference between Mn in aragonite (very low, around 20 μg/g) and in calcite (may be up 30,000 μg/g). No other study has found such high levels of Mn (Figure 3D.10). In contrast, Rao and Adabi (1992) found increasing Mn with increasing aragonite content. Mn has also been found to correlate with Mg, Na, and Sr contents, possibly due to the mineralogical correlation. There is generally more Mn in dolomites than in limestones (Rao and Naqvi, 1977).

In New Zealand bryozoans, correlations of Mn with other co-precipitates are few (Figure 3D.11). Fe shows a slight positive trend, discussed below. Bryozoan calcites cover a wider range of Mn content than do aragonites (Figure 3D.12). The New Zealand bryozoans cover only the lower part of the range exhibited by Tasmanian carbonates.

Mn may reflect salinity, increasing in fresher water (Rucker and Valentine, 1961; Gordon et al., 1970). Renard (1984) states that Mn increases with depth, particularly at the continental shelf break. Mn in New Zealand bryozoans shows no major trend with depth (Figure 3D.13) although there is more scatter in shallower water depths.

An interesting observation made by Robinson (1980) is that Mn content does not change after mineralogical inversion (of aragonite to calcite) and is thus a useful indicator of original mineralogy. In later diagenesis, Mn increases with time (Brand and Morrison, 1985).

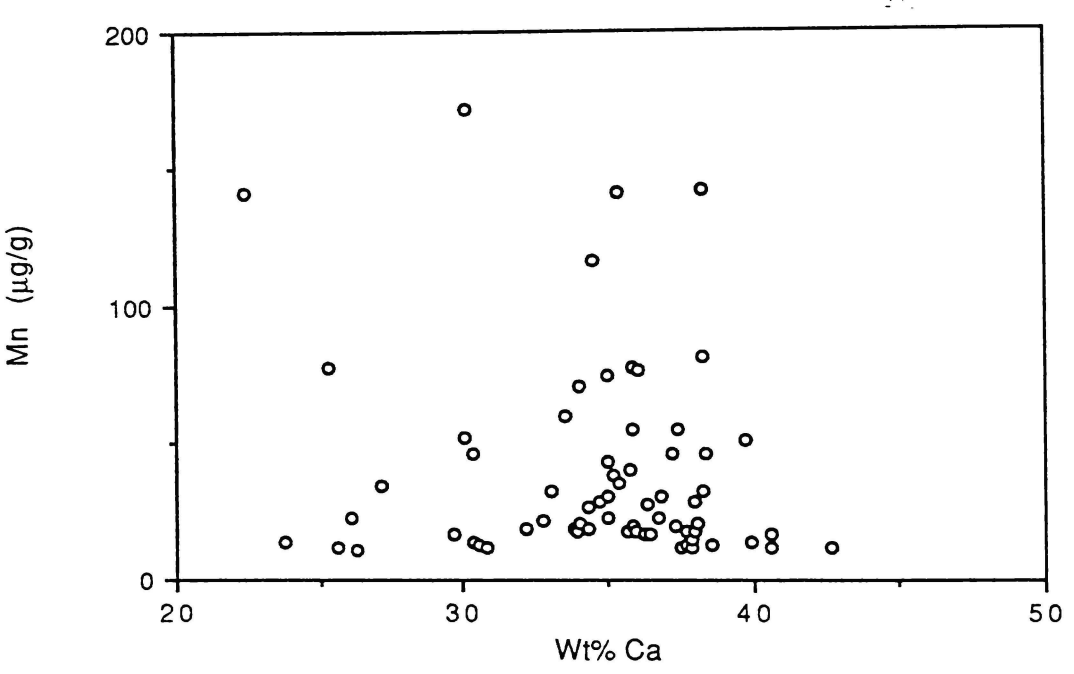


Figure 3D.9: Mn content in relation to Ca in New Zealand bryozoans.

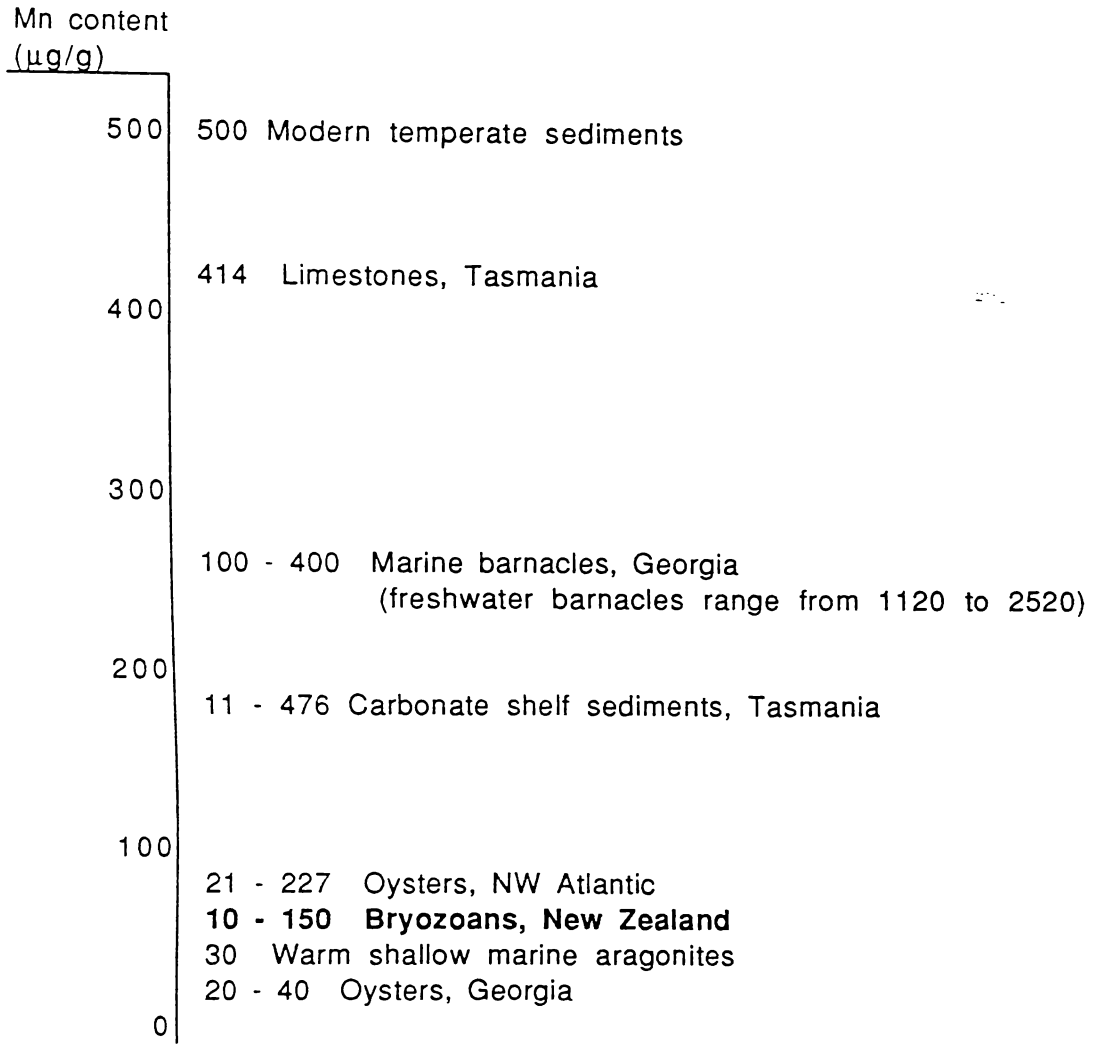


Figure 3D.10: Some published data on the geochemistry of Mn in carbonate components. This study in bold. (Compiled from Rucker and Valentine, 1961; Pilkey and Harris, 1966; Rao and Naqvi, 1977; and Rao, 1981, 1991).

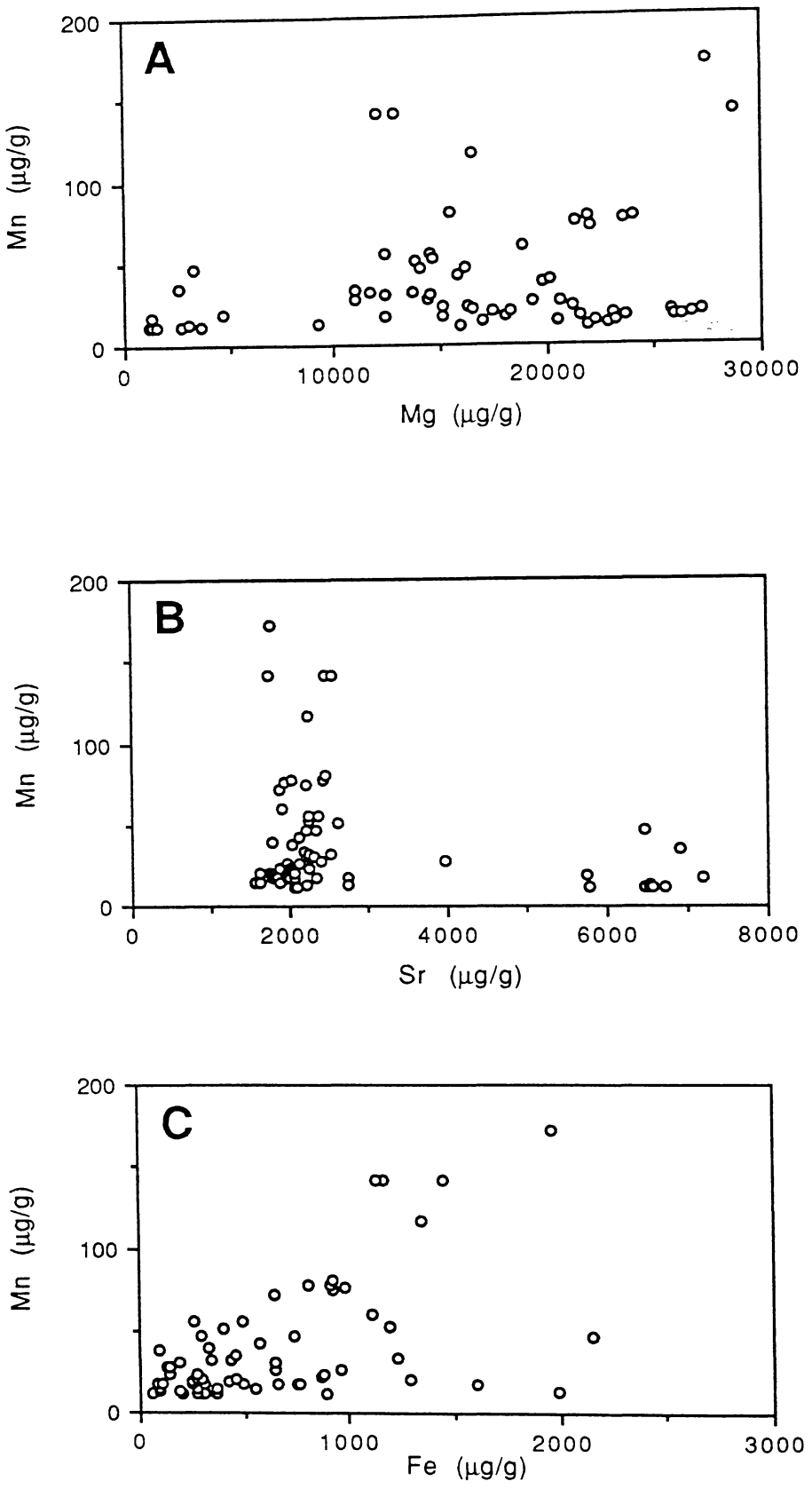


Figure 3D.11: Mn in relation to other co-precipitates Mg (A), Sr (B), and Fe (C) in carbonate in New Zealand bryozoans (excluding rogue data, see text).

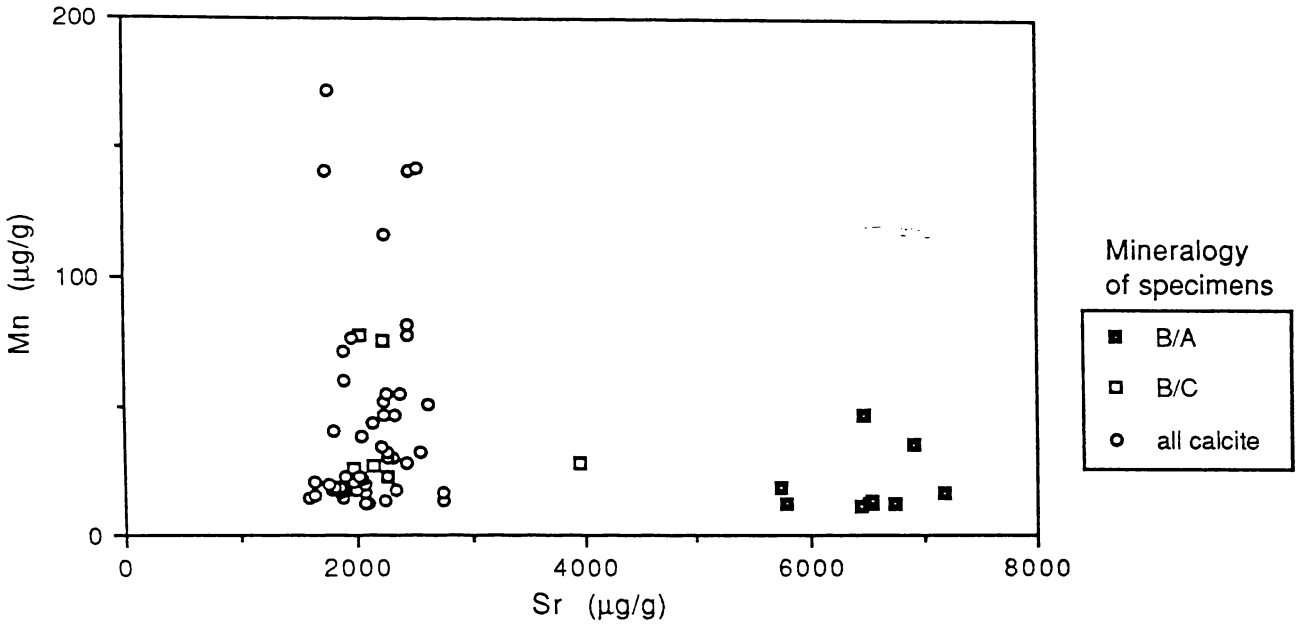


Figure 3D.12: Mn content in relation to Sr in New Zealand bryozoans.

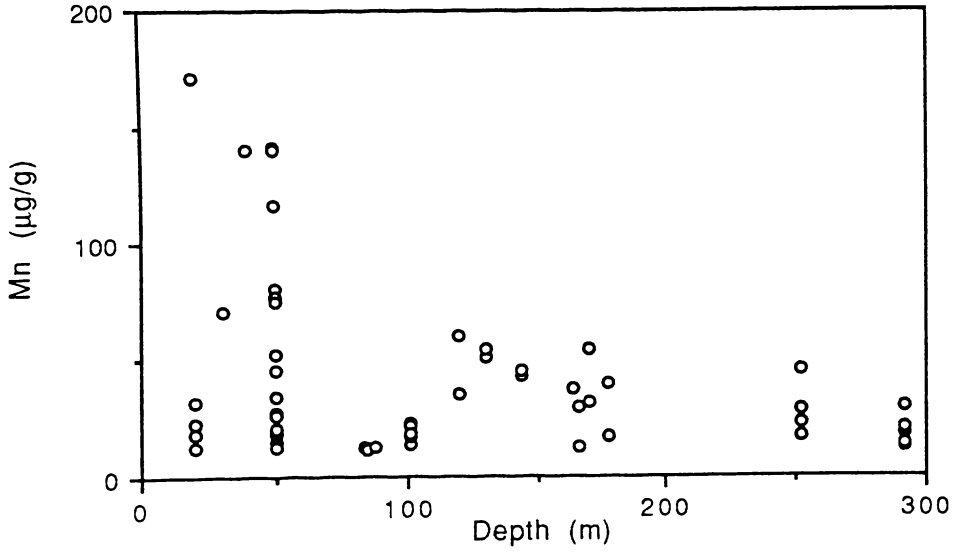


Figure 3D.13: Mn content in relation to water depth in New Zealand bryozoans.

Iron

The site of iron in skeletal carbonate is not known, but the correlation between Fe and Ca is small (Figure 3D.14), indicating it is not entirely substitution.

Iron content is about the same in calcite and aragonite, as far as it has been studied. Rao and Adabi (1992) found that Fe increases with aragonite content, but also that there is a positive correlation with high-Mg calcite. New Zealand bryozoans do not show this mineralogical difference (Figure 3D.15). Fe has been found to vary directly with Mn content, which is roughly the case in New Zealand bryozoans (Figure 3D.16).

Rather little work has been done on iron content of marine carbonates. Calcite skeletons from Georgia have been tested and found to be rather low (Pilkey and Harris, 1966). Tasmanian bryozoan sands are higher than a Tasmanian late Ordovician limestone (Rao and Basnayake, 1992). The New Zealand bryozoan skeletons vary from 50 to 2000 μg/g (with one outlier at 8500, explained below), a similar range to the Tasmanian bryozoans (Figure 3D.17).

One outlying sample from the Hauraki Gulf was extremely high in Fe: 8500 μg/g! The species, *Otionella squamosa*, is a free-living one, mainly aragonite. Another bryozoan from the same sample showed no similar discrepancy in Fe content, nor did any other *O. squamosa* samples, nor the other aragonite specimens. Whatever caused the increase in Fe seems to be unique to this specimen. One possibility is that free-living species sometimes retain the sand grain to which they originally were attached in the center of the colony. In many specimens, this nucleus falls out, particularly after death. This high-Fe specimen may have retained the grain, which could have been a high-Fe mineral (such as magnetite), that enriched the sample in Fe during acid dissolution.

Higher Fe contents have been shown to indicate the terrigenous content of surrounding sediments. Renard (1984) commented that an inverse trend between depth and Fe content indicated the reduction in available terrigenous material once off the shelf. In

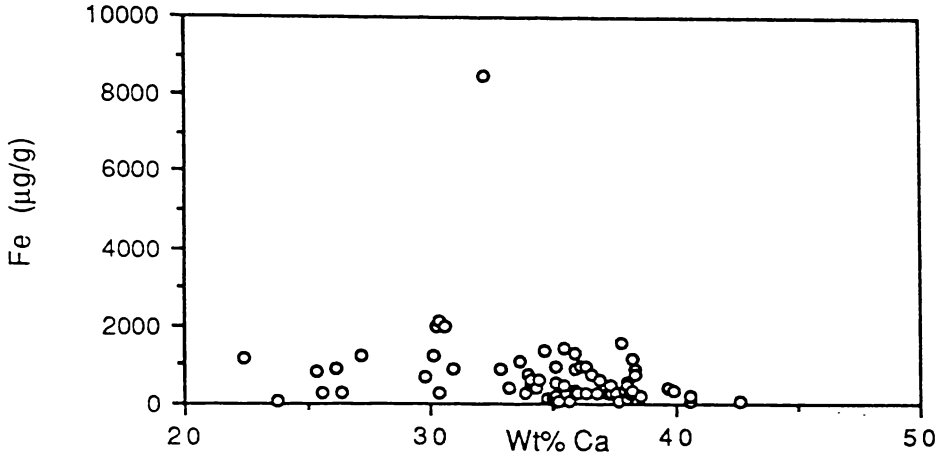


Figure 3D.14: Fe content in relation to Ca for New Zealand bryozoans.

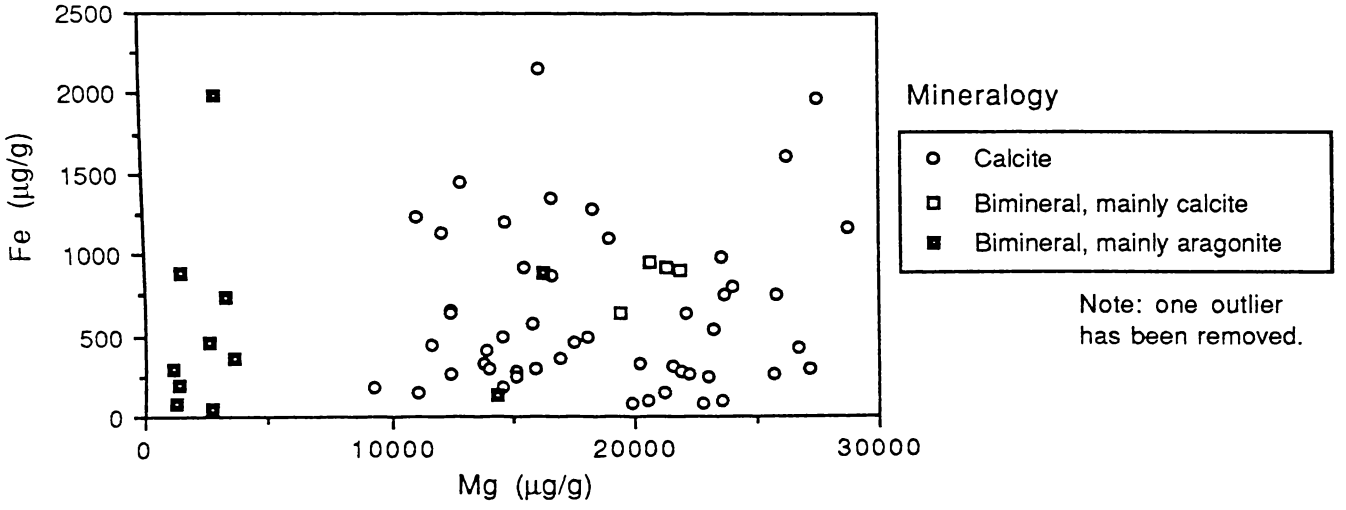


Figure 3D.15: Fe content of bryozoans with different mineralogies.

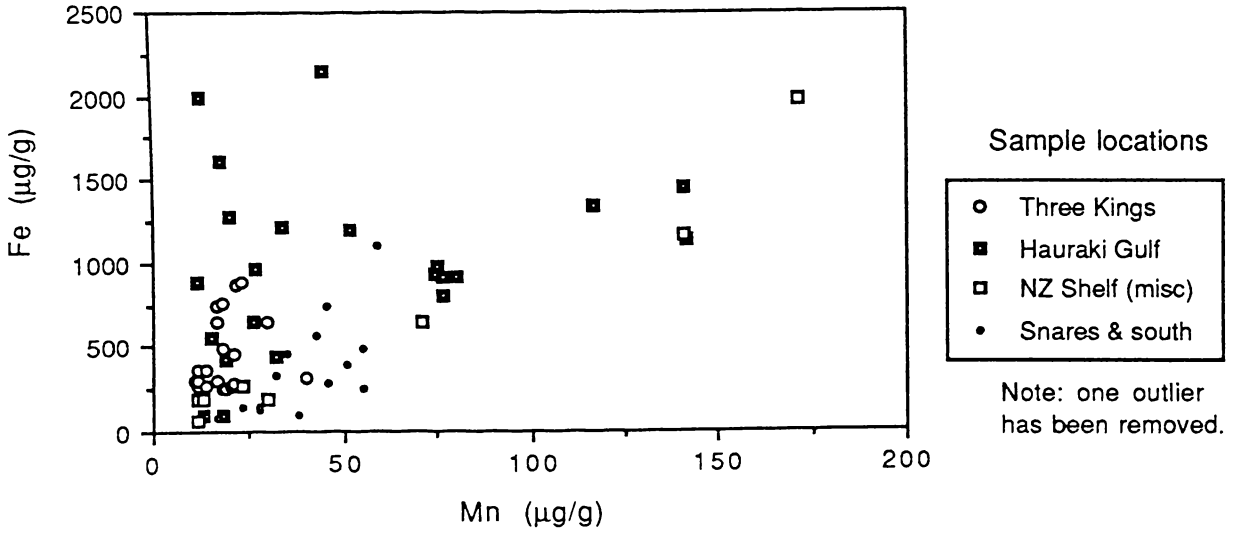


Figure 3D.16: Fe and Mn contents of bryozoans from different locations on the New Zealand shelf.

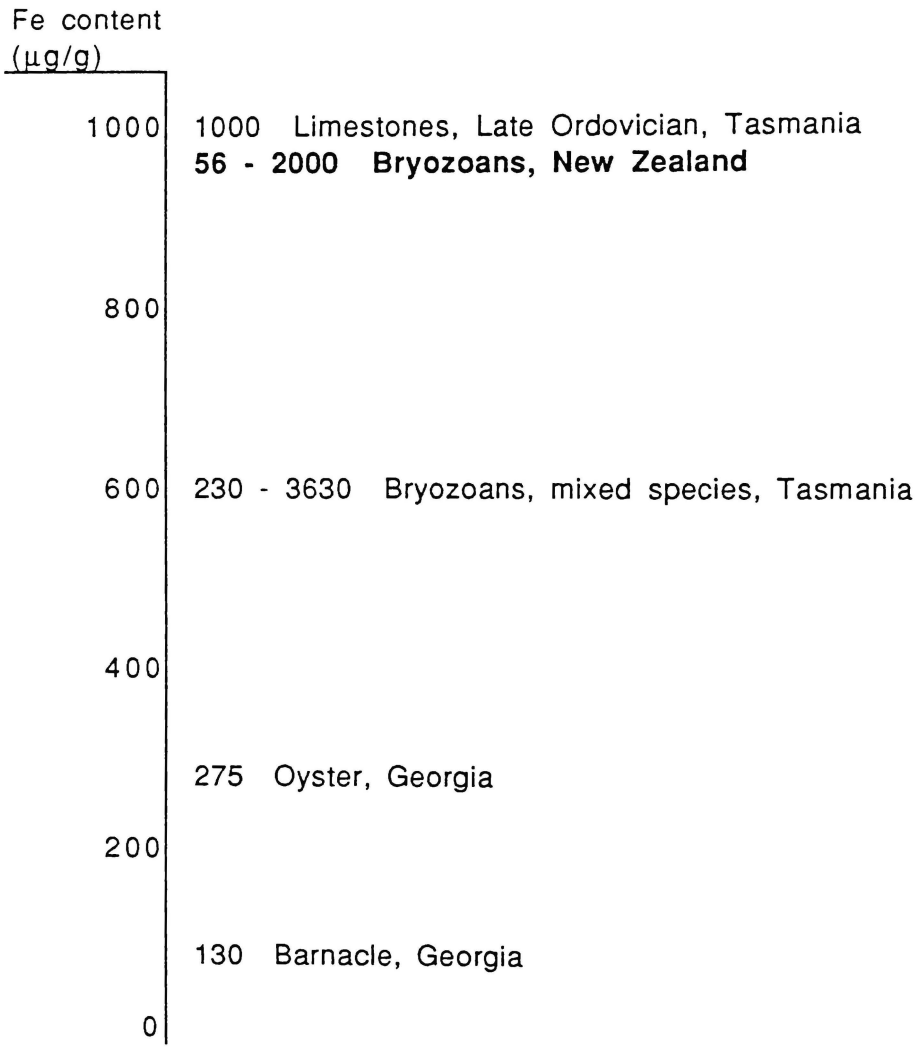


Figure 3D.17: Some published data on the geochemistry of Fe in carbonate components. This study in bold. (Compiled from Pilkey and Harris, 1966; Rao and Basnayake, in press).

the New Zealand shelf samples (Figure 3D.16), the high carbonate areas (Three Kings and Snares Platforms) show less Fe and Mn than their counterparts that are mixed with terrigenous material (Hauraki Gulf and other shelf samples).

2. Stable isotopes in bryozoan skeletons

Many marine organisms secrete a skeleton in which the CO_3 is close to isotopic equilibrium with the CO_2 of ambient sea water (Rao and Green, 1983). Bryozoans have been shown to precipitate carbonate near isotopic equilibrium with sea water (Forester et al., 1973; Rao and Green, 1983; Wefer, 1985). Oxygen ($\delta^{18}O$) and carbon ($\delta^{13}C$) isotopic ratios have been shown to relate to several factors, including carbonate mineralogy, temperature, salinity, productivity, water depth, and diagenesis. It is therefore possible to examine bryozoans for evidence of these associations.

In aragonite, vaterite, and high-Mg calcite, ^{18}O and ^{13}C are enriched relative to low-Mg calcite (Tarutani et al., 1969). New Zealand bryozoans clearly show this isotopic enrichment in aragonites, but not so much in high-Mg calcites (Figure 3D.18). A similar observation was made in Tasmanian bryozoans (Rao and Green, 1983).

$\delta^{18}O$ is an indicator of salinity and should have lower values in fresh water. In ancient limestones, light oxygen isotopes have been used to show the presence of glacial meltwater (Rao and Green, 1983). On the New Zealand shelf, where normal open marine salinities occur (34.3 to 35.7 mg/g), salinity is not likely to be a major influence on isotopic composition.

The most important geological application for oxygen isotopes has been in their relationship to temperature. The very important isotopic record of temperature in deep-sea cores, for example, is dependent on the assumption that organisms at the time precipitated carbonate in isotopic equilibrium with ambient sea water, and that they produced a faithful record of temperature. In fact, experimentation has shown that this is often more or less the case (e.g., Wefer, 1985). A simple binomial relationship

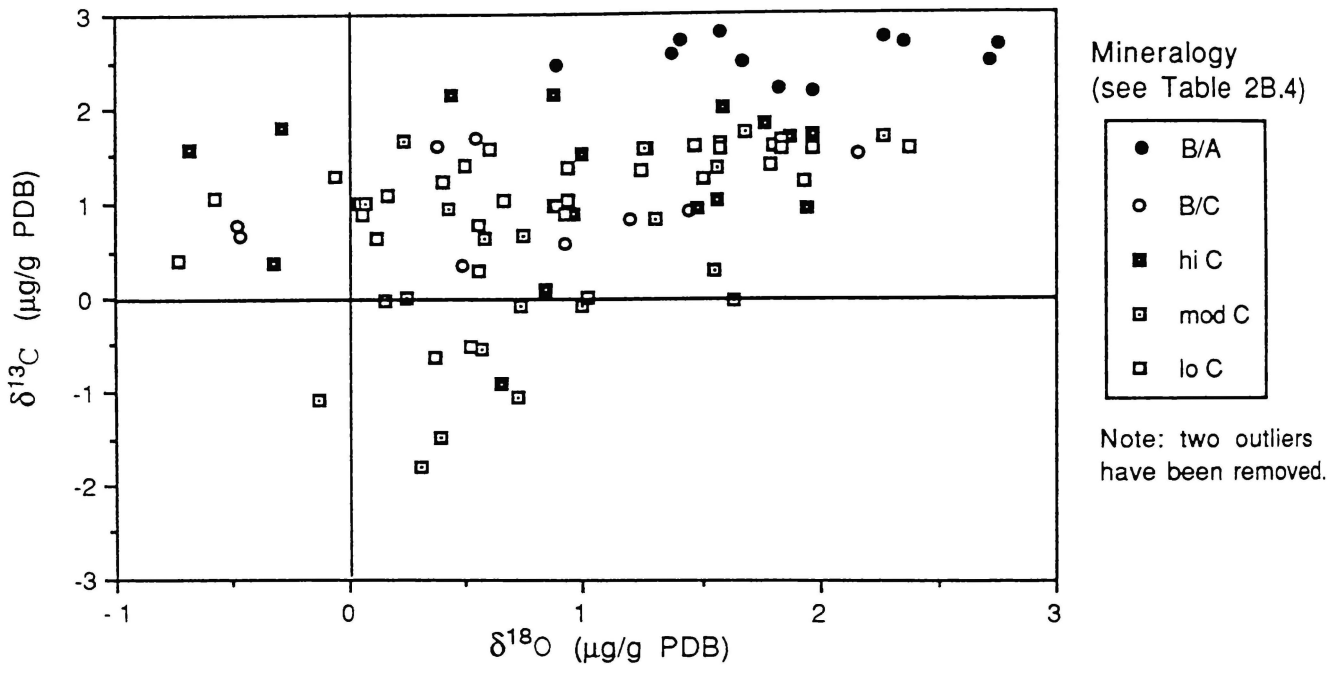


Figure 3D.18: Stable isotopes in New Zealand bryozoans of different mineralogies.

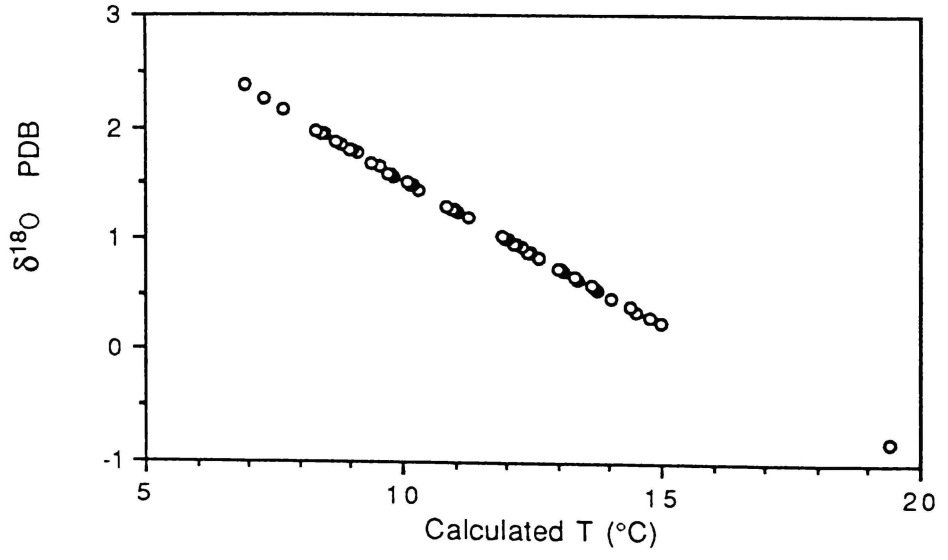


Figure 3D.19: Temperature of formation of New Zealand bryozoan calcite, using calculation of Morse and Mackenzie (1990) (see Appendix Table AI.3).

between $\delta^{18}O$ and temperature of formation is available (see Appendix Table AI.3), and appears to give consistent results in modern carbonates. When this relation (Morse and Mackenzie, 1990) is applied to New Zealand bryozoans, temperatures of 7 to 15°C are obtained (Figure 3D.19). New Zealand shelf bottom temperatures range typically from 9 to 15°C (Rao and Nelson, 1992).

In general, one expects depth to have an effect on isotopic composition. This effect is mainly due to changes of temperature as depth increases (Rao and Nelson, 1992). Superimposed on that is a water mass signature - deep waters often are depleted in ^{13}C, sometimes used as an indication of upwelling (Rao and Green, 1983). Within each geomorphologic province (shelf, slope, deep sea) $\delta^{18}O$ and $\delta^{13}C$ increase with depth (and decreasing temperature), but there are considerable differences between the provinces, particularly as ^{13}C is depleted with depth. The New Zealand bryozoans used in this study were no deeper than 300 m. Within the shelf setting, then, the trend in New Zealand bryozoans is for $\delta^{18}O$ and $\delta^{13}C$ values to increase with depth (Figure 3D.20), consistent with other observations from elsewhere (e.g., Rao and Nelson, 1992).

Diagenesis adds another dimension to isotopic composition. Exposure of marine carbonates to meteoric diagenesis (as in low stands of sea level) slightly lowers the $\delta^{18}O$ ratios, and markedly lowers the $\delta^{13}C$ (-5 to -15 mg/g PDB) due to enrichment of soil in ^{12}C. The New Zealand bryozoans analyzed fall well within the range of marine diagenesis, and therefore were not subaerially exposed. They thus postdate the last glacial lowstand (18 ky BP).

3. Environmental interpretation of bryozoan geochemistry

Given the many influences on geochemistry and isotopic composition in carbonate sediments, it is sometimes difficult to unravel the individual causes of variation. The New Zealand shelf bryozoans in this study are fairly recent (less than 10 ky old), and are all from shelf sediments. Although relict sediments are common on the New Zealand shelf, care was taken in choosing specimens to select the freshest possible.

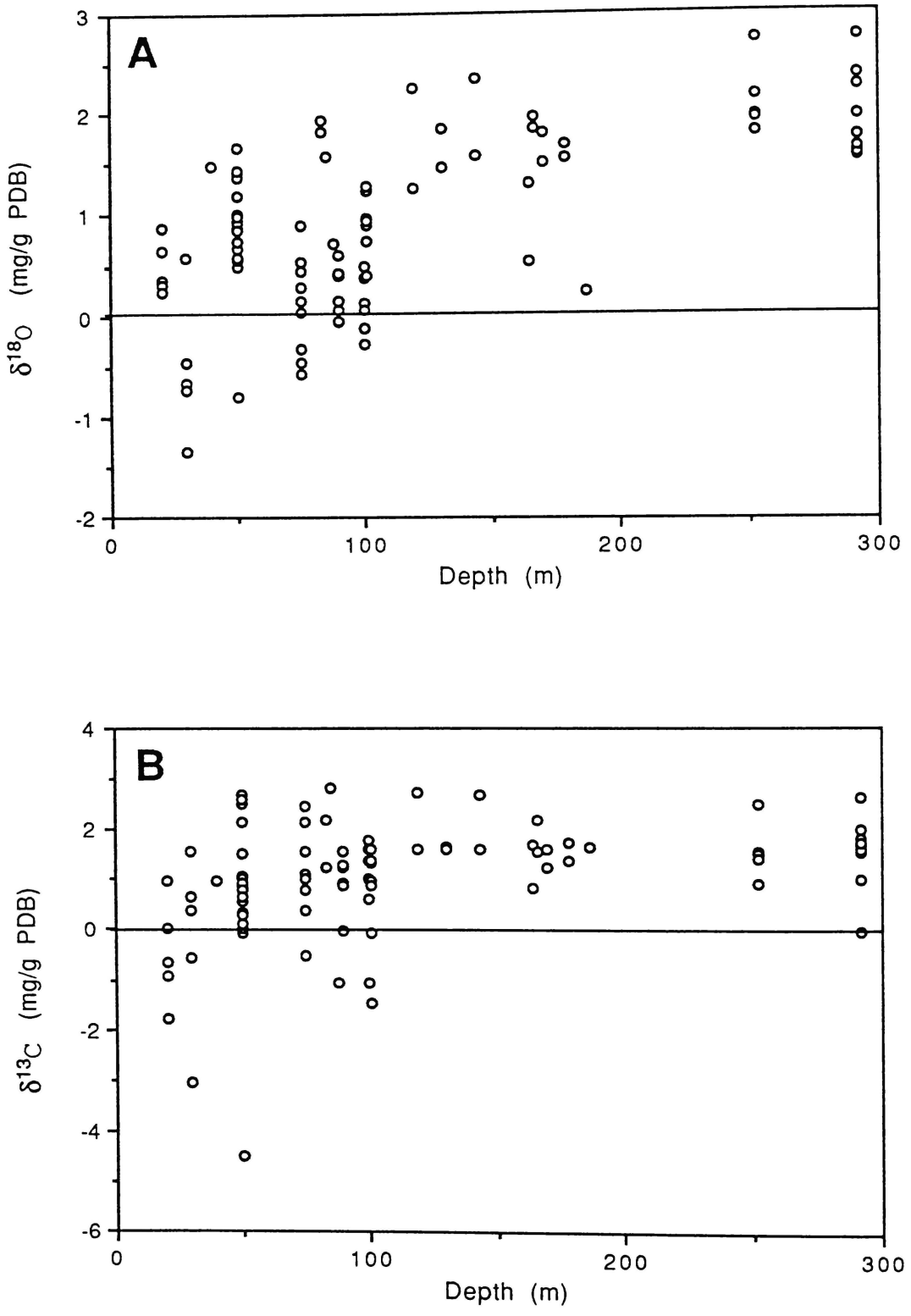


Figure 3D.20: Relationship of stable isotopes $\delta^{18}O$ (A) and $\delta^{13}C$ (B) to depth in New Zealand bryozoans.

This presumably excludes diagenetic effects. The effects of salinity are likewise unlikely to be significant, due to the small range (<1‰) of salinities on New Zealand shelves. Deep water influences may also be considered negligible, as the samples are all from shelf (<300 m) depths.

In order to exclude the effects of mineralogy and phylogenetic variation, examination of the same species over a range of latitudes and depths was undertaken. Four species had more than 5 samples tested and were compared with depth and latitude, including the calcitic *Cellaria immersa* and *Hornera* sp., and the aragonitic *Adeonellopsis* sp. and *Otionella* sp.

Latitudinal variations were not useful in interpreting geochemical variations, nor was a combination of depth and latitude that one might assume would approximate temperature. Depth, however, showed several strong correlations with geochemical measures (Figures 3D.21 to 3D.24). The $\delta^{18}O$ value had the highest correlation with depth in all four species. This correlation has also been found in the Yellow Sea (Jiashi and Shuhui, 1989). Sr was the next most common strong correlation, in calcite only. Fe was strong in some cases and not in others (Figure 3D.25, Appendix Table A3.5).

It seems clear that bryozoans reflect depth with several geochemical factors, most notably $\delta^{18}O$. What is perhaps more important is that even with much of the complexity of variation removed, few simple obvious trends emerge. In contrast, many geochemical studies in tropical environments have revealed useful consistent trends in skeletal carbonate (e.g., see Morse and Mackenzie, 1990). Temperate sediments, with more mineralogically diverse skeletons and with significant terrigenous dilution, are perhaps more complex than tropical carbonates. This complexity may increase the difficulty of relating geochemical and isotopic character of skeletal carbonate to environment.

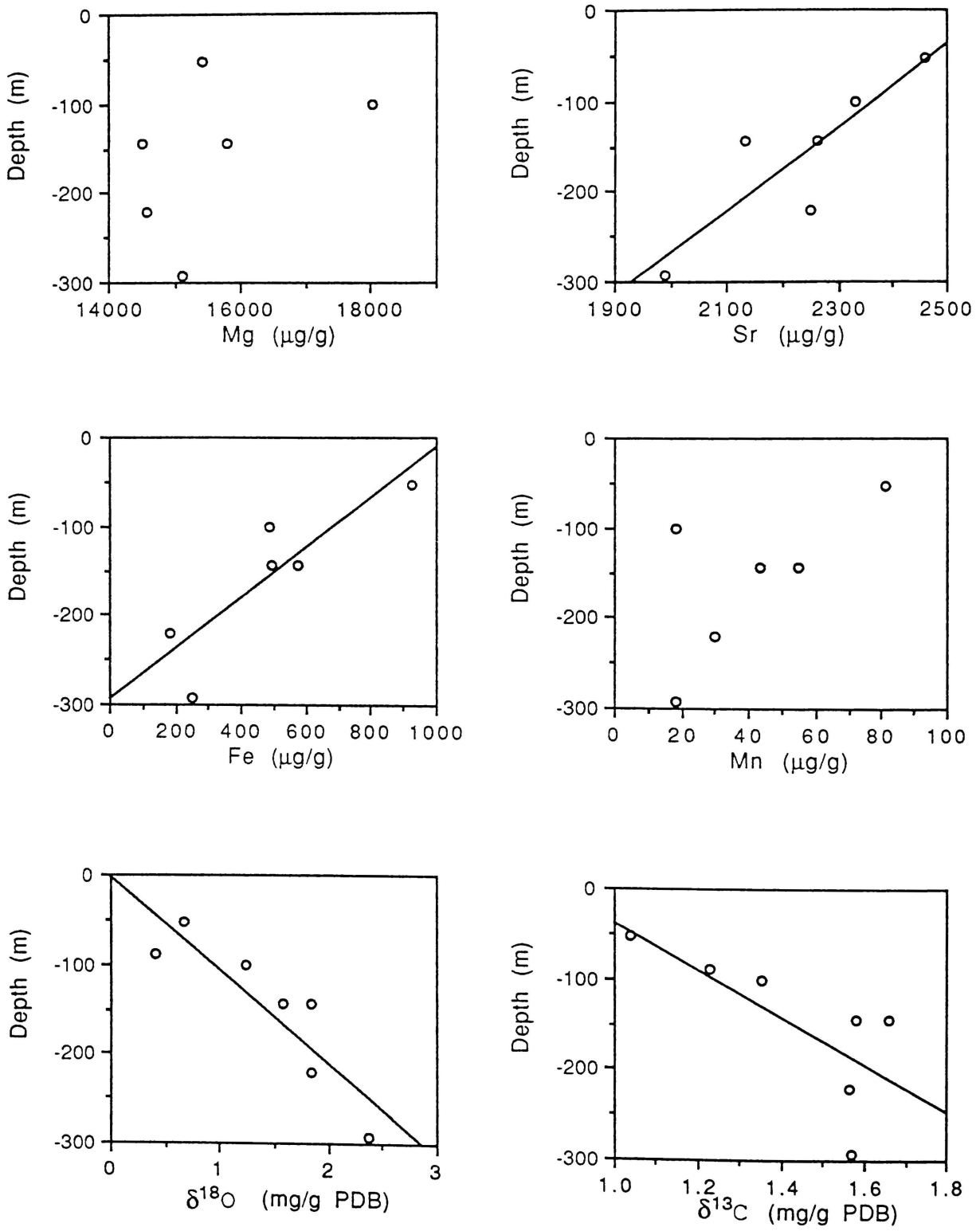


Figure 3D.21: Geochemistry of the moderate-Mg calcite bryozoan *Cellaria immersa* in relation to water depth on the New Zealand shelf. Linear regression line added if R^2 >0.5.

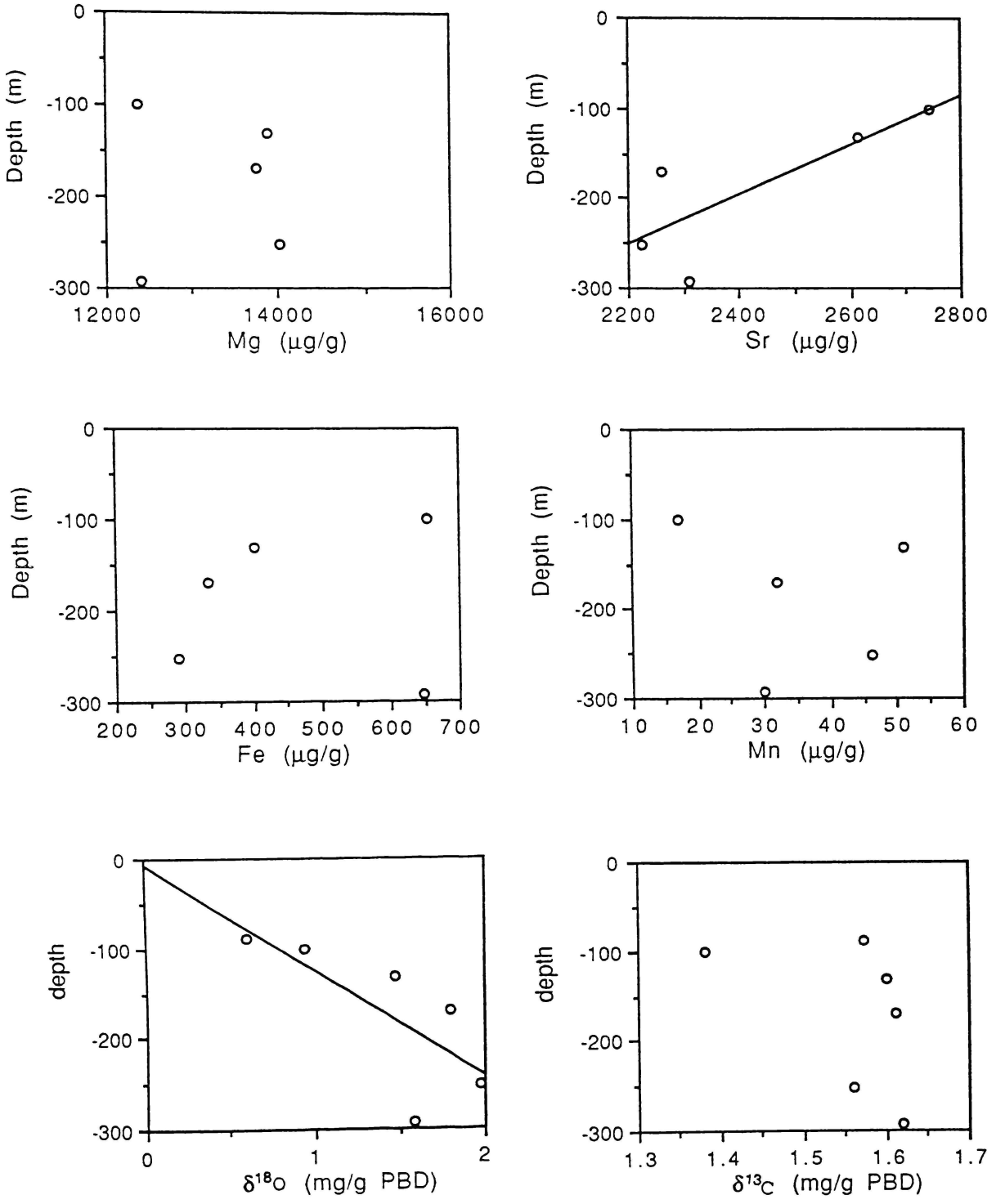


Figure 3D.22: Geochemistry of the low-Mg calcite bryozoan *Hornera* sp. in relation to water depth on the New Zealand shelf. Linear regression line added if R^2 >0.5.

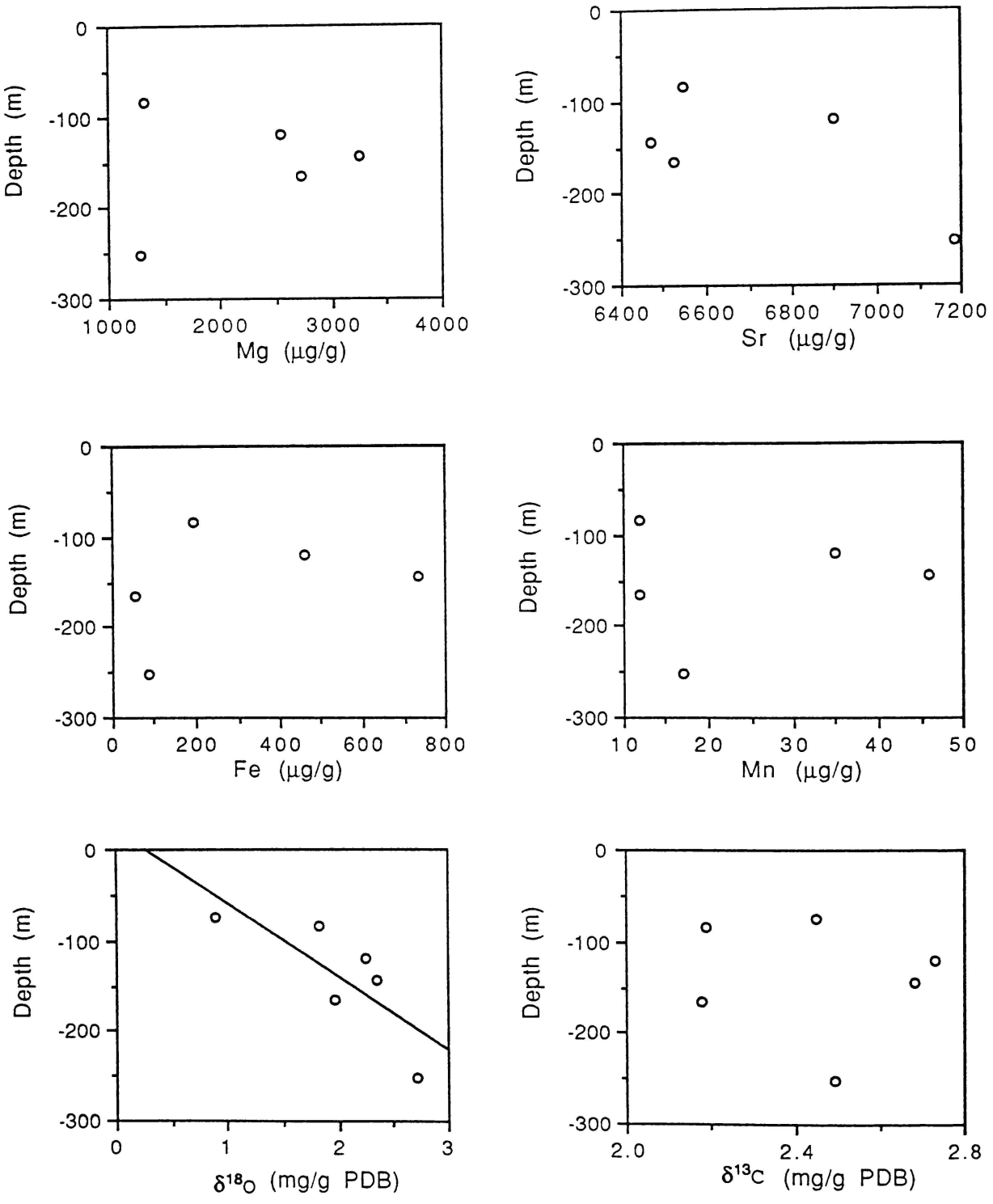


Figure 3D.23: Geochemistry of the mainly aragonite bryozoan *Adeonellopsis* sp. in relation to water depth on the New Zealand shelf. Linear regression line added if R^2 >0.5.

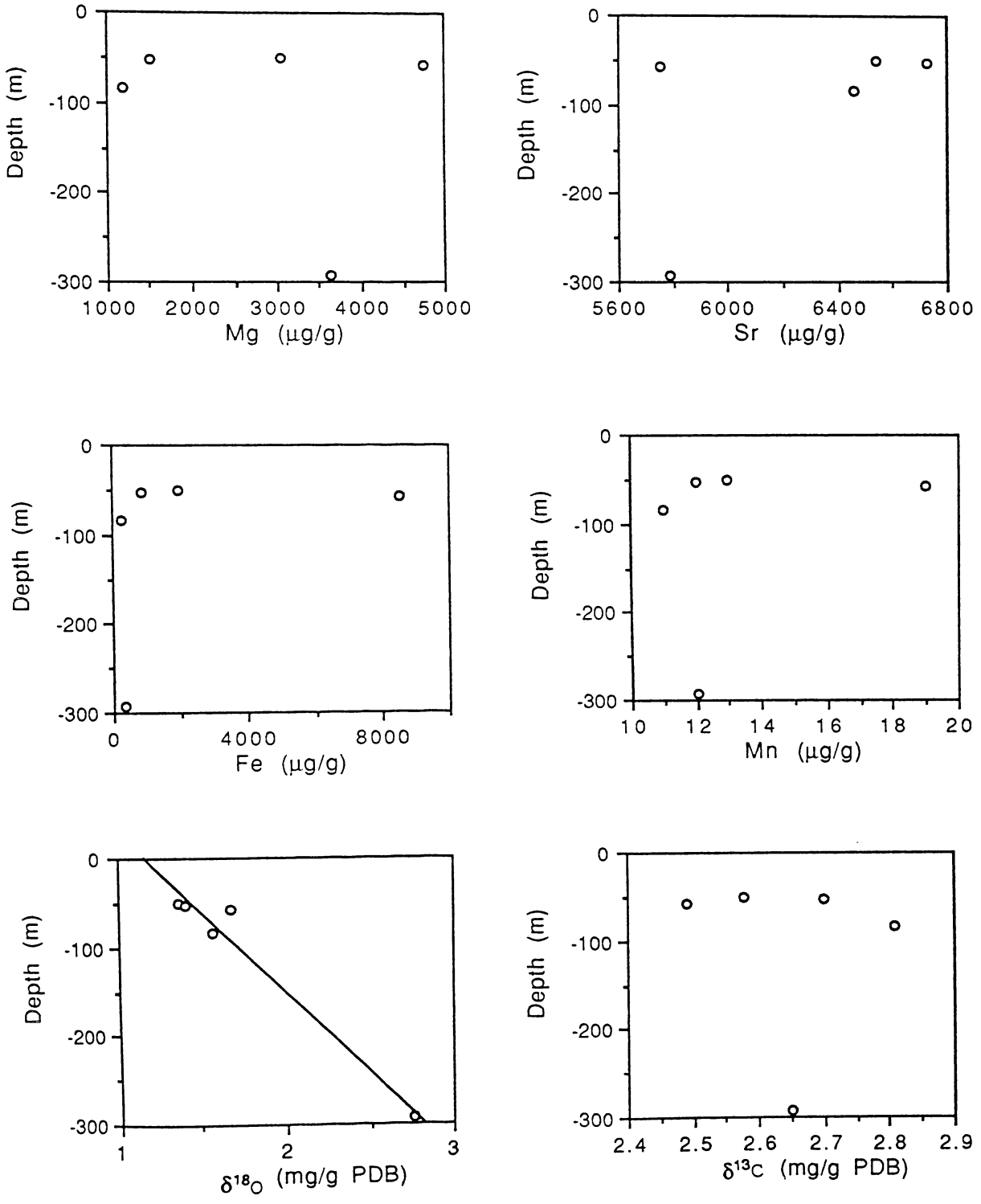


Figure 3D.24: Geochemistry of the aragonite bryozoan *Otionella* sp. in relation to water depth on the New Zealand shelf. Linear regression line added if R^2 >0.5.

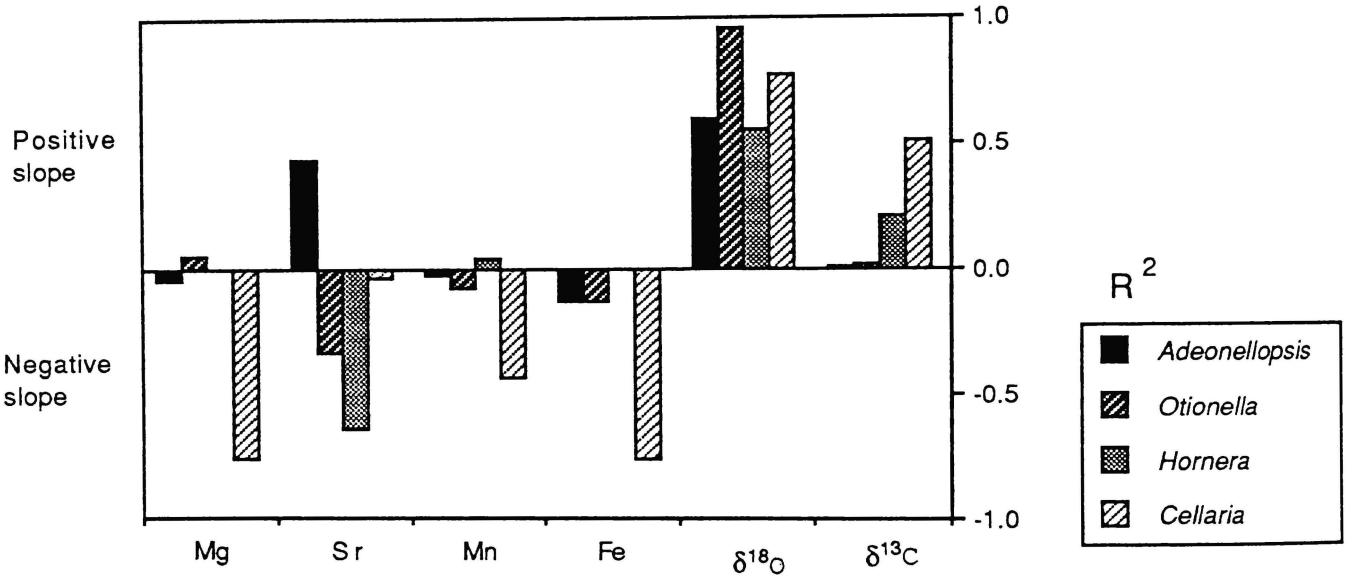


Figure 3D.25: Correlations of geochemical data with depth for four species of New Zealand bryozoans (see Appendix Table A3.5).

4. Geochemistry of New Zealand bryozoans compared to other carbonates

Most of the co-precipitate data obtained for New Zealand bryozoans are consistent with data previously published (Figure 3D.26). The New Zealand data fall within a narrower range, reflecting the smaller area sampled.

In general, warm marine carbonates have rather high $\delta^{13}C$ values (-2 to 5 mg/g PDB), and low $\delta^{18}O$, about -4.0 to 1 mg/g PDB (Figure 3D.27). ^{13}C enrichment is due, at least in part, to presumed algal metabolic activity (Nelson and Smith, 1991), and low oxygen values are due to the higher temperature. The few temperate carbonates studied (almost all Tasmanian) have shown quite a different relationship (Rao and Green, 1983; Rao and Nelson, 1992). $\delta^{13}C$ is lower (-0.2 to 2.0 mg/g PDB), and $\delta^{18}O$ is higher, with a wider range (-2.0 to 2.0 mg/g PDB). New Zealand bryozoans fall in the temperate carbonate field (Figure 3D.28), but with a wider range of $\delta^{13}C$ (-2.0 to 3.0) and higher $\delta^{18}O$ (0 to 3).

New Zealand bryozoans cover a wider isotopic range than New Zealand carbonate sediments, reflecting the averaging effect of bulk sampling. The positive diagenetic trend identified by Rao and Nelson (1992) in Tasmanian carbonates is less obvious in the New Zealand ones. Despite their regional differences both sets of temperate data clearly occupy a different range of values from their tropical counterparts.

E. CONCLUSIONS

New Zealand bryozoans show some interesting geochemical properties, relating to mineralogy, phylogeny, and environment.

Bryozoan aragonite contains twice as much Sr (about 6000 μg/g) as Mg (about 3000 μg/g), whereas bryozoan calcite has nearly 10 times more Mg (20,000 μg/g) than Sr (2000 μg/g). The Fe (50 - 2000 μg/g) and Mn (10 - 150 μg/g) contents are similar in most

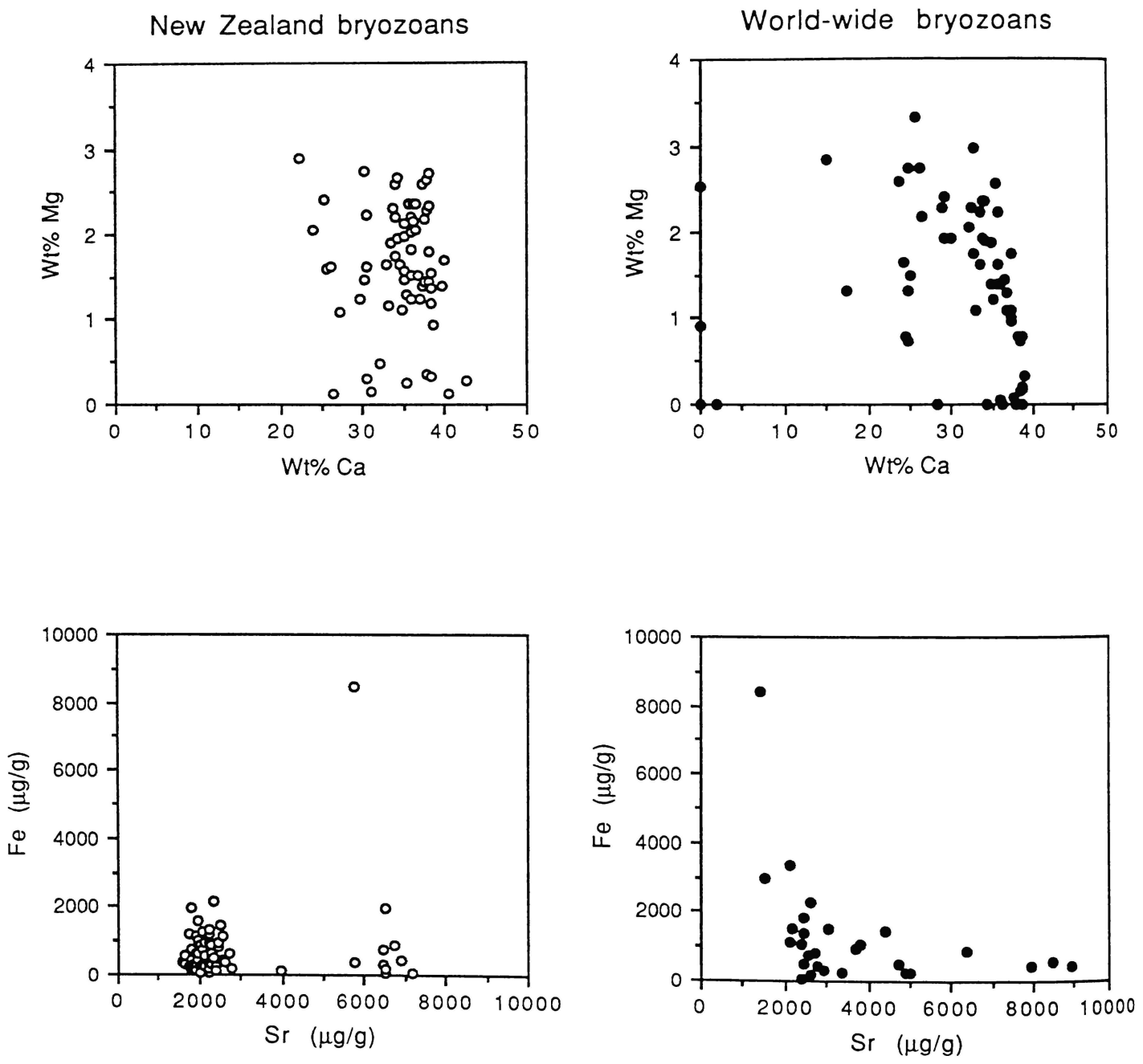


Figure 3D.26: Co-precipitates in New Zealand bryozoans (open circles) and world wide (closed circles).

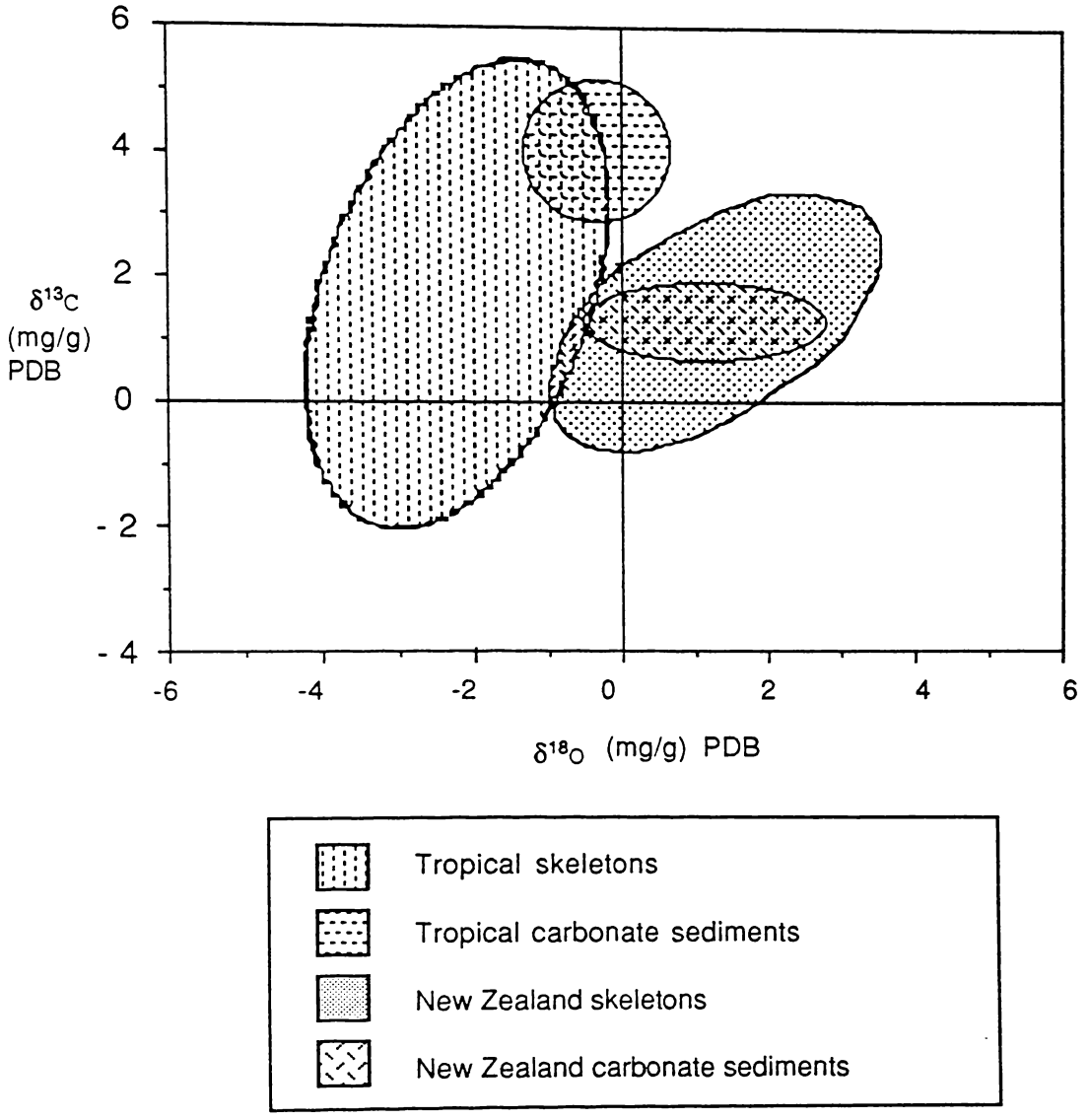


Figure 3D.27: Comparison of New Zealand carbonate stable isotopes with those typical of tropical carbonates (after Rao and Nelson, 1992).

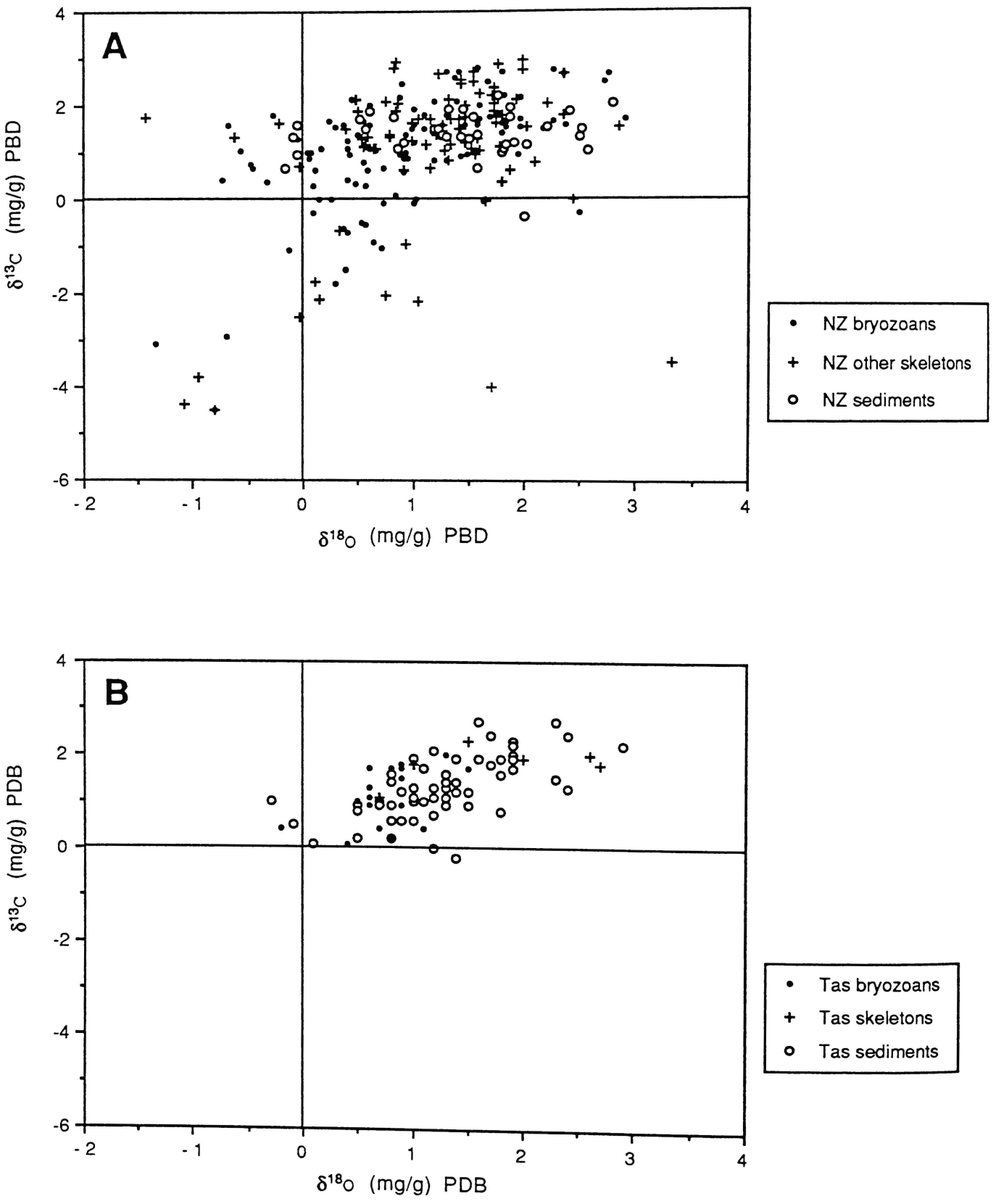


Figure 3D.28: Comparison of isotope data for (A) New Zealand and (B) Tasmanian sediments, bryozoans, and other skeletons (data from this study and Rao and Nelson, 1992).

specimens. Carbon isotope values ($\delta^{13}C$) are generally higher for aragonite (about 3 mg/g PDB) than for calcite (-1 to 2 mg/g PDB), as is $\delta^{18}O$ (1-3 mg/g PDB in aragonite, -1 to 2 mg/g PDB in calcite).

Among the taxa of New Zealand bryozoans, Mg increases in calcite with increasing advancement. Ascophoran cheilostomes (2.4 wt% Mg on average) have higher Mg contents than do anascan cheilostomes (1.6 wt% Mg), which are higher again than cyclostomes (1.4 wt% Mg). This contradicts findings in other marine skeletons (Chave, 1954).

The correlation of $\delta^{18}O$ with sample water depth is quite good ($R^2 > 0.5$) among bryozoan species, probably reflecting temperature change with depth. The predicted temperatures (7-15 °C) from $\delta^{18}O$ values contents agree with actual New Zealand shelf bottom temperatures (9-15°C). Relatively high Fe and Mn contents of skeletons probably reflect the mixed terrigenous nature of many of New Zealand's shelf carbonate sediments. It is perhaps this mixed terrigenous-carbonate composition that makes temperate carbonate geochemistry rather complex, with few simple correlations.

In general, New Zealand bryozoans show similar geochemistry to their counterparts world wide. The $\delta^{18}O$ and $\delta^{13}C$ composition of New Zealand carbonates falls in a similar field to Tasmanian ones, with slightly more scatter. There is clearly a distinctive temperate isotope signature with enrichment in $\delta^{18}O$ relative to tropical carbonates, which reflects the considerable differences in the two environments of deposition.

Chapter 4 Early Sea-floor Diagenesis of Bryozoans

"The world's a scene of changes and to be
Constant, in Nature were inconstancy."

-- *A. Cowley, Inconstancy, 1647*

A. INTRODUCTION

Diagenesis in carbonate sediments has been variously defined; one definition reads: "All the chemical, physical, and biologic changes, modifications, or transformations undergone by a sediment after its initial deposition (i.e. after it has reached its final resting place in the current cycle of erosion, transportation, and deposition), and during and after its lithification, exclusive of surficial alteration (weathering) and metamorphism" (Gary et al., 1972, p. 192). In the case of marine skeletal sediments this poses some difficulty, as sediments undergo many changes (biological, chemical, and physical) before they reach any "final resting place." Indeed, dissolution of bivalve shells may occur in some environments even before the death of an organism (Lewy, 1981). Similarly, abrasion of shells (both weakening and reduction in size) may occur while they are in transit. Reworking of sediments poses a problem with defining how "final" a resting place may be. Morse and Mackenzie (1990) and Tucker and Bathurst (1990) have referred to "early marine diagenesis," which includes changes to sediment at the sediment-sea water interface. Early sea-floor diagenesis is here defined to mean changes that occur to sea-floor sediments after their formation, during transport, and while at rest at the sediment/sea water interface. It may become non-marine (on exposure of sediments) or give way to burial diagenesis with time and accumulation. Skeletal carbonate becomes most susceptible to change when the organic coating of the skeleton decays after death (e.g., Beu et al., 1972).

Diagenesis has been characterized as covering a spectrum of processes from strongly constructive to strongly destructive (Alexandersson, 1979). Generally, early diagenesis in temperate waters tends to be destructive, lacking the chemically precipitated grains and cements that are common in tropical waters (Nelson, 1988b).

Destruction of carbonate sediments can be due to physical processes (abrasion), chemical processes (dissolution), and biological processes (bioerosion). All three types of processes affect bryozoan sediments, and will be discussed below. In addition, bioerosion of skeletal materials from the Hauraki Gulf will be discussed in Chapter 8.

None of these processes exists in isolation. In reality they interact and combine to affect carbonate substrata. For example, a heavily bioeroded grain will have a higher surface area than an uninfested grain and will be more susceptible to dissolution. Or an encrusted grain may be better able to withstand abrasion than a non-encrusted one. Nevertheless, it is useful to simplify the situation by isolating each mechanism and discussing it in detail.

B. THE EFFECT OF ABRASION ON BRYOZOAN SEDIMENTS

1. Introduction

In the process of transport, sediments are subject to physical damage caused by repeated impacts, that is, abrasion. Abrasion may result in polishing, fracturing, scratching, crushing, rounding, loss of external lamina, loss of surface ornamentation, dulling of sharp edges, and disarticulation. There are at least three main reasons why abrasion is of interest to the sedimentologist: transport interpretation, fossilization potential, and carbonate mud production.

The effects of abrasion on sediment grains have been used to estimate the extent of the transport they have undergone. "The physical condition of the carbonate fraction may be the only sedimentary-particle characteristic offering clues to the immediate past history of contintental-shelf sedimentary processes" (Pilkey et al., 1979, p. 284). Skeletal carbonate grains are particularly useful in this regard for two reasons. First, many calcifying organisms have been well-studied in life and therefore the details of skeletal structure before any abrasion takes place are known. This allows assessment of the degree of transport undergone by abraded grains. Second, terrigenous grains may show signs of previous transport conditions which are no longer operating.

Carbonate grains are generally less long-lived and may therefore reflect more recent conditions more accurately.

It seems intuitively obvious that different shapes and sizes and structures of grains will affect their susceptibility to abrasion, although Kuenen (1964) found fairly little influence of size and shape on abrasion (reduction of size) of chert, limestone, and quartzite pebbles. Surface area (Driscoll, 1967) and microstructure (Chave, 1964) are physical characteristics that do appear to affect the rate of abrasion. Other studies have found that degree of decay (Allison, 1986) and consequently temperature (Kidwell and Baumiller, 1990) are important, as well as degree of previous shell damage from other sources, such as bioerosion (Young and Nelson, 1988). Loss through abrasion will strongly affect fossilization potential of a grain. Studies testing the resistance of different types of skeletal grains to physical destruction are summarized in Table 4B.1. The differential resistance of some grains to abrasion leads to differential survival into the fossil record. Abrasion may thus be regarded as a taphonomic process, causing the fossil assemblage to reflect the living assemblage less accurately.

Abrasion may also be an important source of carbonate mud. Carbonate muds are produced by rather different mechanisms in tropical and temperate shelf waters. Carbonate muds in tropical waters are clearly understood to be the product of inorganic precipitation and/or the disintegration of such aragonitic codiacean green algae as *Penicillus* and *Halimeda* spp. (Neumann and Land, 1975). In temperate waters, carbonate muds have been widely described from many localities, including the North Atlantic (Molnia and Pilkey, 1972; Farrow and Fyfe, 1988), off southeast Australia (Blom and Alsop, 1988), and the Black Sea (Trimonis, 1974). At least on shallow temperate shelves, carbonate mud is often low-Mg calcite, not aragonite (Farrow and Fyfe, 1988); it must therefore be of quite different origin from tropical muds. Calcified green algae do not occur in temperate waters, and inorganic precipitation is rare or absent in surficial deposits (Nelson, 1988). Several sources for

Table 4B.1: Results of some published studies on resistance of skeletal material to abrasion.

Material used	Method of study	Results and conclusions	Source
molluscs, algae, bryozoans, corals, echinoids	slow tumbling with chert pebbles, sand, and alone	compact snails most durable algae and bryozoans least durable encrusting has no effect on durability mineralogy has no effect on durability size is important but not wholly controlling microarchitecture and microstructure are important, denser shells more durable	Chave (1964)
bivalves	in situ on two beaches - sand and gravelly sand and subtidal attached and periodically measured	shells with high surface area lose larger percent of shell larger shells lose more in absolute terms more than 5 times more abrasion in gravelly sand than in sand 2 h tumbling approx. 100 h in situ initial rapid weight loss due to loss of surface ornamentation	Driscoll (1967)
live and dead corals	tumbled in sealed and unsealed drums 16 m/min	dead coral made more sediment than live mud production 12-27% septa most abraded	Hoskin et al. (1983)
lightly calcified articulated crustacea	allowed to decay various times tumbled with perspex bars and carborundum dust 11 km in fast current	disarticulation occurs more readily in decayed specimens fresh specimens are fairly resistant state of preservation not a good indicator of distance of transport	Allison (1986)
fossil reptile teeth	tumbled with quartz sand 360 to 480 km transport	some breakage and polishing but very little abrasion reptile teeth are very durable transport does not cause extensive abrasion	Argast et al. (1987)
large aragonitic bivalves fresh and "old"	tumbled 28 or 104 km transport	more mud produced by bioeroded valves more mud produced in early stages as first layer is worn off polishing, size reduction, mud production observed	Young and Nelson (1988)
echinoids	allowed to decay various times tumbled up to 150 h in barrel with internal shelf	tumbling allows for more disintegration than decay alone decayed disintegrate faster than fresh threshold effect of decay, disintegration is more rapid after ligament fibers decay higher temperature affects decay rate degree of aeration of water not as relevant preservation state not a good indicator of transport, also reflects temperature, decay	Kidwell and Baumiller (1990)

temperate carbonate mud have been suggested: bioerosion, settling of zooplankton, and shell abrasion.

Understanding the extent and patterns of abrasion that a particular skeletal sediment component undergoes is of importance in interpreting transport history, in predicting fossilization potential, and in understanding the sources of carbonate mud.

This study aims to determine relative rates of breakdown of different colonial growth forms of New Zealand bryozoans, to examine the effect of apparent state of preservation on durability, and to assess the production of carbonate mud by bryozoans undergoing abrasion.

2. Methods

Bryozoans were picked from sediment samples collected from the New Zealand shelf. The samples were primarily from bryozoan-rich areas such as Snares and Three Kings Platforms (see Figure IC.1). The bryozoans were separated into eight colonial growth forms (described in Introduction and summarized in Figure IB.3). There were insufficient massive forms to make up a sample, and the foliose and unilaminar encrusting forms were combined as they are very similar in shape. Each of the eight growth-form groups was then manually split into two samples, one relatively fresh-looking (called "New") and one relatively degraded-looking ("Old"). These were mainly divided on the basis of colour, polishing, and surface wear. There were thus 16 separate samples. Most of these weighed between 10 and 30 g and were between 20 and 60 cm^3 in volume. The radiate samples were smaller due to the very small size of individuals of this growth form. Each category was assigned a short name, incorporating its growth form and its state of preservation (Table 4B.2).

The samples were not cleaned in any way. It was felt that probing and cleaning would weaken samples and artificially increase abrasion. Although some grains were encrusted and some were broken, many were quite fresh-looking. Most were without obvious interstitial terrigenous material.

Table 4B.2: Descriptions of 16 samples used in abrasion experiment (see Figure IB.2 for growth form definitions).

Sample	State of preservation	Growth form	Initial dry weight (g)	New Zealand genera included
ERde-N	fresh	ERde	13.58	*Mecynoecia, Galeopsis, Platonea*
EF-N	fresh	EFar, EFrt	7.26	*Steginoporella, Cellaria, Melicerita*
ERfe-N	fresh	ERfe	14.35	*Hippellozoon, Iodictyum*
FL-N	fresh	FLmo, FLrt	27.54	*Otionella, Conescharellina*
ENml-N	fresh	ENml,ERma	24.56	*Celleporaria, Celleporina*
ERra-N	fresh	ERra	3.42	*Telopora, Lichenopora, Disporella*
ERro-N	fresh	ERro	16.50	*Cinctipora, Hornera, Adeonellopsis*
ENul-N	fresh	ENul,ERfo	15.71	*Arachnopusia, Steginoporella, Foveolaria*
ERde-O	degraded	ERde	29.66	*Mecynoecia, Galeopsis, Platonea*
EF-O	degraded	EFar, EFrt	32.38	*Steginoporella, Cellaria, Melicerita*
ERfe-O	degraded	ERfe	32.59	*Hippellozoon, Iodictyum*
FL-O	degraded	FLmo, FLrt	60.48	*Otionella, Conescharellina*
ENml-O	degraded	ENml,ERma	35.41	*Celleporaria, Celleporina*
ERra-O	degraded	ERra	8.90	*Telopora, Lichenopora, Disporella*
ERro-O	degraded	ERro	30.96	*Cinctipora, Hornera, Adeonellopsis*
ENul-O	degraded	ENul,ERfo	25.05	*Arachnopusia, Steginoporella, Foveolaria*

Each sample was gently wet-sieved into three size fractions, then dried and weighed. Each sample had no grains smaller than 1 mm at the beginning. The size fractions were: coarse gravel (cg: >4mm, using a -2ϕ sieve), fine gravel (fg: 2-4mm, using a -1ϕ sieve), and very coarse sand (vcs: 1-2mm, using a 0ϕ sieve). These were recombined for tumbling.

Samples were loaded into a Lortone large capacity lapidary tumbler, supporting a molded rubber barrel with a ten-sided interior surface. The barrel was 19.5 cm in diameter, and rotated at 25 rpm. 1200 ml of tap water (pH = 8) was added to make the barrel just over half full. Samples were tumbled for 127 h. Samples were measured at 1, 3, 7, 15, 31, 63, and 127 h from the beginning. No terrigenous sands or pebbles were added due to the very rapid breakdown reported by Chave (1964) in which bryozoans were destroyed in less than one hour!

At each sampling time the entire sample was removed, rinsed free of mud, and gently wet-sieved into seven size fractions. These were cg, fg and vcs as defined above, and coarse sand (cs: 0.5-1mm, using a 1ϕ sieve), medium sand (ms: 0.25-0.5mm, using a 2ϕ sieve), fine sand (fs: 0.125-0.25mm, using a 3ϕ sieve), and very fine sand (vfs: 0.63-0.125mm, using a 4ϕ sieve). Each of the resulting size fractions was dried and weighed. The fraction less than 4ϕ was determined by subtracting the total weight at the interval from the initial weight. All these data are reported in Appendix Table A4.1.

In the final intervals (after 63 and 127 h tumbling), if sufficient mud was available it was collected, dried, and weighed. A small quantity of each sample was analyzed for carbonate content by acidification with HCl and titration with NaOH using a Mettler DL40 RC Autotitrator (programmed as described in Neil, 1991; results listed in Appendix Table A4.2).

The production of mud was approximated by the material lost at each weighing time. To check the accuracy of this approximation, the mud collected in the final intervals

was compared to the % mud calculated by subtraction (Figure 4B.1). There is a good correlation, although the mud calculated is generally slightly greater than that collected, possibly due to some sieving error.

Some of the muds were dried, ground to 200 μm, and analyzed for mineralogy using x-ray diffractometry (see Figure 2B.3 for methods). The mineralogy of the muds was compared to the mineralogies of the dominant species in each sample.

3. Results

A textural stacked histogram was produced for each sample. Figure 4B.2 shows the two extremes of these; the remainder are given in Appendix Figure A4.1.

In the course of the experiment (127 h for most samples) a substantial change occurred in the grain-size distribution characteristics of each sample (Figure 4B.3). There are two simple ways to quantify this change: destruction of the gravel fraction and production of mud (Table 4B.3). Intermediate sizes are not as useful to consider as they are constantly being both destroyed and produced and it is not easy to separate the two.

A measure of susceptibility to abrasion is the rate of decay of the gravel fraction. The percentage weight lost over time describes a kind of mortality curve, where the population is not replenished. These curves (Figure 4B.4) appear to divide the growth forms into three different groups. The most susceptible (multilaminar, and probably radiate and delicate branching) are at 50 to 60% of their original weight in 127 h. The least susceptible (free-living, fenestrate) are at over 85% of their original weight in the same time. Medium range susceptibility (unilaminar, robust branching, and erect flexible) falls between the two at 60 to 85% of original weight remaining after 127 h.

Destruction of coarse material results in the production of new, smaller material. Mud is produced in great quantity in some samples, and in most samples it is over 10% of the total weight after 127 h tumbling. There is, however, significant variation

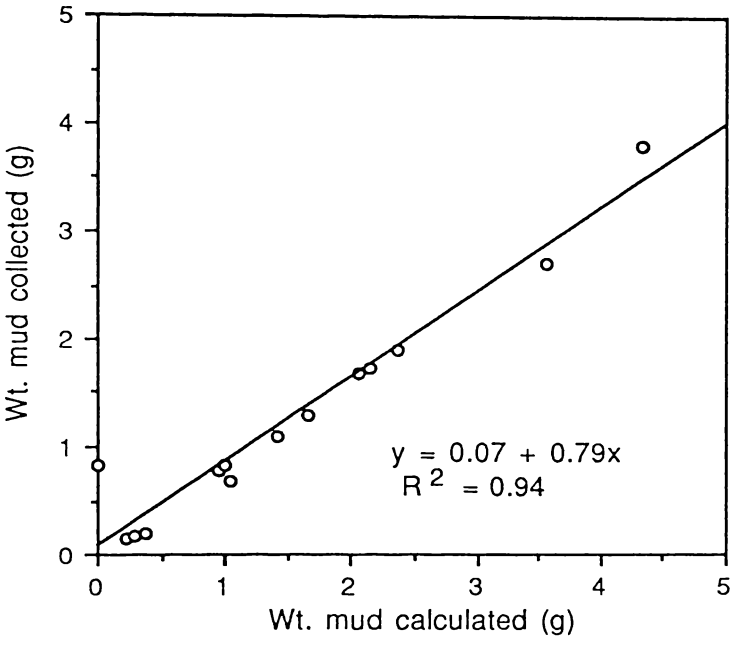


Figure 4B.1: Comparison of mud collected after tumbling and weighed with mud calculated by subtraction.

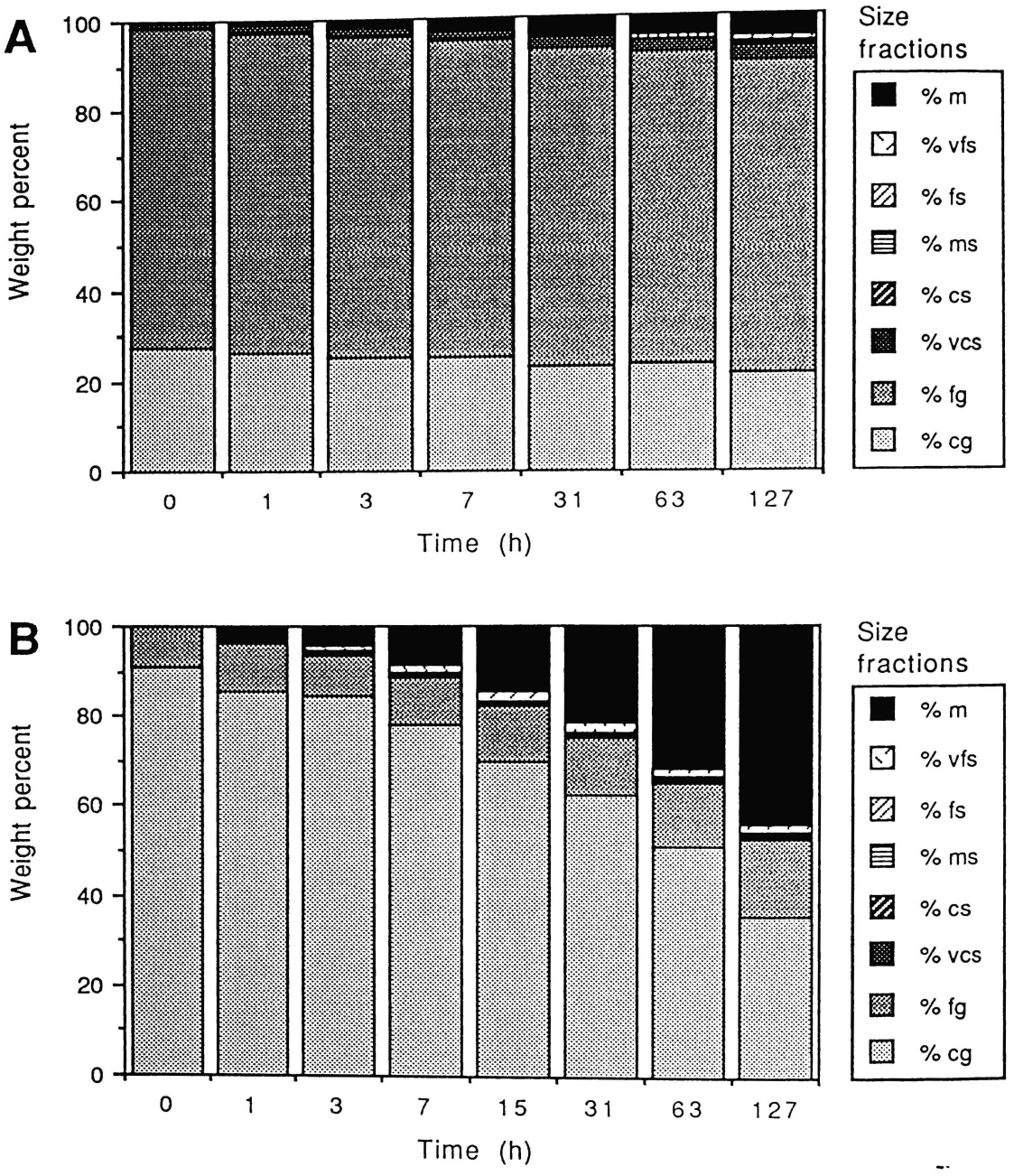


Figure 4B.2: Changes in size fractions due to tumbling with time for two extreme samples (see Appendix Table A4.1 for remaining histograms). (A) FL-N; (B) EN-ml-O.

Size fractions: m - mud (<0.063mm); vfs - very fine sand (0.063-0.125mm); fs - fine sand (0.125-0.25mm); ms - medium sand (0.25-0.5mm); cs - coarse sand (0.5-1mm); vcs - very coarse sand (1-2mm); fg - fine gravel (2-4mm); cg - coarse gravel (>4mm).

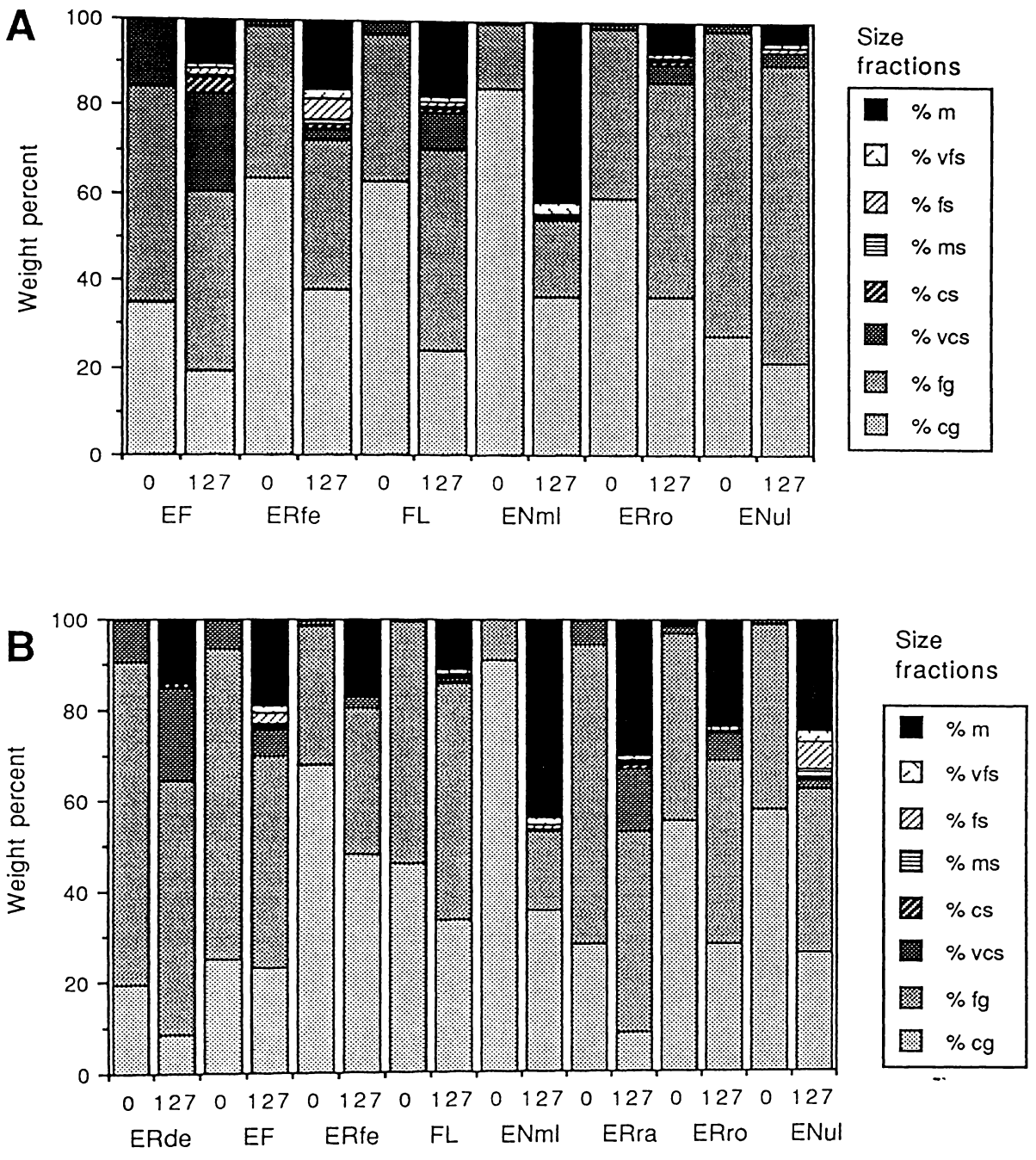


Figure 4B.3: Textural composition of New (A) and Old (B) samples before and after tumbling for 127 h.

Samples described in Table 4B.2; size fractions defined in Figure 4B.2.

Table 4B.3: Abrasion resistance parameters for 16 samples of New Zealand bryozoans (see Table 4B.2).

Sample	% gravel remaining at 127 h	% mud at 127 h
ENml-O	52.8	43.9
ENml-N	54.2	41.9
ERra-O	55.9	29.9
ENul-O	63.0	24.4
ERro-O	70.4	22.8
ERde-O	70.9	12.5
EF-N	71.8	10.5
ERro-N	72.4	18.0
ENul-N	73.4	16.0
EF-O	75.2	20.4
ERfe-O	81.5	15.0
FL-O	86.5	11.1
ERfe-N	87.2	6.8
FL-N	91.8	4.9

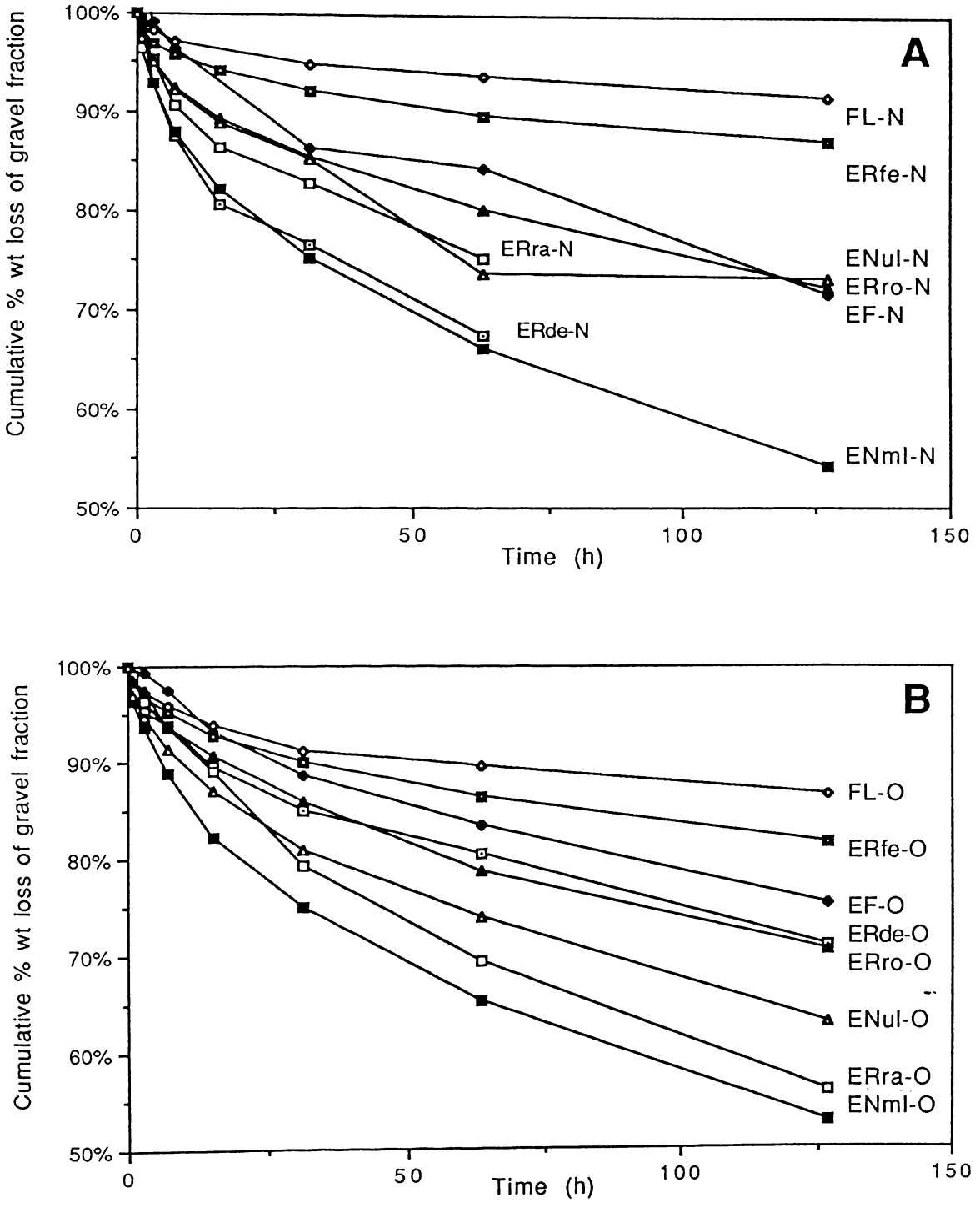


Figure 4B.4: Destruction of gravel fraction (> 2 mm) by tumbling over time for (A) New and (B) Old samples.

Samples described in Table 4B.2.

in the quantity of mud generated among the different growth forms (Figure 4B.5). This mud is 56 to 74% carbonate, with a mean of all samples tested of 63.3% $CaCO_3$ (Appendix Table A4.2).

The multilaminar samples were least resistant to abrasion (samples collected at 127 h were over 40% mud). Unilaminar, radiate, robust and delicate branching, and erect flexible samples were moderately resistant, containing 15 to 40% mud at 127 h. The most resistant to abrasion were fenestrate and free-living samples, which produced less than 15% mud. These hierarchies of resistance will be used in the ensuing discussion (Figure 4B.6).

In all the above comparisons, it should be noted that fresh-looking (New) samples and degraded-looking (Old) samples tend to show the same trends, but that Old samples generally are more susceptible to abrasion, inasmuch as the gravel diminishes faster, and more mud is produced (Figures 4B.4 and 4B.5).

Mineralogy of the mud produced is what would be expected from the mineralogy of the dominant species included in each sample (Appendix Table A4.3, Figure 4B.7). This indicates that the carbonate mud produced is from the bryozoans, rather than any interstitial carbonate (e.g., foraminifera or coccoliths).

4. Discussion

Abrasion as an indicator of transport

Although it is clear that transport may lead to abrasion, the present study indicates that the degree of abrasion of a grain cannot provide evidence for distance of transport. The size and shape of grains are shown here to be the source of much variation in resistance to abrasion. Thus a relatively resistant growth form, such as free-living, showing a similar degree of abrasion to a weaker multilaminar form would in fact have undergone considerably more transport. Similarly, the observation that larger grains break down more readily than smaller grains indicates that initial

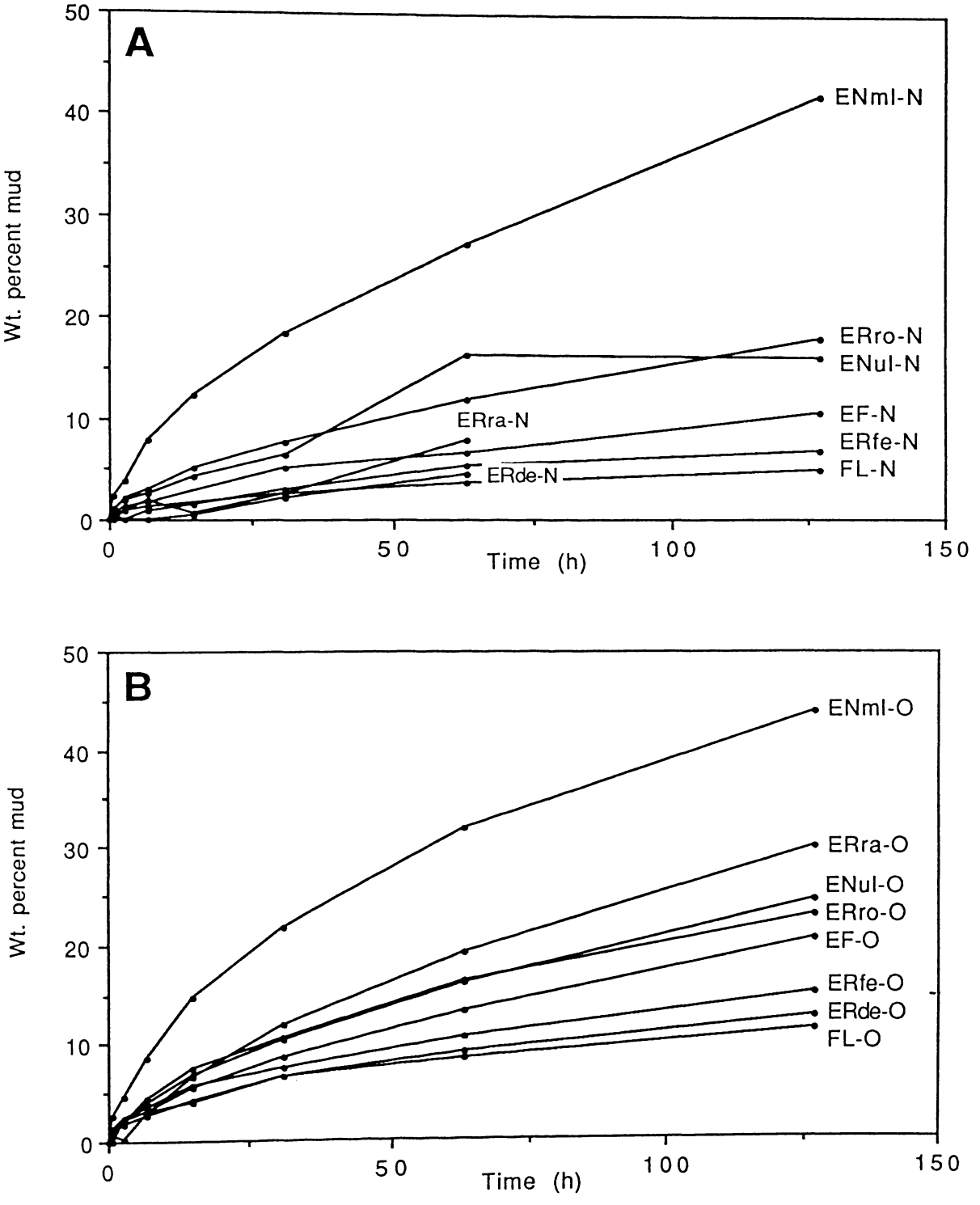


Figure 4B.5: Production of mud fraction (< 0.063 mm) by tumbling over time for (A) New and (B) Old samples.

Samples described in Table 4B.2.

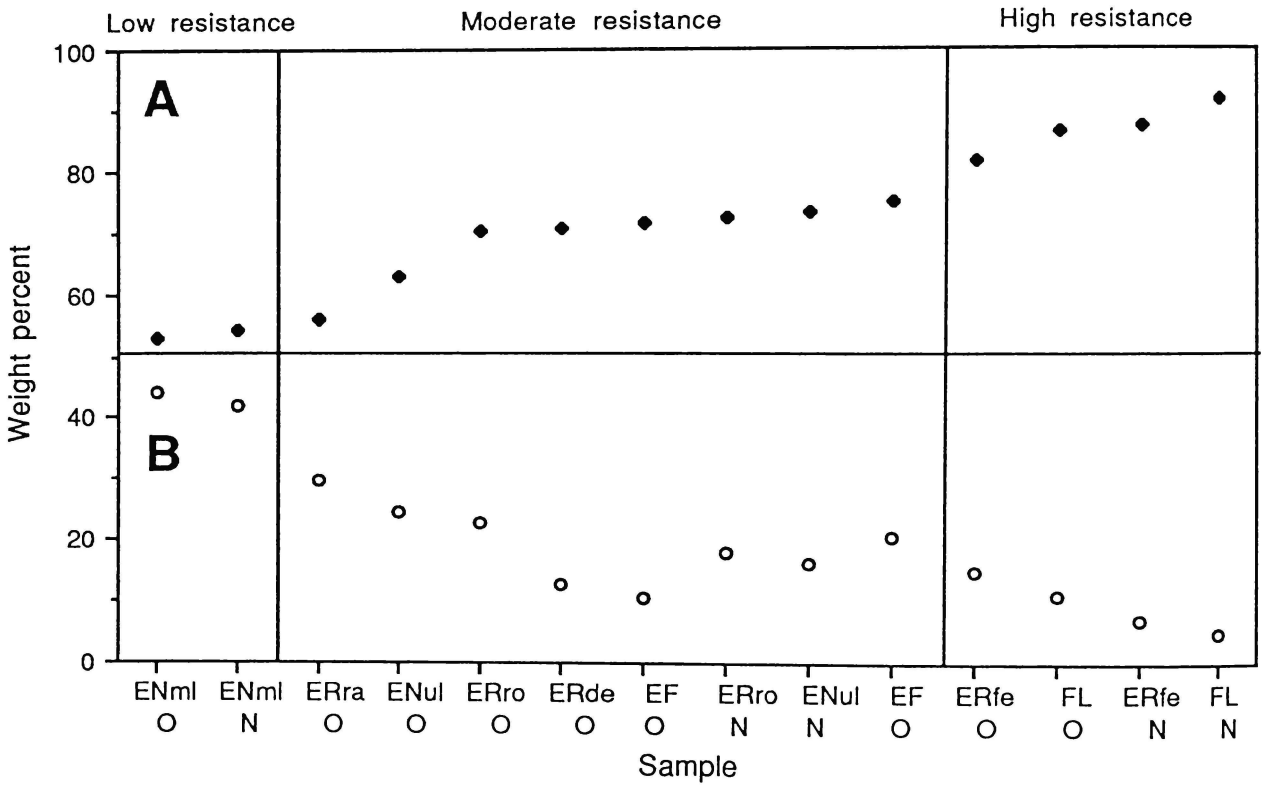


Figure 4B.6: Abrasion resistance parameters for bryozoan samples. (A) Weight percent of original gravel fraction (> 2 mm) remaining after 127 h tumbling. (B) Weight percent of mud (< 0.063 mm) produced after 127 h tumbling. Samples described in Table 4B.2.

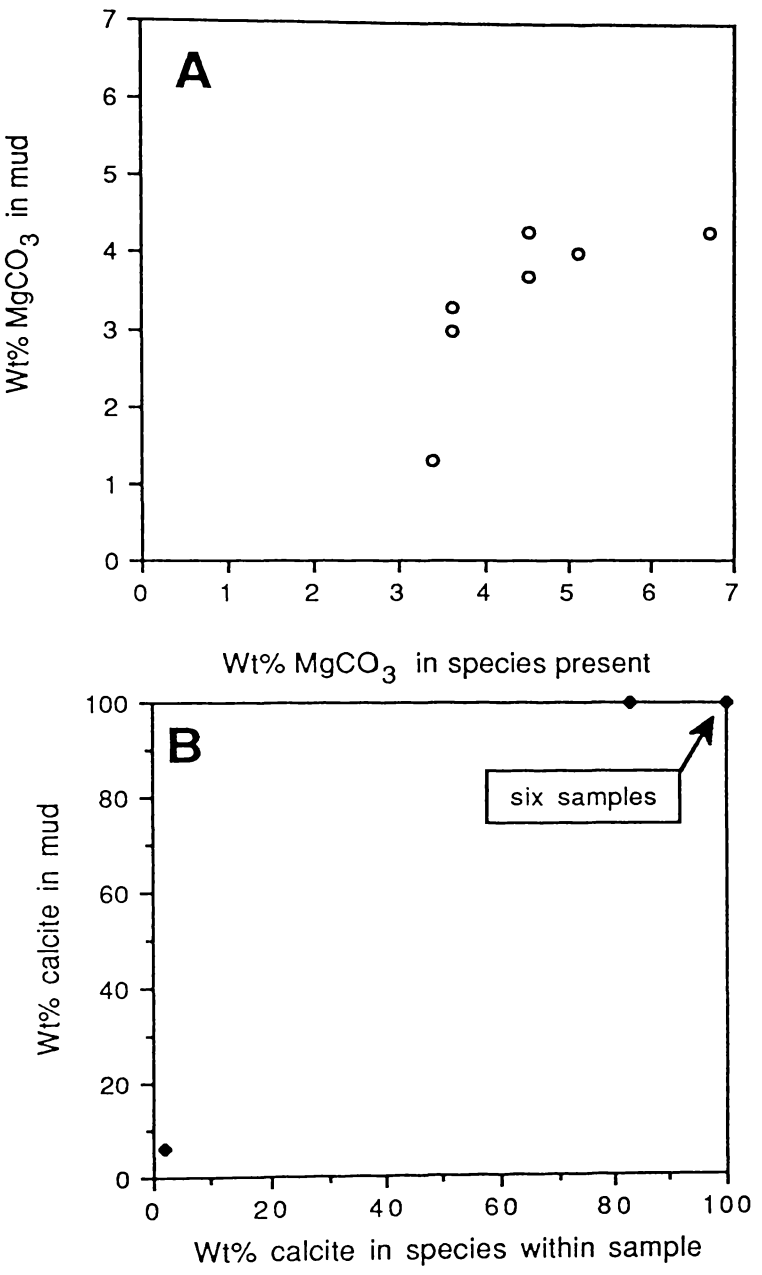


Figure 4B.7: Correlation of mineralogy of species making up tumbling samples with mineralogy of mud produced by abrasion. (A) Mg content, (B) calcite content.

size of a grain - in this case, of a colony - would affect its resistance to abrasion. With the strong effects that other factors have on resistance to abrasion, appearance of grains cannot be used as a reliable indicator of distance of transport. It should also be noted that degree of abrasion cannot be used reliably in determining the age of grains (Powell and Davies, 1990).

The observable effects of abrasion on bryozoans in this study include 1) size reduction; 2) loss of surface ornamentation; 3) polishing; and 4) loss of frontal wall followed by breakdown of side walls (Figure 4B.8). These effects have been observed following approximately 100 km of transport using the calculation of Argast et al. (1987) (Appendix Table A4.4). If mud production in 127 h is 5 to 45%, it follows that in 220 to 2000 km the entire sample could be mud. Similarly, in about 200 to 1000 km of transport all the gravel might be destroyed. The addition of terrigenous material, as would be likely *in situ*, would hasten this breakdown considerably (Chave, 1964).

Abrasion as a taphonomic process

The variation in the effects of abrasion on different growth forms is of interest. Multilaminar encrusting forms are the most susceptible to abrasion, whereas fenestrate and free-living forms are most resistant (Table 4B.3), perhaps due to their thick-walled zooids (Best and Winston, 1984). In addition to colonial growth form, the size of colony and degree of degradation by other means are important in determining the effect of abrasion. Thus one could expect to see smaller, relatively fresher colonies of the free-living and fenestrate types surviving into the fossil record. This is particularly true in the high-energy faunas defined by Nelson et al. (1988a), as summarized in Table 4B.4).

Abrasion as a source of carbonate mud

In this study, by far the commonest size fraction produced by abrasion was that less than 0.063 mm. Plenty of carbonate mud was produced - 46% of the original sample in one case broke down to mud-sized particles. Older-looking samples produced more

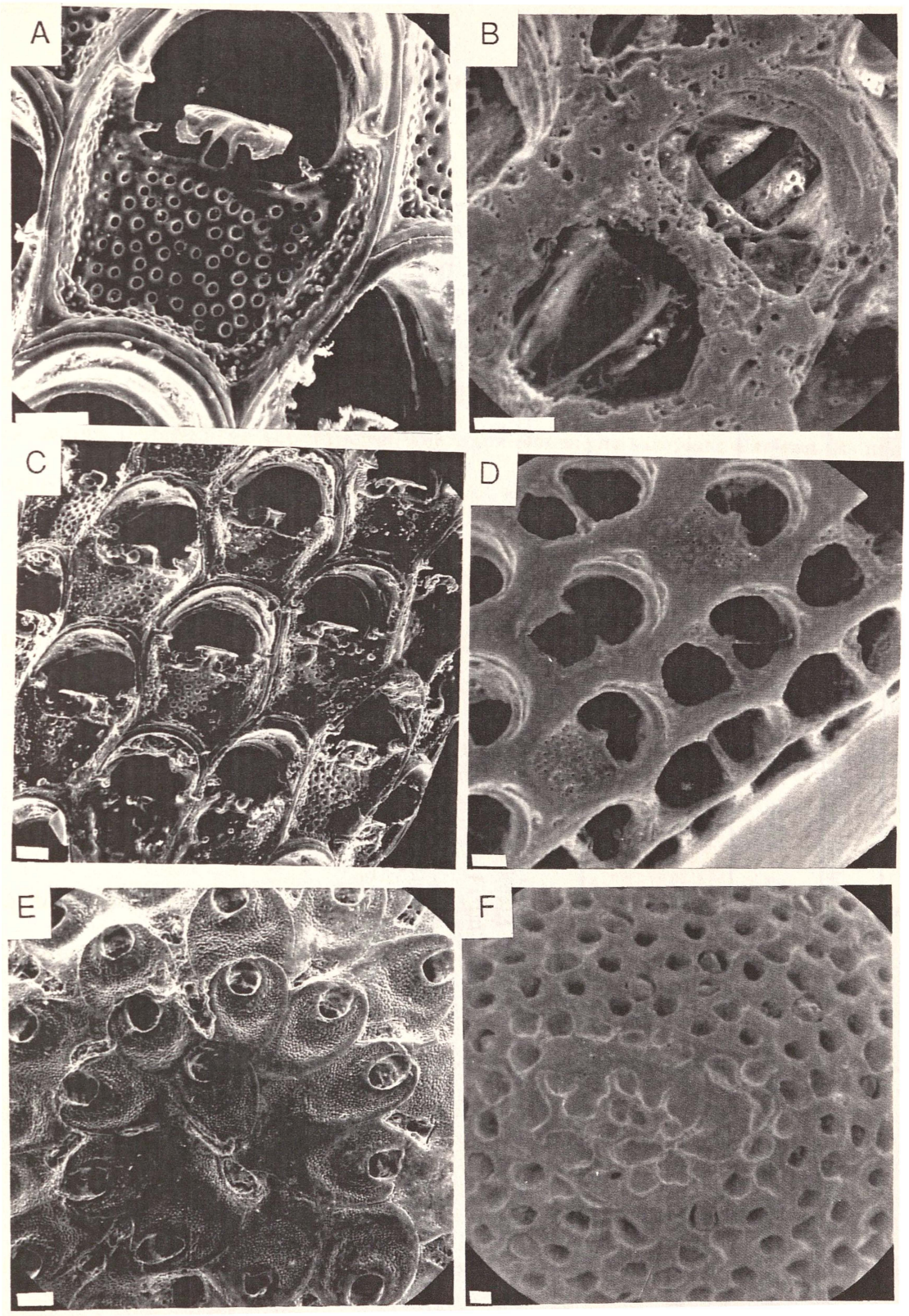


Figure 4B.8: Effects of abrasion on *Steginoporella neozelanica:* (A) fresh zooid, (B) abraded zooid, (C) fresh surface, (D) abraded surface; and on *Otionella squamosa:* (E) fresh surface, (F) abraded surface. Scale bars are 0.05 mm.

Table 4B.4: Predicted effect of resistance to abrasion on bryozoan faunas of the New Zealand shelf.

Hydraulic regime	Low water energy				Moderate water energy								High water energy			
Bryozoan colonial growth forms (Nelson et al., 1988a)	ERfo	ERde	ERfe	ERra	ENml	ERfo	ERro	ERfe	ERra	ERma	EF	FL	ENul	ENml	EF	FL
Resistance to abrasion (l=low m=moderate h=high)	m	m	h	m	l	m	m	h	m	m	m	h	m	l	m	h
Amount of abrasion expected	little				some								much			
Possible faunal assemblage	little change				expect ENml to decrease ERfe and FL would increase somewhat								expect FL to increase as ENml disappears others damaged			
Carbonate mud	little produced				some produced, may settle								some produced, but will not settle			

mud than fresh-looking samples, but the trends among growth forms are broadly similar.

One obvious point relates to the source of this mud. Bryozoans have a particularly porous structure, with myriads of cavities in which detrital particles may be caught. Tumbling probably helps to loosen those particles and they then form part of the mud produced. However, in all samples over 50% of the mud produced was carbonate, which matched the mineralogy of the bryozoans in the samples. One can assume from the degree of wear of the samples that the carbonate resulted from abrasion of bryozoans.

5. Conclusions

Abrasion in bryozoans is not a reliable indicator of transport history or of age, as the effects of growth form, size, and degree of previous diagenesis may affect the process of abrasion.

Abrasion may be a taphonomic process in bryozoans. Some growth forms, particularly free-living, erect flexible, and fenestrate, tend to resist abrasion, whereas others will break down under the same conditions. A skewed fossil record could be the result, with the completeness of a fossil fauna strongly affected by the hydraulic regime in which it underwent early diagenesis (Figure 4B.9).

Carbonate mud may be produced by abrasion of bryozoans. Multilaminar forms produce a considerable amount of mud. That mud has been shown to be about 63% carbonate, and consistent mineralogy indicates it derives principally from the bryozoans rather than any interstitial carbonate. Further implications for paleoenvironmental analysis and temperate limestones will be discussed in Chapter 11.

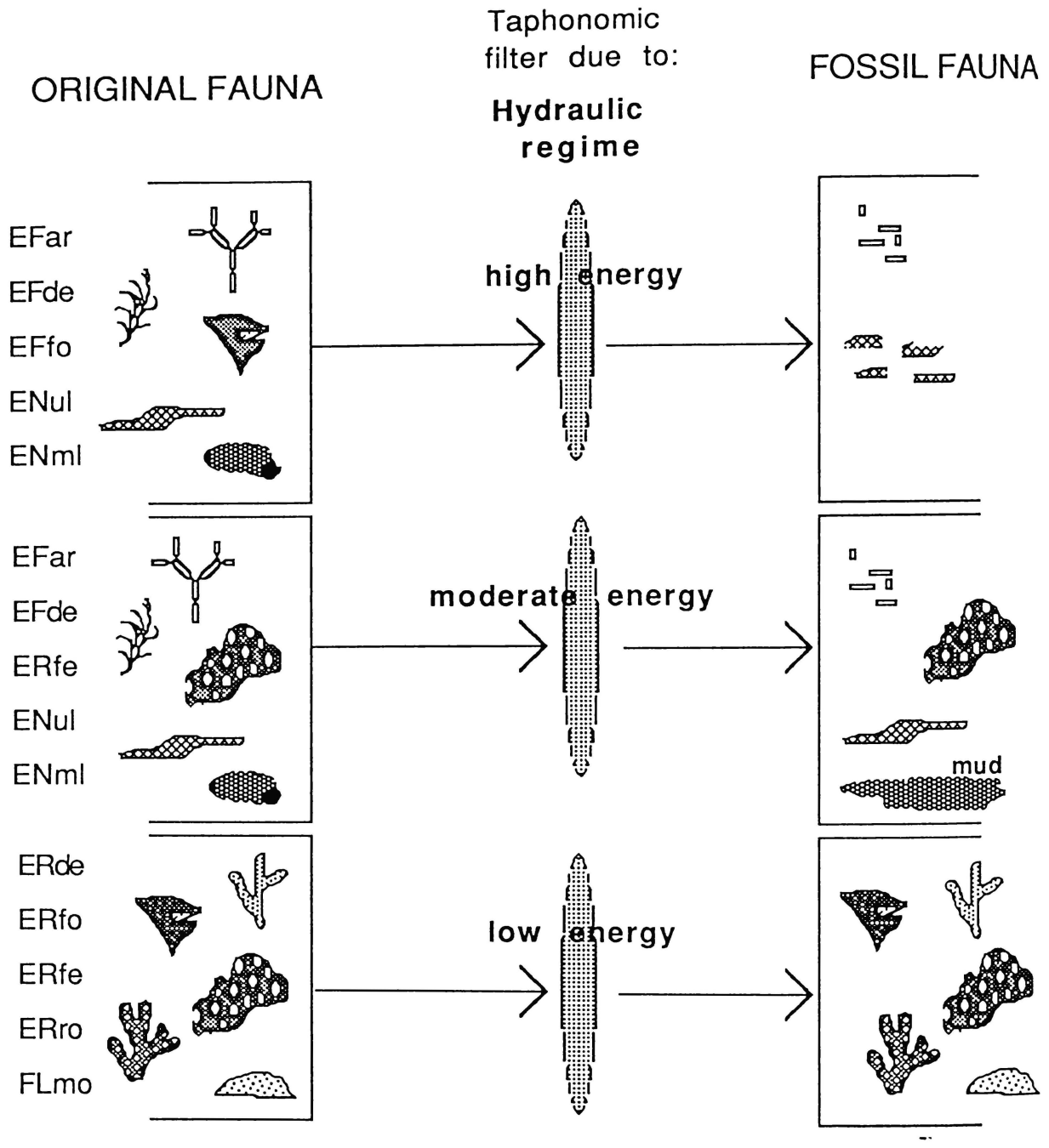


Figure 4B.9: A possible model for the taphonomy of abrasion and the effect of hydraulic regime on bryozoan sediments. Growth form abbreviations as in Figure IB.3.

C. BIOLOGICAL DIAGENESIS AND BRYOZOANS

1. Introduction

Biological diagenesis is the sum of the changes occurring to sediments due to the action of living organisms. These can include destructive mechanisms such as boring and scraping, and constructive mechanisms such as encrusting. Encrusting is a process involving substrate recognition and preference on the part of a settling larva, followed by attachment, adhesion, and growth. Destruction can be mechanical (crushing, drilling) or chemical (dissolving a tunnel), or involve both processes (such as that used by clionid sponges, which chemically etch around an area and then dislodge the loosened chip).

Most taxa contain some organisms that are agents of biological diagenesis (Table 4C.1). Among encrusters, those organisms that settle on anthropogenic structures (called "foulers") receive the most attention (Soule and Soule, 1977). Among eroders, the clionid sponges have received a great deal of study, as their effects are strongly felt from coral reefs to temperate shelf sediments (e.g., Neumann, 1966; Young and Nelson, 1988).

Biological diagenesis is world-wide. It has been mainly studied in the tropics, but certainly occurs in temperate areas (Farrow and Fyfe, 1988). There has been a suggestion that bioerosion is dominantly chemical in the tropics and mechanical in temperate latitudes (Warme, 1975). In terms of vertical distribution, bioerosion by photosynthetic organisms tends to be limited to the photic zone (Perkins and Halsey, 1971). Micro-boring fungi have been found as deep as 5000 m (Tudhope and Risk, 1985). It is interesting that bioerosion by benthic organisms appears to be limited to the vicinity of the sediment/water interface. Burial significantly limits the occurrence of borings (May and Perkins, 1979).

Many studies have attempted to quantify the rate at which erosion by organisms is affecting local rock (usually limestone), sediments, and reefs (Table 4C.2). Clearly

Table 4C.1: Some agents of biological diagenesis (after Farrow and Fyfe, 1988).

Mechanism used	Principal agents	Accessory agents
Boring/tunneling	clionid sponges endolithic algae bivalves	naticid gastropods phoronid worms fungi bryozoans bacteria
Scraping/rasping	grazing gastropods	chitons
Breaking/crushing	crabs regular echinoids birds	mammals (otters, walrus)
Encrusting/attaching	barnacles bryozoans worms	algae diatoms sponges coelenterates brachiopods

Table 4C.2: Some published rates of bioerosion by marine organisms. Erosion is measured as surface retreat or as volume or weight of material removed.

Location	Agents	Downward erosion rate (mm/y)	Volume/wt erosion rate (/m^2/y)	Source
California	gastropods	0.25	778 mm^3	North (1954)
S. Devon	limpets	1.5		Southward (1964)
Caribbean	clionid sponges		23 kg $CaCO_3$	Neumann (1966)
California	gastropods	10	154 g	McLean (1967)
Oregon coast	bivalves and abrasion	12		Evans (1968)
Atlantic Canada	clionid sponges	40		Evans (1969)
North Sea	echinoderms	2 to 5		Krumbein and Van der Pers (1974)
Caribbean	clionid sponges	1	250 g to 3 kg	Rutzler (1975)
Curacao	clionid sponges		2.5 to 3.3 kg	Bak (1976)
Aldabra Atoll	chitons	0.038	40.2 g	Taylor and Way (1976)
Barbados	macroinvertebrates	0.07 to 0.54	70 to 540 cm^3	McGeachy and Stern (1976)
Caribbean	diademid echinoids		10 kg	Hunter (1977)
St. Croix	clionid sponges		0.2 to 3.3 kg	Moore and Shedd (1977)
Jamaica	clionid sponges		0.2 to 1.9 kg	Moore and Shedd (1977)
Bermuda	clionid sponges and fish	1.3		Bromley (1978)
Adriatic	algae and grazers	0.1 to 1.0		Torunski (1979)
Hawaii	net dissolution		6.5 kg	Smith et al. (1981)
Gulf of California	polychaete worms		107 cm^3	Pepe (1983)
Grand Cayman Is.	clionid sponges	5	8 kg	Acker and Risk (1985)
Davies Reef, Australia	algae and fungi		350 g	Tudhope and Risk (1985)
Hudson Canyon	fish and crustaceans	0.13 to 0.18		Twichell et al. (1985)
Caribbean	bivalves	10		Mearns (1986)
County Clare, Ireland	bivalves	1.3 to 10		Trudgill and Crabtree (1987)
County Clare, Ireland	echinoids	3 to 15		Trudgill et al. (1987)
Gulf of California	bivalves, sponges, sipunculans	0.3	150 to 300 cm^3	Stearly and Ekdale (1989)

some organisms are more effective at removing material than others. Clionid sponges and echinoids are among the most effective agents, removing up to tens of kg of material per m^2 per year! The few studies in which the net effect of many different organisms, some growing, some encrusting, and some eroding, has been considered indicate a much smaller effect, but it is interesting that the net effect is destructive (McGeachy and Stern, 1976; Smith et al., 1981). One should note that both these inclusive studies are from tropical regions, where diagenesis is held to be dominantly constructive.

Biological diagenesis is important from several points of view. The sedimentologist is interested in the diagenetic effects. Bioerosion is important in increasing porosity and surface area of grains, allowing dissolution to have a greater effect. Abrasion is more effective on bioeroded grains (Young and Nelson, 1988). Maceration may be accelerated by microborers removing organic sheaths and laminae from shells. All these mechanisms typically produce very fine material (Perkins and Halsey, 1971) which may be transported away or may increase local turbidity. An ecologist may be interested in bioerosion as a destroyer of hard substrates, thus limiting settling (Driscoll, 1967), and as a provider of new microhabitats by excavation. Bioerosion may increase breakage and aid the propagation of asexually reproducing organisms (Hallock, 1988). The paleontologist may see bioerosion primarily as a limitation on the eventual fossil record, as is any selectively destructive process (Perkins and Halsey, 1971). However, borers make easily preserved and informative trace fossils, which may indicate paleoenvironment, particularly with regard to hydraulic energy level (Bromley, 1978).

2. Bryozoans as bioeroders

One of the least studied and most underestimated boring taxa are the endolithic bryozoans. Most compilations of agents of bioerosion do not even mention bryozoans (e.g., Farrow and Fyfe, 1988). Pohowsky (1978) points out that these organisms have been neglected by zoologists and paleontologists. It appears that they have been overlooked by most sedimentologists too!

Boring bryozoans are from the suborder Ctenostomata (see Appendix Table AI.1 for detailed systematic information). This is a non-calcifying taxon, including such genera as *Penetrantia, Immergentia*, and *Spathipora*. Apparently the non-calcifying colonies find protection from currents and from turbidity within the dead shells they invade. Unlike many boring organisms, the boring bryozoans are filter-feeders (like the rest of the phylum) and thus each zooid is provided with access to open water. Most modern endolithic bryozoans choose as substrate mollusc shells, barnacle plates, or worm tubes; fossil bryozoan borings have also been found in brachiopods and crinoids (Ryland, 1970).

Bryozoans bore by dissolving the host shell with phosphoric acid, produced at the growing tips of the colony (Ryland, 1970), causing pitting of the host (Pinter Morris, 1975). This behaviour is not parasitic, as the host shells are usually, but not always, dead (Pohowsky, 1978). Their distribution is world-wide and they are considered widespread to at least 400 m water depth (Warme, 1975). Boring bryozoans are not limited to the marine environment, but can be found in lacustrine and subaerial (occasionally wetted) environments too (Golubic et al., 1975). They have been found in shells as early as the Ordovician (Pohowsky, 1978).

Boring bryozoans typically have long thin (10-20 μm in diameter) stolons linking zooids that have openings to the surface of the shell. The aperture (up to 1 mm across) where the organism emerges to feed may have a diagnostic shape (Soule and Soule, 1969). The dendritic or ramifying colonies will grow in their preferred direction regardless of the structure of the host shell (Pohowsky, 1978).

The anonymity of the endolithic bryozoans is not surprising. They are small and rather aberrant forms of a little-known suborder. Nevertheless, Pohowsky (1978) puts a good case for his thorough investigation of the group. Since at least the Upper Ordovician, bryozoans have been making identifiable trace fossils with evidence of soft-part morphology. These fossils have been preserved at times when other

organisms have not. The information they contain about the evolution of bryozoans and about paleoenvironment is not inconsiderable.

Few endolithic bryozoans have been recorded in New Zealand (e.g., Silen, 1956; Gordon, 1984, 1986). Three species are recorded from the Leigh Marine Reserve (Gordon and Ballantine, 1977) of which at least two are undescribed (Dr. D.P. Gordon, pers. comm.). A few other records can be found in the paleontological literature (Table 4C.3). Hosts, when noted, are molluscs.

The species are poorly known and no systematic study of boring bryozoans has been done for New Zealand. No data are available on population densities, nor of substrate preferences. It is quite impossible to estimate the rate of destruction of carbonate sediments by bryozoans. If they were sufficiently widespread and/or rapid in excavation, boring bryozoans might be an important element in sea-floor diagenesis of carbonate sediments.

3. Bryozoans as encrusters

The modern importance of bryozoans to many scientists lies not in their erosive capability, but in their encrusting habit. Like many benthic filter-feeders, most bryozoans attach themselves to a substrate. When they do this to a ship and significantly disrupt the streamlining of the hull, they are called "foulers." There are more than 50 species of bryozoans that have been found on ships, pleasure craft, and fishing boats (Ryland, 1970). One genus, *Watersipora*, is one of the most resistant organisms known to copper-based anti-fouling paints (Ryland, 1970). *Watersipora* has extended its natural range extensively through this ability to foul ships, and two species arrived in New Zealand between 1956 and 1982. It is now common in New Zealand ports and harbours (Gordon and Mataawari, in press).

Bryozoans don't settle only on ships. In fact, larvae have been shown to search out their substrate of choice (Ryland, 1970), which may be shells, sand, rocks, other bryozoans, or algae. Many bryozoans prefer a hard substrate, with the major

Table 4C.3: Some recorded New Zealand endolithic bryozoans (Soule and Soule, 1969; Gordon and Ballantine, 1977; Pohowsky, 1978; Gordon, 1980; Gordon, pers. comm.).

Species	Host	Location	Age
Immergentia atypica	*Crepidula* *	Waipara Gorge	Tertiary
Immergentia sp.	dead shell gravel	Leigh	Recent
Immergentia zelandica	*Buccinulum* **		Recent
Penetrantia irregularis	*Mytilus* †		Recent
Penetrantia parva	*Maoricolpus*	Leigh	Recent
	Thais †	Leigh	Recent
Penetrantia spp. indet.	*Alcithoe* ***	Wanganui	Pliocene
Terebripora sp.	*Cookia* †	Leigh	Recent

† Borings found on shells of living molluscs.
* Published as *Maoricrypta*
** Published as *Euthria*
*** Published as *Leporemax*

exception of the free-living forms. Soule and Soule (1977) report work on coral reefs, where bryozoans are among the first colonizers of dead coral areas but avoid living coral. Encrusted areas of reef were more resistant to breakage. A commensal relationship between some hermit crabs and encrusting bryozoan colonies allows the bryozoan to grow free of fine particulates, and perhaps aids in feeding and cross-fertilization.

Encrusting involves recognition of substrate, settling, attachment, and adhesion. The investment of the organism in searching out an appropriate place and then producing adhesive is repaid by the protection, stable base for feeding, and reduction in spatial competition that the substrate provides. Most encrusting bryozoans have a flat circular encrusting habit giving little resistance to waterflow and thus little risk of breakage. Some encrusting bryozoans may etch depressions in their substrate (Pinter Morris, 1975).

Growth rates of bryozoans have been discussed in detail in Chapter 1, Section D, and data for New Zealand species are given there (see Table 1D.2). The effect of encrustation by bryozoans on the eventual fate of sediment is not known, although some possibilities suggest themselves. Encrusting by bryozoans may be important in strengthening substrate. Encrustation might influence the resistance to abrasion of a given substrate. It seems likely that a heavily encrusted shell might be more resistant to boring. As there is evidence of choice of substrate (Ryland, 1970), some substrates may be more or less strengthened than others, which would contribute to possible distortion of the fossil record.

4. Bryozoans as substrates

There is little information in the literature about the bioerosion or encrustation of bryozoans. Endolithic algae may be important (Boney, 1975). Winston (1983) notes that older regions of colonies may be extensively bored while the younger regions are quite fresh. Most biological impacts on bryozoans, however, are likely to be after death, as many bryozoans are equipped with defenses against intruders.

Interestingly, polymorphism (that is, the forming of specialized zooids) is most important in the cheilostomes, the most heavily calcified group. The two defensive heterozooids are the avicularia (in which the zooidal operculum is modified into a snapping mandible) and the vibracula (operculum modified into a lashing bristle). These both deter settlers and predators, as well as preventing the deposition of fine particulates (Ryland, 1970). Another mechanism for avoiding encrustation is the molting of the fouled outer body layer, so far described in only one free-living bryozoan (Winston and Hakansson, 1989).

After the death of a colony, bioerosion may occur. There are bryozoans that particularly seek out other bryozoans, both as substrate for encrusting and for boring. *Harmeriella terebrans* bores into cheilostome bryozoans (Pohowsky, 1978). Mollusc spat (e.g., *Mytilus* and *Pecten*) may preferentially settle on or near bryozoans (Moore, 1973). Entoprocts, hydroids, and even barnacles are known to settle on bryozoans (Ryland, 1970). This catalogue aside, very little information is available on bryozoans as substrate (e.g., Osman and Haugsness, 1981).

An investigation into New Zealand bryozoans as substrate was designed. Specimens of the free-living bryozoan *Otionella squamosa* were immersed for 3, 9, and 12 month periods between layers of fine nylon mesh at a site open to the sea at Cape Rodney in 14 m water depth (details of methodology in Chapter 8, Section B). The samples were initially as fresh as possible and free of encrustation. They were weighed before and after immersion.

Of the 13 samples retrieved, four had lost some weight, but the majority had not (Appendix Table A4.5, Figure 4C.1). Samples had some visible evidence of boring (Figure 4C.2) but it was superficial and minor. This is in contrast to molluscs included in the same study which were heavily encrusted (see Figure 8C.4).

Many bryozoan specimens from New Zealand shelf sediments were examined for signs of boring or encrustation, using a scanning electron microscope (SEM). Coccoliths

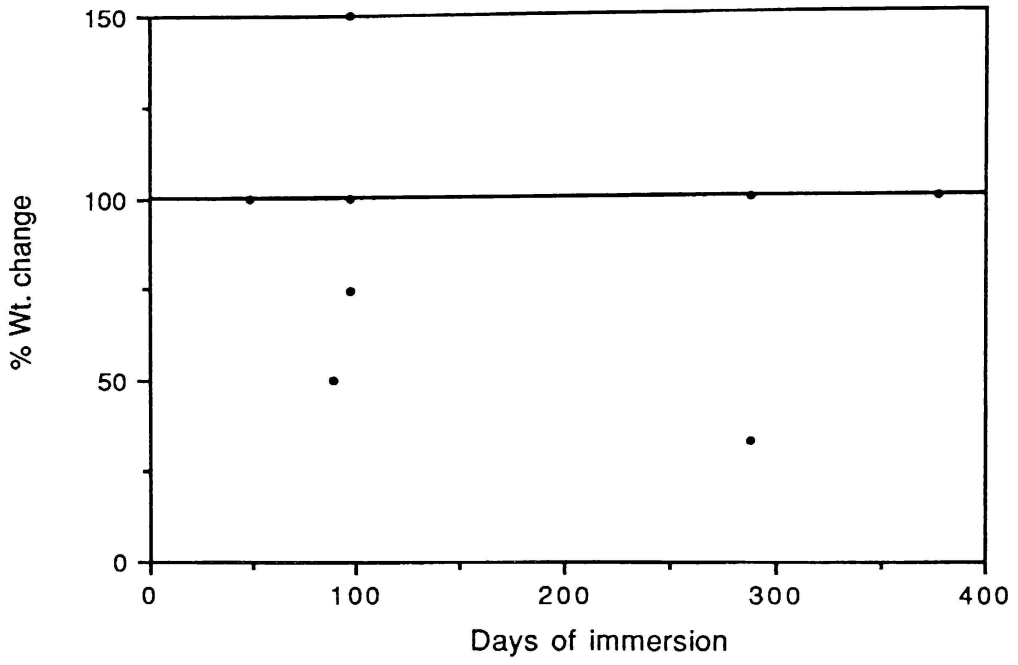


Figure 4C.1: Change in weight over time for 13 specimens of immersed *Otionella squamosa*.

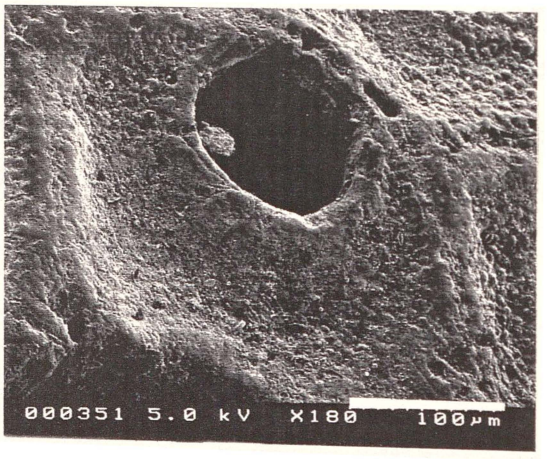


Figure 4C.2: One zooid of the free-living bryozoan *Otionella squamosa* after 12 months immersion, showing some mainly superficial boring.

were fairly common in the pores of even very fresh specimens (Figure 4C.3). Of some interest are the diatoms encrusting bryozoan surfaces. Boden (1988) suggests that similar diatoms etch skeletal carbonates, and indeed they appear to do so on New Zealand bryozoans (Figure 4C.4).

The effect of encrustation and boring on bryozoan skeletons may thus be minor in the short term on the New Zealand shelf. However, long residence times at the sea water/sediment interface are experienced by carbonates in New Zealand, and biological diagenesis may become important in the longer term. Bored bryozoan material has been observed to be brittle and weak (Winston, 1983) and one might imagine that encrusted bryozoans may have increased resistance to other diagenetic forces.

5. Conclusions

Bryozoans are overlooked and seldom mentioned in studies of bioerosion. This is partly because they are most important in the less-well-studied temperate carbonate sediments. No doubt the fact that bryozoans are small and difficult to identify has contributed to the problem. They have, however, proved to be active in nearly all types of biological diagenesis. They may be bioeroders, encrusters, and substrates, and as such they should be of interest to paleontologists and sedimentologists. Bioerosion and encrustation by bryozoans may be locally important in carbonate budgets, and in influencing the fate of carbonate sediments. The effects of bioerosion and encrustation on bryozoan sediments are little known, but may be of significance, particularly in the long term (1000s of years).

D. INFLUENCES ON DISSOLUTION OF BRYOZOAN SEDIMENTS

1. Introduction

In addition to physical and biological effects, the carbonate skeletons of marine organisms are susceptible to a wide variety of chemical changes, especially following death. In the well-studied tropical shallow marine environment, chemical diagenesis

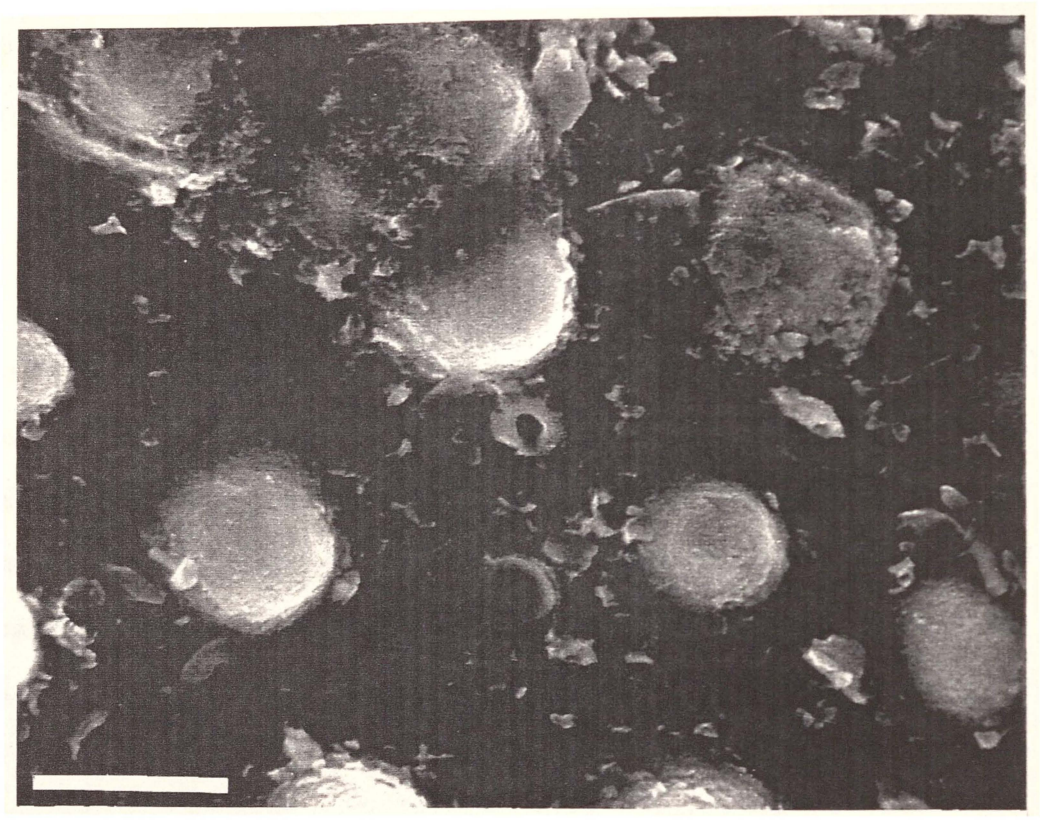


Figure 4C.3: Scanning electron micrograph of the surface of a zooid of *Otionella squamosa* showing coccoliths encrusting. Scale bar is 0.01 mm.



Figure 4C.4: Diatoms encrusting the surface of *Mecynoecia purpurascens*. Arrow indicates where frustule has broken, showing etching into surface. Scale bar is 0.01 mm.

is usually constructive, with widespread precipitation of intra- and inter-granular carbonate cements from supersaturated sea water and the general preservation of skeletal grains, including the metastable minerals aragonite and high-Mg calcite (e.g., Tucker and Bathurst, 1990). Indeed, inorganically precipitated sediments such as ooids and aggregates may form. In the cold abyssal depths, chemical diagenesis is destructive, involving the dissolution of carbonate and the eventual destruction of carbonate skeletal remains (e.g., Berger, 1970). The depth-related vertical sequence of diagenetic regimes has been well-studied (e.g., Li et al., 1969; Thunell et al., 1981). As Alexandersson (1979) points out, however, the horizontal or spatial distribution of diagenetic regimes is not as well studied and the nature of carbonate diagenesis in shallow waters outside the tropics is presently imperfectly known.

Temperate-water assemblages do not generally contain the same types of organisms as tropical ones. A study of the dissolution of corals or codiacean algae (e.g., Walter and Morse, 1984) would not be applicable to temperate sediments. The important carbonate sediment producers in temperate zones are bryozoans, barnacles, and molluscs (Nelson, 1988b), but there have been few studies on the dissolution behaviour of these groups.

Although several studies of the mineralogy of bryozoans are available (Schopf and Manheim, 1967; Rucker and Carver, 1969; Poluzzi and Sartori, 1974), the effect of these different mineralogies on dissolution is not known. Bryozoans are a particularly informative skeletal group to study in regard to potential dissolution effects because they comprise a range of mineralogies, including low-Mg to high-Mg calcite, aragonite, and bimineralic forms (see Figure 2B.3), and their colonial growth forms are extremely variable, ranging from compact, discoidal, free-living forms to delicately branching, erect forms (Nelson et al., 1988a). They provide the opportunity to study dissolution of a variety of different forms and mineralogies, so gaining insight into the influences of shape and mineralogy. In the following sections a laboratory dissolution experiment on bryozoans of various mineralogies and morphologies is described and discussed.

2. Methods

Collection and preparation of specimens

Fresh bryozoan material representing 13 of the commonest species of sediment-forming bryozoans in New Zealand waters was picked from collections of shelf carbonate sediments from the Three Kings and Snares Platforms, off northern and southern New Zealand, respectively (see Figure 2B.1). Ten unencrusted specimens of approximately equal size were selected from each study species; they were first cleaned by immersion in bleach, and then gently probed both physically and ultrasonically, then measured (length, width, height) and weighed.

Classification of species

Each species was classified according to mineralogy and morphology (Table 4D.1). Bryozoan morphology, in effect an indication of surface area available for acid dissolution, was classified according to colonial growth form (see Figure IB.3). It became necessary to further combine these growth form groups into four morphological classes (1 to 4) in order to limit the number of possible combinations with mineralogy. Branching forms were separated into Delicate (class 1) and Robust (3) categories. Encrusting and foliose forms were classified as Planar (2), and free-living, multilaminar, and discoid forms were classified as Compact Solid (4).

The mineralogy of each species was determined by x-ray diffraction (XRD) of many specimens from around New Zealand (see Appendix Table A2.3). The mean mineralogy for each species was used for the experimental specimens, as dissolution and powdering for XRD are both destructive, thus mutually exclusive. Carbonate mineralogy consists of two aspects: calcite to aragonite ratio, and weight percent Mg substitution for Ca in calcite. Mineralogical classes (A to D) were chosen to reflect these. The mainly calcite species were divided into low-Mg (0-3 wt% $MgCO_3$)(class A), moderate-Mg (3-5 wt% $MgCO_3$)(B), and high-Mg (>5 wt% $MgCO_3$)(C) calcite classes, and the species with less than 50% calcite were classified as aragonite (D). The 13 study species combine these two variables to fill 11 of the possible 16 combinations of mineralogy and morphology (Figure 4D.1).

Table 4D.1: Morphological and mineralogical data and classifications for 13 species of New Zealand bryozoans.

Bryozoan species	MORPHOLOGY		MINERALOGY		
	Growth form	Morph. class	% Calcite	Wt% $MgCO_3$	Min. class
Adeonellopsis sp.	ER ro	3 - robust branching	3	5.7	D - Aragonite
Celleporina costazii	EN ml	4 - compact solid	99	5.6	C - High-Mg calcite
Chiastosella splendida	EN ul	2 - planar	86	5.7	C - High-Mg calcite
Foveolaria cyclops	ER fo	2 - planar	63	6.0	C - High-Mg calcite
Galeopsis porcellanicus	ER de	1 - delicate branching	100	6.4	C - High-Mg calcite
Hornera sp.	ER ro	3 - robust branching	100	1.4	A - Low-Mg calcite
Iodictyum yaldwyni	ER fe	3 - robust branching	100	6.8	C - High-Mg calcite
Lichenopora sp.	ER ra	4 - compact solid	100	4.5	B - Moderate-Mg calcite
Mecynoecia purpurascens	ER de	1 - delicate branching	100	1.7	A - Low-Mg calcite
Otionella squamosa	FL mo	4 - compact solid	2	6.0	D - Aragonite
Steginoporella magnifica	EN ul	2 - planar	97	4.4	B - Moderate-Mg calcite
Steginoporella neozelanica	EF rt	3 - robust branching	100	3.7	B - Moderate-Mg calcite
Telopora buski	ER ra	1 - delicate branching	100	2.8	A - Low-Mg calcite

Growth forms defined in Figure IB.3.
Mineralogy as determined by XRD (see Appendix Table A2.3).

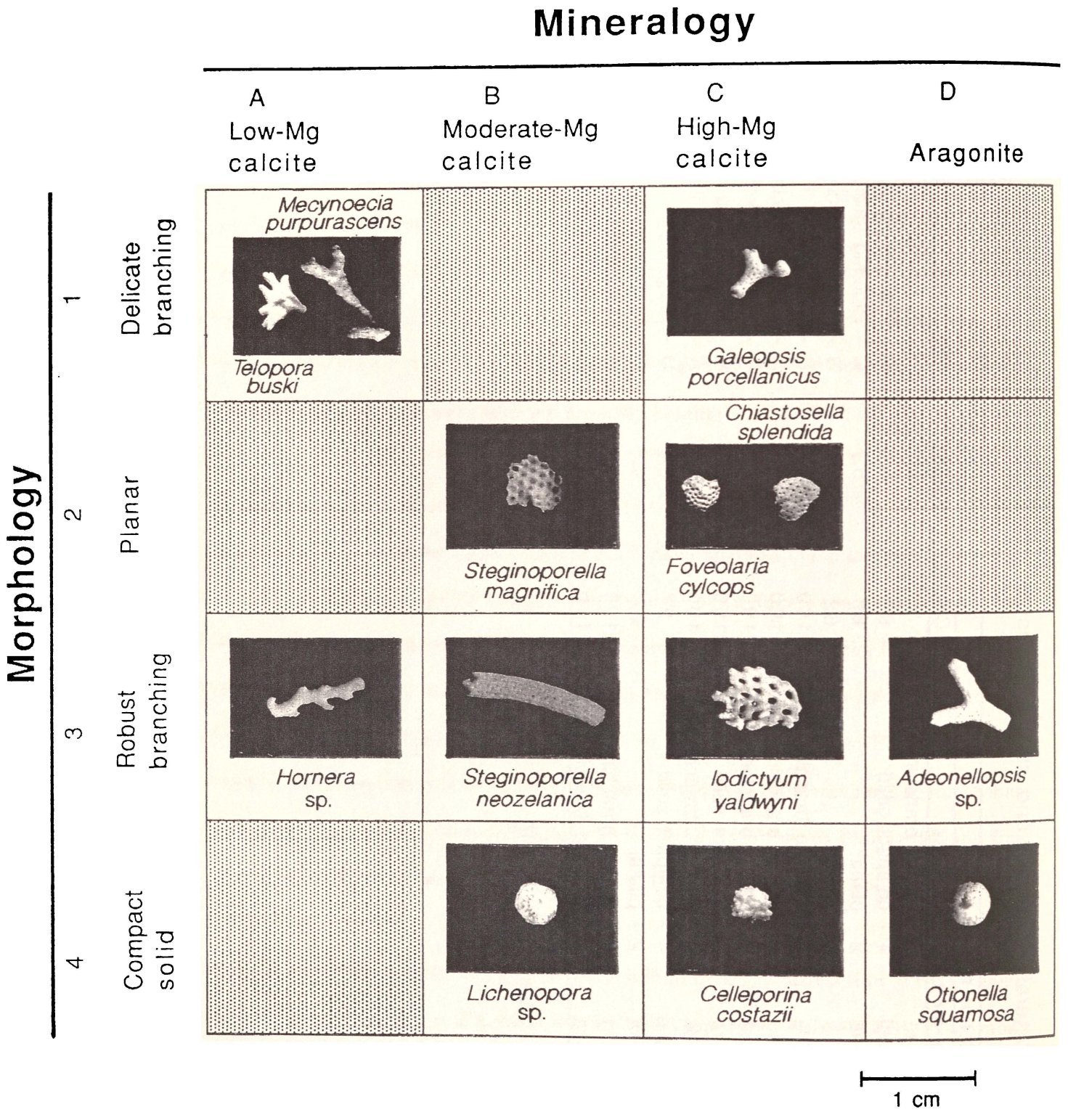


Figure 4D.1: Mineralogical and morphological classifications of 13 species of New Zealand bryozoans.

Acid bath experimental design

An acid bath dissolution experiment was designed along the lines described by Flessa and Brown (1983). The method was modified as follows: 1 l of 1% acetic acid instead of 5 l of 4% acetic acid was used because bryozoans are so much smaller than the large molluscs studied by Flessa and Brown (1983). 4% acetic acid was too strong for bryozoans, dissolving grains so fast that a detailed dissolution history was unobtainable. The smaller volume of solution was checked by immersing 10 g of carbonate sediment into 1 l of 1% acetic acid whose pH rose from 2.6 to 3.9 in 12 h. This is a sufficiently small change that the acid will still dissolve carbonate after 12 h. All ten replicate experiments showed the same pH history, so it should not affect results. Flessa and Brown's (1983) experiment changed from pH 3 to pH 5 in 24 h.

In order to obtain an informative dissolution history, one needs a weight-loss curve with several points. Preliminary tests showed that all grains would reach at least half their original weight within 12 h. Examinations were thus made at 0.5 h intervals for the first 3 h, at 1 h intervals for the subsequent 6 h, and from then on at 3 h intervals until all specimens reached less than half their original weight. At each interval, specimens were removed from the acid, rinsed in distilled water, dried in a 40°C oven until returned to dry weight (4 to 5 min), weighed, examined, and described. The skeletal sets were then re-immersed and the whole bath was stirred. After a total of 390 min, all specimens having reached at least one half their original weight, the remaining specimens were collected and dried.

Measurement of dissolution rate

Dissolution rates were characterized using 3 measurements:

(1) W30 - The percent of weight lost after 30 min was calculated for each specimen and the mean for each species determined. This measure describes only the preliminary dissolution history, but is unlikely to be affected by changes in pH over time in the acid bath.

(2) DHL - Dissolution half-life, the time required for a specimen to reach half of its initial weight, was interpolated from graphs of dissolution curves. The mean DHL was calculated for each species.

(3) TTD - Total time of dissolution was recorded for each specimen and a mean calculated. In practice, TTD is the sample time at which it was no longer possible to weigh the specimen.

Statistical methodology

In any natural system it is expected that there is some variation within species because not all specimens are exactly equal. Hence ten replicates of each species were dissolved. This makes comparison of species more reliable.

It is necessary to distinguish between genuine physical and chemical effects and unpredictable random effects such as small variations in pH. To accommodate this an analysis of covariance (Neter and Wasserman, 1974) was used to test the effects of various characteristics of the specimens on their dissolution rate. The analysis of covariance was run using the GLM procedure of SAS software (SAS Institute, 1985).

DHL was used as the measure of dissolution to be analyzed, and the initial weight of each specimen was set to be a covariate, that is, it is agreed to be of importance and therefore must be part of the analysis, but it is not one of the variables in which we are particularly interested. Mineralogy, morphology, and their interaction were the other variables used.

Patterns of dissolution

Typical specimens were selected, then partially dissolved. They were mounted, sputter-coated with gold, and photographed using a scanning electron microscope.

3. Results

Dissolution histories

The results (Appendix Tables A4.6 and A4.7) show that considerable variation in dissolution rate exists among different species. Cumulative percent weight loss of each specimen over time is non-linear, probably due to changes in pH (for all curves, see Appendix Figure A4.2). Mean cumulative percent weight loss curves for each species are shown in Figure 4D.2.

Dissolution parameters

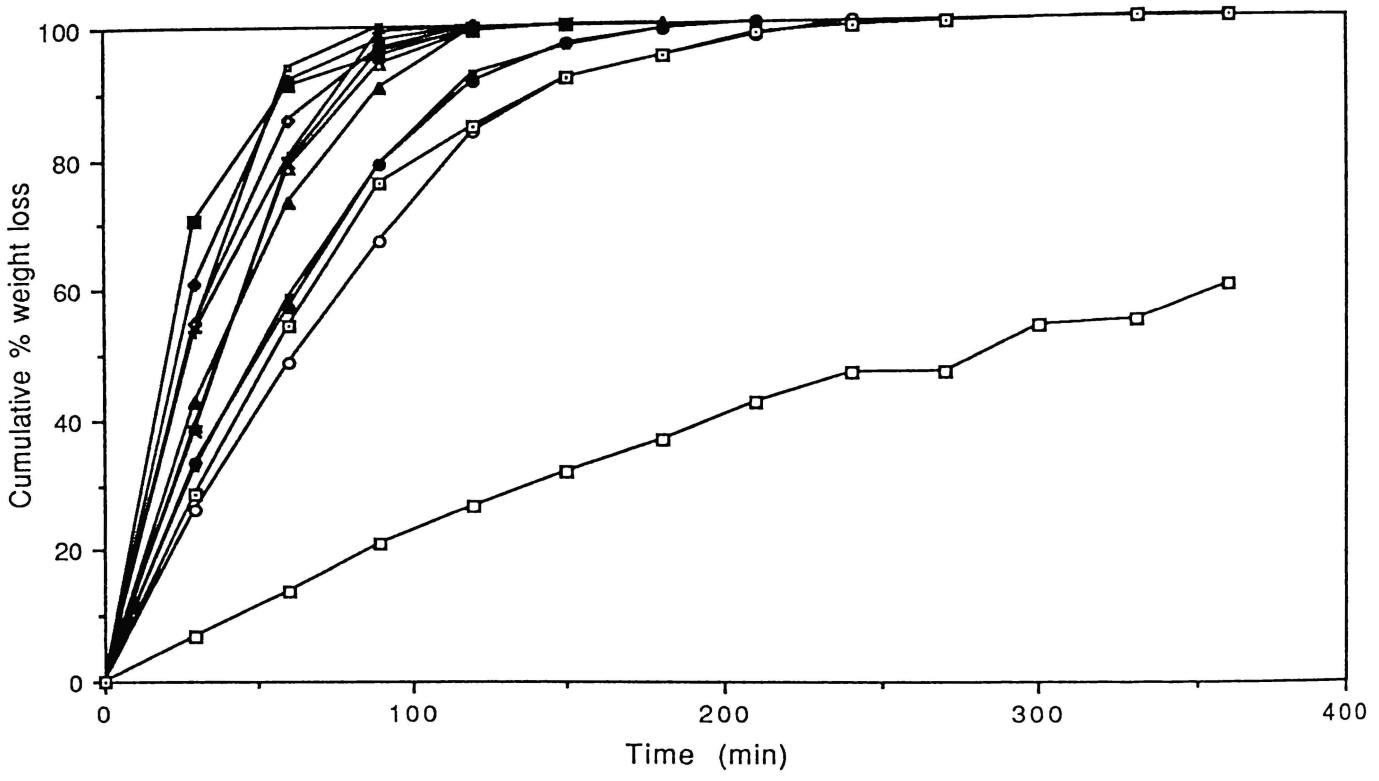
The three dissolution parameters calculated for each specimen (in Appendix Table A4.8) were then averaged to find a mean for each species (Table 4D.2). They exhibit similar patterns (Figure 4D.3).

Statistical analysis

Individual comparisons for each shape and mineralogy class were calculated, using the t-statistic. Results are given in Figure 4D.4. It shows that the difference in dissolution half-life (DHL) between the different mineralogies in morphological class 3 (robust branching) is not significant. Of particular interest is the fact that only shape class 2 (planar) reacts as one might have anticipated, with the more stable carbonate mineralogies showing a slower dissolution rate. In the delicate branching class and the compact solid class, the hierarchy of DHL is in fact reversed on the basis of mineralogical stability alone. This is clearly shown by the extremely long-lasting nature of *Otionella squamosa*, which is nearly all aragonite, but very compact. Table 4D.3 shows clearly that all four variables in the analysis of covariance are important in predicting dissolution half life.

Patterns of dissolution

Different growth forms dissolved in different patterns (Table 4D.4). It would be useful to extend the scope of this experiment to determine if these are common within growth forms. In all cases, however, the main effect of dissolution was the loss of identifiable features (Figure 4D.5).



	Growth form	Mineralogical class
Adeonellopsis sp.	ERro	B / A
Celleporina costazii	ENml	hi C
Chiastosella splendida	ENul	hi C
Foveolaria cyclops	ENul	hi C
Galeopsis porcellanicus	ERde	hi C
Hornera sp.	ERro	lo C
Iodictyum yaldwini	ERfe	hi C
Lichenopora sp.	ENra	mod C
Mecynoecia purpurascens	ERde	lo C
Otionella squamosa	FLmo	B / A
Steginoporella magnifica	ENul	mod C
Steginoporella neozelanica	EFrt	mod C
Telopora buski	ERra	lo C

Figure 4D.2: Mean cumulative percent weight loss curves for each of 13 species of New Zealand bryozoans subject to dissolution.

Table 4D.2: Mean dissolution parameters for dissolved bryozoan species.

Bryozoan species	Abbreviation in Figure 4D.3	Morph. class	Min. class	Mean DHL (min)	Mean TTD (min)	Mean W30 (%)
Adeonellopsis sp.	As	3	4	50	153	34
Celleporina costazii	Cc	4	3	66	180	26
Chiastosella splendida	Cs	2	3	30	93	54
Foveolaria cyclops	Fc	2	3	24	84	71
Galeopsis porcellanicus	Gp	1	3	40	75	38
Hornera sp.	Hs	3	1	51	165	33
Iodictyum yaldwyni	Iy	3	3	57	180	29
Lichenopora sp.	Ls	4	2	28	63	55
Mecynoecia purpurascens	Mp	1	1	30	63	61
Otionella squamosa	Os	4	4	283	390+	7
Steginoporella magnifica	Sm	2	2	33	114	43
Steginoporella neozelanica	Sn	3	2	39	114	39
Telopora buski	Tb	1	1	28	88	55

Morphology and mineralogy classes as in Table 4D.1.
DHL - Dissolution half-life, TTD - Total time to dissolution, W30 - % wt lost at 30 min.

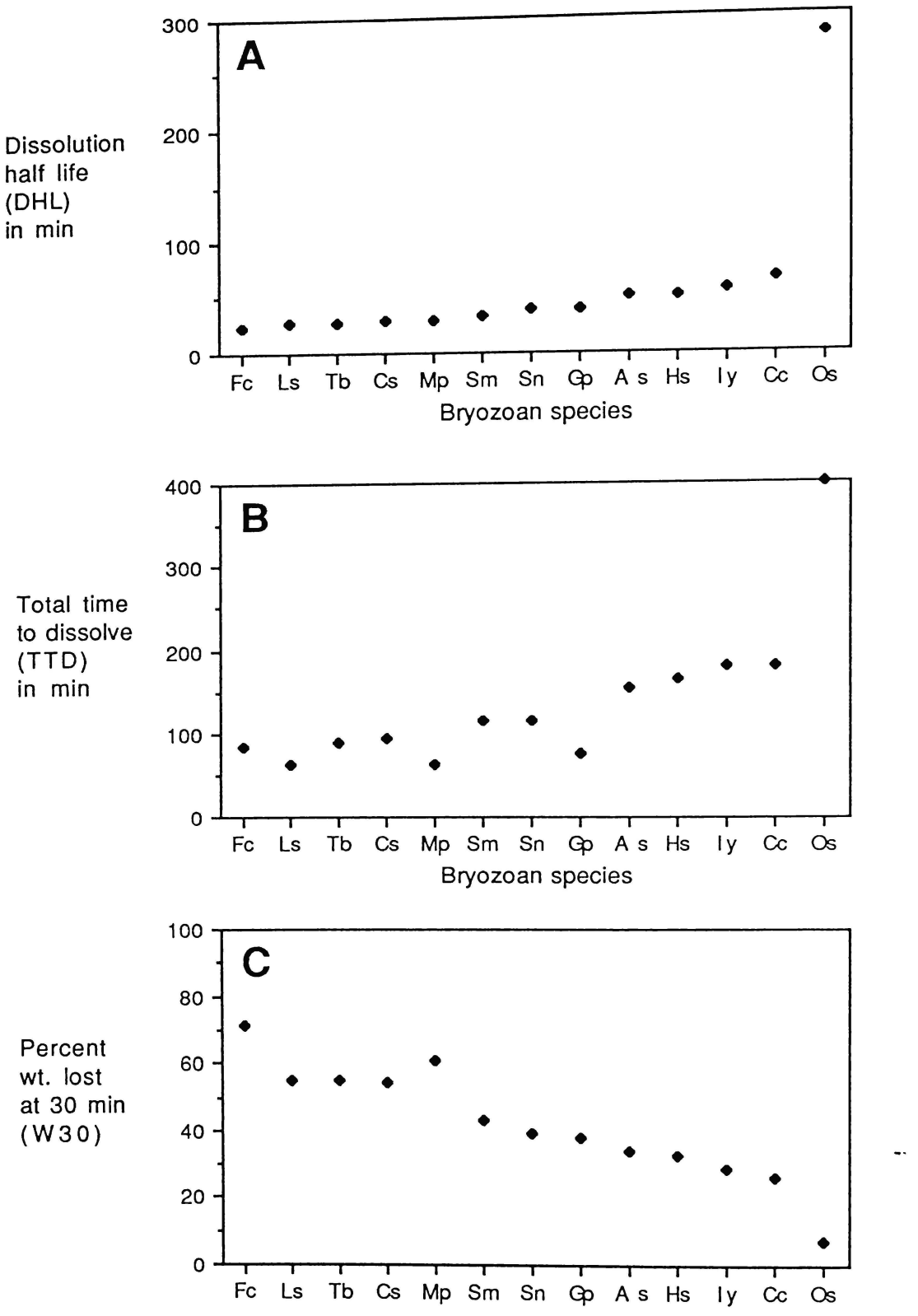


Figure 4D.3: Dissolution parameters for each of 13 species of New Zealand bryozoans. Abbreviations for species defined in Table 4D.2.

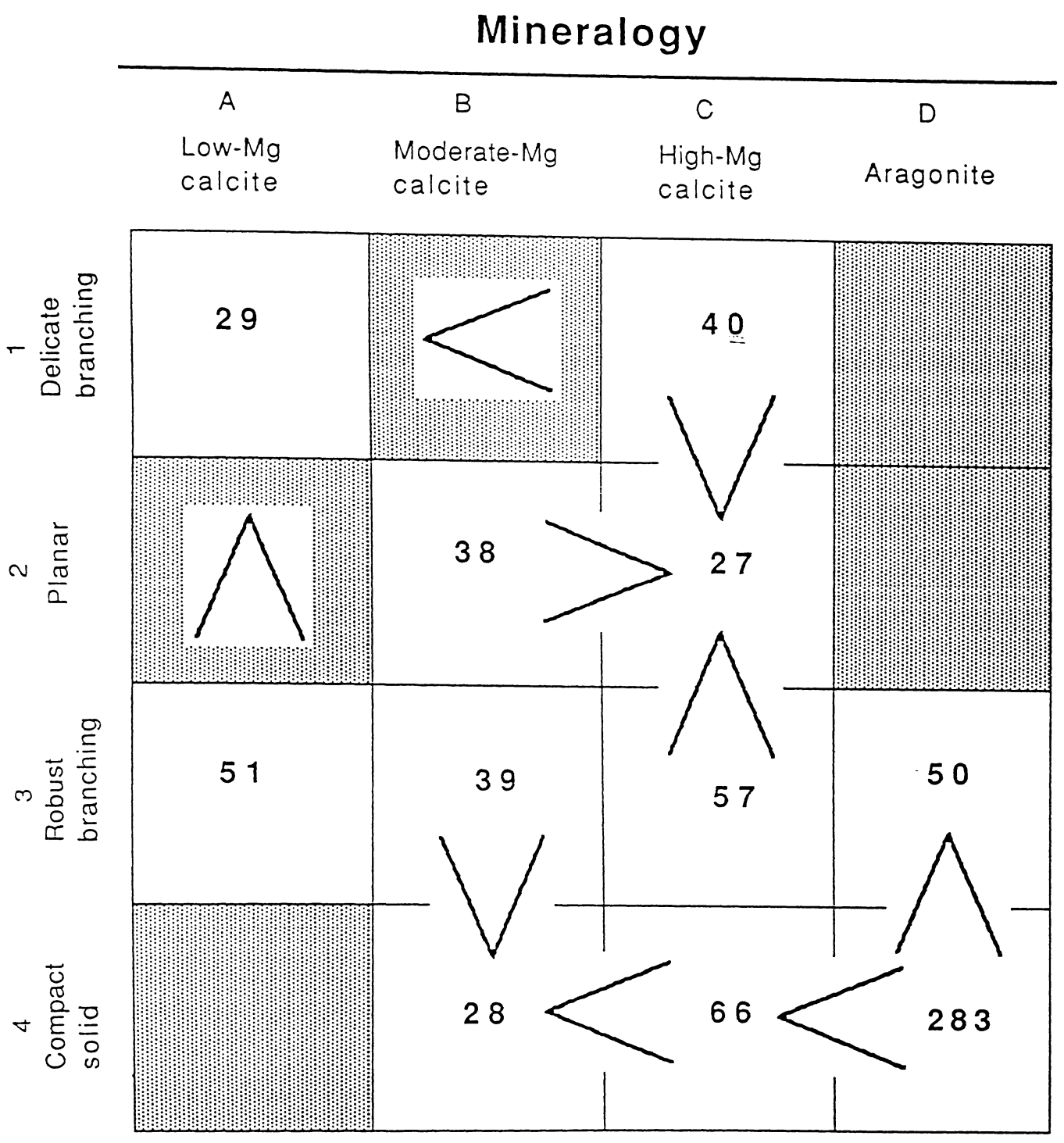


Figure 4D.4: Significant differences in dissolution half-life between the mineralogical and morphological classes of bryozoans. Mean dissolution half-life (DHL) is shown in minutes for each class of tested bryozoans. Greater than and less than symbols are entered only to indicate statistically significant differences in DHL between classes. Where no symbol appears, DHLs are not significantly different.

Table 4D.3: Statistical results of analysis of covariance, using log of DHL to satisfy assumption of variance homogeneity.

Variable	F-value	p-value
Morphology	15.47	0.0001
Mineralogy	24.52	0.0001
Min/Morph interaction	11.34	0.0001
Initial weight	19.64	0.0001

Table 4D.4: Patterns of dissolution in some bryozoans.

Species	Initial reaction	Later reaction
Adeonellopsis sp.	thins	become even thinner
Celleporina costazii	loses surface structure	becomes a smooth sphere
Chiastosella splendida	thins	crumbles
Foveolaria cyclops	thins	crumbles
Galeopsis porcellanicus	branches break off	crumbles to bits
Hornera sp.	no immediate change	thins
Iodyctyum yaldwynii	thins	crumbles but still identifiable
Lichenopora sp.	thins, crumbles	
Mecynoecia purpurascens	branches break off	crumbles to bits
Otionella squamosa	loses whole layers	gets sugary, nucleus protrudes
Steginoporella magnifica	thins	crumbles
Steginoporella neozelanica	thins, holes enlarge	becomes even thinner
Telopora buski	loses fingers	crumbles to bits

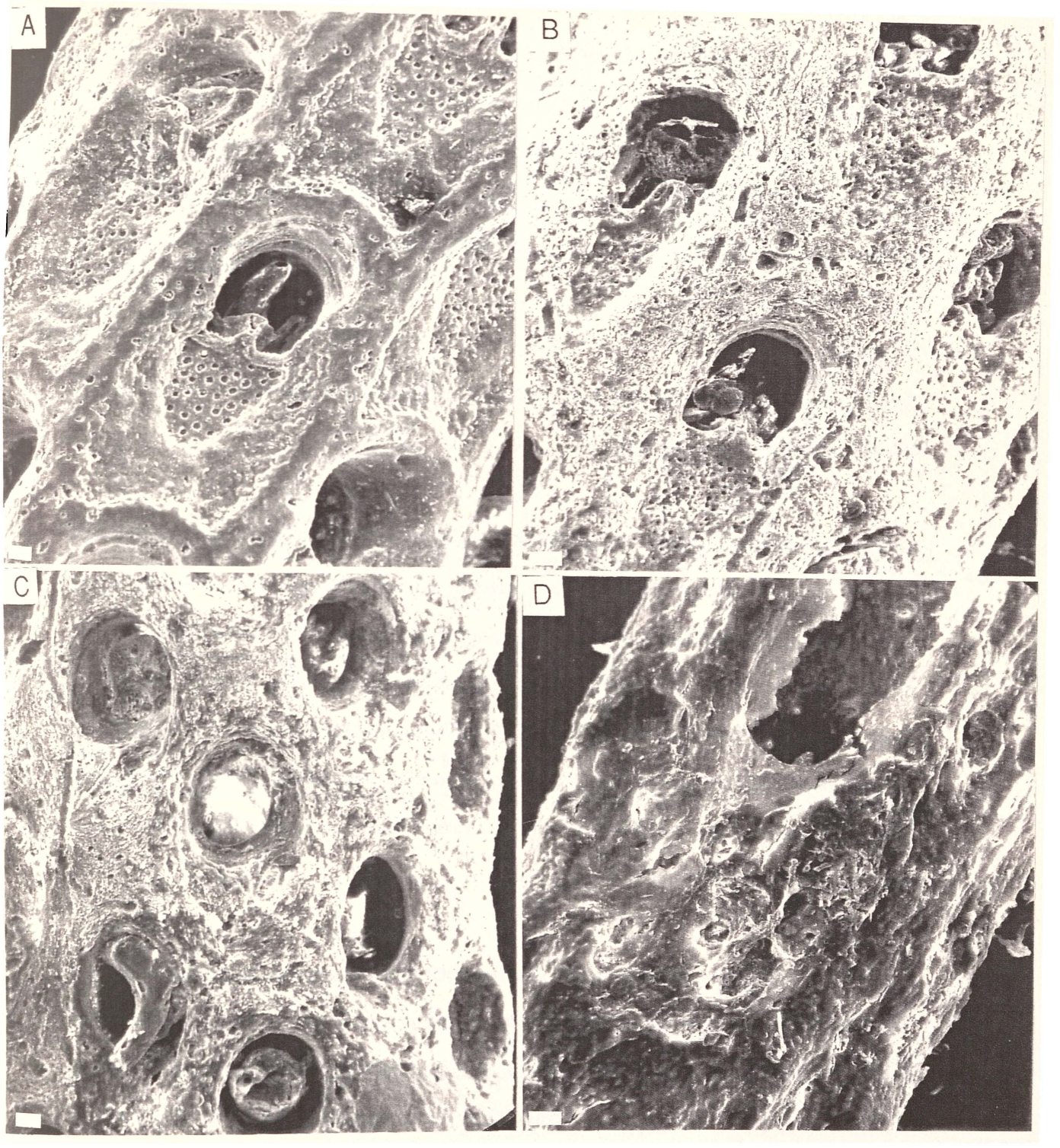


Figure 4D.5: Changes in *Steginoporella neozelanica* with increasing dissolution. A - Specimen removed from sediment and cleaned. B - Specimen in 1% acetic acid for 30 min, 86% of original weight. C - Specimen in acid for 60 min, 80% of original weight. D - Specimen in acid for 90 min, 60% of original weight. Scale bar = 0.1 mm.

Influences on dissolution of bryozoans

If dissolution rate were dependent entirely on mineralogy, one would expect an increase in DHL with decreasing wt% $MgCO_3$, and that aragonite species would have quite low DHLs. This does not occur. If shape were the major determining factor, one would expect an increase in DHL with increasing compactness of growth form. This does occur in some groups.

Two examples illustrate the relative importance of shape and mineralogy in determining rate of dissolution.

Chiastosella splendida and *Celleporina costazii* have very similar mineralogies, but are of very different shapes (Figure 4D.6). If mineralogy were the dominant determinant of dissolution, one would expect these two bryozoans to share similar dissolution histories. However, *C. costazii* dissolves more slowly than *C. splendida*. Each measure of stability (DHL, TTD, W30) reflects the same degree of difference: *C. costazii* is nearly twice as resistant to dissolution as *C. splendida* (Figure 4D.6). This difference in dissolution behaviour may be explained by the initial shapes of the two species, or by the difference in initial weight.

It is also constructive to look at two species with similar growth forms but different mineralogies. *Hornera* sp. and *Adeonellopsis* sp. are both erect, robustly branching forms. *Adeonellopsis* is the least mineralogically stable bryozoan in this study, being mainly aragonite with small amounts of moderate-Mg calcite. *Hornera* is mineralogically highly stable, consisting of low-Mg calcite (Figure 4D.7). Thus, one would expect *Adeonellopsis* to be far more prone to dissolution than *Hornera*.

In fact, it is statistically impossible to differentiate between *Adeonellopsis and Hornera* based on the dissolution parameters (Figure 4D.7). The two species have dissolved at effectively the same rate, despite the fact that *Adeonellopsis* generally had a lower initial weight than *Hornera* to begin with.

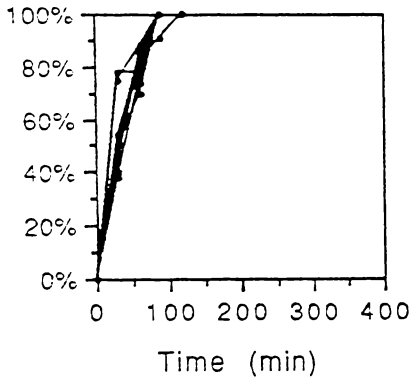
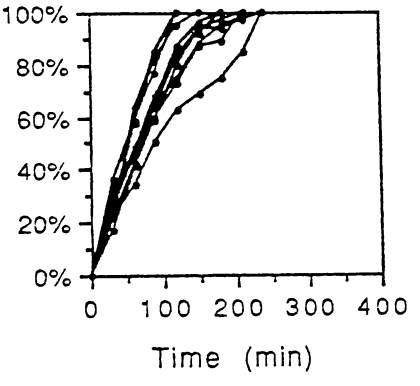
	Chiastosella splendida	*Celleporina costazii*
Mineralogy	Nearly always calcite (mean 86.3%) Moderate-Mg content (mean 5.7 wt% MgCO3)	Nearly always calcite (mean 98.7%) Moderate-Mg content (mean 5.6 wt% MgCO3)
Morphology	Unilaminar Encrusting on a surface Planar fragments	Multilaminar Encrusting around a nucleus Roughly spherical compact solid
Mean initial weight	12 mg	29 mg
Cumulative percent weight loss curves		
Dissolution parameters mean DHL mean TTD mean W30	 30 min 93 min 53.50%	 66 min 189 min 26.50%

Figure 4D.6: Data and results for two species of bryozoans that have similar mineralogy but different morphology.

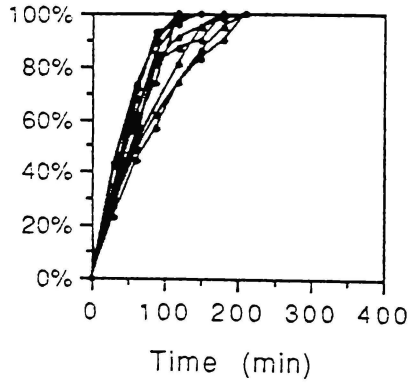
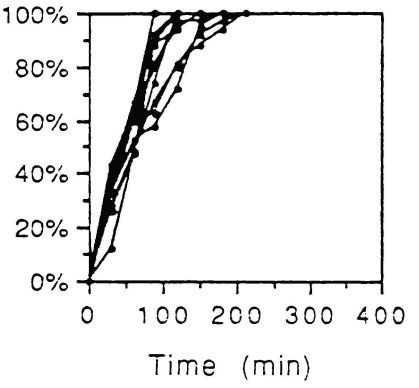
	Hornera sp.	*Adeonellopsis* sp.
Mineralogy	Always calcite (mean 100%) Low-Mg content (mean 1.4 wt% MgCO3)	Mainly aragonite (mean 3% calcite) Moderate-Mg content in calcite (mean 5.7 wt% MgCO3)
Morphology	Robust branching	Robust branching
Mean initial weight	45 mg	21 mg
Cumulative percent weight loss curves		
Dissolution Parameters		
mean DHL	51 min	50 min
mean TTD	165 min	153 min
mean W30	32.50%	33.50%

Figure 4D.7: Data and results for two species of bryozoans that have similar morphology but different mineralogy.

These examples seem to show that, in bryozoans at least, shape (reflecting surface area) is a more important control on dissolution rate than mineralogy. A simple model in which mineralogical stability affects dissolution rate is not sufficiently detailed. The analysis of covariance shows that other factors must be considered, including morphology, initial weight, and the interaction of mineralogy and morphology.

Dissolution of other skeletal carbonates

A similar conclusion was reached by Flessa and Brown (1983) concerning the dissolution rates of 16 macro-invertebrate carbonate skeletons. For example, although a low-Mg calcite oyster was the slowest to dissolve, the fastest dissolving of their samples was a low-Mg calcite barnacle plate. The barnacle was 20 times more soluble than the oyster, despite being of similar mineralogy. Intermediate in dissolution rate were skeletons of aragonite and of higher-Mg calcite. Flessa and Brown (1983) explained these effects in terms of surface area presented to the solution, determined by the shape of the skeletal remains of the organisms.

Factors besides shape and mineralogy may be important in whether a sediment grain dissolves or not and, if so, how fast. Degree of infilling is important in organisms with hollow spaces, such as foraminifera (Keir and Hurd, 1983). Porosity and surface architecture will affect dissolution (Chave, 1964). In addition, microstructure, roughness, and grain size have been found to be important (Walter and Morse, 1984). Other structural features such as organic coatings and even crystallite morphology (Henrich and Wefer, 1986) may influence dissolution. Marine bryozoans are usually highly porous, having very detailed and complex surface architecture. While there is variation in growth form, however, there does not appear to be a great difference among species in overall surface complexity.

Dissolution of carbonate in temperate waters

In temperate shallow marine environments, diagenesis has been described as both constructive and destructive. Cementation is rare, but has been noted (Alexandersson, 1974; Rao, 1981a). Most commonly, however, temperate-latitude diagenesis has been labelled as destructive, involving abrasion, bioerosion (Young and Nelson, 1988), maceration (sensu Alexandersson, 1979), and dissolution, particularly affecting the mineralogically metastable carbonate skeletons (Nelson, 1988a). Alexandersson (1978a, b, 1979) described the symptoms of undersaturation in carbonate sediments from the Skaggerak: etching, corrosion of margins, internal dissolution, and eventual disintegration of biogenic carbonate grains into their component pieces. By interpretation of petrographic state he characterized the diagenetic regime to be strongly destructive and attributed this to dissolution due to undersaturation of sea water with respect to calcium carbonate. In the Baltic Sea, Lewy (1975, 1981) attributed the fragility of skeletal carbonates to destruction by micro-organisms of organic sheaths and internal organic lamellae. He also, however, invoked dissolution to account for etching and some of the damage observed. Others (e.g., Young and Nelson, 1988; Blom and Alsop, 1988) have placed greater emphasis on bioerosion as an agent of shell degradation in temperate-latitude deposits.

Pytkowicz (1965) showed that outer-shelf depth waters (>100 m) in the southeast Pacific were undersaturated with respect to $CaCO_3$. Peterson (1966), however, found no undersaturation above several 100 m depth and Berger (1970) found undersaturation only below about 1000 m. It is thus problematic whether or not shallow temperate waters are undersaturated with respect to calcium carbonate. If they are, it seems most likely that undersaturation occurs periodically, probably with changes in temperature, as suggested by Lewy (1975). Nevertheless, undersaturation leading to dissolution has been observed in some shallow temperate locations (Chave et al., 1962; Chave, 1964; Lewy, 1975, 1981; Alexandersson, 1978a; Aller, 1982; Nelson and Bornhold, 1983).

Patterns of dissolution

The fact that different growth forms go through different processes of disintegration while under the influence of dissolution may be of interest to paleoecologists. If differential dissolution behaviours were known in detail among growth forms, it might be useful for interpretation of relative ages or relative time spent in undersaturated waters. Also, some growth forms may remain recognizable longer than others, thus biasing the fossil record.

Taphonomy of dissolution

If dissolution were occurring regularly on temperate shelves, it would be a significant factor in reducing the number of organisms that pass into the fossil record over time. As a potential taphonomic process it deserves greater study. Indeed, there is indirect evidence for dissolution on temperate shelves in the rock record in the form of nontropical carbonate deposits with mineralogically-biased fossil assemblages, limited numbers of species, and/or corroded and otherwise damaged shells, all of which point to submarine (sea-floor) dissolution (e.g., Beu et al., 1972; Nelson, 1978). On the Scott shelf, Canada, for example, Nelson and Bornhold (1983) inferred that high-Mg calcites lose their Mg by incongruent dissolution and that aragonitic skeletons dissolve preferentially. A comparable situation has been reported from New Zealand shelf carbonates (Nelson et al., 1988b). Throughout the rock record, the disappearance of aragonitic forms has been documented (e.g., Chave, 1964) and it is assumed that this is mainly due to dissolution acting on the metastable aragonite.

Dissolution is thus a taphonomic process; it is one of the natural filters limiting the completeness of the fossil record (Figure 4D.8). In addition to reducing the skeletal remains available for fossilization, dissolution adds calcium carbonate to the sea for future calcification. Fossil assemblages reflect a mineralogical filter, for example aragonitic organisms are either recrystallized or absent in many fossil assemblages (e.g., Beu et al., 1972). However, in taxa like the bryozoans, where there is considerable variation in shape, morphology may also be of importance in

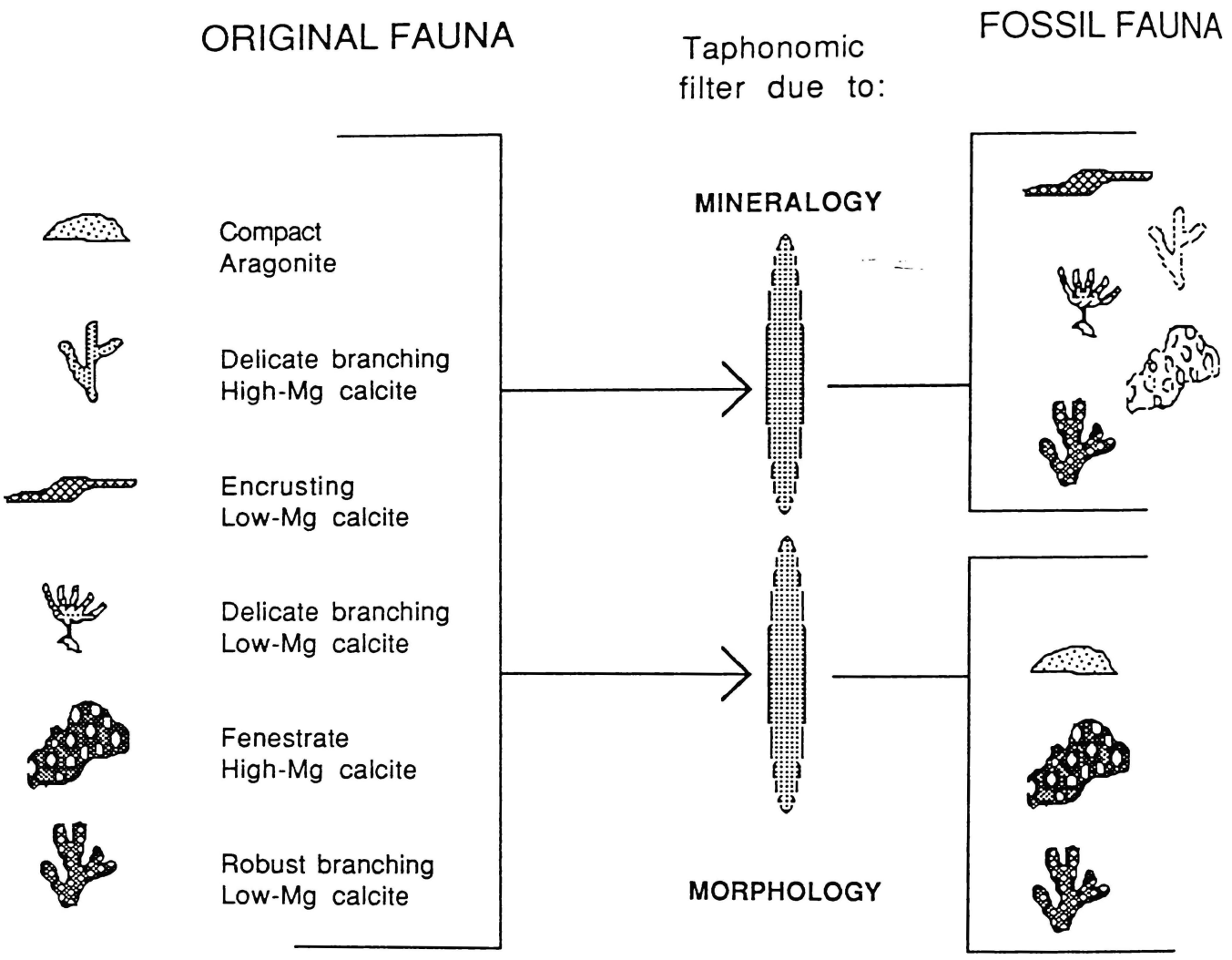


Figure 4D.8: Dissolution taphonomy of bryozoans. A theoretical fauna is preserved differently depending on the relative importance of mineralogy or morphology as a filter. Dashed outlines indicate Mg leached.

determining the fossilization potential of an individual or colony. These two different "filters" would deliver very different fossilized faunas from the same population.

On tropical shelves, dissolution of calcium carbonate is uncommon and early submarine cementation may protect small delicate colonies. Temperate shelf waters, however, are less saturated and sometimes periodically undersaturated with respect to calcium carbonate and may show some dissolution of carbonate sediments. This difference may be reflected in the fossil record. It may be possible to interpret a bryozoan fossil record of robust and compact colonies as one in which dissolution has had its effect, and therefore as a temperate assemblage.

5. Conclusions

The results of this laboratory simulation of dissolution of bryozoan colonies show that morphology interacts with mineralogy to determine dissolution rate. Initial weight is also important. This indicates that large robust colonies are more likely to withstand dissolution than small delicate ones. This effect interacts with mineralogy to determine susceptibility to dissolution. Other temperate-marine taxa have also been shown to dissolve in response to factors other than mineralogy.

Dissolution patterns and differential resistance to dissolution may result in certain growth forms surviving into the fossil record, whereas others may not. Fossil assemblages from temperate-marine shelf environments may therefore not only reflect loss of aragonitic species, as is well known, but also the loss of small delicate specimens. This may well be a difference in character between tropical and temperate assemblages. A further discussion of the bryozoan fossil record will be made in Chapter 11.

Part Two Carbonate Sediments of the Hauraki Gulf

Bryozoans are major components of many of New Zealand's shelf carbonates. These have been investigated from Three Kings Plateau (Nelson et al., 1982) to the Snares Platform (Head, 1985), including Otago shelf (Probert et al., 1979) and the Wanganui Basin (Gillespie, in prep.) (see Figure IC.1). Most of these deposits vary from 50 to 95% $CaCO_3$, and bryozoans average 20 to 40% of the skeletal fraction (Nelson et al., 1988b). The less-extensive Hauraki Gulf carbonate deposits are of interest as they include more terrigenous material and are very patchily distributed within the Gulf. Based on the sediments map of Carter and Eade (1980), a program of sediment sampling was devised to sample the high-carbonate areas of the Gulf. Texture, carbonate content, skeletal components, and ages of the sediments were determined, and facies described. An investigation into bioerosion of carbonate in the Gulf was also undertaken.

Chapter 5 describes the study area, and Chapter 6 gives the results of analysis of sediments. Facies are determined in Chapter 7. Bioerosion in the Gulf is considered in Chapter 8, and Chapter 9 gives an interpretation of the data, including late Quaternary history and controls on facies distribution. Later, in Chapter 12, carbonate-clastic transitions are discussed with the Hauraki Gulf as an example.

Chapter 5 Area of Study: The Hauraki Gulf

"It is the drawback of all seaside places that half the landscape is unavailable for purposes of human locomotion, being covered by useless water." *N. Douglas, Alone*

A. LOCALITY

The Hauraki Gulf is a shallow, semi-enclosed sea spanning latitudes 36°00' to 37°10'S and longitudes 174°40' to 175°30'E on the northeast coast of the North Island, New Zealand (Figure 5A.1). To the east lies the Coromandel Peninsula and to the west the North Auckland Peninsula. In the south the Gulf shallows to form the Firth of Thames, and beyond the Firth lies the Hauraki Lowland. The Gulf is thus enclosed on three sides, and is open only to the north and northeast, with Little Barrier Island and Great Barrier Island forming the seaward boundary of the Gulf. This window of exposure accounts for the Maori name "Hauraki," which means "north wind."

The Gulf has an average water depth of about 40 m. It can be divided into an inner Gulf with depths shallower than 30 m, and an outer Gulf with depths ranging from 30 to 100 m. This study is primarily concerned with the outer Gulf, incorporating the area from Tiritiri Matangi Island in the southwest to Great Barrier Island in the northeast (Figure 5A.1C).

B. CLIMATIC SETTING

The Hauraki Gulf has a temperate climate with maritime moderation. There is not much seasonal variation - the diurnal temperature range is approximately equal to the mean annual temperature range of 15 to 23°C (Morton and Chapman, 1968). Generally the area has warm summers, cool winters, and abundant rainfall (annual mean is 1165 mm) (Figures 5B.1 and 5B.2), based on data recorded at Leigh (36°16'S, 174°50'E).

New Zealand is dominantly subject to westerly winds. The Hauraki Gulf is protected from these by the land to the west. In summer, easterlies and northeasterlies become important in the Gulf, and it is from the east and northeast that most gales come

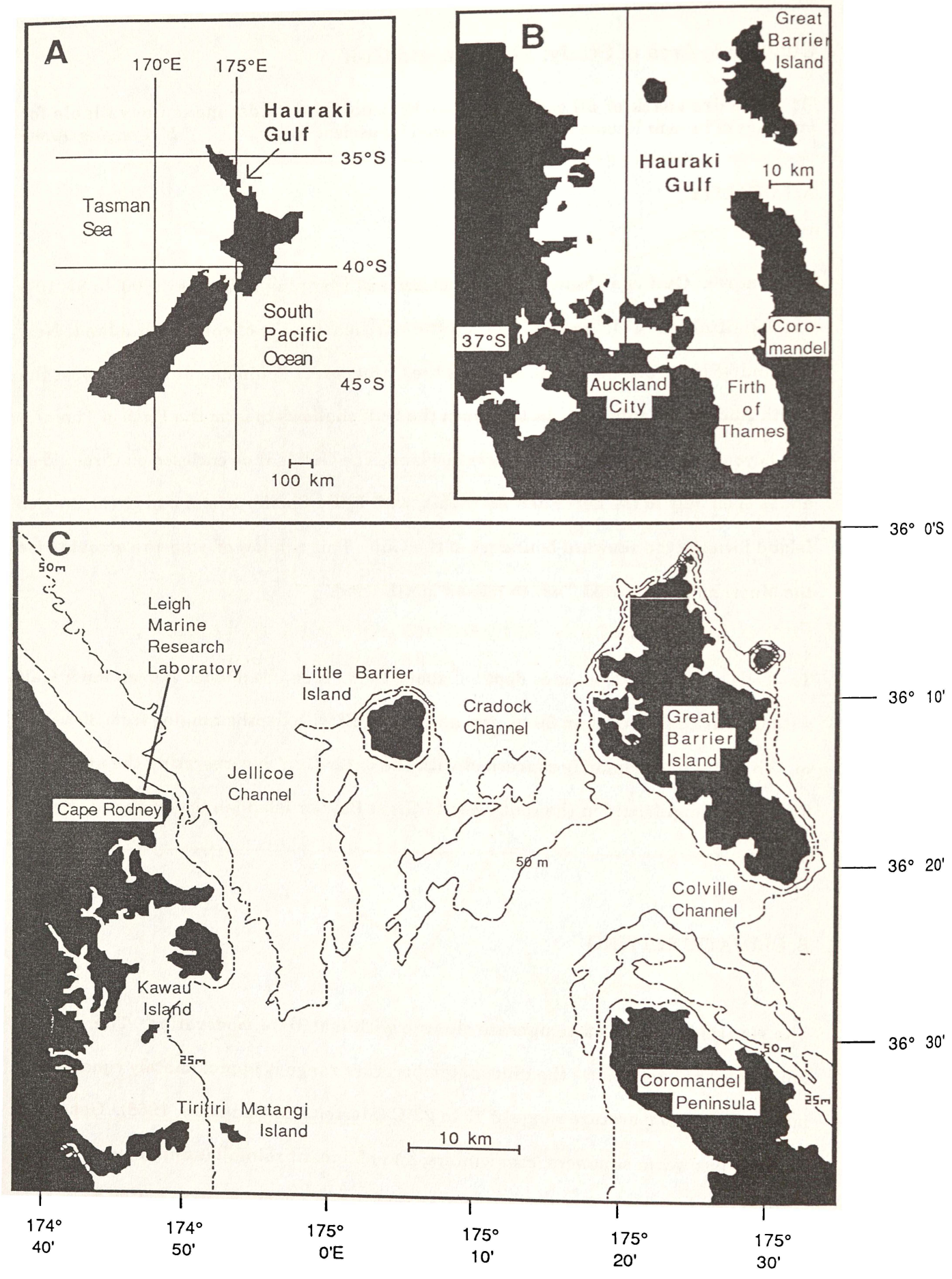


Figure 5A.1: Location of the Hauraki Gulf in New Zealand (A); the Hauraki Gulf (B); and the study area, the Outer Hauraki Gulf (C).

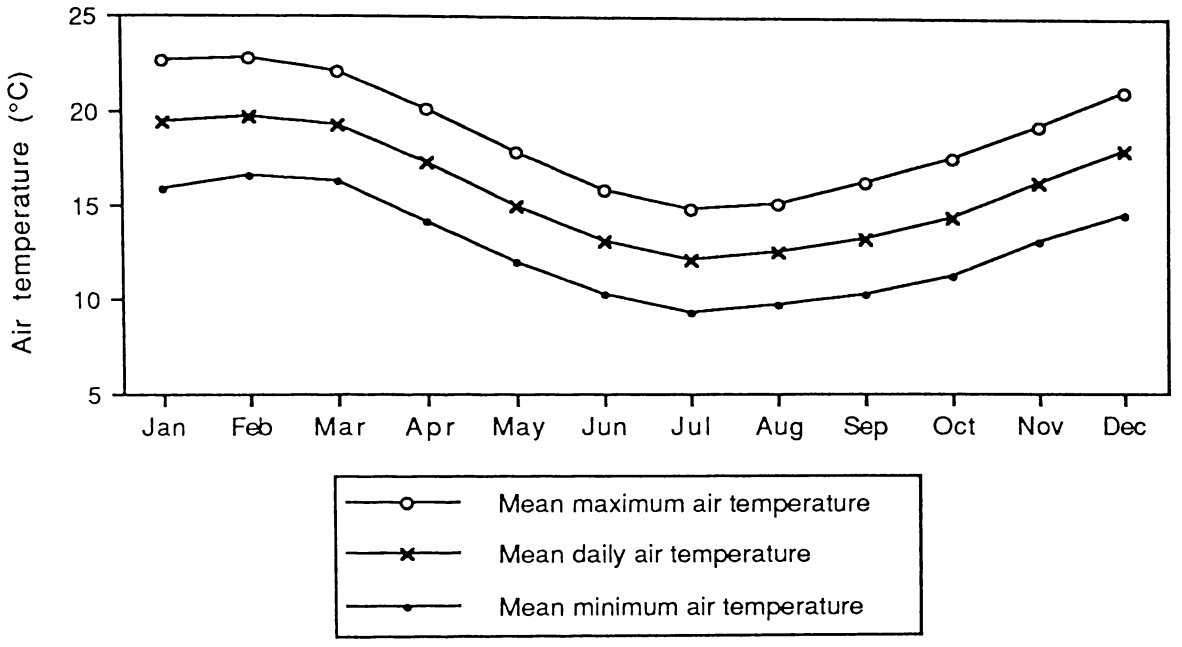


Figure 5B.1: Monthly temperature variations at Leigh. Mean taken from data for 22 years (Evans, 1990).

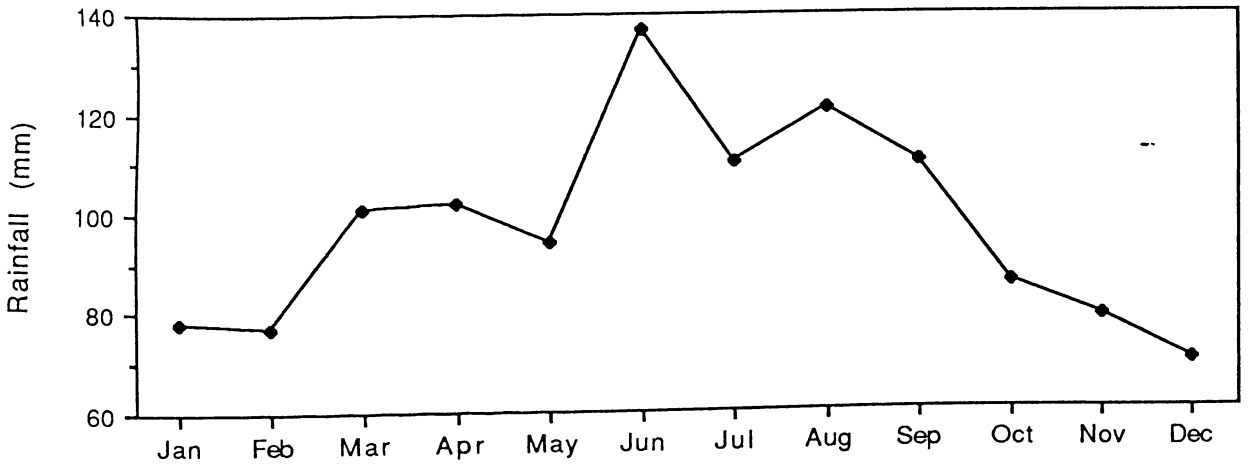


Figure 5B.2: Monthly variations in mean rainfall at Leigh, based on data for 22 years (Evans, 1990).

(Augustin, 1984) (Figure 5B.3). These onshore winds tend to hold water in the Gulf. It requires several days of offshore winds to blow surface waters out of the Gulf, to be replaced at depth by oceanic water (Jillett, 1971). A numerical circulation study in the Gulf has shown that sea surface currents are almost entirely a response to local wind direction (Proctor and Greig, 1989).

C. HYDRAULIC SETTING

1. Sea water

Sea-surface temperatures at Leigh vary from 14 °C in winter to 21 °C in summer (Figure 5C.1). Temperatures in the Gulf itself are a bit cooler (13 to 20 °C)(Jillett, 1971). Temperature profiles in the Gulf (Paul, 1968; Jillett, 1971) show a seasonal development of thermal stratification. Isothermal profiles occur in winter, but in spring a thermal gradient develops and by January a thermocline is evident. In autumn the water mixes to become isothermal again. The thermocline is irregular in depth and duration, and appears to respond to local wind direction and speed rather than any underlying circulation of water masses. Temperature varies from year to year depending on the El Nino Southern Oscillation (ENSO).

Salinity in the outer Gulf shows some minor variation (from 34.9 to 35.5 ppt). An early spring low gives way to a late autumn high, as seen in sea surface salinity measurements at Leigh (Evans, 1990) and in the Jellicoe Channel (Jillett, 1971) (Figure 5C.2). Jillett (1971) found that subsurface salinities were less variable (35.0 to 35.4 ppt at 45 m in 1964).

The inner Gulf is, understandably, much more turbid than the outer Gulf. At some times the euphotic zone in the inner Gulf may not reach bottom (Grace, 1983). In contrast, the outer Gulf is clearer and cleaner than the inner Gulf waters, irrespective of the season (Jillett, 1971). The outer Gulf does show more variation in turbidity than the inner Gulf, and is clearest in winter (Jillett, 1971).

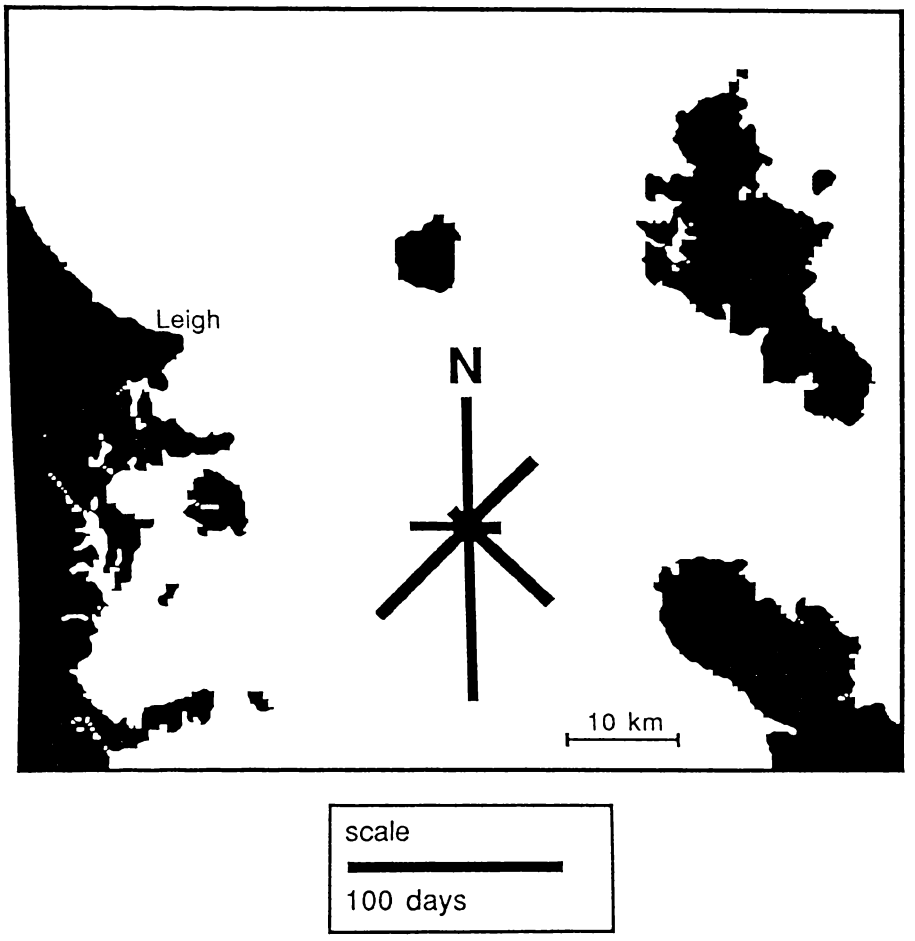


Figure 5B.3: Frequency of wind directions over Leigh. Wind directions at 9 am averaged over 15 y. Data from Augustin (1984).

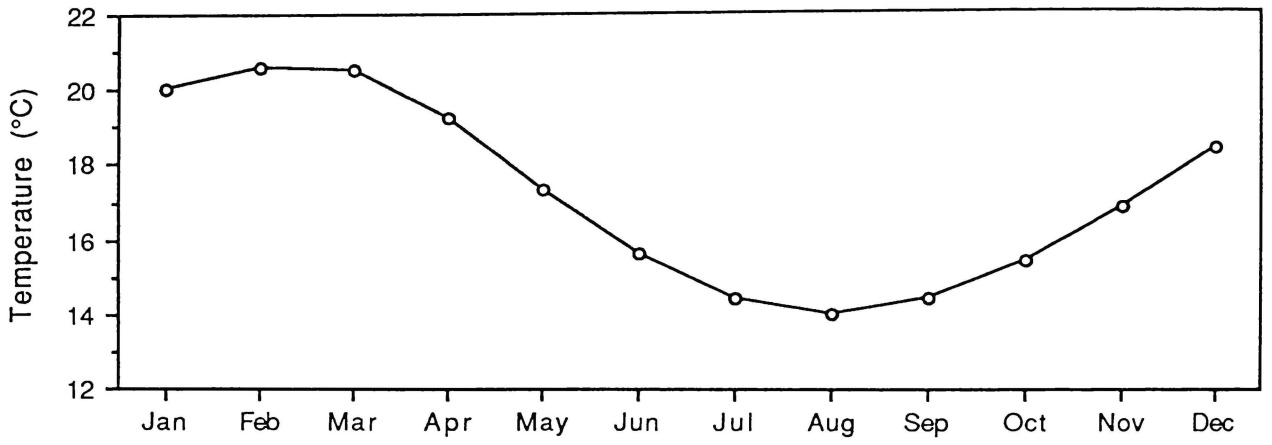


Figure 5C.1: Monthly sea surface water temperatures at Leigh. 22 year means (Evans, 1990).

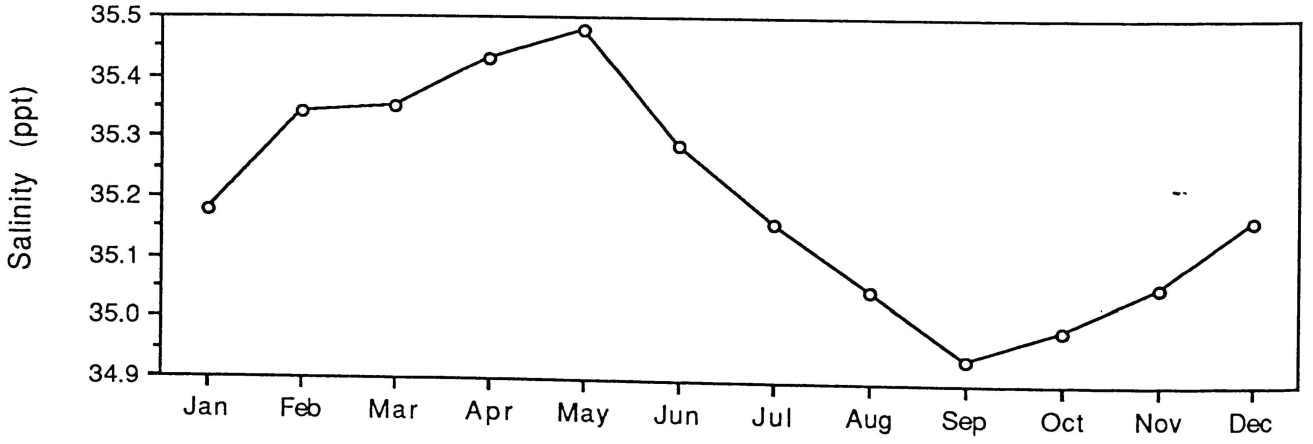


Figure 5C.2: Monthly sea surface salinity at Leigh. 22 year means (Evans,1990).

2. Waves

The Gulf's protected position limits the directions in which major waves may develop. Northeasterly swells are the most common and the largest in the Hauraki Gulf (Morton and Chapman, 1968). Rough days in which waves exceed 2 m in height occur most often in late summer. Maximum daily wave height at Leigh averages around 1.2 to 1.4 m, although in storms it can exceed 5 m. These large storm waves may create temporary high-velocity bottom currents capable of transporting sediment. They may also increase shore erosion.

A wave refraction computer simulation (run by the author using the method of Black and Healy, 1981) using data from the 18-20 July 1978 cyclone results in storm bottom velocities at Leigh ranging from 1 to 3.8 m/s (Appendix Figure A5.1). Even the most conservative values will cause sediment transport, uplift and bottom scour, at least in the shallower depths (to 23 m in the model).

3. Currents

The main oceanic current in the Hauraki region is the southeast-trending East Auckland Current (Figure 5C.3A). This current is produced by the Tasman Current interacting with the subtropical Trade Wind Drift. The East Auckland Current moves southeast and is deflected by the shelf break at the entrance to the Gulf. Most New Zealand oceanic currents are slow-moving (.03 to .08 m/s; Carter, 1975), but in storm conditions the East Auckland Current may reach 1.5 m/s to the east of Great Barrier Island (Bowman and Chiswell, 1982).

There may be some semi-permanent currents operating within the Hauraki Gulf. Proctor and Greig (1989) modelled two possibilities (Figure 5C.3B). In a wind-driven hypothesis, persistent northerly winds cause shallow water to flow into the Gulf from the north. Water flows south and then east, most of it exiting the Gulf north of Great Barrier Island, and the remainder via the Colville Channel. This is similar to the intermittent wind-driven circulation described by Greig (1990). The second hypothesis is that the East Auckland Current drives the inflow from the north, again with most of the

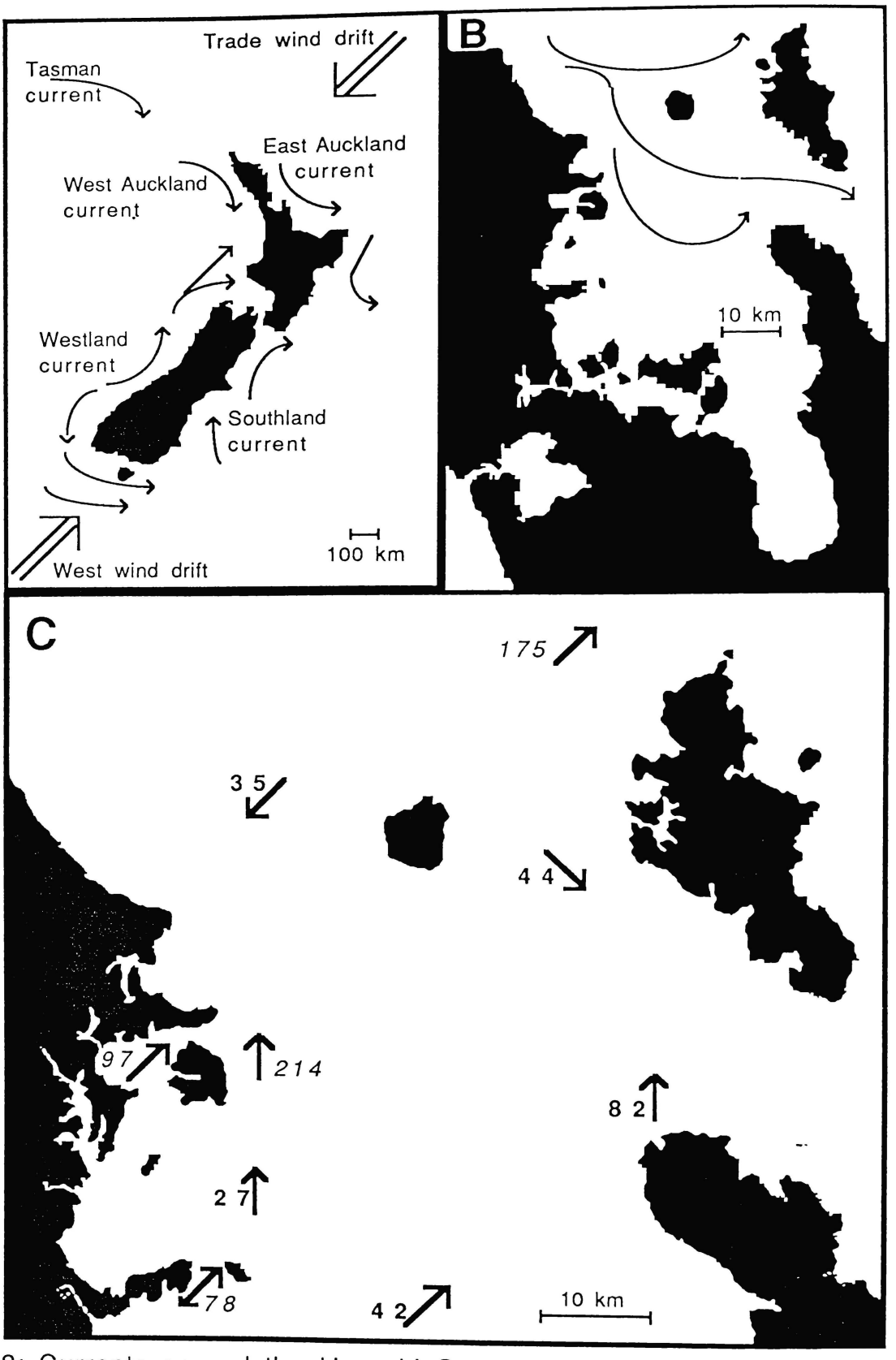


Figure 5C.3: Currents around the Hauraki Gulf. (A) Surface currents around New Zealand (Carter, 1975). (B) Theoretical wind-forced circulation in the Hauraki Gulf (Greig and Proctor, 1988). (C) Current velocities (cm/s) for several locations in the Hauraki Gulf.

Bold numbers are maxima measured with current meters in midwater (Greig, 1990); italicized numbers are maximum surface tidal streams calculated from RNZN Charts 522 and 5321.

outflow in the northeast, although some movement would penetrate as far south as Tiritiri Matangi Island before turning northeast to outflow at the Colville Channel (Proctor and Greig, 1989).

Under some wind conditions there are fairly strong (up to 30 cm/s) shore-parallel currents, particularly with northwest or southeast winds (Proctor and Greig, 1989).

4. Tides

The Hauraki Gulf is subject to a semidiurnal tide with vertical ranges of 1.9 to 2.9 m and a period of 12.42 h. A counterclockwise standing tidal wave enters the Gulf at the Colville Channel and north of Great Barrier Island. There is a net overall counterclockwise circulation (Greig, 1990). Surface spring tidal currents may be quite strong (over 2 m/s) in the Colville Channel, the Jellicoe Channel, and east of Kawau Island (Greig and Proctor, 1988). The swiftest currents occur (and are predicted by numerical models) at Cape Colville (Figure 5C.3C). Currents up to 0.82 m/s have been measured in mid- stream (Greig, 1990), which would allow initiation of transport for sand-sized material (Sternberg, 1971).

D. GEOLOGIC SETTING

1. Tectonics

The Hauraki Gulf is part of a larger tectonic feature: the Hauraki Rift. This rift extends over 250 km from Whangarei to the Taupo Volcanic Zone, and is 20 to 30 km wide (Hochstein et al., 1986). The rift is a series of basins and faults that trend NW-SE (340°), the largest of which is the Hauraki Fault. Part of the backarc region of the Hikurangi trough, it is a down-dropped basin in an extensional basin-and-range type topography (Kamp, in press).

2. Subsurface geology

Rocks in the Hauraki area are of three main types: underlying greywackes, sedimentary rock sequences, and several volcanic groups. The indurated Permian to Jurassic

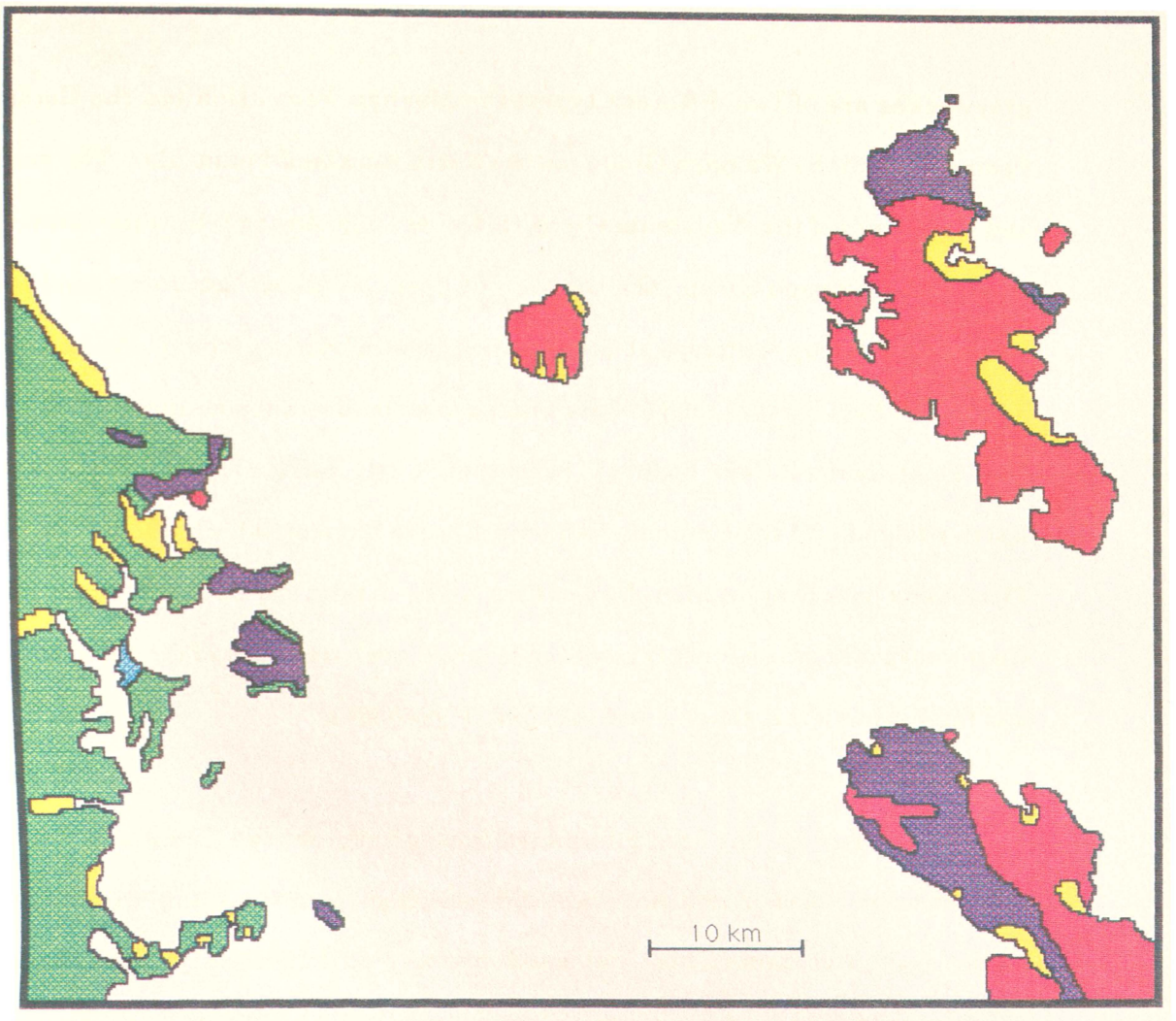
greywackes are of two different types: the Moehau Formation (on the Coromandel Peninsula) and the Waipapa Group (on the North Auckland Peninsula). The mudstones and sandstones of the Waitemata Group (of Upper Oligocene age) lie unconformably over much of the Waipapa Group. One outcrop of Upper Cretaceous micaceous sandstone (the Mangakahia Group) outcrops at Snells Beach (west of Kawau Island). Volcanics on the North Auckland coast of the Gulf are limited to a small outcrop of upper Pliocene basalt at Ti Point (south of Cape Rodney). In contrast, Little Barrier Island and much of Great Barrier Island and the Coromandel Peninsula are blanketed with Middle Oligocene to Pleistocene mainly andesitic volcanics from a now-extinct volcanic zone (Skinner, 1976). Quaternary alluvial sediments form the Hauraki lowland, south of the Firth of Thames, and flank other rivers flowing into the Gulf (Figure 5D.1).

The offshore geology has been interpreted from seismic surveys (Thrasher, 1986). Two distinct seismic "basements" have been differentiated: an igneous unit (probably related to the extinct volcanic zone) and a sedimentary unit (probably greywacke). The sedimentary record overlying seismic basement may be up to 1200 m thick (Figure 5D.2), the thickest deposit being just west of the Coromandel Peninsula (Thrasher, 1986). Much of this is likely to be Tertiary and Quaternary sedimentary deposits .

3. Surficial sediments

New Zealand shelf sediments are generally modern and relict terrigenous deposits, with only locally abundant biogenic material (Carter, 1975). Although the major carbonate sediment occurrences are located on platforms to the far north and far south of New Zealand, smaller more localized occurrences do occur in many shelf areas (Nelson et al., 1988b). Some of these lie in the Hauraki Gulf.

Surficial sediments in the inner Hauraki Gulf are terrigenous mud or sandy mud (Carter and Eade, 1980). The outer Gulf consists mainly of sand deposits, though there are large areas that are dominantly mud. Several distinct areas of calcareous sediment have been recorded to the northwest of Little Barrier Island, north and northwest of Cape Colville,



Major rock types:

- Quaternary sediments (alluvium, dunes)
- Cenozoic volcanic and associated intrusive rocks
- Tertiary sedimentary rocks
- Mesozoic micaceous sandstone
- Mesozoic greywacke and argillite

Figure 5D.1: Simplified onshore regional geology of outer Hauraki Gulf (after Thompson, 1960, 1961; Schofield, 1967; and Skinner, 1976).

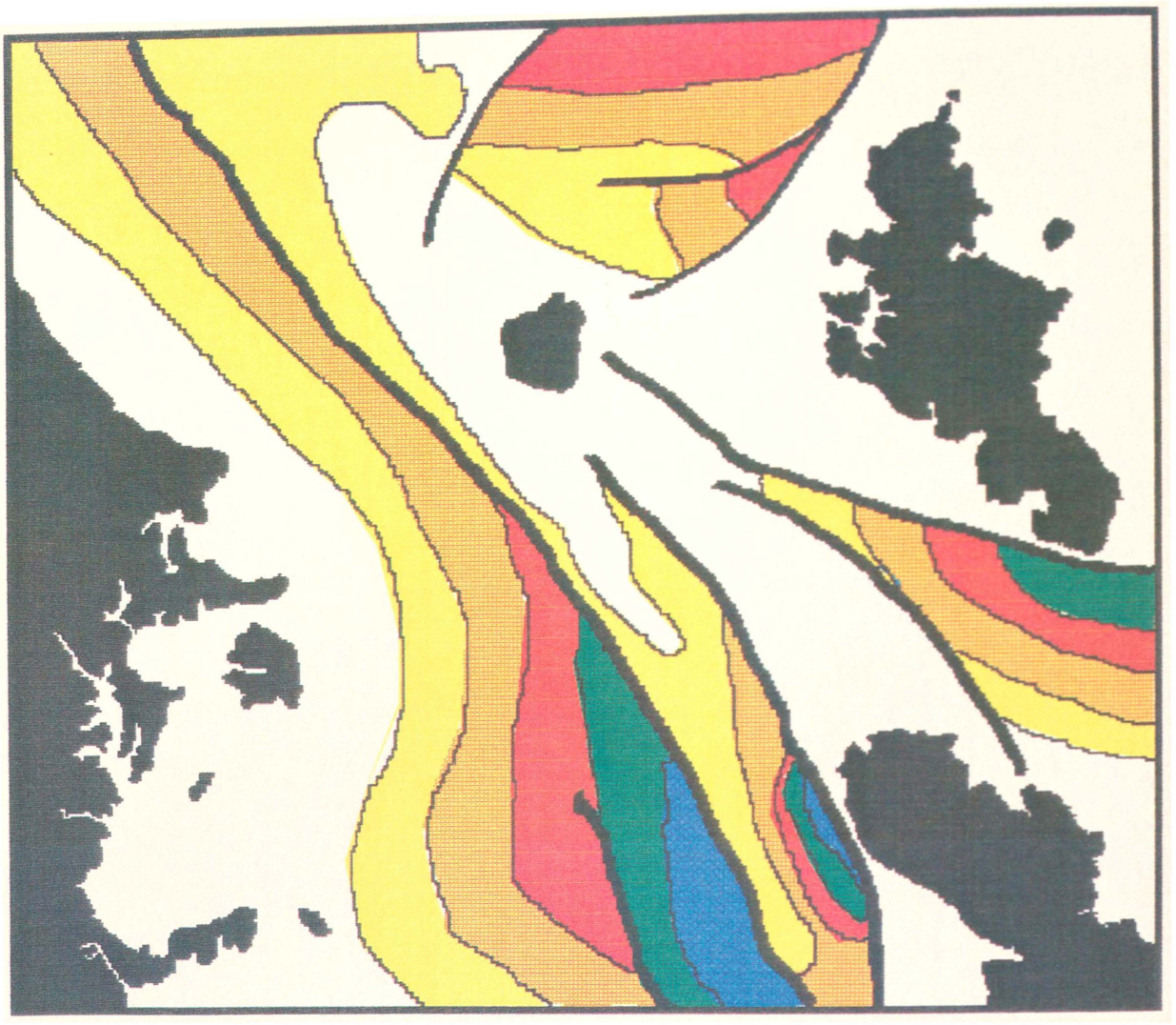
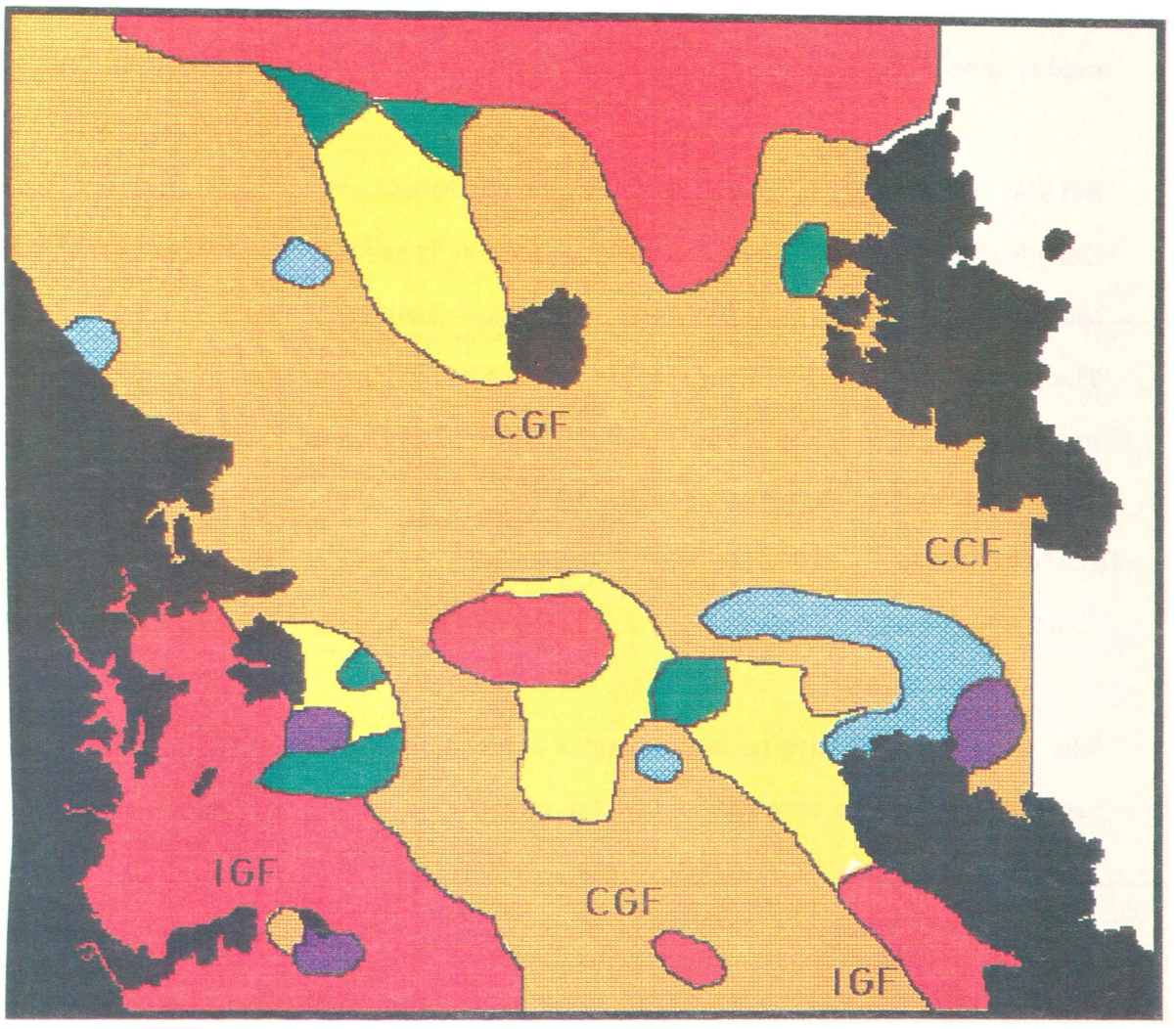


Figure 5D.2: Tertiary and Quaternary sedimentary thickness overlying seismic (and probably geologic) basement in the outer Hauraki Gulf (after Thrasher, 1986).



Major sediment types

- calc-sandy calc-Gravel
- sandy calc-Gravel
- muddy calc-Sand
- calc-gravelly calc-Sand
- terrigenous sand
- terrigenous mud

Greig's (1982) facies shown in bold print:

CCF Colville Channel Facies

CGF Central Gulf Facies

IGF Inner Gulf Facies

10 km

Figure 5D.3: Surficial sediments in the outer Hauraki Gulf (after Carter and Eade, 1980).

and southeast of Kawau and Tiritiri Matangi Islands (Carter and Eade, 1980). These areas are combinations of calc-gravel and calc-sand, usually including some terrigenous mud or sand (Figure 5D.3).

Several workers have grouped these sediments into facies. Greig (1982) defined a Colville Channel Facies of coarse skeletal-rich gravelly sand as reworked relict sediment (palimpsest), and a Central Gulf Facies made up of gravelly carbonate and muddy sand. The poorly sorted Central Gulf Facies was deposited at a lower sea level stand and is now becoming covered by modern muds similar to Greig's Inner Gulf Facies of modern terrigenous muds and sandy muds (Figure 5D.3).

E. BIOTIC SETTING

The Hauraki Gulf contains many species of marine plants and animals. The Leigh region alone contains over 900 species of described organisms, and undoubtedly that list is incomplete (Figure 5E.1). Of these, the most important numerically are the molluscs (bivalves and gastropods), followed by the arthropods (crabs and barnacles), chordates (mainly fish), and bryozoans (sometimes called moss animals). In terms of carbonate sediment production, the molluscs, barnacles, and bryozoans are the important contributors.

F. PURPOSE

The purpose of Part Two of this study is to describe and characterize the carbonate sediments of the outer Hauraki Gulf. It will include results of analysis of sediments collected from the Hauraki Gulf (presented in Chapter 6); descriptions of carbonate facies present in the outer Gulf (Chapter 7); and discussion of implications of these facies in terms of overall sedimentology of the Gulf (Chapter 9). The relation of the Hauraki Gulf carbonates to other carbonate deposits found in mixed terrigenous/biogenous settings and discussion of these and the temperate carbonate sediment model will be addressed later in Chapter 12.

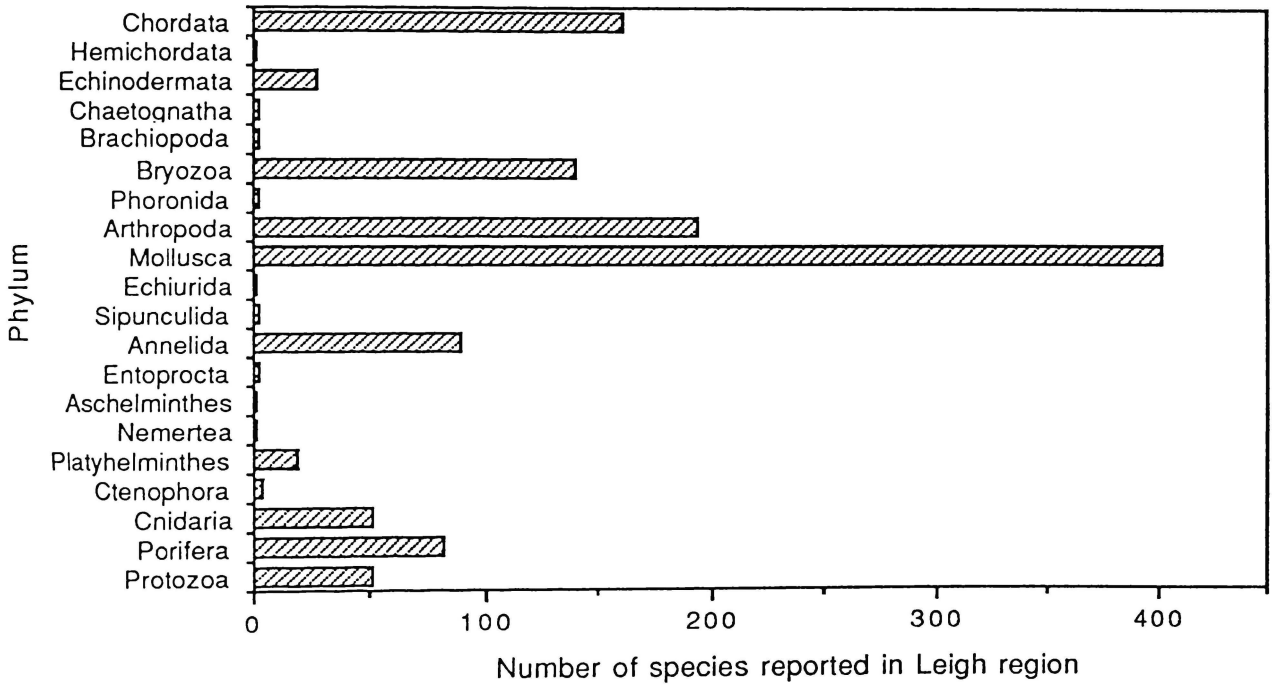


Figure 5E.1: Occurrence of marine phyla in the Leigh region (data collected over 16 years, in Ballantine and Gordon, 1979).

Chapter 6 Sediment Characteristics

"The Walrus and the Carpenter were walking close at hand.
They wept like anything to see such quantities of sand:
'If this were only cleared away,' they said, 'it would be grand!'"

Lewis Carroll, Through the Looking Glass, 1872

A. SAMPLE COLLECTION

Sediment samples were collected from the vicinity of the high-carbonate areas defined on Carter and Eade's (1980) map of the surface sediments of the outer Hauraki Gulf (Figure 5D.3). 146 samples were taken from southeast of Tiritiri Matangi Island (T samples), the Colville Channel (C samples), southeast of Kawau Island (K samples), and northwest of Little Barrier Island (L samples) (Figure 6A.1). They were collected using a Smith-McIntyre grab sampler from the University of Auckland Research Vessel *Proteus* and the trawler *Defender* out of Whitianga. The Smith-McIntyre grab sampler generally collects about 2 kg of sediment. Sample locations were determined by radar. Another 50 samples were requested from University of Auckland archives and the New Zealand Oceanographic Institute collections. They were small splits of larger samples and were primarily used as supplements to the complete samples collected, and to determine where those sediment samples should be taken. Photographs and descriptions of two cores were requested from the New Zealand Oceanographic Institute collections (see Figure 9B.2). Details of the locations of all samples used are listed in Appendix Table A6.1.

Underwater photographs of the bottom were made at several locations where high-carbonate sediment had been collected (locations on Figure 6A.1). A frame-mounted camera was winched to the bottom and then triggered as the boat drifted, resulting in a series of photographs on a transect. Each photograph covered an area of approximately 1.5 m^2.

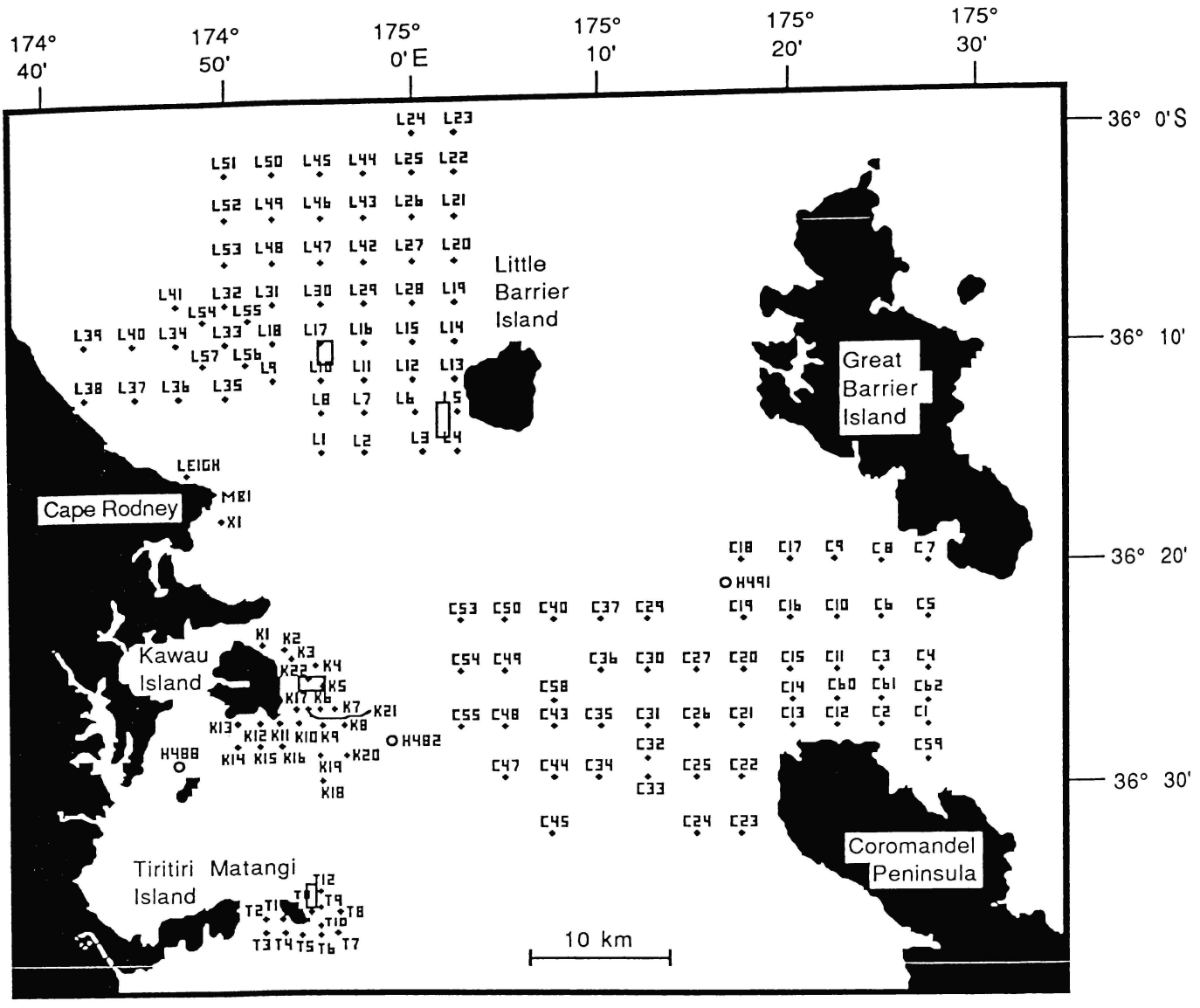


Figure 6A.1: Sediment sample locations in the outer Hauraki Gulf (details in Appendix Table A6.1).

B. SAMPLE ANALYSIS

Sediment samples were divided into four random splits, two small ones (50 to 100 g dry) and two larger splits. One large split was stored wet in airtight dark jars for future reference. University of Waikato Archive numbers are given in Appendix Table A6.1. The sediment analysis methods used here are mainly as described in Nelson (1982) and are summarized in Figure 6B.1.

The second large split was wet-sieved through a 1 mm sieve and the resulting very coarse sand and gravel material was dried. If the bulk sample contained more than 50% $CaCO_3$, 5 g of this coarse fraction was removed and analyzed for skeletal components (detailed methodology described below in Section E) and species present. The remainder was used in other experiments (such as determining the skeletal mineralogy of the bryozoans, reported in Chapter 2).

A small split was wet-sieved through 2 mm and 0.063 mm sieves to yield gravel (> 2 mm), sand (0.063 to 2 mm), and mud (< 0.063 mm) fractions. The sand and gravel fractions were dried and weighed. The mud was allowed to settle, then made up to 1 l with water and vigorously stirred, then 25 ml was withdrawn and dried on pre-weighed filter paper. When multiplied by 40 this gave the quantity of mud in the sample. The weight percents of mud, sand, and gravel were calculated and used to determine textural classes of sediment (based on Folk, 1968). In some samples, the mud fraction was further analyzed for carbonate content using an auto-titrator (see Section C, below).

The other small split was air dried and part of it was used to determine the carbonate content. The sample was weighed, all carbonate was dissolved by exposure to 1 N HCl, and the sample was rinsed, dried, and weighed again.

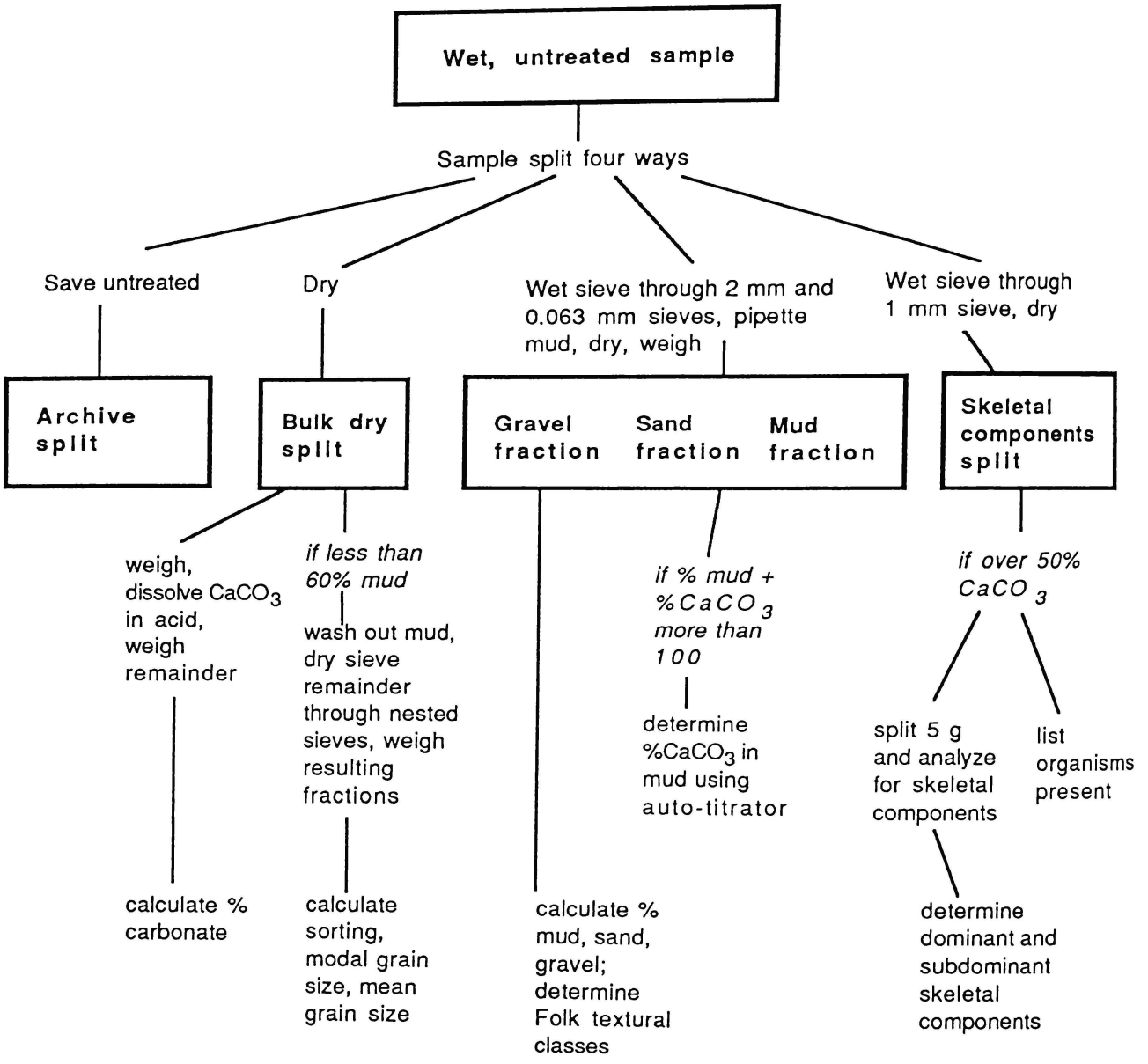


Figure 6B.1: Procedures used in analysis of sediment samples.

For samples with more than 60% mud, no further analysis was done. For many samples, however, most of the dried split was used for a detailed textural analysis of the sand and gravel fractions. The mud was rinsed out of the sample, then the dry sand and gravel was dry-sieved through nested sieves of 4mm, 2mm, 1mm, 0.5mm, 0.25mm, 0.125mm, and 0.063mm meshes. These size fractions were weighed and the data analyzed. Sorting, mean grain size, and modal grain size were determined, but only for the sand and gravel fractions.

The results of these analyses are given in Appendix Table A6.2, and will be reported in more detail below.

C. CARBONATE CONTENT OF SEDIMENTS

The calcium carbonate content of samples ranged from 11 to 93 %. This degree of variation reflects the patchy distribution of carbonates in the Hauraki Gulf (Figure 6C.1). Despite the effort to sample high-carbonate areas based on Carter and Eade's (1980) surficial sediments map, it is clear that many of these samples are not truly "carbonate," raising the question of the reliability of the published map. Indeed, only seven samples resemble the typical shell hash found on the major carbonate sectors of the New Zealand shelf, such as at Three Kings (Nelson et al., 1988b). Only 22 of the 146 samples analyzed may be considered true carbonates (>50% $CaCO_3$).

Although low-carbonate sediments occur at all depths (Figure 6C.2), high-carbonate samples tend to be at fairly shallow depths. None of the samples with greater than 60% $CaCO_3$ was found at depths greater than 60 m, although sampling extended to 90 m. Most of these moderately shallow high-carbonate sediments are found quite near land (Figure 6C.1). Only a few in the Jellicoe Channel (e.g., L33) are away from land.

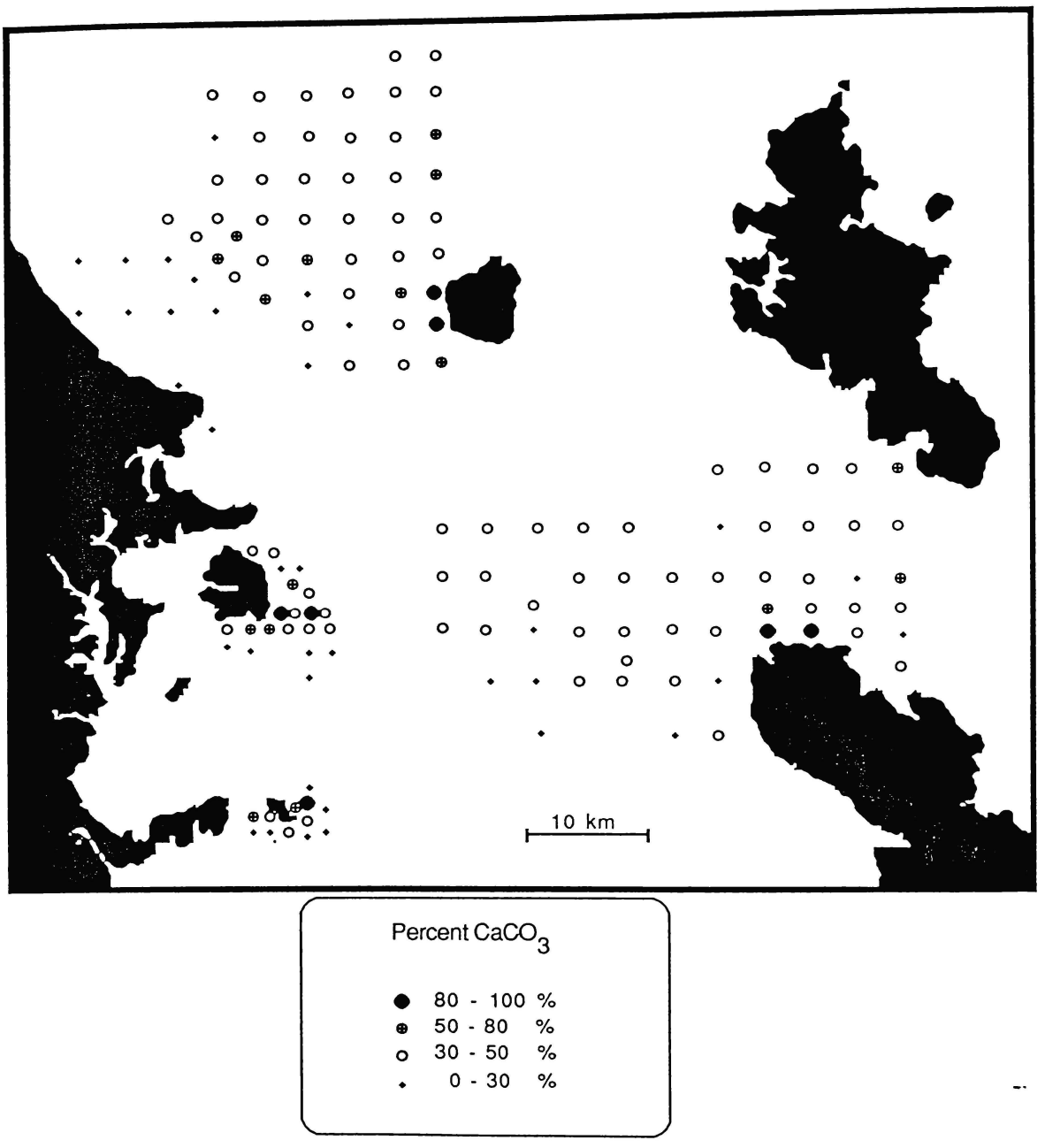
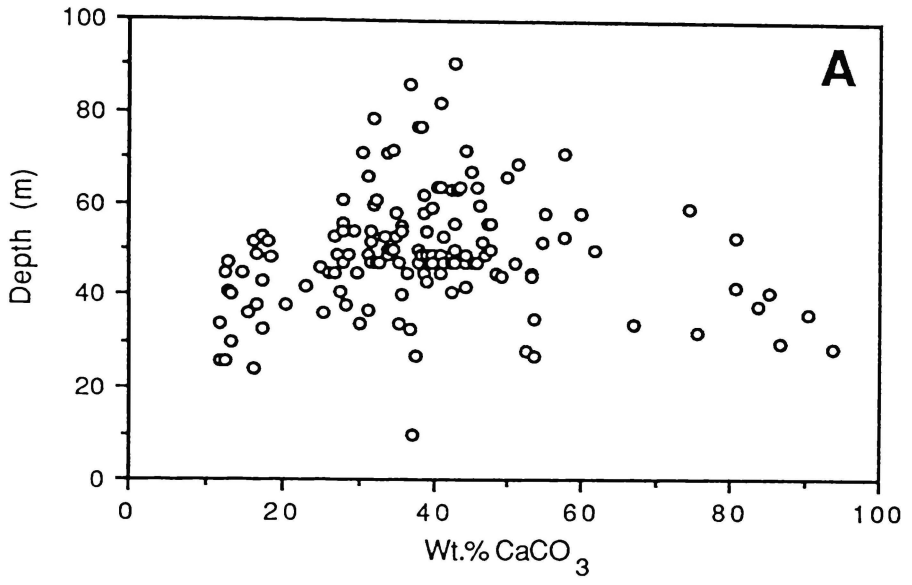


Figure 6C.1: Percent calcium carbonate in outer Hauraki Gulf sediments (data in Appendix Table A6.2).



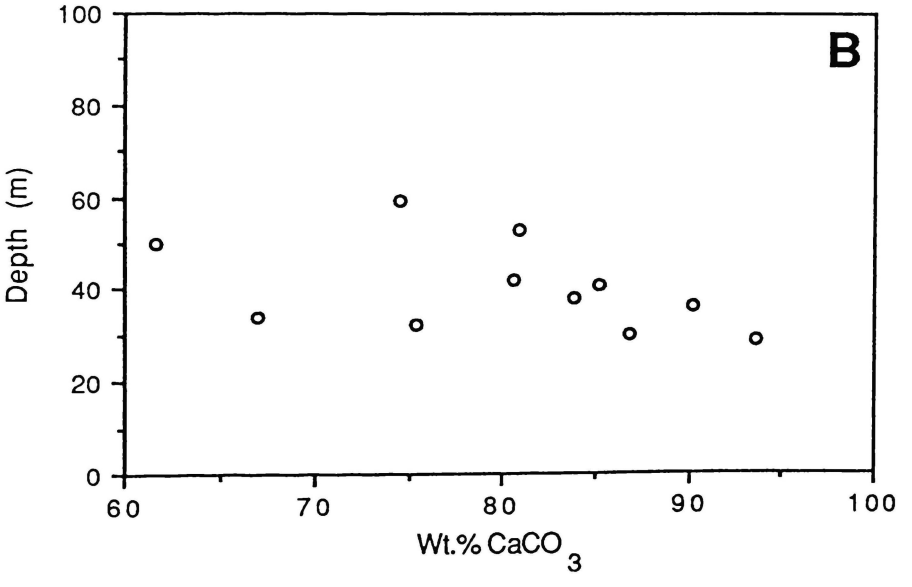


Figure 6C.2: Correlation of carbonate content with depth for (A) all samples and (B) samples with > 60% carbonate.

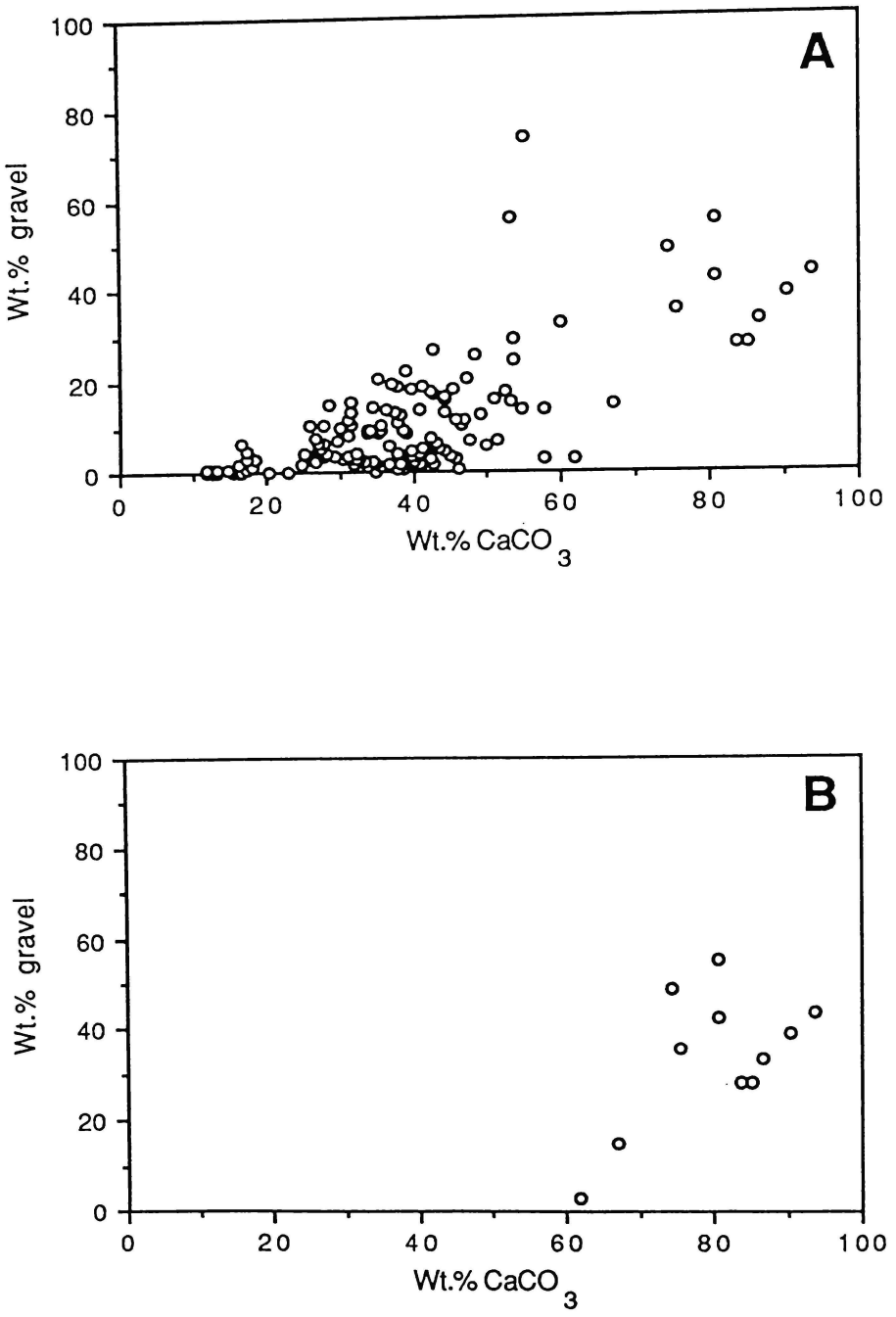


Figure 6C.3: Correlation of carbonate content with percent gravel for (A) all samples and (B) samples with > 60% carbonate.

High-carbonate sediments also tend to have a large gravel fraction (Figure 6C.3). This indicates, and is confirmed by hand specimen observations, that much of the carbonate material is coarse.

Is there, then, any carbonate mud in the Hauraki Gulf? A simple method of answering this is to add the % mud to the % $CaCO_3$. If the sum is greater than 100, at least some of the mud must be carbonate. Figure 6C.4 shows that seven samples are very high in mud content, and yet also have an appreciable amount of carbonate. One sample was included that is below the line but is fairly high carbonate and yet has some mud (K17). The mud fractions of these eight samples were analyzed for carbonate content using a highly accurate auto-titrator. Results (Appendix Table A6.2) show that all eight samples have some carbonate mud (from 4 to 16%).

In most samples, the carbonate mud is a very small part of the total mud fraction (Figure 6C.5), although in K17, the highest-carbonate sample, it appears that all the mud is carbonate. In the field, mud in K17 was reddish in appearance, whereas mud in the T samples was dark grey. Even in the lowest carbonate sample (T4), carbonate mud is less than half the total carbonate. These carbonate mud samples are concentrated around Tiritiri Matangi Island, although one is located east of Kawau Island (Figure 6C.6). The significance of carbonate mud in temperate carbonates will be addressed in Chapter 12.

D. SEDIMENT TEXTURE

Sediment samples cover a wide range of textural classes. Percent gravel ranges from 0 to 73%, sand from 4% to more than 99%, and mud from 0 to 97%. As a result, many of Folk's (1968) classifications are represented (Figure 6D.1). The slightly gravelly classes have been eliminated from Folk's original classification scheme (as suggested by Andrews, 1973) as the accuracy of wet sieving is inadequate to make the distinction. Coarser sediments (sandy and muddy sandy gravels) are found in small patches that

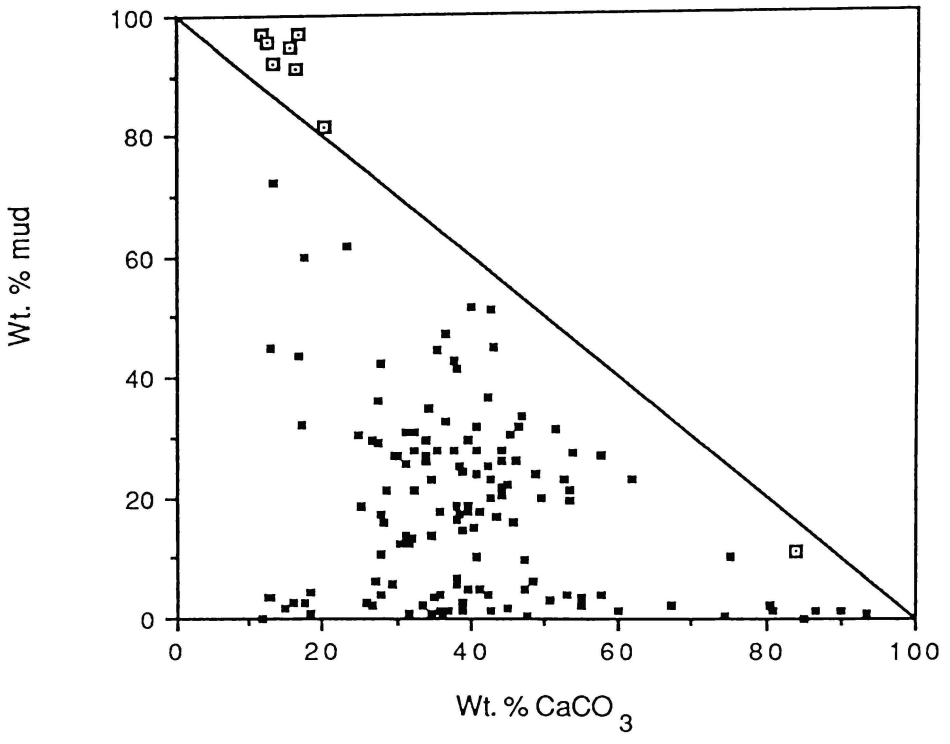


Figure 6C.4: Correlation of carbonate content with percent mud. Samples above the line must have some carbonate mud. Outlined samples are described in more detail in Figure 6C.5.

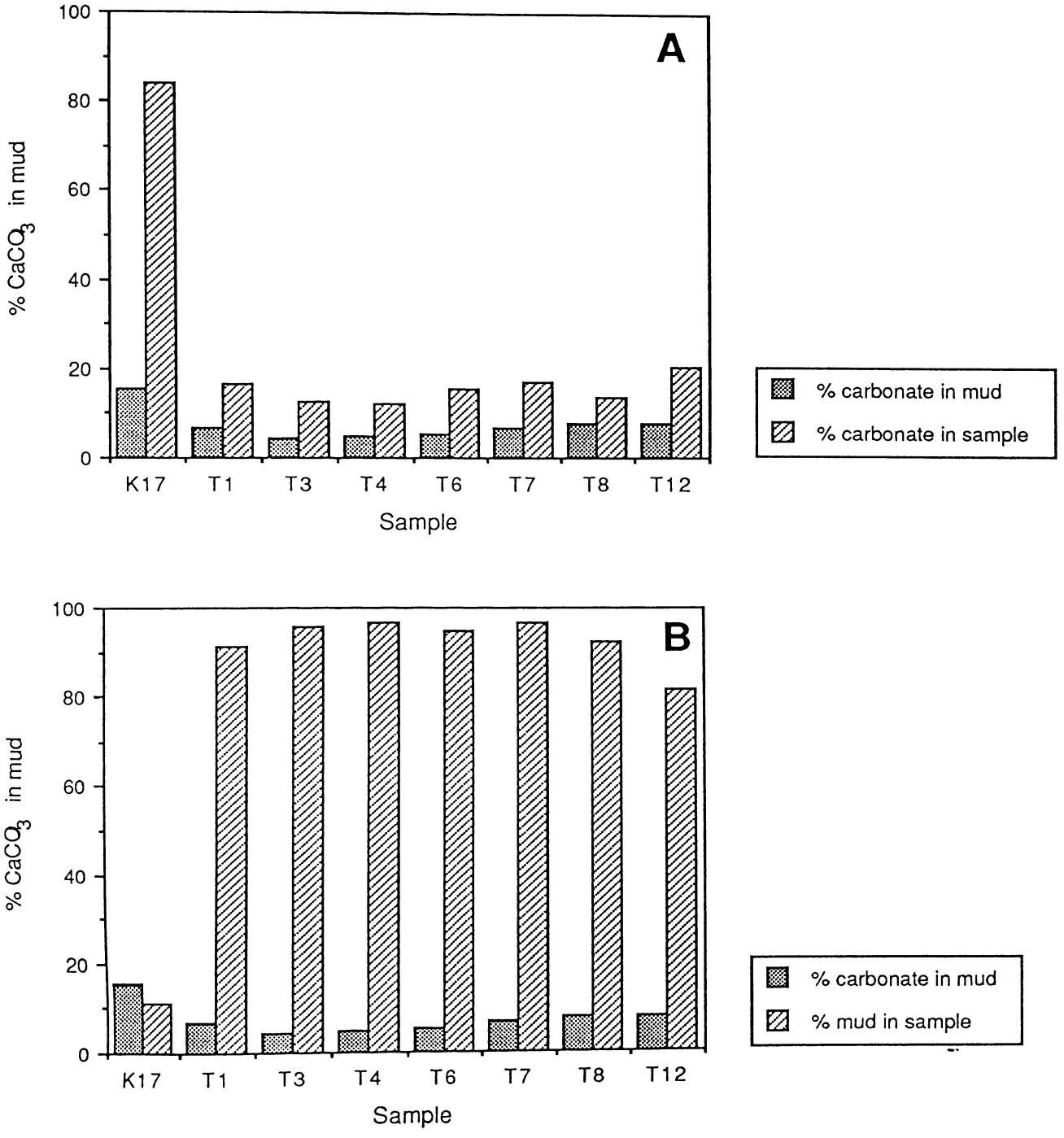


Figure 6C.5: Comparison of carbonate mud fraction with (A) total carbonate and (B) total mud for selected sediment samples.

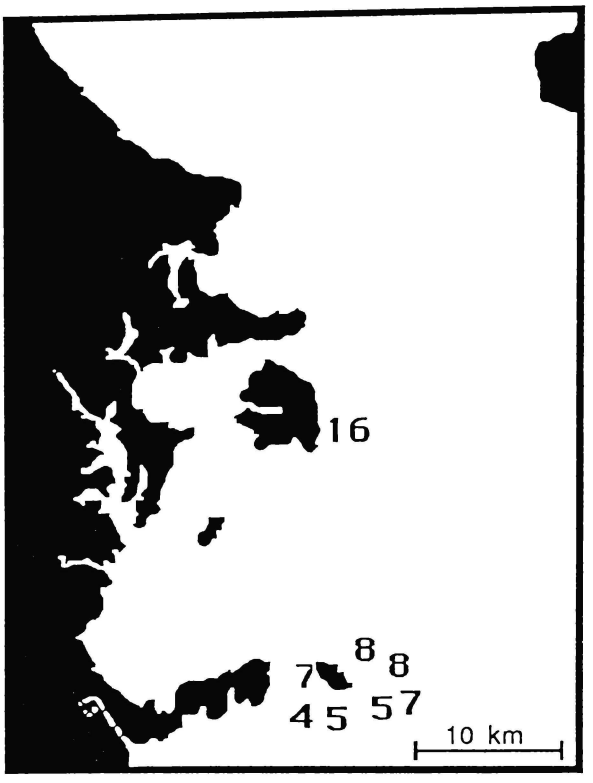


Figure 6C.6: Percent carbonate in mud fraction of eight selected sediment samples, chosen because of their high combined percents of mud and calcium carbonate.

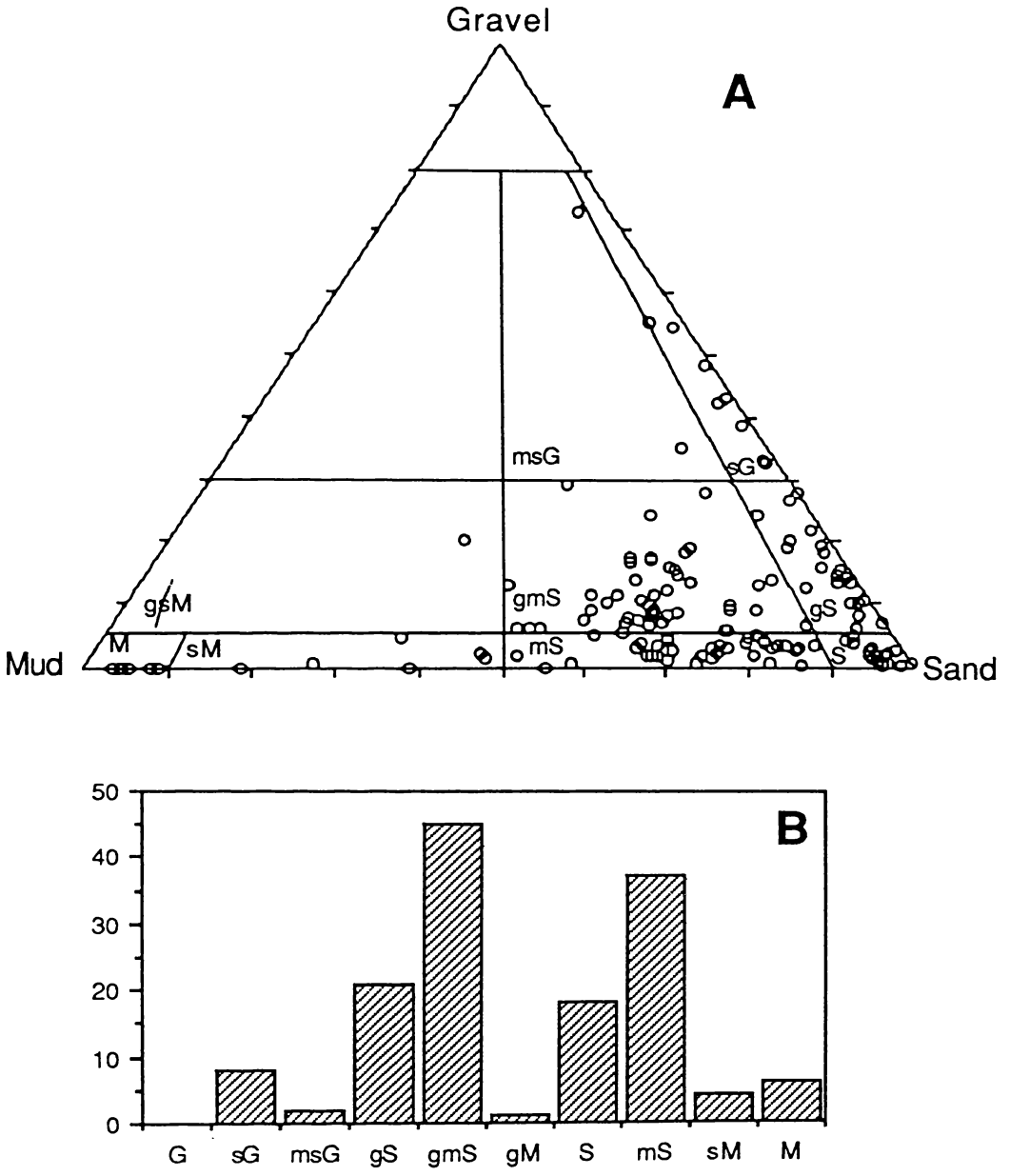
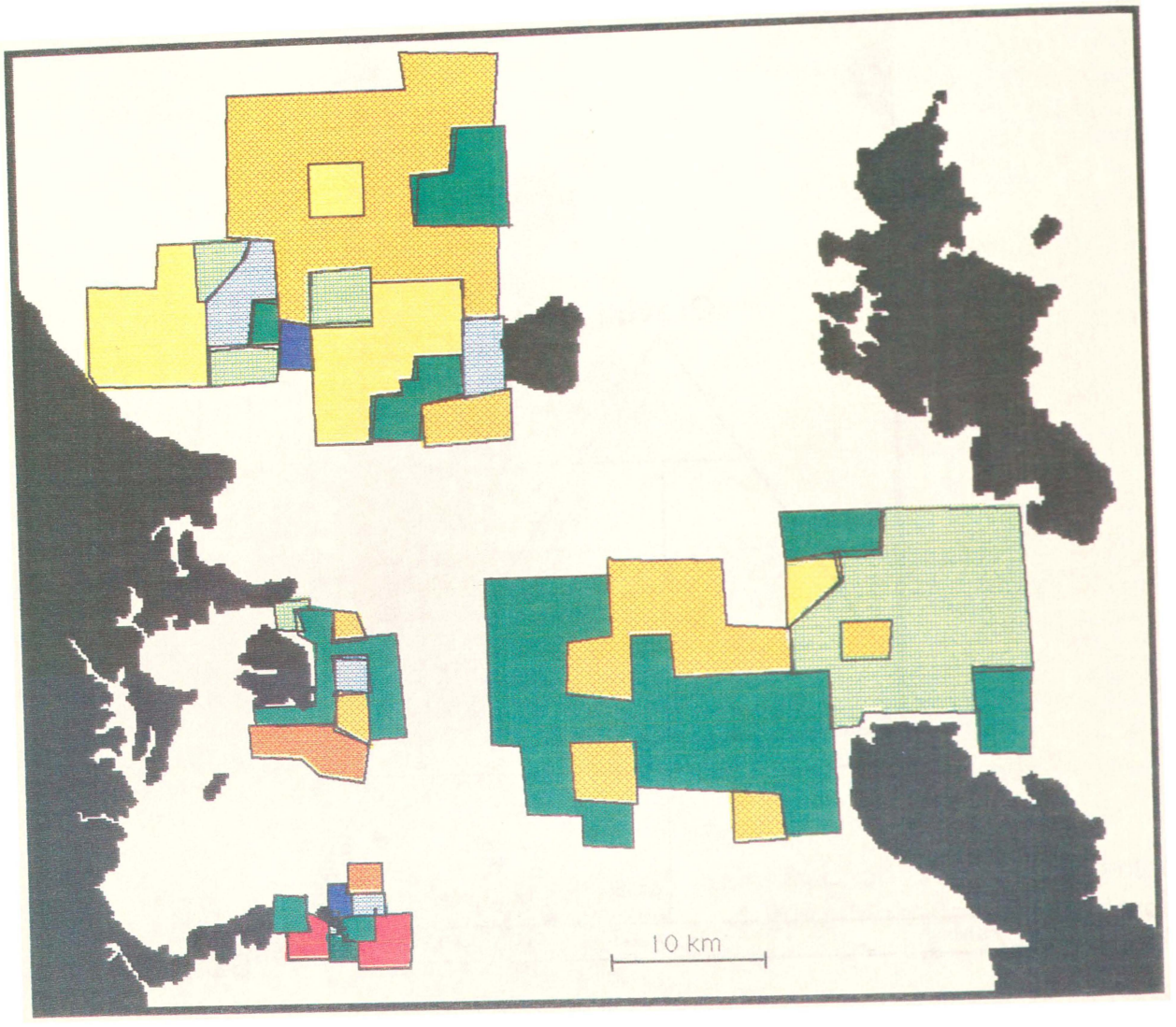


Figure 6D.1: Textural classification (after Folk, 1968) of outer Hauraki Gulf sediments. (A) Ternary diagram and (B) histogram showing frequencies of classes. Abbreviations: G - gravel, g - gravelly, S - sand, s - sandy, M - mud, m - muddy.



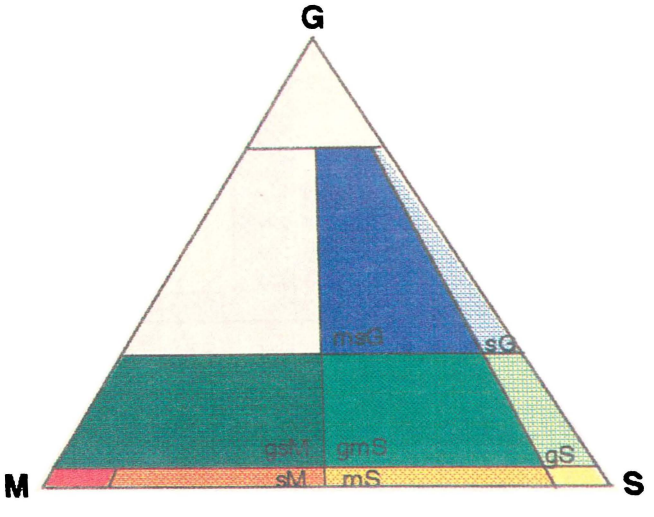


Figure 6D.2: Distribution of textural classifications for outer Hauraki Gulf sediments. Classification after Folk (1968) but with "slightly gravelly" classes merged with non-gravel classes.

roughly coincide with the occurrence of high-carbonate sediments (compare Figure 6C.1). Very muddy sediments (mud and sandy mud) are found near Tiritiri Matangi Island and Kawau Island only. All the more "open ocean" sediments are mainly sand (Figure 6D.2).

Modal grain size ranges from mud (less than 0.063 mm) to coarse gravel (more than 4 mm)(Figure 6D.3). By far the most common size modes are fine sand (0.125 to 0.250mm) and medium sand (0.25 to 0.5mm). Locally coarse patches again coincide with high carbonate regions. It is interesting that the two extremes (coarse gravel and mud) are located so close together southeast of Tiritiri Matangi Island.

Mean grain size (of the sand and gravel fraction) follows a similar pattern (Figure 6D.4). Most mean grain sizes are between 0.125 and 0.5 mm. A coarser area in the Colville Channel is indicated, as is a patch between Pakiri Beach (north of Cape Rodney) and Little Barrier Island (centered on sample L33).

Sorting of the sand and gravel fraction was calculated for samples with less than 60% mud. The sorting coefficient ranges from 0.66 to 2.18. Most samples are poorly sorted, a few are very poorly sorted, and a few are moderately sorted (Figure 6D.5). The sorting does not follow the distribution pattern of the other textural parameters. For example, the samples from west of Little Barrier Island are just as poorly sorted as those to the north, although they differ in coarseness and carbonate content. Sorting does not appear to be much related to mean grain size (Figure 6D.6). Hydraulically equivalent grains of carbonate and siliciclastic material are of different sizes, which results in misleadingly poor sorting in a mixed terrigenous/biogenous sediment (Nelson, 1977). This is reflected in the Hauraki Gulf sediments, as sorting is best in sediments with low and high $CaCO_3$ contents and worst in intermediate (more mixed) sediments (Figure 6D.7).

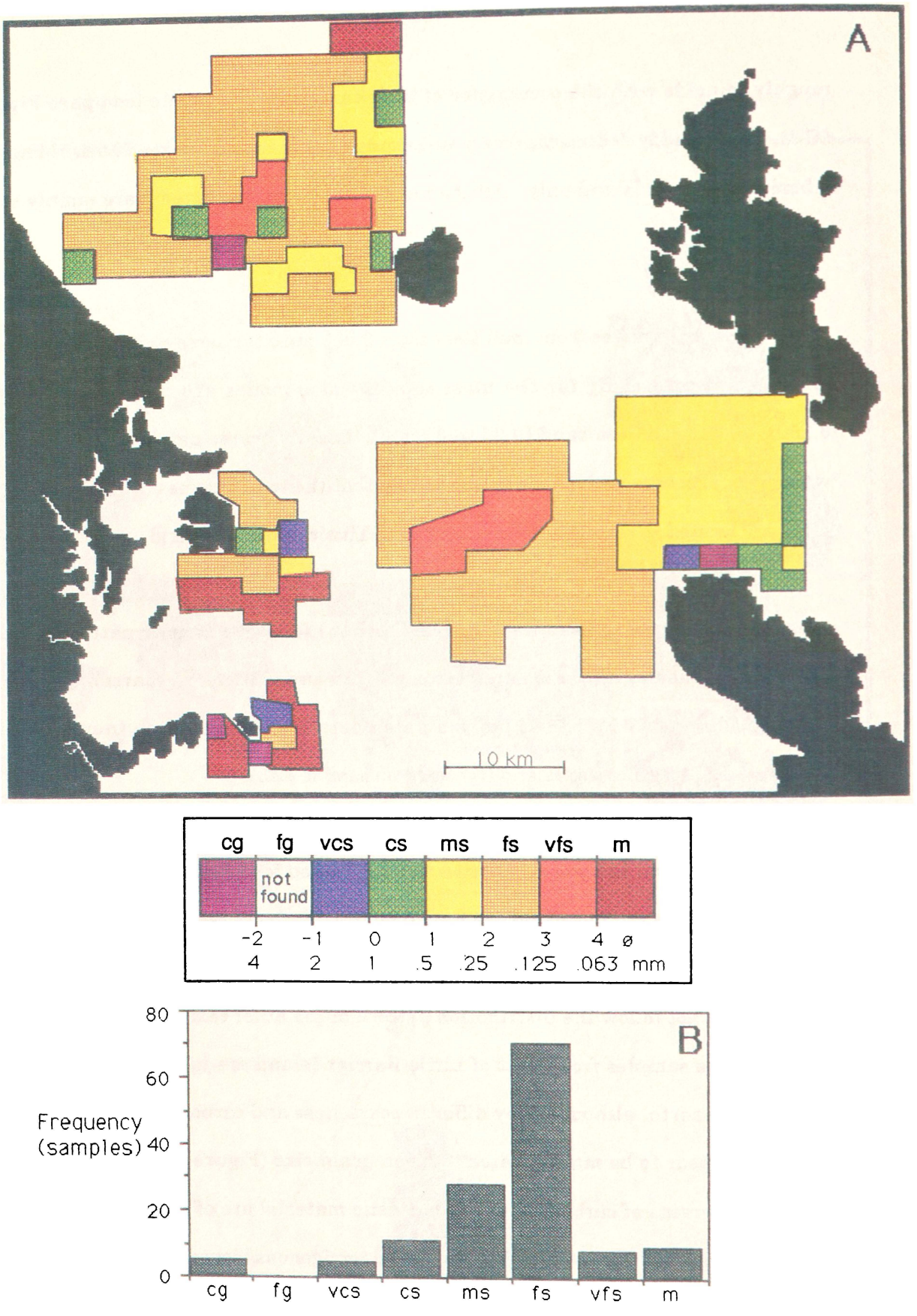


Figure 6D.3: Modal grain size fractions of sediments in the outer Hauraki Gulf. (A) Distribution map and (B) frequency histogram. Abbreviations as in Figure 6D.1.

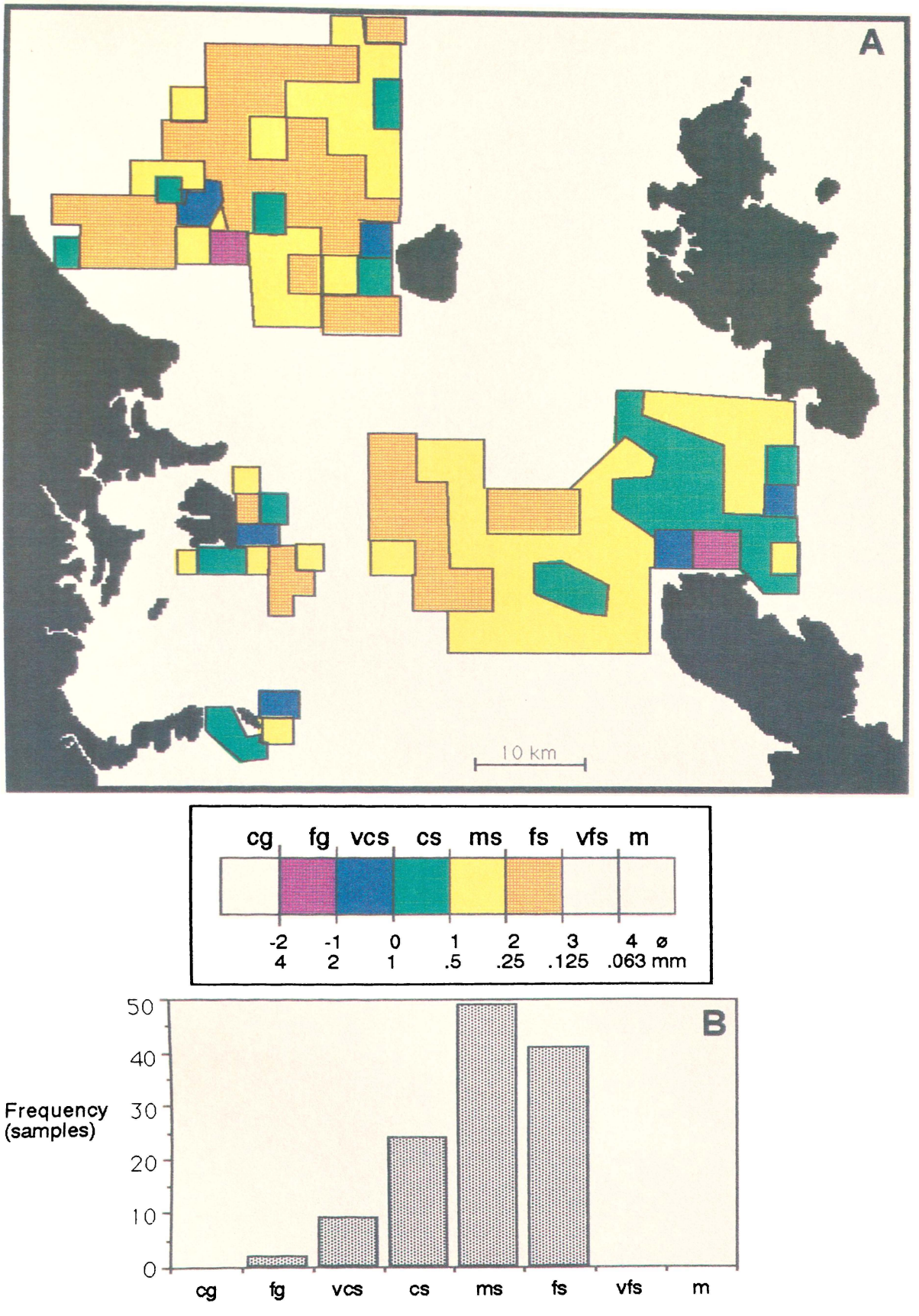
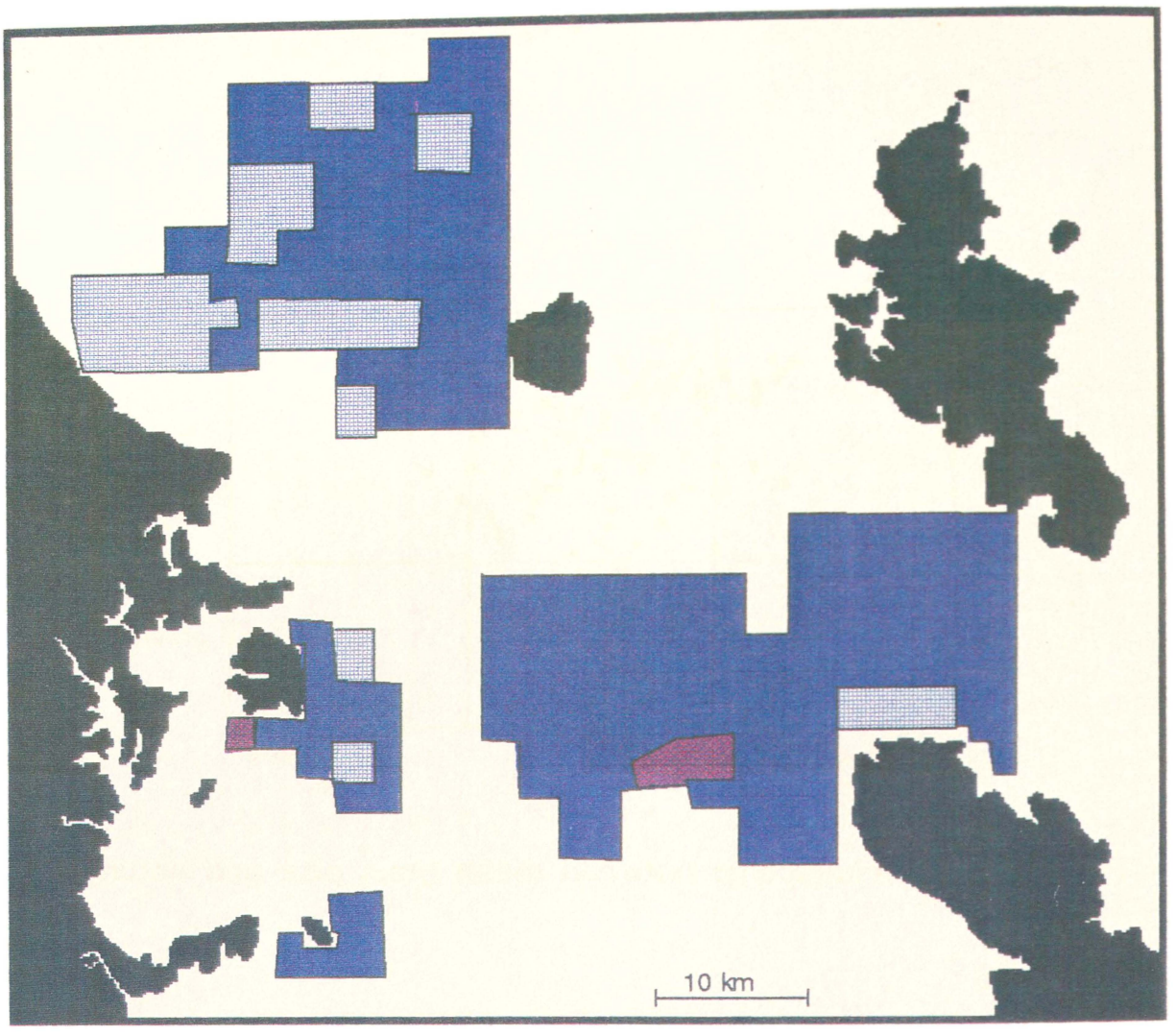


Figure 6D.4: Mean grain size (sand and gravel fractions) for samples containing less than 50% mud in the outer Hauraki Gulf. (A) Distribution map and (B) frequency histogram. (Abbreviations as in Figure 6D.1)



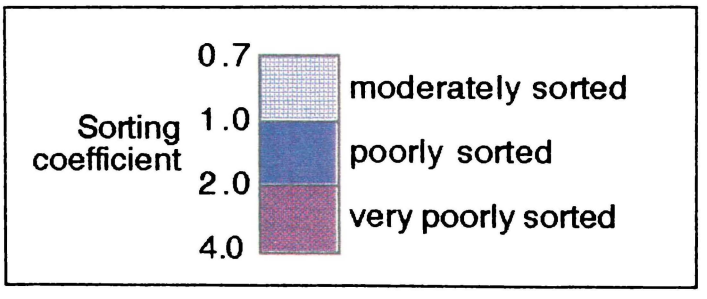


Figure 6D.5: Sorting of sediments in the outer Hauraki Gulf.

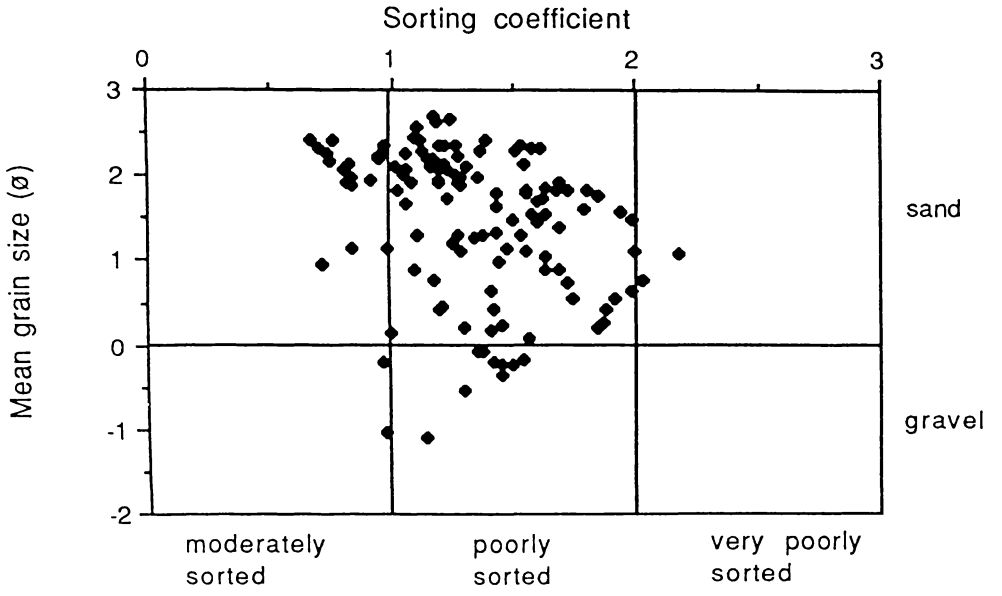


Figure 6D.6: Relationship between mean grain size and sorting.

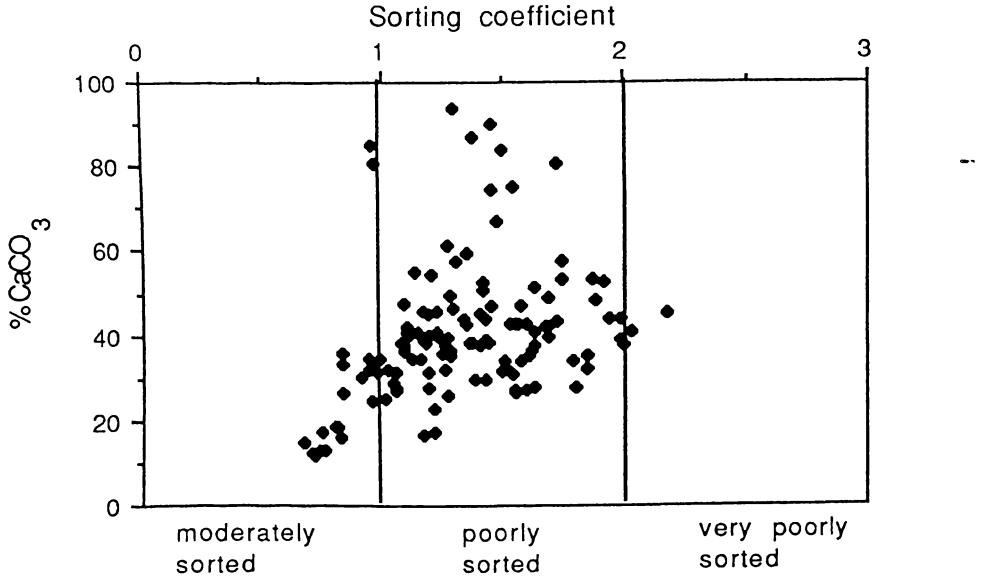


Figure 6D.7: Relationship between calcium carbonate content and sorting.

E. SKELETAL COMPOSITION

There are several possible methods of determining skeletal composition of a sediment. The simplest is grain-counting, in which the number of grains from each taxon is counted. This is really only useful when grains are all much the same size, as there is a strong bias towards small grains. Point-counting is a method in which grains that are covering certain points on a grid are counted. This method approximates surface area covered by a grain, but does not take into account the third dimension. Thus, a sample of grains where some are flat and others are spherical or highly arched would give a distorted result. The third method is the most direct - content by weight. In this method all the grains from each taxon within the sample are weighed and a weight % is calculated. This seems the most reasonable method to use, if possible, because other sedimentological parameters are measured in weight percent (such as % $CaCO_3$). Figure 6E.1 compares these three methods for two samples. All three methods give similar results - bivalves are dominant, barnacles and gastropods are subdominant. Note that grain counting underestimates barnacles and bryozoans. The weight method gives the best representation of minor groups and was used in this study. It is only comparable to the other two methods if the weight per individual is consistent. Barnacle plates are usually a consistent size; bryozoans are less consistent; and size and shape are not at all consistent in mollusc fragments.

For each sample in which the % $CaCO_3$ was greater than 50%, 5 g of sediment from the >1mm split were separated into 11 biogenic groups and weighed. Results are listed in Appendix Table A6.3.

In all but one case, bivalves are the dominant producers of carbonate, ranging from 36 to 93% of the carbonate greater than 1mm (Figure 6E.2). Common sub-dominant classes (>10%) include barnacles, bryozoans, and gastropods (Figure 6E.3). In one case corals were sub-dominant (due to a large *Flabellum rubrum* skeleton). Minor classes

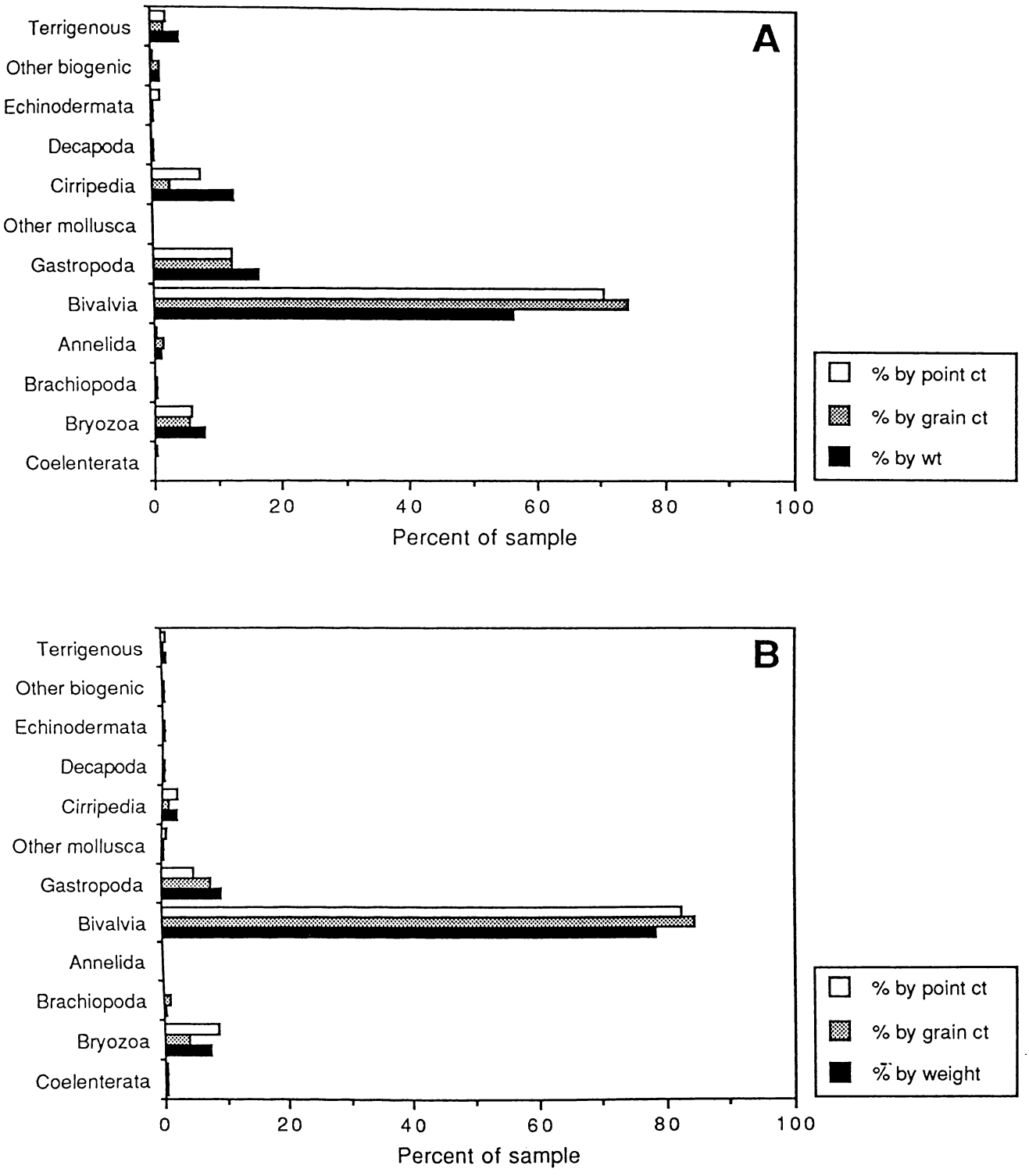


Figure 6E.1: Comparison of results from three methods of determining skeletal compositions of (A) sample AMS-L1 and (B) sample AMS-L2. Point counts were of >300 points, grain counts were of >1500 grains, and weight percents used >5 g sample.

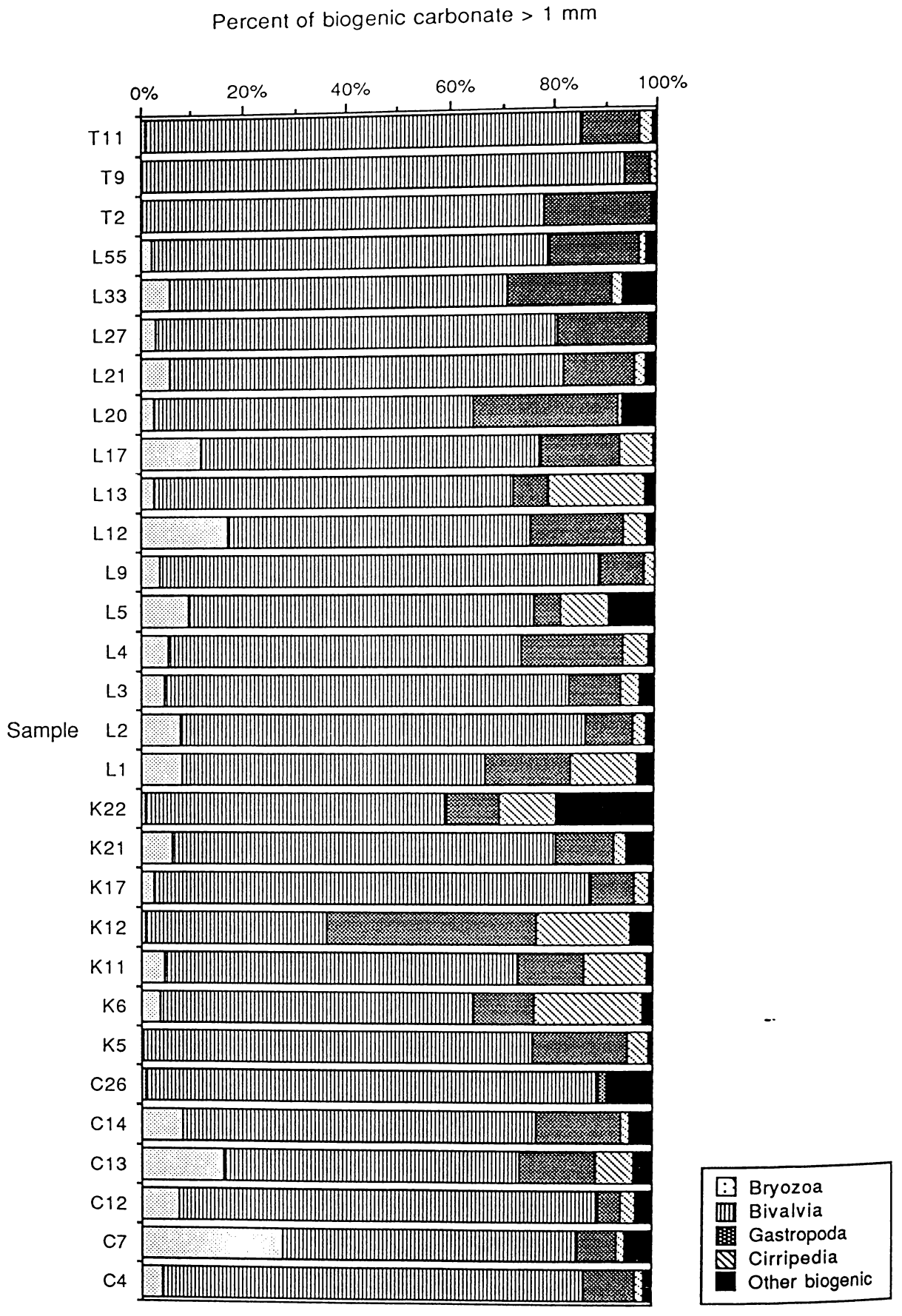


Figure 6E.2: Dominant and subdominant skeletal components of thirty samples from the outer Hauraki Gulf (data in Appendix Table A6.3).

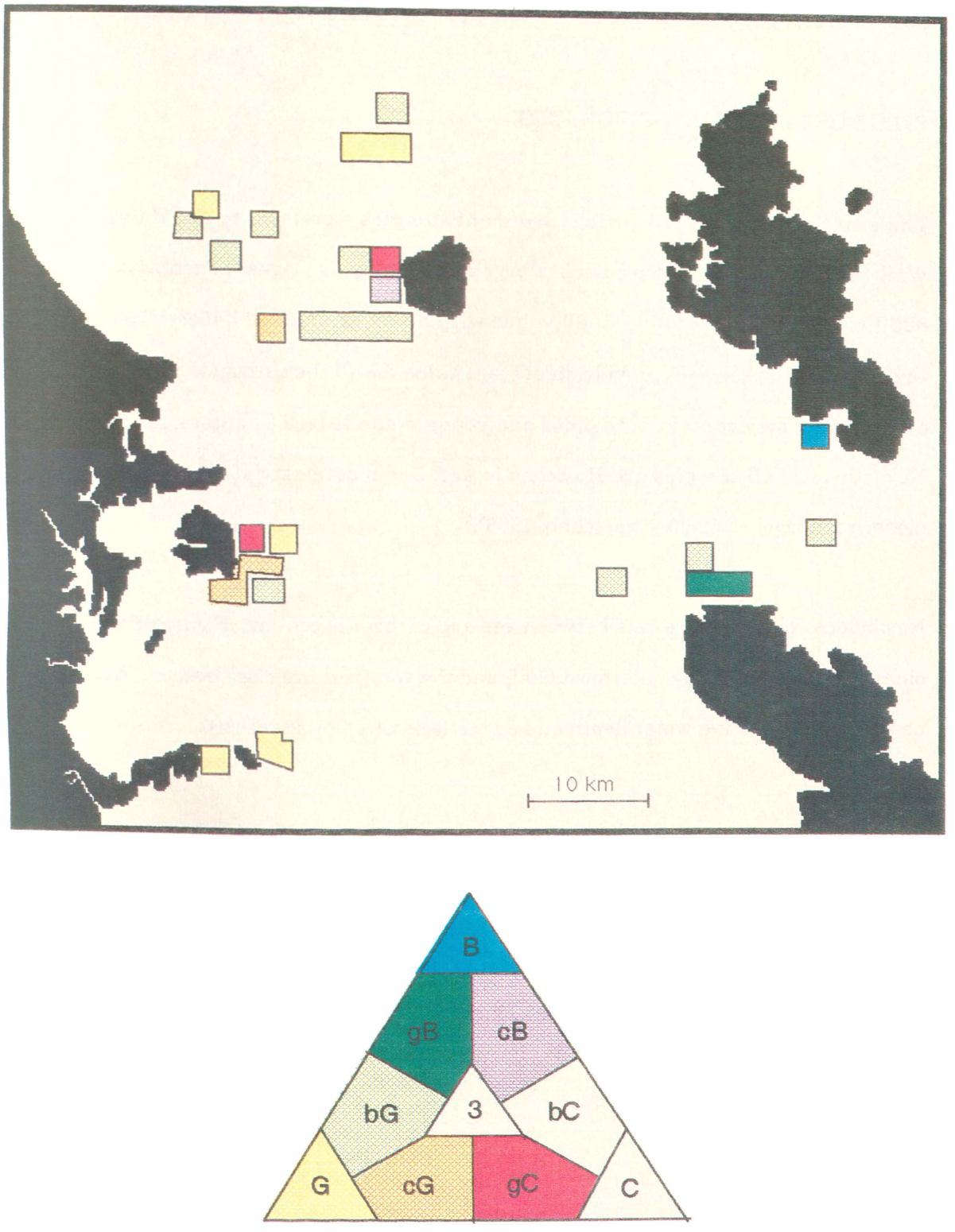


Figure 6E.3: Subdominant skeletal components in some sediments in the outer Hauraki Gulf. B - bryozoans, C - cirripedes, G - gastropods.

(1 to 10%) include echinoids, corals, brachiopods, and calcified worm tubes. There does not appear to be any obvious distributional pattern to these groups.

Species present in each sample were recorded and are listed in Appendix Table A6.4.

F. AGE OF SKELETAL CARBONATES

The gravel fractions of 15 surface sediment samples were sent to the University of Waikato Radiocarbon Dating Laboratory for age analysis. Ages ranged from 1750 to 8250 y, mainly about 3000 - 4000 y, but with an older mean of 4462 y (Table 6F.1, Figure 6F.1). These ages provide an average value for all the carbonate in the sample - each sample may contain both older and younger shells (see Chapter 8, Table 8C.1). Nevertheless, all samples are Holocene in age, and most post-date the attainment of modern sea level at 6,500 y ago (Gibb, 1986).

No obvious relationship exists between age and carbonate content (Figure 6F.2A). The oldest samples are in the outermost Gulf, and the youngest are close inshore. A broadly positive trend relating water depth and age reflects this (Figure 6F.2B).

Table 6F.1: Radiocarbon ages of samples.

Notes: Conventional (Libby) age reported.
UWRL = University of Waikato Radiocarbon Dating Laboratory.

Sample	Sediment texture	% $CaCO_3$	Water depth (m)	Radiocarbon Age (y)	Error (y)	U.W.R.L. Number
AMS-C8	gravelly sand	36	40	2970	± 60	Wk-1814
AMS-C12	sandy gravel	81	53	2910	± 60	Wk-1815
AMS-C29	gravelly muddy sand	40	49	3300	± 60	Wk-1816
AMS-C45	gravelly muddy sand	28	47	1750	± 60	Wk-1817
AMS-K19	muddy sand	13	41	3430	± 230	Wk-2254
AMS-K22	gravelly muddy sand	53	44	3850	± 60	Wk-1818
AMS-L4	gravelly muddy sand	62	50	3390	± 60	Wk-1819
AMS-L10	sand	27	53	4940	± 250	Wk-2260
AMS-L17	gravelly sand	55	52	7910	± 70	Wk-1820
AMS-L23	muddy sand	40	80	8090	± 300	Wk-2259
AMS-L30	muddy sand	39	62	8250	± 390	Wk-2258
AMS-L40	sand	13	47	4790	± 170	Wk-2257
AMS-L51	muddy sand	34	71	3510	± 230	Wk-2256
AMS-T9	sandy gravel	94	29	2900	± 60	Wk-1821
AMS-T10	gravelly muddy sand	30	34	4940	± 250	Wk-2255
	MEAN			4462		

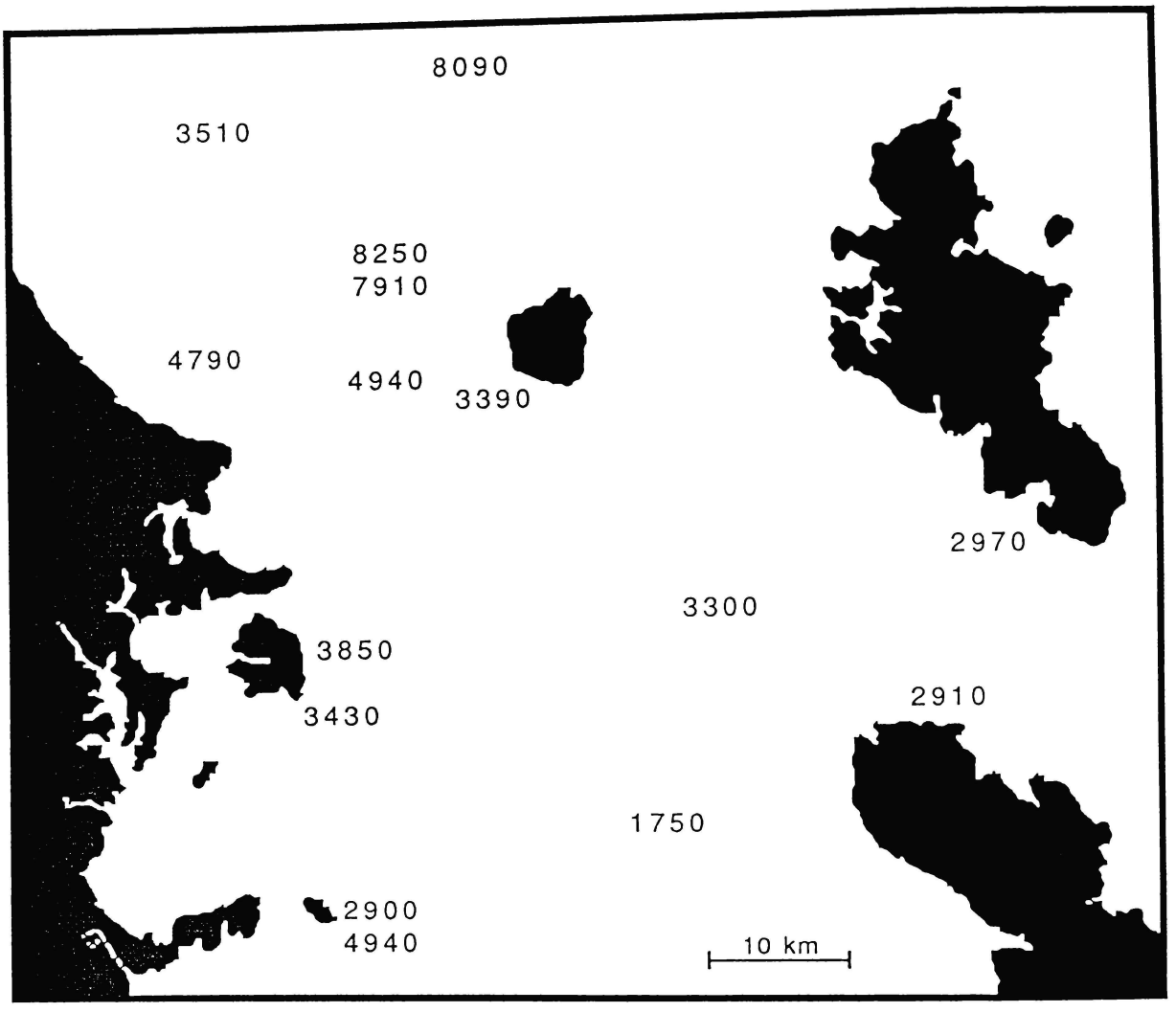


Figure 6F.1: Radiocarbon ages (y) for the gravel carbonate fraction of selected surficial sediment samples from the outer Hauraki Gulf.

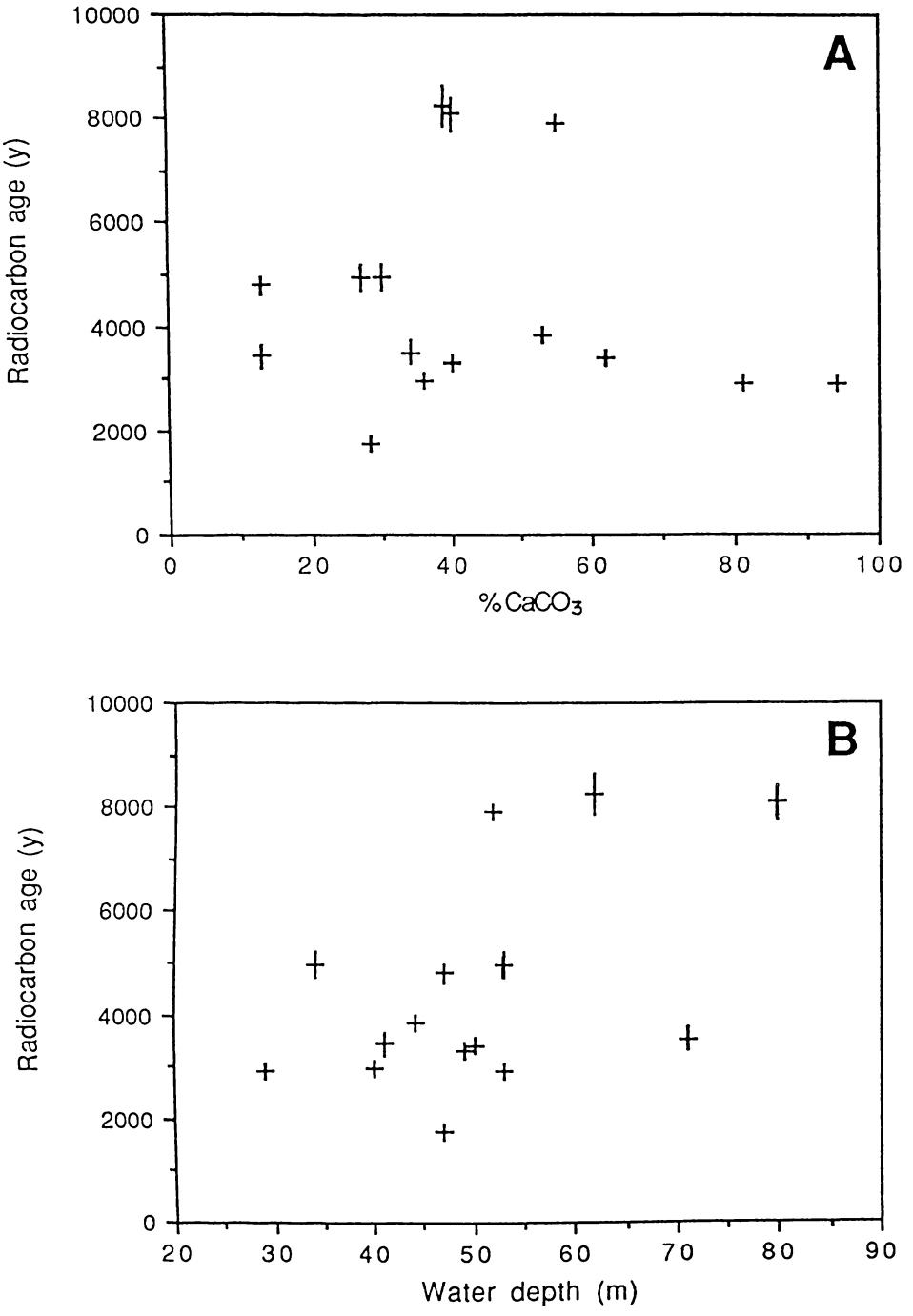


Figure 6F.2: Relationship between radiocarbon ages of outer Hauraki Gulf sediments and their carbonate content (A) and water depth (B).

Chapter 7 Carbonate Sediment Facies

"Life is made up of marble and mud."

N. Hawthorne, The House of Seven Gables, 1851

A. INTRODUCTION

Descriptions of sediment texture and composition for dozens of samples are cumbersome and not easily interpreted. The next step is to group samples according to their characteristics, and to make interpretations based on these groups.

The concept of facies is widely used despite varying definitions. In one textbook (Krumbein and Sloss, 1963) it has been called the "sum of lateral changes," the "sum of lithologic and paleontologic characterisitics of a sedimentary deposit at a given place," and the "sum of all the primary characteristics" of a sediment. Originally, facies was used to describe lateral changes within a stratigraphic unit, that is, environmental differences in sediments deposited at one time. Some use facies to describe a suite of characteristics (an abstract usage), others to actually refer to deposits or layers (a concrete usage). In addition, there is the possibility of using facies in a purely descriptive manner (a muddy sand facies) or with a genetic component (a deltaic facies). Walker (1983) described all these possibilities in detail, and decided on a concrete descriptive definition of facies, with the understanding that facies would subsequently be used for interpretation.

In discussing the sediments of the Hauraki Gulf, Walker's (1983) facies concept will be used. Since sediment analysis focussed particularly on the carbonate sediments of the Gulf, and little has been discussed about the terrigenous composition of the samples, the facies defined will not be truly complete. As nearly all samples are of mixed terrigenous and biogenic material, some discussion of terrigenous material will be required. The main goal of this chapter, however, is to define a set of carbonate sediment facies in the Gulf.

B. METHODS USED IN DETERMINATION OF FACIES

Sedimentary analysis produces large tables of multivariate data, involving many variables (e.g., % mud) and many cases (i.e., sediment samples). One way to group such data is by cluster analysis (Velleman, 1988). Cluster analysis imagines a multi-dimensional space with each variable making up an axis, and plots each case in the space. It measures the distance between points in this high-dimensional space, and groups the cases accordingly. In hierarchical clustering, one begins with each case making up its own group (there are as many clusters as cases). The next step is to combine the two closest clusters. This step is repeated until all the cases are in one large group and no more combining is possible. The cluster tree diagram that results shows these sequential combinations. There are two ways of measuring the distance between clusters, and thus two methods of clustering, namely single-linkage and complete-linkage. They tend to give somewhat different results. The relationship between individual cases may not vary, but the arrangement of the clusters can. In the following analyses, complete-linkage clustering was used, as it produced a few large clusters rather than many small ones. The cluster analysis used in this study is part of the program "Data Desk Professional" (Velleman, 1988).

Once the cluster analysis defines a set of groupings for the data, it is then necessary to characterize the groups. This involves returning to the data and deciding what basis the groupings have in reality.

C. TEXTURE

A cluster analysis was carried out on the textural parameters: % mud, sand, and gravel; mean grain size; and sorting coefficient. This resulted in four groups (Figure 7C.1). Complete textural data were not available for some samples because they were almost all mud. Those samples were placed in a fifth group.

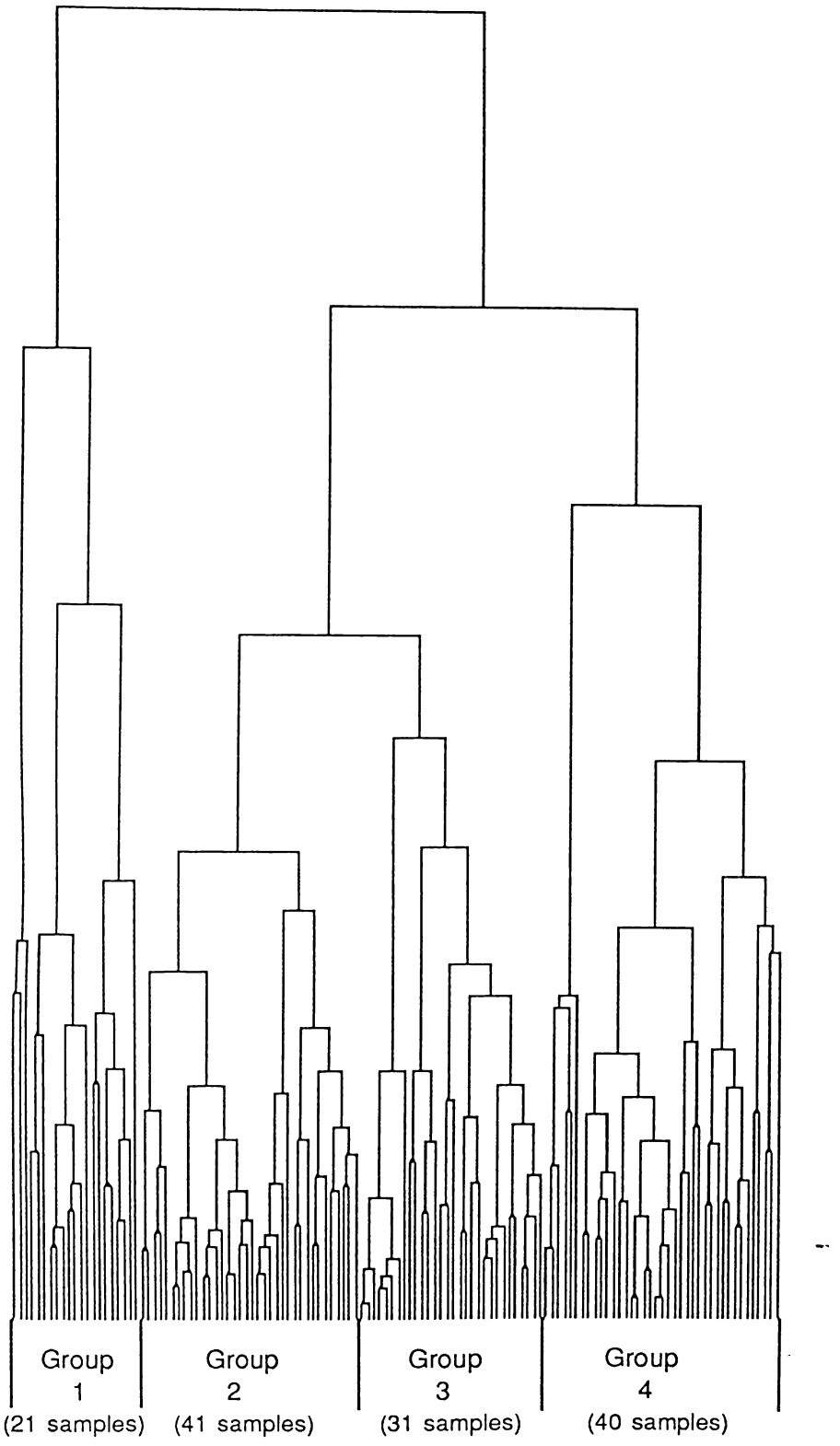


Figure 7C.1: Tree diagram of results of cluster analysis on textural parameters (% mud, sand, and gravel, mean grain size, and sorting), showing four textural groups. A fifth "wholly mud" group is not shown here.

Analysis of the textural data based on these groupings clearly reveals the distinguishing features. Bulk texture (% mud, sand, and gravel) is clearly different between the groups (Figure 7C.2). Mean grain size in group 1 is coarser than in the other groups (Figure 7C.3). Sorting shows less variation (Figure 7C.3). Not surprisingly, the groups tend to occupy different Folk textural classes (Figure 7C.4) and to have different modal grain sizes (Figure 7C.5). Textural data are given by groups in Appendix Table A7.1. Summaries of the groups are listed in Table 7C.1, and means for each parameter are shown in Figure 7C.6.

Group 1 encompasses 21 samples. They are generally low in mud (mean 4%) and have a high gravel content (up to 74%). Mean grain size is coarse sand, and modal grain size is mainly in the range of medium to very coarse sand. Folk textural classifications are sandy gravel and gravelly sand. Sorting is poor.

The 41 samples of Group 2 are considerably different. Gravel is very low in abundance (mean 5%), and mud comprises up to 32%. Mean grain size is consequently much finer than Group 1 (fine sand), as is modal grain size (fine sand). Samples classify mainly as muddy sand, though sometimes gravelly. Sorting is somewhat better than Group 1, but still poor.

Group 3 contains 31 samples, which include low mud and gravel contents (sand fraction is 76 to 99%, mean 91%). The mean grain size and modal grain size are medium sand. Folk textural classifications are mainly gravelly sand and sand. This group shows the best sorting, but is still only just moderately sorted.

The 40 samples comprising Group 4 contain considerable gravel (up to 29%) and mud (up to 62%), thus the % sand (mean 51%) is the least of any group. The sorting is the poorest of the groups. Mean grain size is medium sand, and modal grain size varies considerably, but is mainly fine sand. The Folk textural classification is mainly gravelly muddy sand.

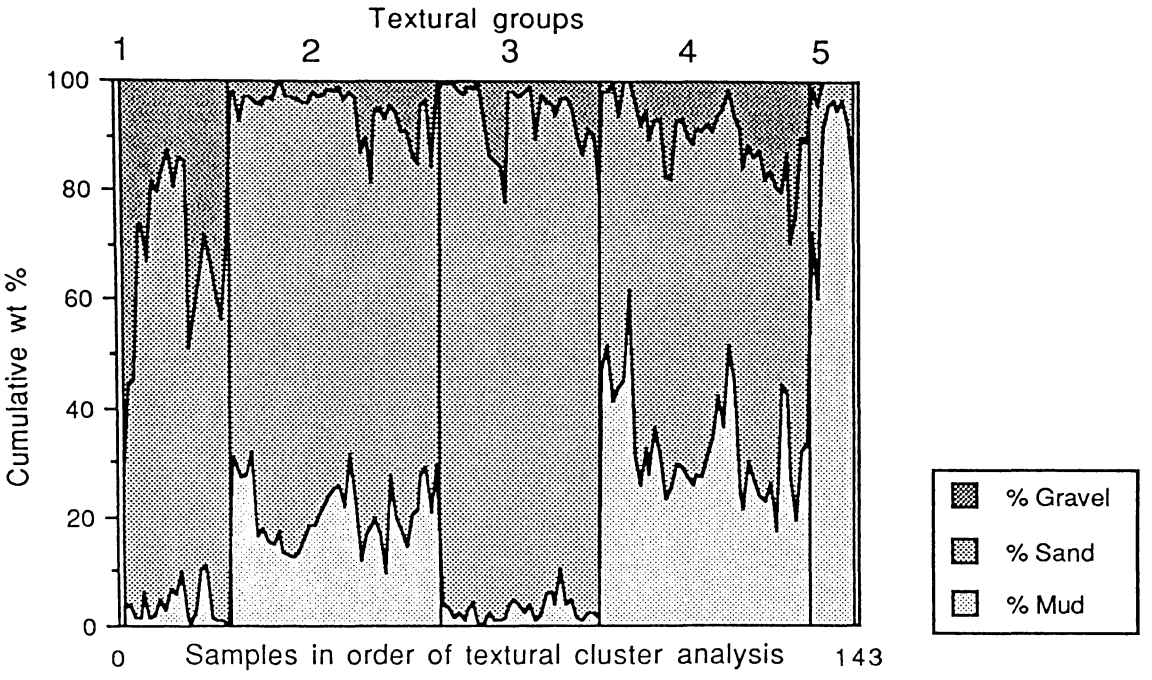


Figure 7C.2: Texture of sediment samples grouped by cluster analysis.

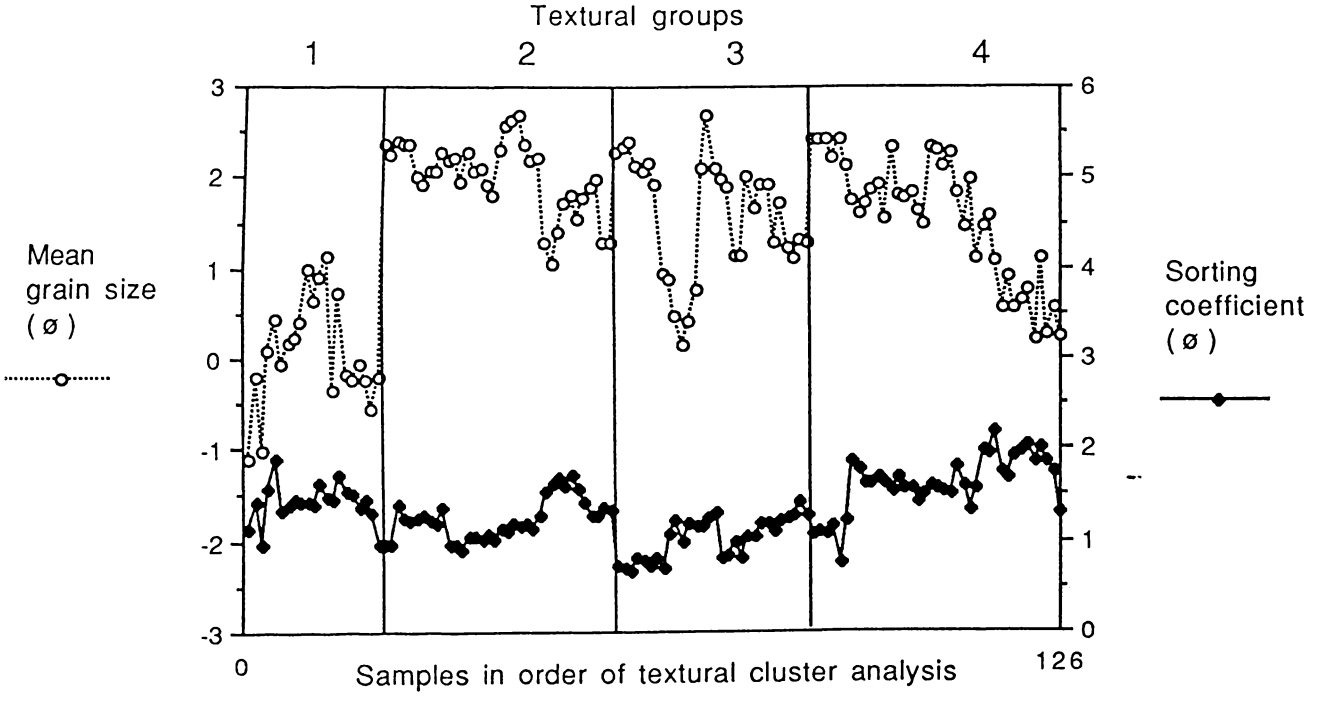


Figure 7C.3: Mean grain size and sorting coefficients for sediment samples within the textural groups.

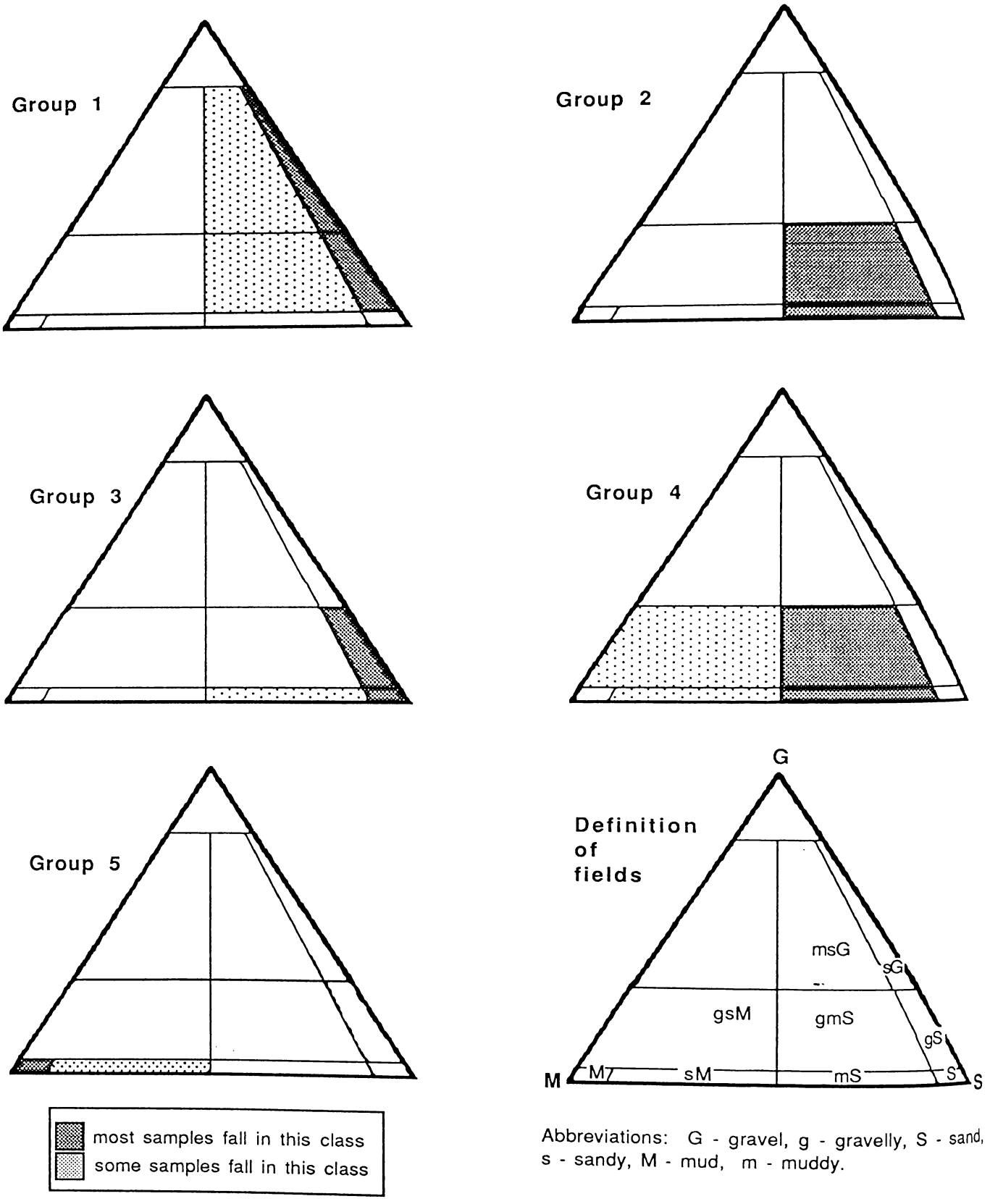


Figure 7C.4: Textural classifications (after Folk, 1968) for each of the textural groups.

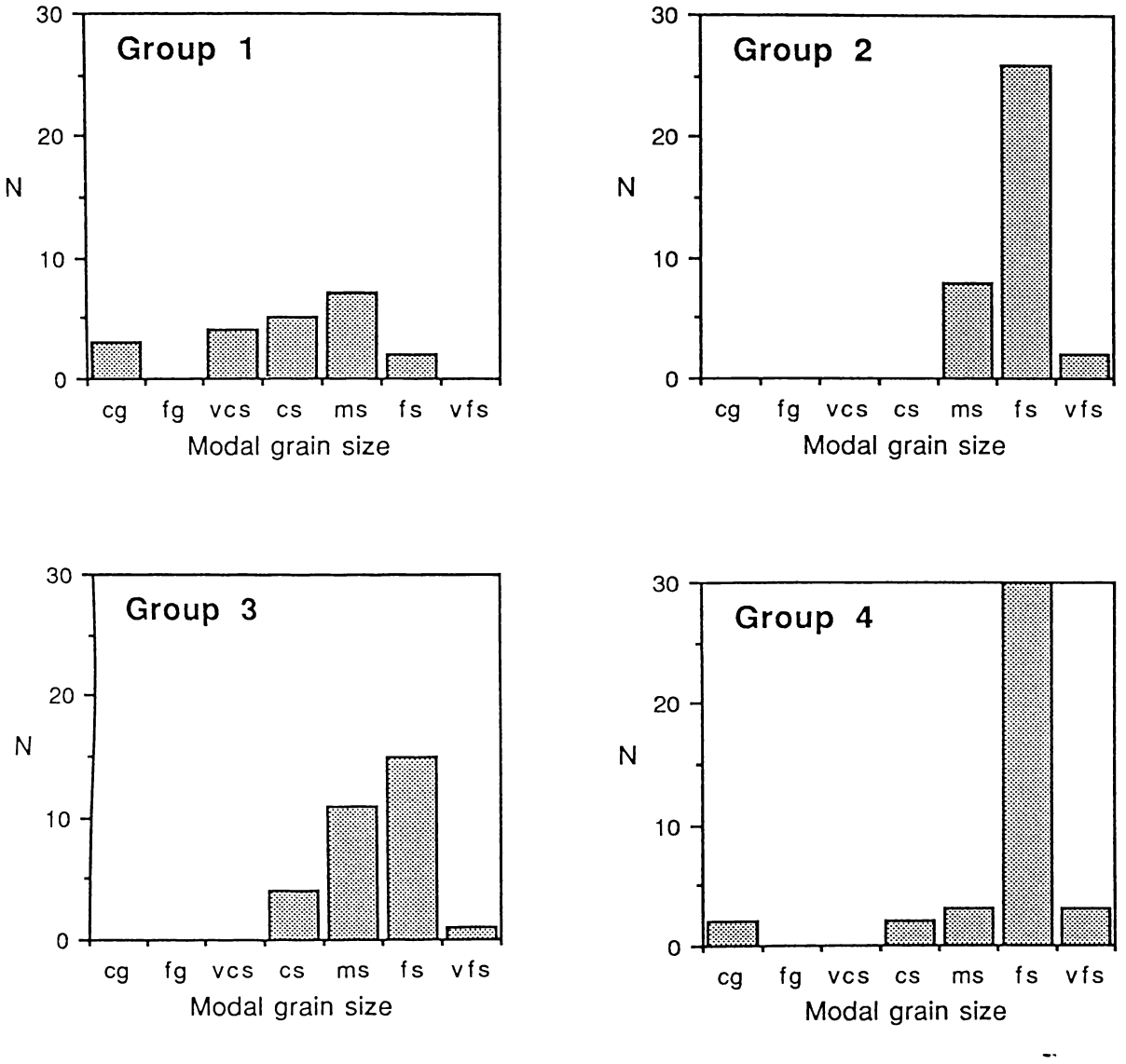


Figure 7C.5: Modal grain size (sand and gravel fraction) of four textural groups.

Abbreviations: cg - coarse gravel (>4mm), fg - fine gravel (2-4mm), vcs - very coarse sand (1-2mm), cs - coarse sand (0.5-1mm), ms - medium sand (0.25-0.5mm), fs - fine sand (0.125-0.25mm), vfs - very fine sand (0.063-0.125mm).

Table 7C.1: Descriptive parameters for the five textural sediment groups in the outer Hauraki Gulf.

Parameter	Group 1	Group 2	Group 3	Group 4	Group 5
Number of samples in group	21	41	31	40	9
% Mud range	0 to 11	10 to 32	0 to 11	18 to 62	60 to 97
% Mud mean	4	21	3	33	87
% Sand range	22 to 81	63 to 86	76 to 99	35 to 67	3 to 35
% Sand mean	64	74	91	57	13
% Gravel range	13 to 74	1 to 18	0 to 22	0 to 29	0 to 5
% Gravel mean	33	5	6	10	<1
Dominant classifications	sG, gS	mS, gmS	S, gS	gmS	M
Minor classifications	msG, gmS	-	mS	mS, sM, gsM	sM
Dominant modal grain sizes	ms,cs	fs, ms	fs, ms	fs	-
Minor modal grain sizes	vcs,cg,fs	vfs	cs, vfs	vfs, ms, cs, cg	-
Mean grain size range (Ø)	-1.11 to 1.14	1.04 to 2.68	0.14 to 2.32	0.21 to 2.43	-
Mean of calculated mean grain size (Ø) within sand and gravel fractions	0.07 (cs)	2.01 (fs)	1.58 (ms)	1.55 (ms)	- - - -
Sorting coefficient range (Ø)	0.96 - 1.88	0.91 - 1.72	0.70 - 1.43	0.76 - 2.18	-
Sorting coefficient mean (Ø)	1.42 (poor)	1.25 (poor)	1.03 (poor)	1.61 (poor)	- -
Overall textural description	Sandy gravel	Muddy fine sand	Medium sand	Gravelly muddy medium sand	Slightly sandy mud

Notes: Textural classifications after Folk (1968). Modal grain sizes, mean grain sizes, and sorting coefficient are calculated using the gravel and sand fractions only. Mean grain size and sorting measured in phi (Ø).

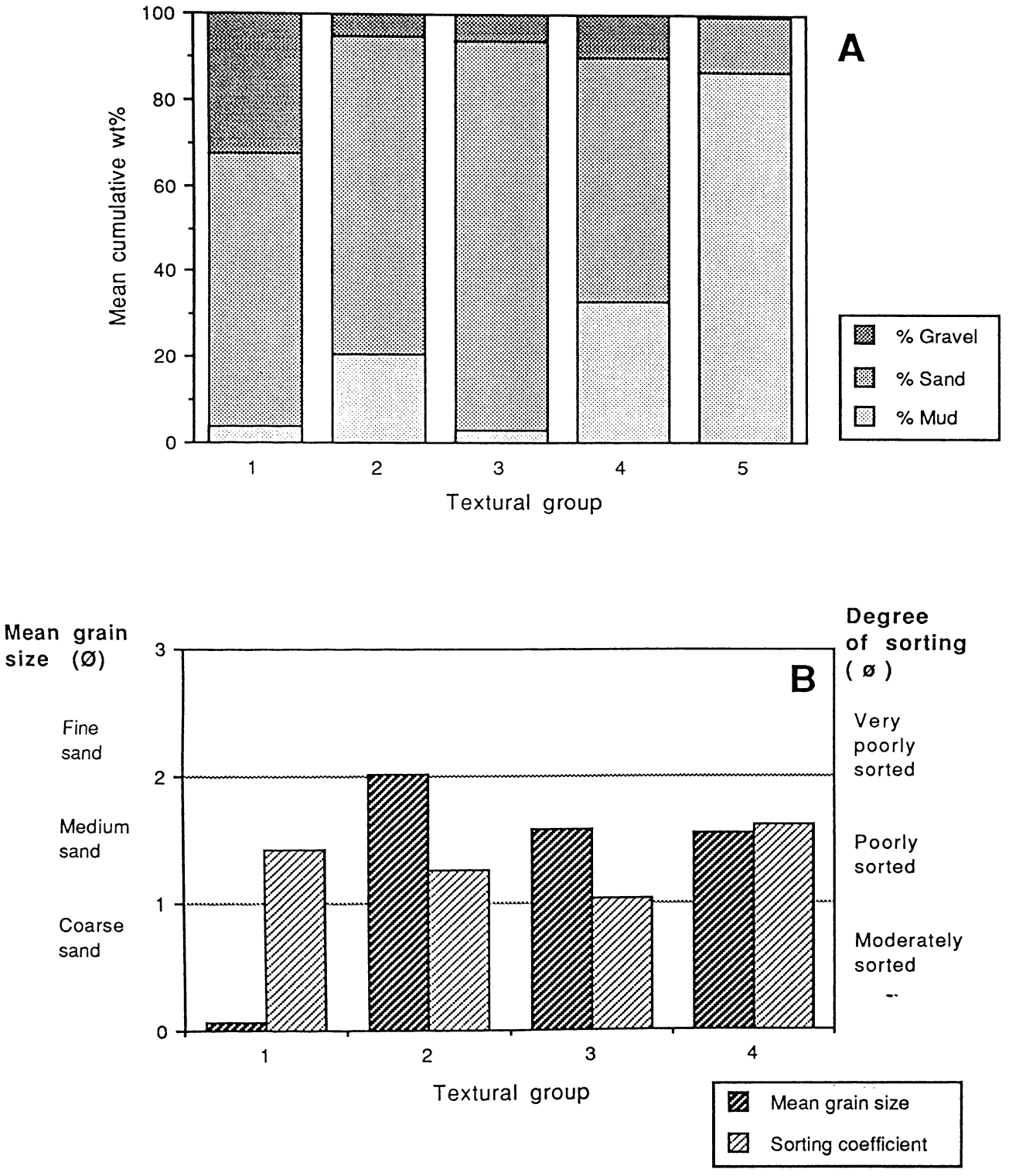


Figure 7C.6: Mean textural parameters (A) bulk texture and (B) mean grain size and sorting for each of the textural groups.

Group 5 is made up of the 9 samples that were not analyzed in detail due their very fine texture. Mud is dominant (mean 87%) and the remaining sediment is nearly all sand (gravel mean is < 1%). The Folk textural classification is mud or sandy mud.

D. CALCIUM CARBONATE CONTENT

The content of calcium carbonate in Hauraki Gulf sediments ranges widely, from1 2 to 94%, with the majority of samples in the "moderate" carbonate category (20 to 60 %) (Figure 7D.1). The $\%CaCO_3$ of the five textural groups is quite systematic (Figures 7D.2 and 3, Table 7D.1). Group 1 contains all the high carbonate sediments (>60%) and has a mean of 65%. Group 5 contains only low carbonate (<20%) sediments and has a very low mean (16%). Groups 2, 3, and 4 are all moderate carbonate sediments with means between 30 and 40% $CaCO_3$.

E. SKELETAL COMPONENTS

Thirty samples were examined in detail for their skeletal components. These data were also clustered, in an attempt to find significant differences between biological facies. The resulting cluster tree diagram (Figure 7E.1) shows two reasonably distinctive groups (A and B), and several individual samples that are unusual and assigned to Group C. Total skeletal composition is illustrated in Figure 7E.2 (data in Appendix Table A7.2).

The first group, A, is dominated by bivalves (mean 64%), with subdominant bryozoans, gastropods, and barnacles. Echinoids are sometimes also important.

Group B is also bivalve dominated (mean 79%), but more so than in Group A. Gastropods are a subdominant component, bryozoans and barnacles are only of minor importance, and brachiopods are sometimes conspicuous though of minor abundance.

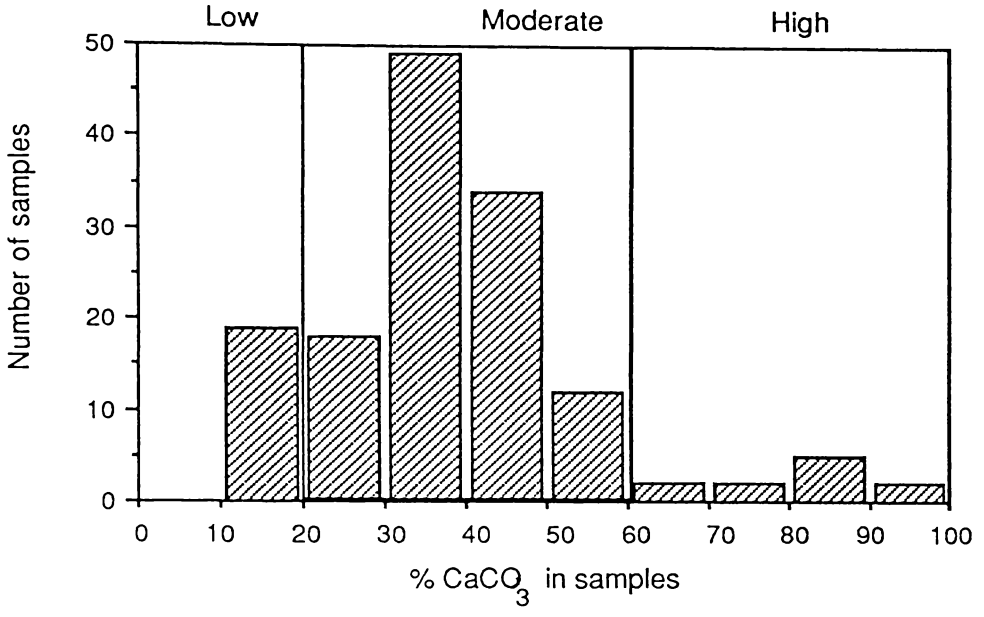


Figure 7D.1: Frequency histogram of carbonate content in sediment samples from the outer Hauraki Gulf.

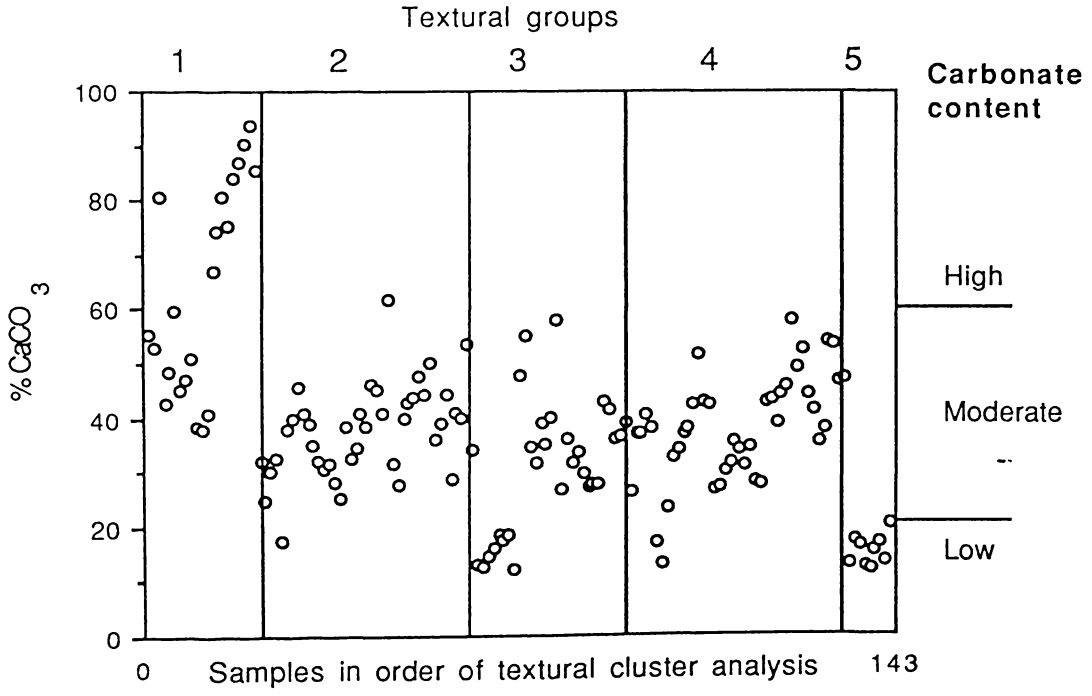


Figure 7D.2: Calcium carbonate content of each of the textural groups of sediments from the outer Hauraki Gulf.

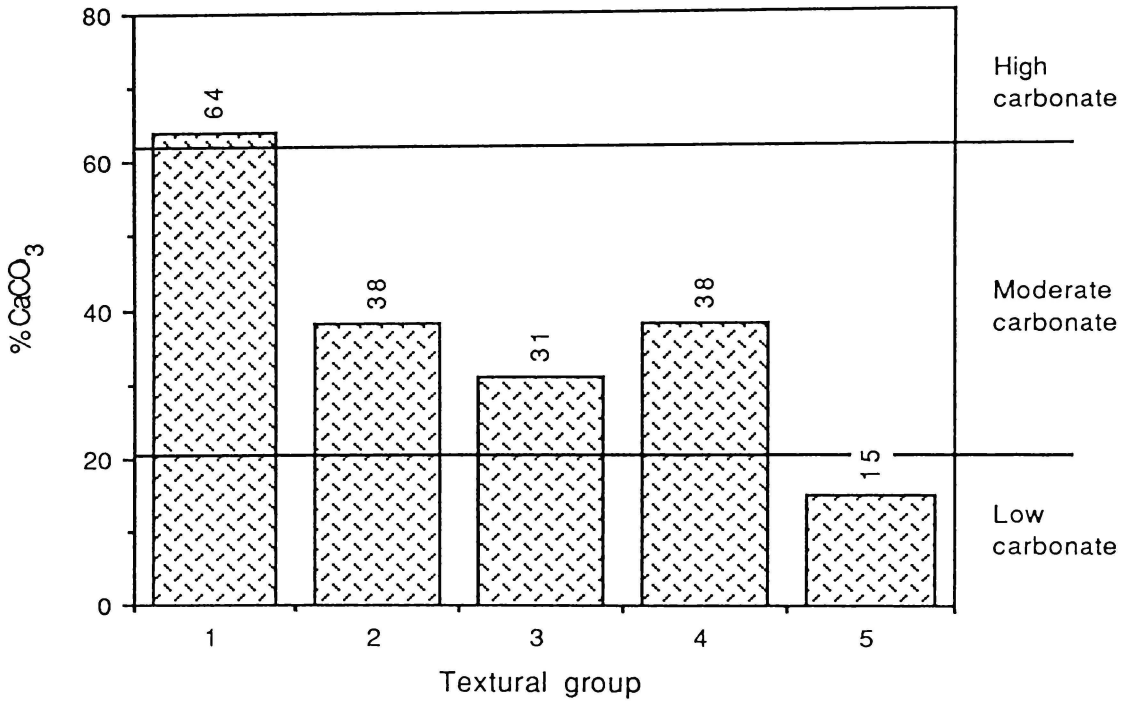


Figure 7D.3: Mean calcium carbonate content of each of the textural groups of sediments from the outer Hauraki Gulf.

Table 7D.1: Percent carbonate of the five textural groups.

Group One		Group Two		Group Three		Group Four		Group Five	
Sample	%$CaCO_3$	Sample	%$CaCO_3$	Sample	%$CaCO_3$	Sample	%$CaCO_3$	Sample	%$CaCO_3$
L09	55.1	L45	32.0	L40	12.9	L44	36.8	K14	13.3
C04	53.0	K04	24.8	L39	12.7	L23	40.2	K15	17.6
C12	80.8	C47	29.9	L37	14.7	L50	38.0	T01	16.4
C60	42.7	C30	32.6	L57	16.2	K20	16.8	T03	12.6
C20	48.4	C44	17.3	L36	18.5	K19	13.0	T04	12.0
L33	59.8	L03	38.0	L34	17.4	K18	23.2	T06	15.5
C11	45.2	C27	39.6	L01	18.4	C58	32.5	T07	16.9
C02	47.3	L29	45.7	L38	11.9	C35	34.0	T08	13.4
C14	50.8	L28	40.6	L54	47.7	K02	36.7	T12	20.4
C16	38.2	L14	38.7	L17	54.8	C33	37.9		
C10	38.1	L53	34.9	C62	34.7	C23	42.2		
C18	40.9	L48	32.1	C05	31.5	L20	51.4		
C07	67.0	L26	30.6	C61	38.9	C53	42.8		
L55	74.4	L49	31.4	L16	35.0	C31	42.4		
L05	80.5	K09	28.1	L15	39.7	C55	26.6		
T11	75.3	K03	25.2	L12	57.7	C43	27.3		
K17	83.8	L22	38.2	L10	26.7	T10	30.0		
L13	86.7	C15	32.4	L08	35.8	K10	31.4		
K06	90.2	L46	34.7	L32	31.5	C48	35.5		
T09	93.6	L31	40.8	L11	33.6	C36	33.9		
C13	85.2	L30	38.5	L07	29.4	C54	31.3		
		L18	46.1	C19	27.2	C49	34.3		
		L42	45.1	L35	27.8	C45	28.0		
		L25	40.9	L52	27.7	C24	27.6		
		L04	61.7	L47	42.5	L24	42.8		
		C21	31.7	L41	41.2	K08	43.0		
		C01	27.9	C08	35.8	C50	38.9		
		C26	39.6	C06	36.4	C40	44.2		
		L56	42.6	C09	39.0	C34	45.6		
		L19	43.6	C03	26.0	L21	57.8		
		L06	47.4	K01	37.0	K05	48.9		
		L43	44.4			K12	52.5		
		L27	49.8			C25	44.2		
		L02	35.7			C32	41.1		
		C17	38.8			T05	35.5		
		K21	44.1			K13	37.7		
		C22	28.8			T02	53.7		
		C29	40.8			K11	53.4		
		C37	39.6			C59	46.5		
		K22	53.3			K07	46.9		
		L51	34.0						
max	93.6		61.7		57.7		57.8		20.4
min	38.1		17.3		11.9		13.0		12.0
mean	65.4		37.6		31.0		38.2		15.9

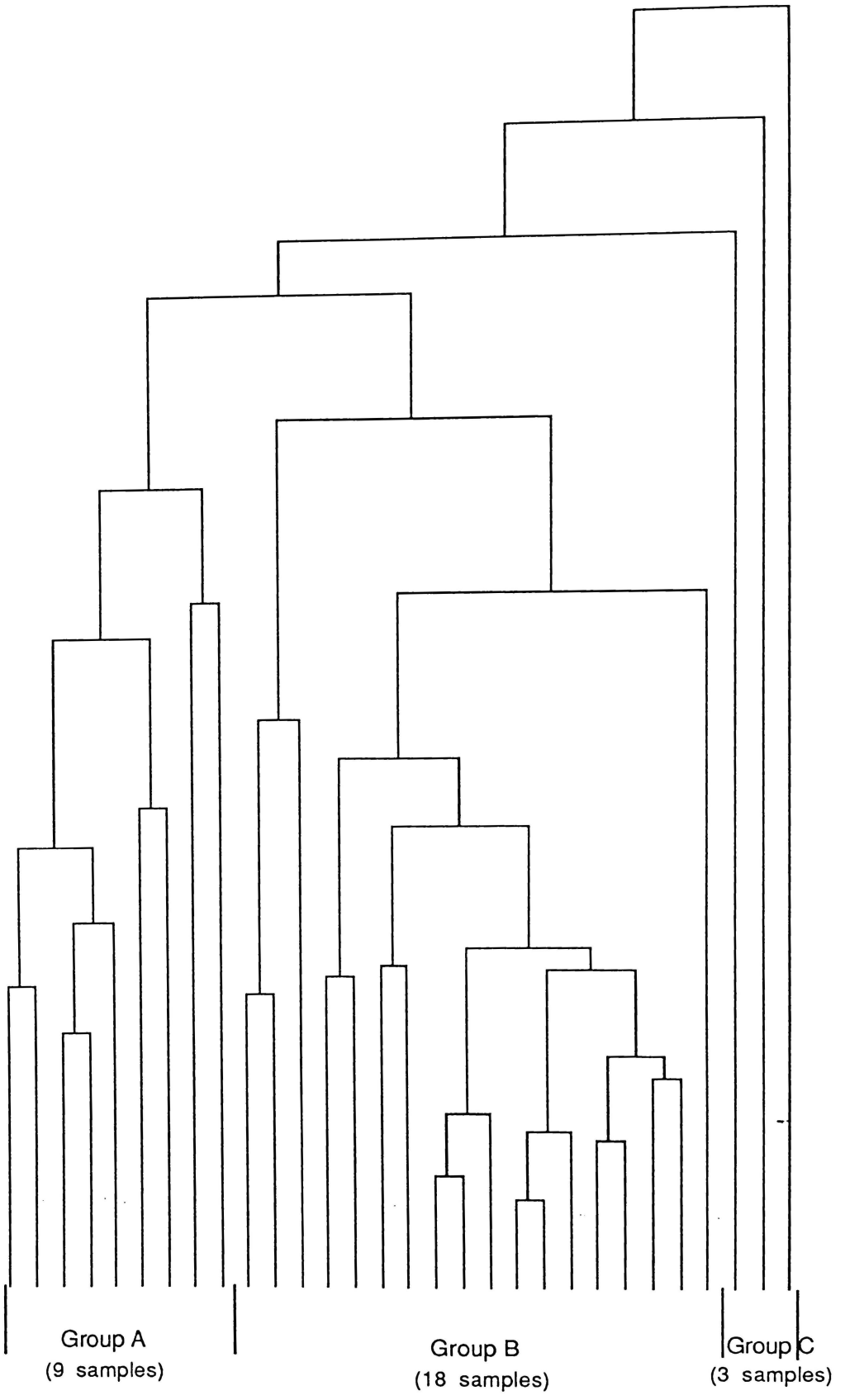


Figure 7E.1: Tree diagram of results of cluster analysis on skeletal components (data in Appendix Table A7.2), showing three main groups.

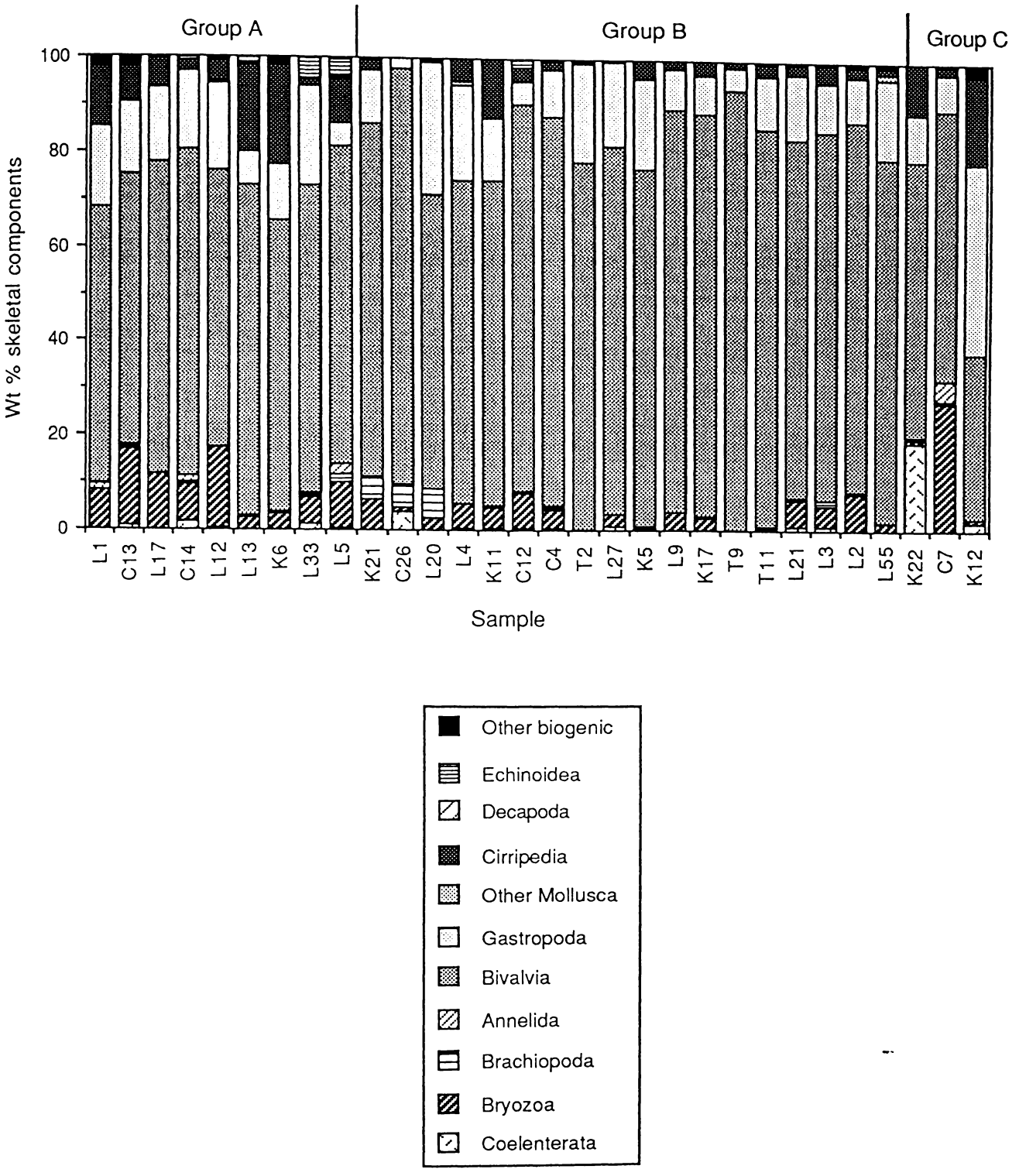


Figure 7E.2: Major skeletal components of samples within the three skeletal groups.

Group C comprises the "rogue" samples, where a single very large skeleton, such as the coral *Flabellum rubrum*, has thrown off the percentages and given misleading data. In all three, the bivalve percentage is artificially low because of the effect of this single large grain.

The relationship between these skeletal groups (A and B) and textural groups 1 to 4 is shown in Figure 7E.3 (textural group 5 has too little carbonate to allow reasonable discussion of its skeletal components). Group 3 is entirely of the skeletal Group A (about 65% bivalve with three subdominant components), whereas Groups 2 and 4 are mainly from skeletal Group B (80% bivalve with gastropods subdominant). Group 1 contains both skeletal Groups A and B. This may be because Group 1 had the most samples analyzed for skeletal components due to its high $CaCO_3$ and high gravel content.

F. AGE OF SKELETAL CARBONATES

Radiocarbon ages determined for Hauraki Gulf carbonates are mainly between 2900 and 5000 years (Table 6F.1; Figure 6F.1). Three much older samples (7910 - 8250 y) and a somewhat younger sample (1750 y) extend the range. There is little correlation between textural groups and radiocarbon ages of shells. Group 1 contains the youngest carbonates and, on examination, has the freshest shells. Carbonate in groups 2, 3, and 4 appears to be of a similar age (means from 4500 to 5000). Relatively young and relatively old shells are found within the same facies. Skeletal material in the low-carbonate groups (2, 3, and 4) may have similar histories, or have similar proportions of relict to modern shells. Shells dated from Firth of Thames surface sediments have been found to be less than 1750 y old (Naish, 1990); a similar age may be applied to group 5 sediments in the outer Gulf.

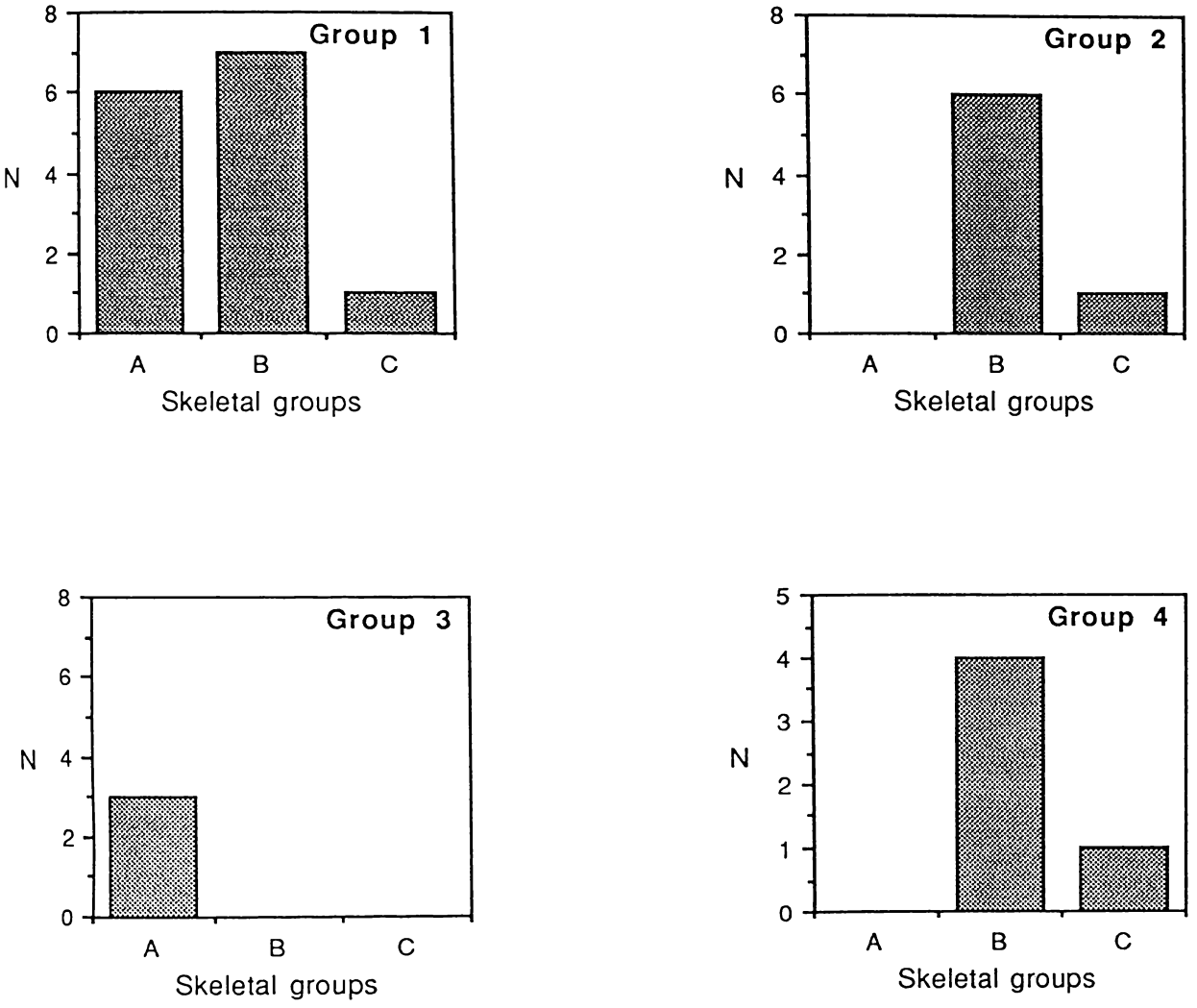


Figure 7E.3: Skeletal groups within four of the textural groups (group 5 has insufficient carbonate to classify).

Table 7F.1: Radiocarbon ages for the five textural groups.

Textural Group	Sediment sample	Radiocarbon age	Mean for group
1	AMS-C12	2910	2905
	AMS-T09	2900	
2	AMS-C29	3300	4460
	AMS-K22	3850	
	AMS-L30	8250	
	AMS-L51	3510	
	AMS-L04	3390	
3	AMS-C08	2970	5153
	AMS-L10	4940	
	AMS-L40	4790	
	AMS-L17	7910	
4	AMS-K19	3430	4553
	AMS-C45	1750	
	AMS-L23	8090	
	AMS-T10	4940	
5	not enough carbonate		--

G. CONCLUSIONS

A combination of properties (texture, carbonate content, skeletal components, and age) are used to place outer Hauraki Gulf sediment samples into groups.

Group 1 is a poorly sorted sandy gravel, high in carbonate, bivalve dominated with bryozoans, barnacles, and gastropods subdominant, and fairly young, about 3000 years old.

Group 2 is a poorly sorted muddy fine sand, with moderate carbonate content, strongly bivalve dominated with gastropods subdominant, and carbonates date mainly from about 3000 to 4000 years BP.

Group 3 is a moderately sorted medium sand, with moderate carbonate content, bivalve dominated with bryozoans, barnacles, and gastropods subdominant, and carbonate ages are very variable, from 2970 to 7910 years old.

Group 4 is a poorly sorted gravelly muddy medium sand, with moderate carbonate content, strongly bivalve dominated with gastropods subdominant, and covers the widest range in ages (1750 to 8090 y).

Group 5 is a slightly sandy mud, with low carbonate content and few skeletal components which may be quite young (<1750 y old).

Comparison of these groups with previously defined facies, definition of sedimentary facies, their distribution (e.g., see Figure 9A.1), and the late Holocene history of the outer Hauraki Gulf will be considered in Chapter 9. Implications and importance of such mixed carbonate-terrigenous sediments, and potential analogues of the Gulf sediments will be discussed in Chapter 12.

Chapter 8 Bioerosion in the Hauraki Gulf

"There is no one who can return from there
To describe their nature, to describe their dissolution...
Until we reach the places where they have gone."
Song of the Harper, translated from the Egyptian by W.K. Simpson, c. 2600 BC

A. INTRODUCTION

Hauraki Gulf carbonates are bivalve-dominated. Examination of these bivalve shells immediately reveals that they are degraded-looking, often encrusted, bored, and pitted (Figure 8A.1). In general, Hauraki Gulf sediments show few signs of abrasion. Even quite thin shells are often found whole. Evidence of dissolution of shells is equally difficult to find; there is no sign of the extreme fragility of shells reported by Alexandersson in the Skaggerak (1978a). There is, however, considerable evidence of biological diagenesis. Holes, tunnels, and borings indicate the importance of bioerosion in Hauraki Gulf carbonates.

Several questions arise. What organisms are encrusting and bioeroding in the Hauraki Gulf? Which of the two processes is more important? At what rate and under what controls is biological diagenesis occurring? The purpose of this chapter is to report on an experiment undertaken to determine short-term rates of bioerosion (if any) in bivalves in the Hauraki Gulf, and on the ages of bioeroded shells from Hauraki Gulf sediments. Possible controls on bioerosion rates, such as season, mineralogy of substrate, and age of substrate, will be investigated.

B. METHODS

Shells of common New Zealand bivalves were obtained from living organisms, scraped free of organic material, dried under very low heat, broken into pieces of approximately 1 cm^2, and weighed. *Perna canaliculus* (mussel), *Austrovenus stuchburyi* (cockle), *Chlamys delicatula* (gem scallop), and *Paphies australis* (pipi) were all treated in this way. Fragments of *Pecten novaezelandiae* were removed from several sediment samples from

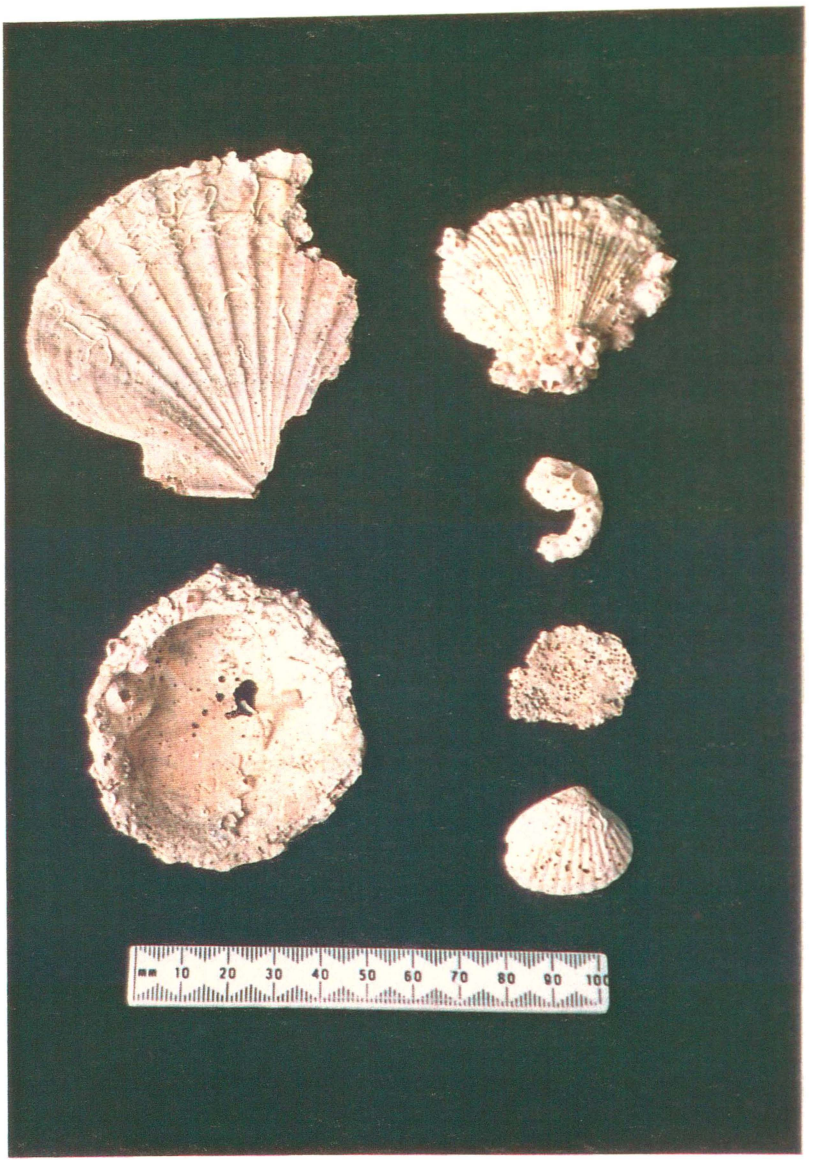


Figure 8A.1: Shells from Hauraki Gulf sediments showing bioerosion.

the Hauraki Gulf and included in the experiment untreated. They were chosen on the basis of looking nearly fresh, at worst only slightly bioeroded. XRD analysis of mineralogy showed that three of these bivalves are aragonitic and two calcitic with no measurable Mg (Table 8B.1, Figure 8B.1).

Sample containers were manufactured from plastic jars with screw-top lids as described by Tudhope and Risk (1985) (Figure 8B.2). One piece of shell from each species was suspended between layers of 250 μg nylon mesh, secured by the screwed-on lid. Free access to sea water was assured by the removal of the bottom of the container, and of the inner part of the lid; while movement or abrasion was prevented by the mesh. These containers were secured to a stainless steel rack, 0.3 m off the sea floor, which was weighted, moored, and marked by buoy. The mooring site was off Cape Rodney in 14m water depth, on a small rocky ledge covered in kelp and surrounded by sandy flats (Figure 8B.3).

Twenty-five such containers were deployed in August, 1990. The samples were checked (by SCUBA) after 1 month to ensure that the mooring remained securely in place. One sample had come loose and was replaced. Five samples were collected at 3 monthly intervals from the initial mooring date, although one collection had to be skipped due to bad weather and the loss of the marker buoy. Samples were thus collected at 3, 9, 12, and 15 months from deployment. At the 9-month-collection, four new containers were deployed, and one was collected three and six months later. At the time of writing, 7 samples remain in the sea; thus the results from 21 containers are reported here (Figure 8B.4).

Collected samples were rinsed in 50% ethanol, dried, and weighed to an accuracy of 0.001 g. Percent weight change over time was calculated. Specimens were examined under binocular microscope, and any encrustation or apparent bioerosion was noted. Several specimens were selected for SEM examination and photography. These were either

Table 8B.1: Molluscan species used in bioerosion experiment.

Species	Common name	Mineralogy	Condition	Treatment
Austrovenus stutchburyi	cockle	Aragonite	alive	animal removed, dried
Chlamys delicatula	gem scallop	Calcite	alive	animal removed, dried
Paphies australis	pipi	Aragonite	alive	animal removed, dried
Pecten novaezelandiae	scallop	Calcite	dead	removed from sediment
Perna canaliculus	mussel	Aragonite	alive	animal removed, dried

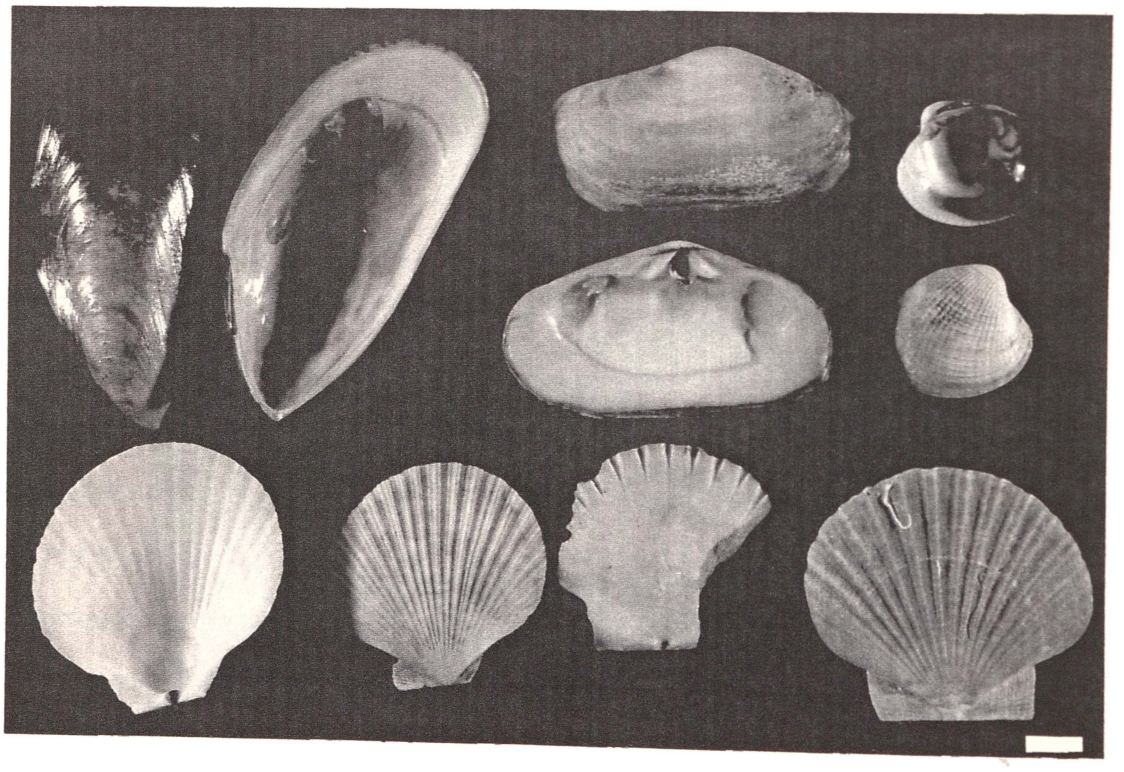


Figure 8B.1: Examples of the species used in bioerosion experiment.
Top row: *Perna canaliculus, Paphies australis, Austrovenus stutchburyi;*
Bottom row: *Chlamys delicatula, Pecten novaezelandiae.*
Scale is 1 cm.

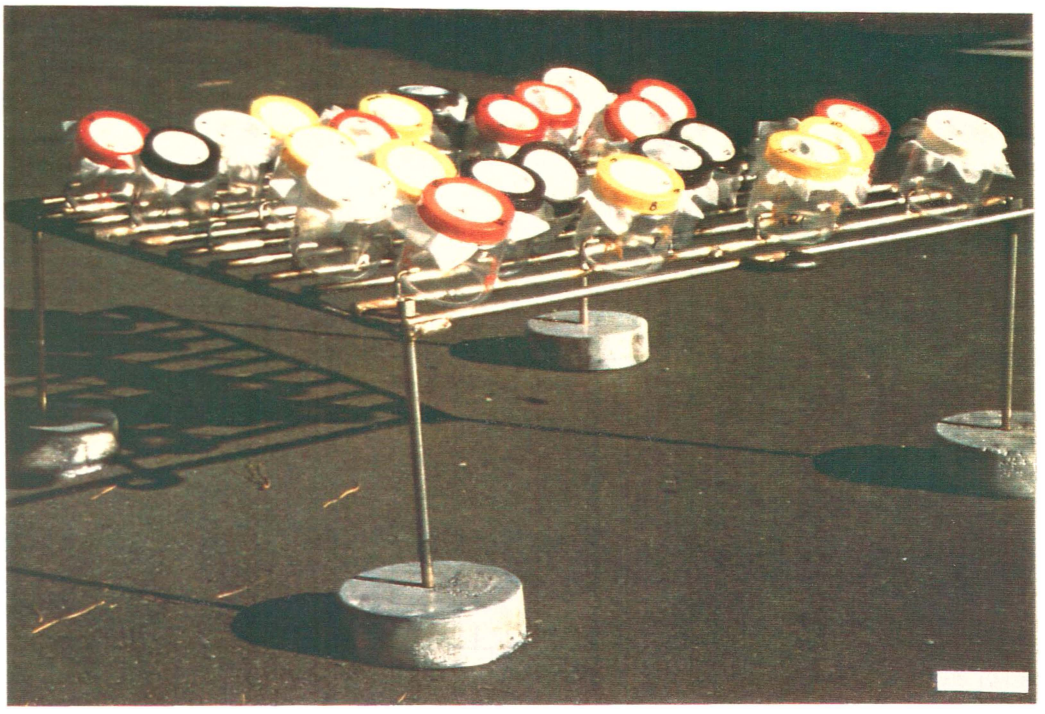


Figure 8B.2: Sample containers on sample rack, used in underwater experiment. Scale is 10 cm.

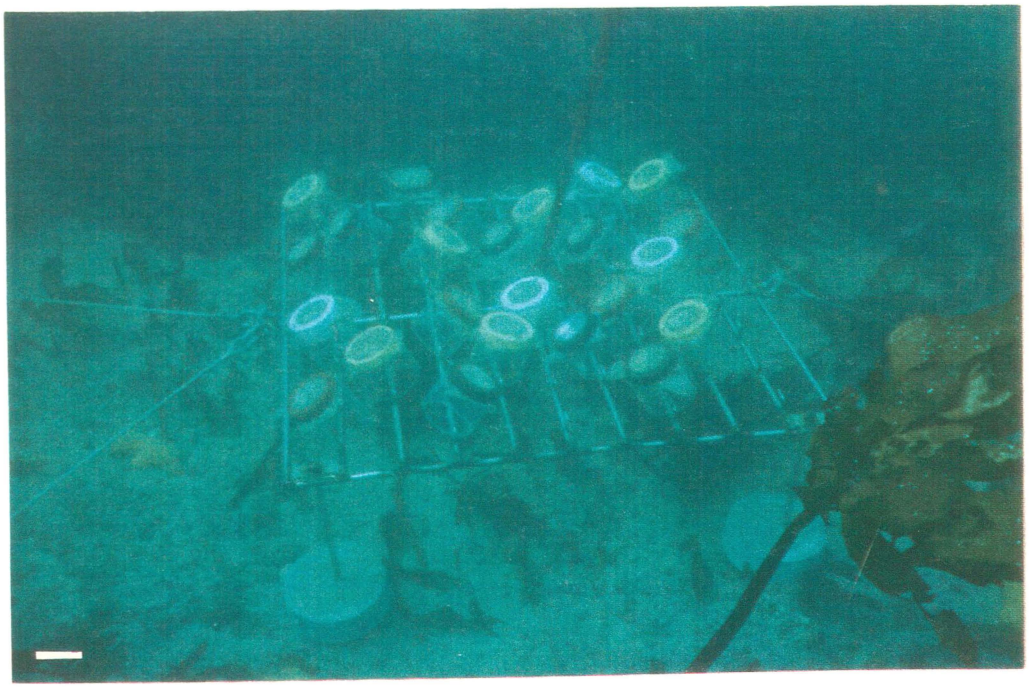


Figure 8B.3: Sample apparatus underwater, fastened to rocks with pitons and stainless steel wire. Scale is 10 cm.

		TIME OF COLLECTION				
		November 1990	May 1991	August 1991	November 1991	TOTAL DEPLOYED
TIME OF DEPLOYMENT	August 1990	**3 mo** 4	**9 mo** 5	**12 mo** 5	**15 mo** 4	18
	September 1990	**2 mo** 1				1
	May 1991			**3 mo** 1	**6 mo** 1	2
	TOTAL COLLECTED	5	5	6	5	21

Figure 8B.4: Bioerosion study design. Bold numbers indicate time of immersion, other numbers indicate number of samples in each treatment.

mounted and sputter-coated, ~~while~~ or cast in "Petropoxy" resin, ground, and the carbonate dissolved, to form a cast of internal structures, which was then sputter-coated.

In order to determine a time scale for bioerosion, a second experiment was undertaken. Mollusc shells of a single species were removed from a single Hauraki Gulf sediment sample and categorized as to the extent of bioerosion: fresh, light, moderate, and heavy. The shells were photographed (Figure 8B.5) and their ages determined using radiocarbon dating. Sample information is given in Table 8B.2.

C. RESULTS

All weight change results for all submerged specimens, along with calculations made, are given in Appendix Table A8.1. In many specimens, % weight change was negligible, less than 5%. In more extreme cases, weight change varied from 15% gain to 25% loss. One specimen of *Pecten* that lost 89% of its original weight in 9 months was excluded from subsequent analysis, as it is thought to have broken during handling. Weight percent change for each sample over time is given in Figure 8C.1. Mean weight changes for all species are given in Figure 8C.2. There is considerable variation among species, which appears to increase with immersion time.

Samples and sample containers were encrusted with algae, worms, barnacles, and bryozoans (Figure 8C.3). Sample containers immersed for 3 months were lightly encrusted, mainly with barnacles and algae. Longer immersion times resulted in heavier encrustation. After 12 months, pomatoceran worms were up to 9 cm long, barnacles were thickly grouped, and encrusting bryozoan colonies up to 3 cm across had developed (see Chapter 1, Section D). The encrusting biota inside the mesh were somewhat different, presumably limited by larval size. Pomatoceran and *Spirorbis*-type worms, bryozoans, and red algae were found. Very few barnacles settled inside the mesh. In addition, foraminifera, brachiopods, and agglutinating worms were found on specimens. All specimens in the 12-month immersion were heavily encrusted (Figure 8C.4).



Figure 8B.5: *Pecten novaezelandiae* in various stages of degradation. These are representative of the samples submitted for radiocarbon dating.

Table 8B.2: Bioeroded shells from Hauraki Gulf sediments submitted for radiocarbon dating.

Sediment sample	Species	Extent of bioerosion
L57	*Pecten novaezelandiae*	none (live)
L55	*Pecten novaezelandiae*	light
L55	*Pecten novaezelandiae*	moderate
L55	*Pecten novaezelandiae*	heavy
L13	*Tawera spissa*	almost fresh
L13	*Tawera spissa*	light
L13	*Tawera spissa*	moderate
L13	*Tawera spissa*	heavy
T11	*Struthiolaria papulosa*	light
T11	*Struthiolaria papulosa*	moderate
T11	*Struthiolaria papulosa*	heavy

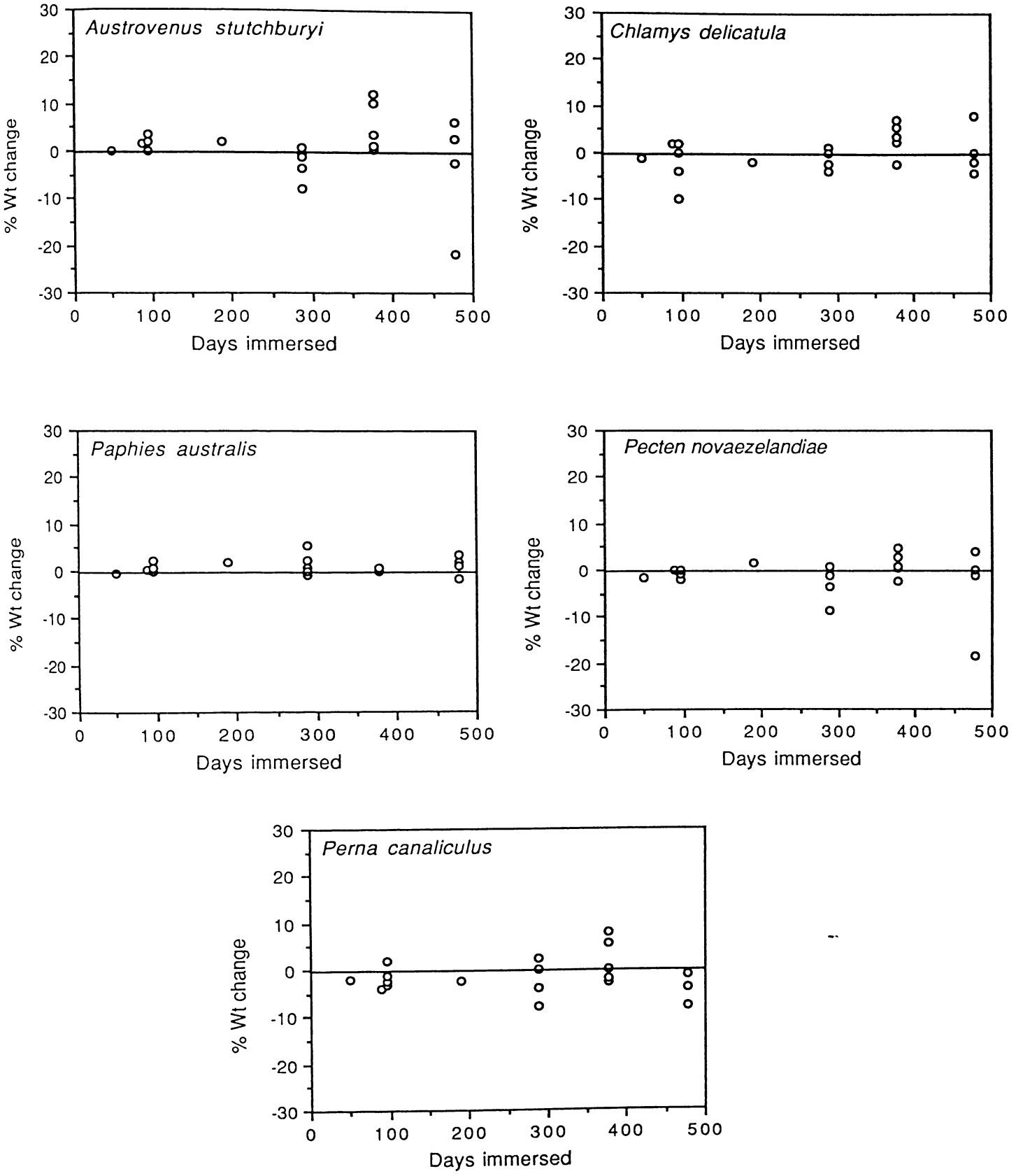


Figure 8C.1: Percent weight change over time for each of five molluscs, immersed at Cape Rodney for up to 15 months.

			TIME OF COLLECTION			
			November 1990	May 1991	August 1991	November 1991
TIME OF DEPLOYMENT	August 1990	*Austrovenus*	+1.4	-2.5	+5.5	-3.8
		Chlamys	-3.0	-1.0	+3.2	+0.4
		Paphies	**3** +0.8	**9** +1.6	**12** +0.5	**15** +1.2
		Pecten	-0.7	-3.5	+1.2	-3.9
		Perna	-1.3	-1.9	+1.8	-5.2
	September 1990	*Austrovenus*	+0.0			
		Chlamys	-1.3			
		Paphies	**2** -0.3			
		Pecten	-1.4			
		Perna	-1.9			
	May 1991	*Austrovenus*			+1.7	+2.0
		Chlamys			+1.8	-2.1
		Paphies			**3** -0.2	**6** +2.1
		Pecten			+0.0	+1.7
		Perna			-4.0	-2.4

Figure 8C.2: Mean results of bioerosion study. Bold numbers show immersion time in months, other numbers give mean % weight change.



Figure 8C.3: Sample containers removed after immersion for three months (left) and 12 months (right).



Figure 8C.4: Specimens after 12 months immersion showing encrustation.

Binocular microscope examination revealed little evidence of bioerosion. The majority of large borings were seen on the *Pecten* shells. Of the other four species, only *Chlamys* showed any macroscopic evidence of bioerosion: two shells showed superficial tracks.

Specimens with evident erosion, as well as specimens with relatively large weight changes, were examined more closely using SEM. In general, microborings had a patchy distribution. Large areas of shell were apparently unbored (Figure 8C.5A), and in those areas with borings, they were concentrated near the surface of the shell (Figure 8C.5B). Encrustation was clearly evident, both of macroorganisms (coralline algae, bryozoans, worms) and of microorganisms (diatoms, coccoliths) (Figure 8C.5C and D).

Several natural shells from Hauraki Gulf sediment samples were examined in the same way. Borings were extensive enough to allow some preliminary groupings to be made. Four major types of bioeroders were identified (Figure 8C.5) using published photographs and descriptions (e.g., Perkins and Halsey, 1971; Young and Nelson, 1988). Differentiation as to larger taxon is based primarily on the size and morphology of the borings; in most cases no attempt is made to identify species.

The largest excavations found are up to 2 mm across, and may be quite extensive. The holes are lined with subspherical pits, diagnostic of the boring sponges of the family Clionidae (Figure 8C.6A). These sponges chemically etch roughly semispherical chips from shells on which they settle. In New Zealand, the most common boring sponge is *Cliona celata* (Morton and Miller, 1968). This species is a major borer in Californian waters, and corresponds to the trace fossil *Entobia geometrica* (Stearley and Ekdale, 1989).

Much smaller holes lead to smooth tunnels that branch at a 90° angle and are 20-30μm in diameter (Figure 8C.6B). The tunnels have irregular swellings and tend to lie parallel to the surface of the shell. These are similar to the borings of *Ostrobium queketti* of the Canadian Pacific (Young and Nelson, 1988), and are thus likely to be a similar green

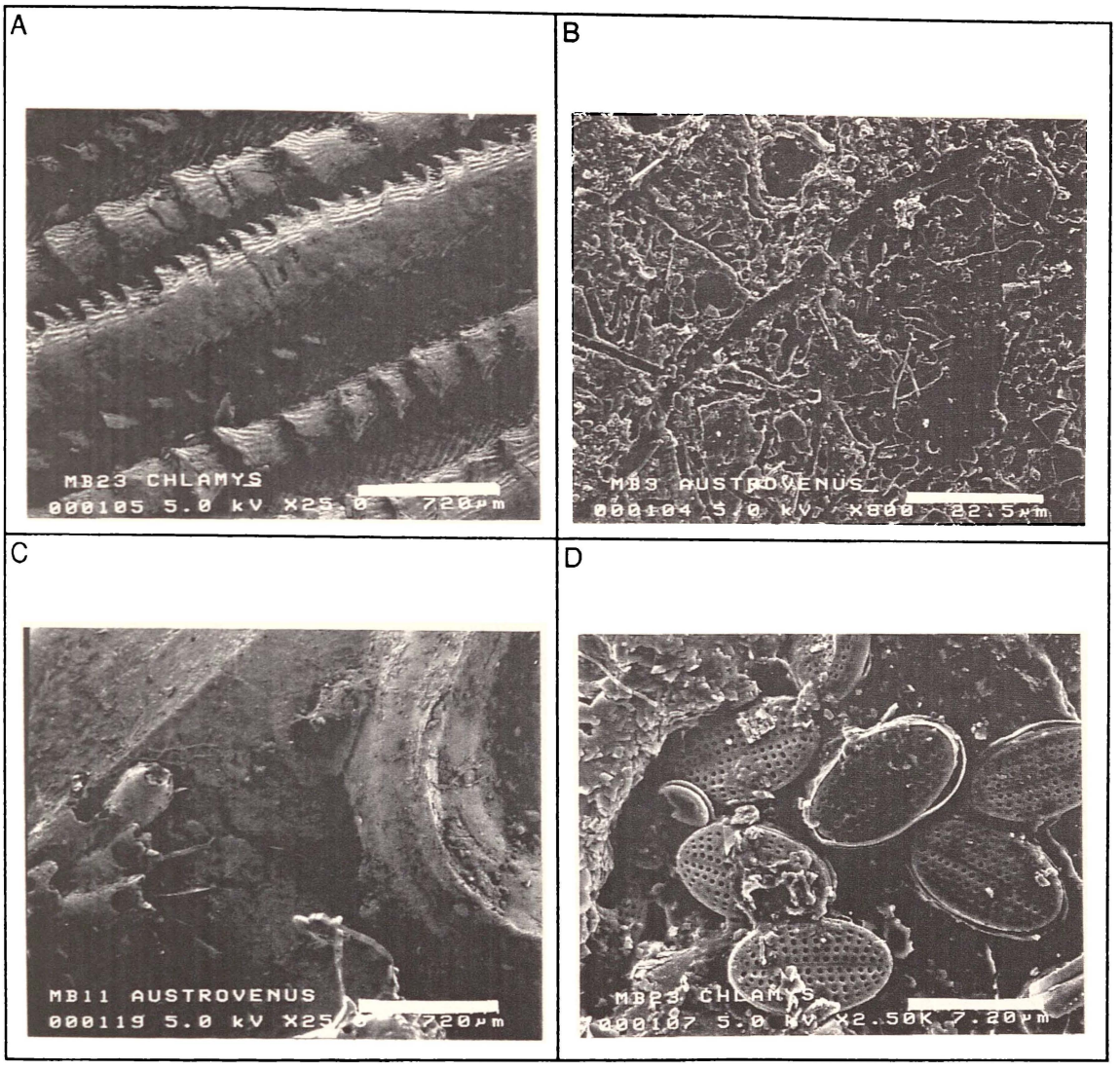


Figure 8C.5: Scanning electron micrographs of bioerosion and encrustation on experimental specimens. (A) Unbored shell, (B) superficial boring, (C) encrusting organisms, (D) encrusting microorganisms.

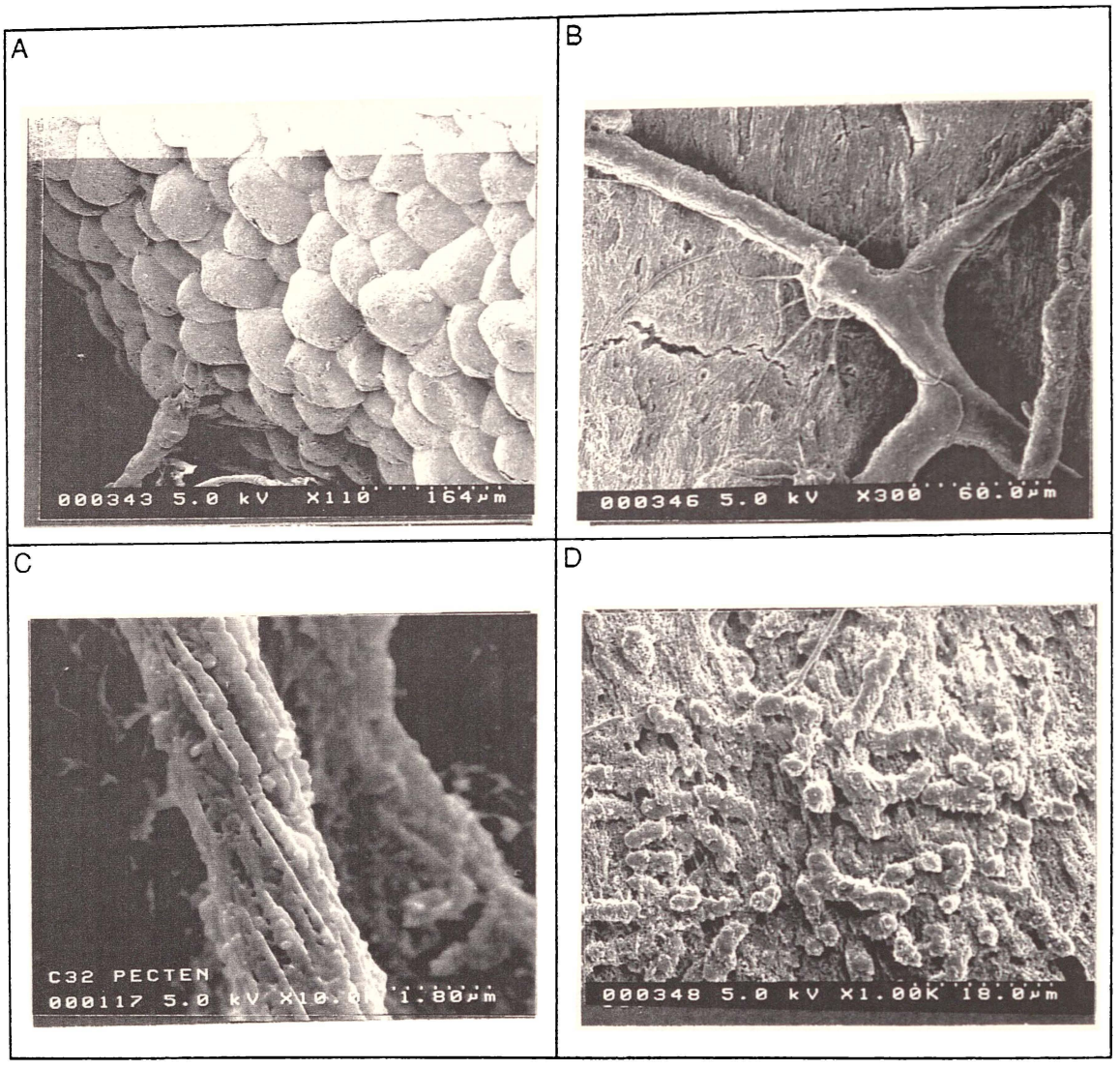


Figure 8C.6: Scanning electron micrographs of bioerosion in specimens from Hauraki Gulf sediments. (A) Clionid sponge, (B) green algae, (C) fungal hyphae, (D) prokaryote - perhaps blue-green algae.

alga. Algae are thought to bore into shells for protection from grazers. As they are photosynthetic, there is a light-dependent distribution, with a maximum depth limit depending on water clarity. Most studies place this maximum around 50 m water depth (Perkins and Halsey, 1971).

Borings of even smaller diameter join stellate sacs with fine thread-like projections (Figure 8C.6C). The disk-like sacs are 20 - 50 μm in diameter, and are joined by irregular tunnels of about 10 μm diameter. The finer projecting borings are only 1 μ in diameter, and do not connect with other sacs. The very fine nature of these threads leads to the identification of these borings as the products of fungi. The sacs are reproductive structures (sporangia). Fungi have been identified as a widespread and early infester of shell material. They may prefer molluscan substrate, perhaps due to easier access to organic material present for food (Perkins and Halsey, 1971).

Convoluted vermicular tunnels found in tangled groups (Figure 8C.6D) are similar to published photos of bacterial borers, but are several times larger (3-4 μm in diameter). Annulations may indicate that the borer in question is a blue-green alga (Young and Nelson, 1988). At best this group can only be identified as some sort of prokaryote, possibly a blue-green alga.

The natural specimens showed more extensive bioerosion than the experimental ones, and less encrustation. None of the specimens observed showed any cements or infilling of borings, as are common in the tropical shelf environment (e.g., Bathurst, 1975). Neither was there any evidence of dissolution features. As abrasion was prevented by the sample container, experimental shells can be assumed to have been subject only to weight gain by encrustation and weight loss by bioerosion.

Radiocarbon ages (Table 8C.1) range from modern (less than 40 y) to 1320 y. The three species studied show considerable variation in time scale (Figure 8C.7). Heavily bioeroded shells of *Tawera spissa* are several times older than *Pecten novaezelandiae*

Table 8C.1: Ages of bioeroded shells from Hauraki Gulf sediments as determined by radiocarbon dating (see Appendix Table A8.2 for details).

Extent of bioerosion	*Pecten novaezeladiae*	*Tawera spissa*	*Struthiolaria papulosa*
None (live)	Modern	--	--
Almost fresh	--	720 ± 220 y	--
Light	Modern	1160 ± 200 y	Modern
Moderate	Modern	1320 ± 210 y	Modern
Heavy	350 ± 190 y	1170 ± 240 y	840 ± 210 y

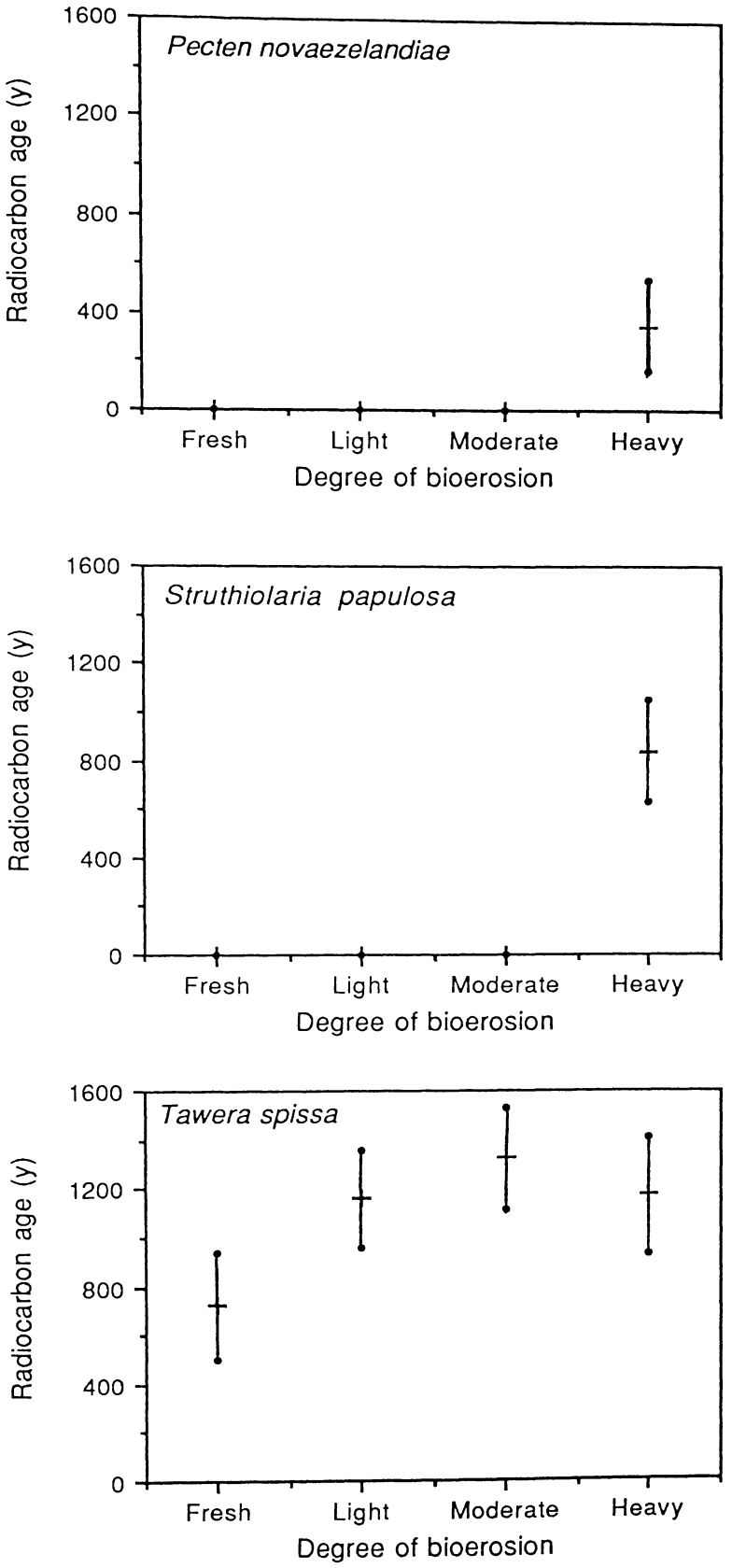


Figure 8C.7: Radiocarbon ages of mollusc shells from the Hauraki Gulf, displaying varying degrees of bioerosion.

shells. Indeed, fresh-looking *T. spissa* specimens, retaining color patterns and delicate surface architecture, are already several hundreds of years old.

D. DISCUSSION

1. Overall regime

The experimental specimens show very little bioerosion in the course of 15 months exposure. In contrast, encrustation is common. An overall weight gain, particularly over the first 12 months, reflects this (Figure 8D.1). Even if bioerosion did occur, carbonate losses would be offset by the addition of carbonate through encrustation. Bioerosion seems to be a long-term process, and extensive bioerosion is not developed in the time-frame of one or two y. Encrustation, however, occurs far more rapidly. Within only three months shells may be quite heavily encrusted.

It is possible in sedimentology to describe sediment grains as relict or "older" based on physical appearance, including the degree of encrustation (e.g., Carter, 1975). The evidence given here suggests that this is inappropriate and that extent of bioerosion may be a better indication of relative age. Indeed, heavily bioeroded grains may be quite old (> 1000 y). Very worn shells removed from Hauraki Gulf sediments are seldom encrusted; perhaps as they age and become more fragile it is more difficult for encrusting species to adhere to the shell.

In fact, encrustation and bioerosion are processes that behave differently over time. The effects of bioerosion are irreversible; shell that is bored away cannot be replaced. Thus over time, weight loss is cumulative. The only limit on bioerosion is the initial size and weight of the shell. Encrustation, however, can be periodic. A worm tube may be knocked off a shell; a bryozoan may be grazed. Larval settlement may replace these losses, but weight gain will not be cumulative over time. There may be an upper limit of how much encrusting fauna and flora a given shell can host at a time.

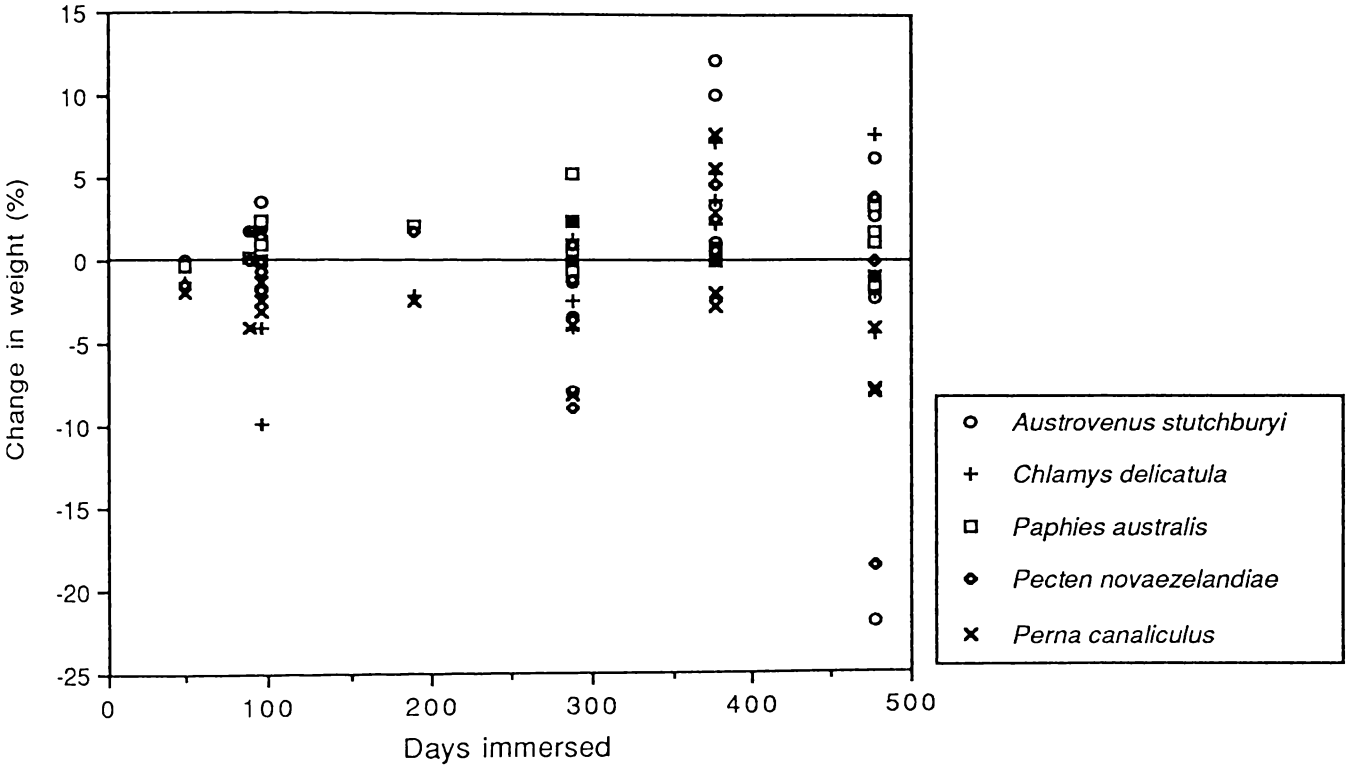


Figure 8D.1: Percent weight change over time for mollusc shells immersed at Cape Rodney.

A conceptual model of the change in shells over time due to biological activity (Figure 8D.2) shows initial weight gain due to encrustation offsetting bioerosion, followed by eventual weight loss due to the increasing cumulative effects of bioerosion. The experimental samples immersed for a short time (15 months or less) are on the positive slope, early in time. The natural samples, subject to more exposure, occur on the negative slope.

The trend of this model is similar to that described for sediments on the Great Barrier Reef (Tudhope and Risk, 1985), in which the initial period in which encrustation outweighed bioerosion was about 100 days. Over a year, the sediments suffered a mean weight loss of 1.7% in shallow (5m) water depth, and somewhat less in deeper water (18m). The experimental Hauraki Gulf shells described here take longer: encrustation outweighs bioerosion even after 12 to 15 months, depending on the species. However, in 12 months, mean weight change varies from 4% lost to 5% gained - far more variation than is found on the Great Barrier Reef.

2. Controls

There are undoubtedly many controls on biotic distribution and rates of bioerosion and encrustation. A bathymetric/photic control on the distribution of algae has been mentioned above. Clionid sponge populations increase in size with depth in Californian waters (Stearley and Ekdale, 1989). Other environmental factors are likely to be important. Stearley and Ekdale (1989) found lower diversity in a muddy quiet environment than in clear, well-aerated waters. No doubt temperature and salinity are important. Comparison with a similar tropical experiment indicates that bioerosion rates may be slower in colder waters (see Tudhope and Risk, 1985). In the long term, however, bioerosion is important in temperate waters, as cementation and sedimentation are slow (Nelson, 1988b), increasing the residence time in which a particular shell will be exposed to bioerosive agents. As this study has only examined one location, environmental controls cannot be evaluated. Other controls may, however, be investigated.

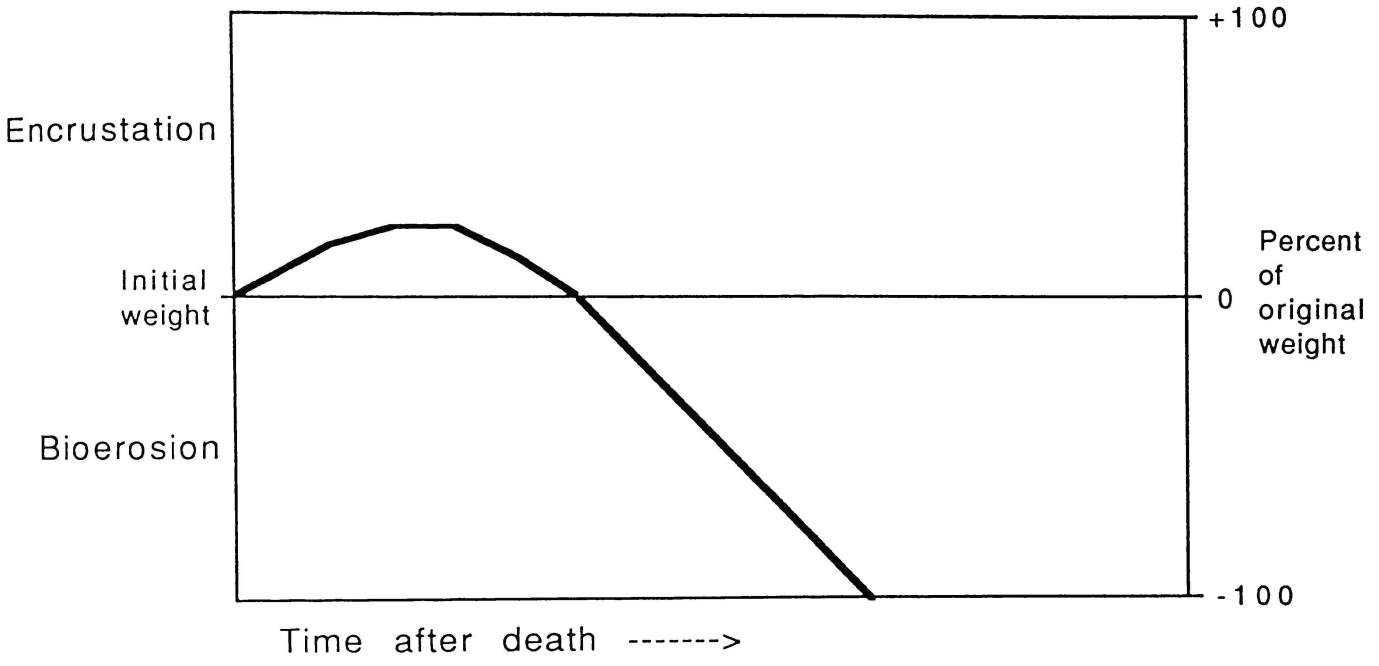


Figure 8D.2: Conceptual model of weight change in a shell over time.

It seems reasonable that biological activity would depend on the season of the year. Encrustation rates should be affected by times of larval settlement and growth rates. Bioerosion may be affected by temperature and/or light changes over time. This experiment covers less than two years, and temperatures in New Zealand waters may vary from year to year (Evans, 1990). There is thus no assurance that this study is representative. Comparison of two different three-month periods, one from August to November (spring) and the other from May to August (winter), shows no clear trend (Figure 8D.3). The short term of this study limits further analysis of the effects of season.

Another important control on bioerosion is the character of the substrate. Radiocarbon dates point to major differences in bioerosion rates among species. The mechanism by which substrate and bioeroders interact to create this species-specific rate of weight change is not clear. Certain shells may have more "appeal" to bioeroders, or may be more resistant to attack. Both mineralogy and degree of previous erosion were examined in the experimental study. No significant differences occur between the weight change in aragonite and low-Mg calcite shells over time (Figure 8D.4A). The *Pecten* specimens removed from natural sediment samples were somewhat more degraded prior to the experiment, and may have been less resistant, or have provided more surface area to potential borers. One would thus expect greater weight loss from the *Pecten* specimens than from fresh specimens. Particularly in the later stages of the experiment (nine months onward), this may be the case (Figure 8D.4B).

3. Rates of bioerosion

Radiocarbon dates of shells with different extents of bioerosion provide something of a temporal framework for the conceptual model. There is a wide range of ages, but, in general, heavy bioerosion of a whole shell may take 100s to 1000s of years. Extrapolating from the radiocarbon ages, a *Tawera spissa* shell may take 2000 y to disintegrate, whereas a *Pecten novaezelandiae* may only take 500 y. These differences make it difficult to generalize about an overall rate of bioerosion for the Hauraki Gulf.

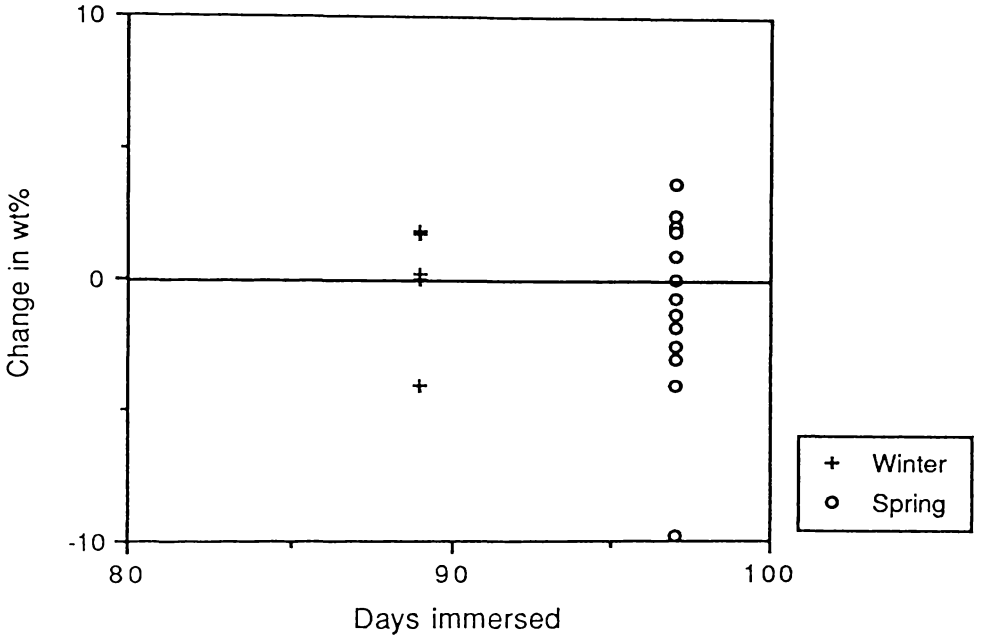


Figure 8D.3: Seasonal differences in weight change during immersion for 3 months.

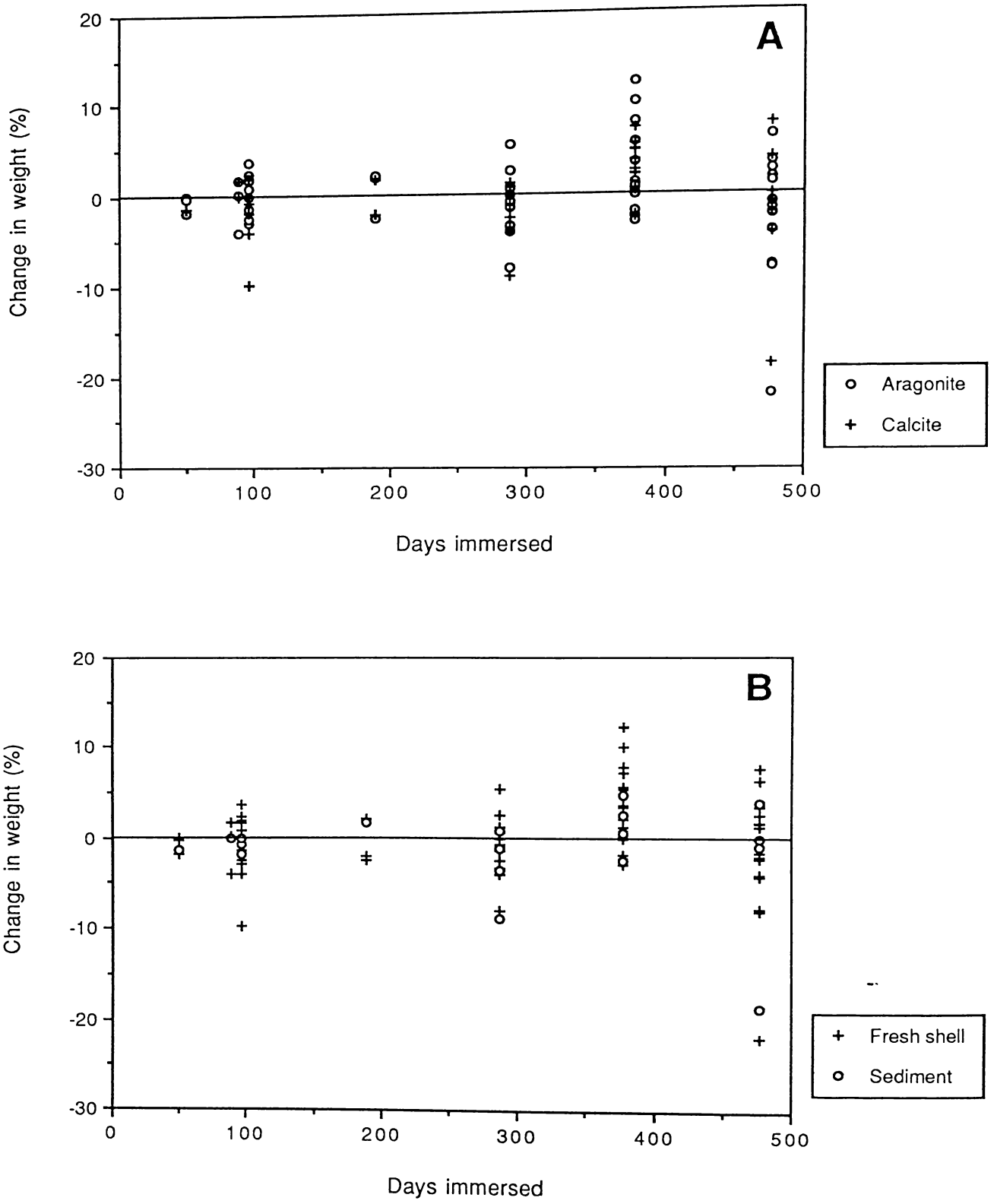


Figure 8D.4: Relationship of substrate characters with weight change during immersion. (A) Mineralogy and (B) original condition of substrate.

4. Geological importance of bioerosion

The biological process of excavating spaces in dead shells is of some geological importance. The algae and fungi in Hauraki Gulf sediments dissolve carbonate while boring. This adds $CaCO_3$ to sea water and removes it from sediment, eventually decreasing the proportion of carbonate to terrigenous material in a bulk sediment. Clionid sponges excavate chips and fine material from shells. This reduces the grain sizes of sediment, destroys large identifiable shells, and may produce carbonate mud (Perkins and Halsey, 1971). Carbonate mud does occur in Hauraki Gulf sediments (see Chapter 6, Section C). If bioerosion reduces sediment size, this may result in increased transport as mean grain size decreases. Another result of producing carbonate mud may be to put more sediment into suspension, a net loss to the original deposit. In addition, bioerosion weakens grains and makes them more susceptible to other forms of damage, such as abrasion (Young and Nelson, 1988). Thus bioerosion may be a major destructive force in the Hauraki Gulf, with a net effect of removal of biogenic carbonate from the sedimentary record. Bioerosion appears to act at different rates on different substrates. It may be possible to produce a hierarchy of susceptibility to bioerosion among New Zealand molluscs, perhaps reflected in the fossil record.

It is important to note that temperate bioerosion is slow enough to require long residence times at the sediment-sea water interface in order to destroy a significant portion of a shell. Very slow sedimentation is necessary to allow the 100s to 1000s of years required. In regions of carbonate accumulation on the New Zealand shelf (Kamp and Nelson, 1988) and in temperate carbonates generally (Nelson et al., 1988b), sedimentation rates of <5 cm/ky have been described. Given a certain amount of surface sediment movement, it is certainly possible that shells would remain at the sediment-sea water interface long enough to be severely damaged or destroyed by bioerosion.

E. CONCLUSIONS

Bioerosion is important in Hauraki Gulf carbonate sediments. *In situ* sea-floor experiments show that bioerosion is outweighed by encrustation in the short-term. Bioerosion is a longer-term process and extensive bioerosion is thus a better indicator of relative age of a grain than is encrustation. Heavily bioeroded shells have been dated at 350 to 1320 y old, with considerable variation among species.

Four major bioeroders are found in the Hauraki Gulf samples: clionid sponges, green algae, fungi, and some prokaryotes. No cementation or infilling is evident in borings. Distribution of these organisms may be environmentally controlled, with perhaps seasonal differences in rates of bioerosion. Mineralogy of substrate has no effect on bioerosion, but previous diagenesis of the specimen may. An older, more eroded grain sustains greater bioerosion than a fresh one.

Destruction of shells by bioerosion in the Hauraki Gulf takes on the order of 100s to 1000s of years. Although bioerosion is slower than in a tropical example, often slow rates of sedimentation (<5 cm/ky) allow long residence time at the sediment-sea water interface, thus enabling bioerosion to act for many years.

Bioerosion destroys sediments by dissolution, by weakening grains, and by reducing grain size. It may thus increase transport potential and decrease resistance to abrasion. The Hauraki Gulf sediments may reflect the effects of bioerosion in the loss of carbonate with time, and the presence of carbonate mud. A further discussion of the effects of bioerosion on the eventual rock record will be made, and the problem of carbonate mud will be examined, in Chapter 13.

Chapter 9 Interpretation of Hauraki Gulf Sediments

"A handful of sand is an anthology of the universe."

D. McCord, Once and for All, 1929

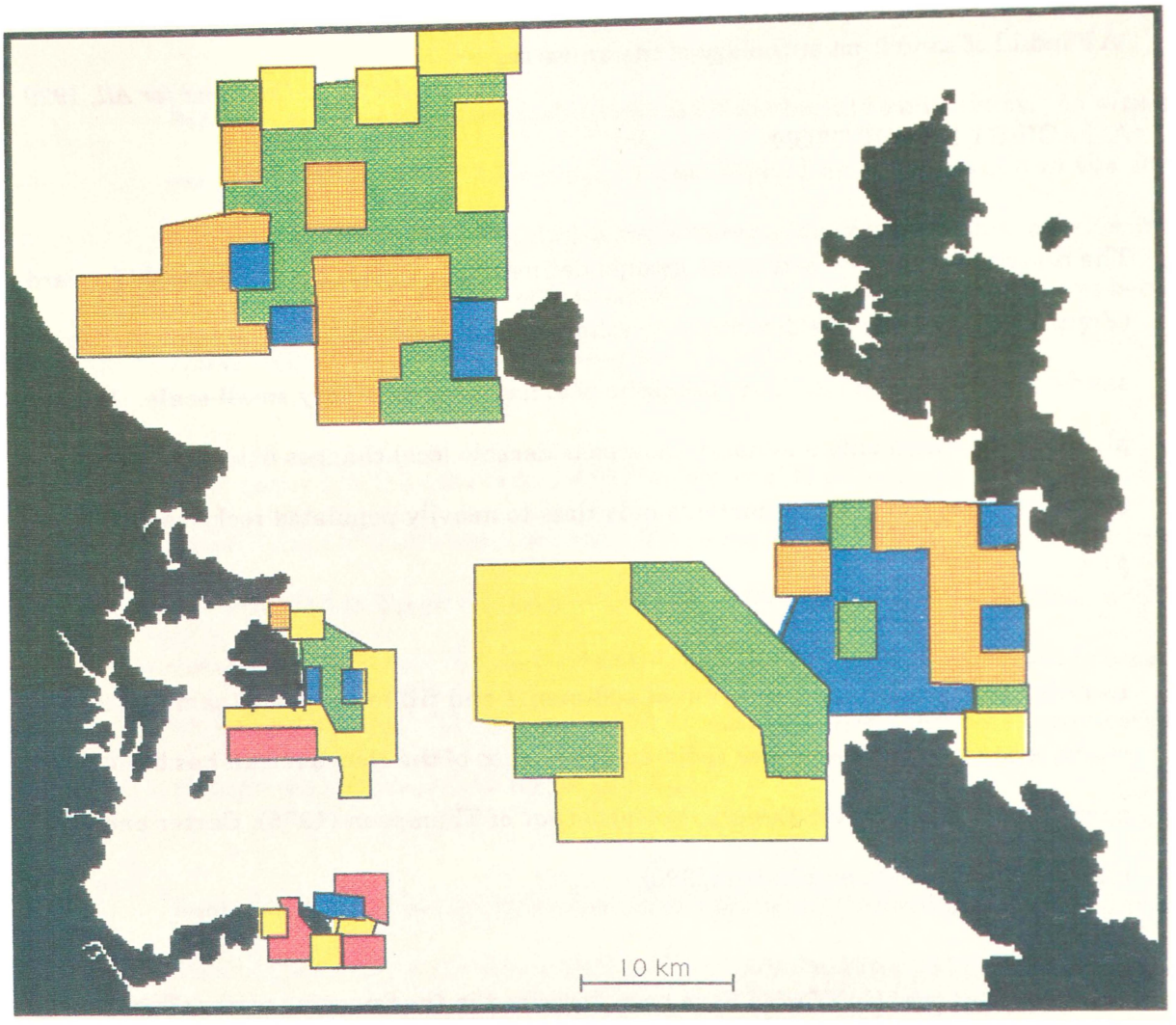
A. FACIES DISTRIBUTION

The distribution of the sediment groups defined in Chapter 7 is not straightforward (Figure 9A.1). They are distributed rather patchily, particularly the high-carbonate sandy gravel of group 1. This patchiness exists even at a very small scale. Bottom photographs taken only 8 m apart show considerable local changes in bottom sediments and character, from rather barren sandy flats to heavily populated rocky reefs (Figure 9A.2).

In order to refine the distribution of sediments and fill in areas not sampled in this study, a comparison with other sedimentary studies of the Hauraki Gulf has been made, particularly Greig's (1982) work, but also that of Thompson (1975), Carter and Eade (1980), Hilton (1990), and Naish (1990).

Although Hauraki Gulf facies have been described in the foregoing works (Table 9A.1), the mosaic-type distribution of sediments in the outer Hauraki Gulf suggests that facies names that include geographical location are perhaps inappropriate. Thus purely descriptive, brief names have been chosen to allow further discussion. They are the high-carbonate gravel facies, the muddy sand facies, the sand facies, and the mud facies.

Group 1 (high-carbonate gravel facies) corresponds to Greig's (1982) Colville Channel Facies (CCF), and to Thompson's (1975) central zone gravelly carbonates. Thompson indicated that this facies was found to the north, west, and south of Little Barrier Island, although Greig found it to be restricted to Colville Channel. Carter and Eade (1980) showed gravels and sands with >50% $CaCO_3$ in these locations as well as east of Kawau and Tiritiri Matangi Islands. This study found this coarse facies to be located in much smaller patches than those mapped by Carter and Eade (1980).



Facies

1 High-carbonate sandy gravel

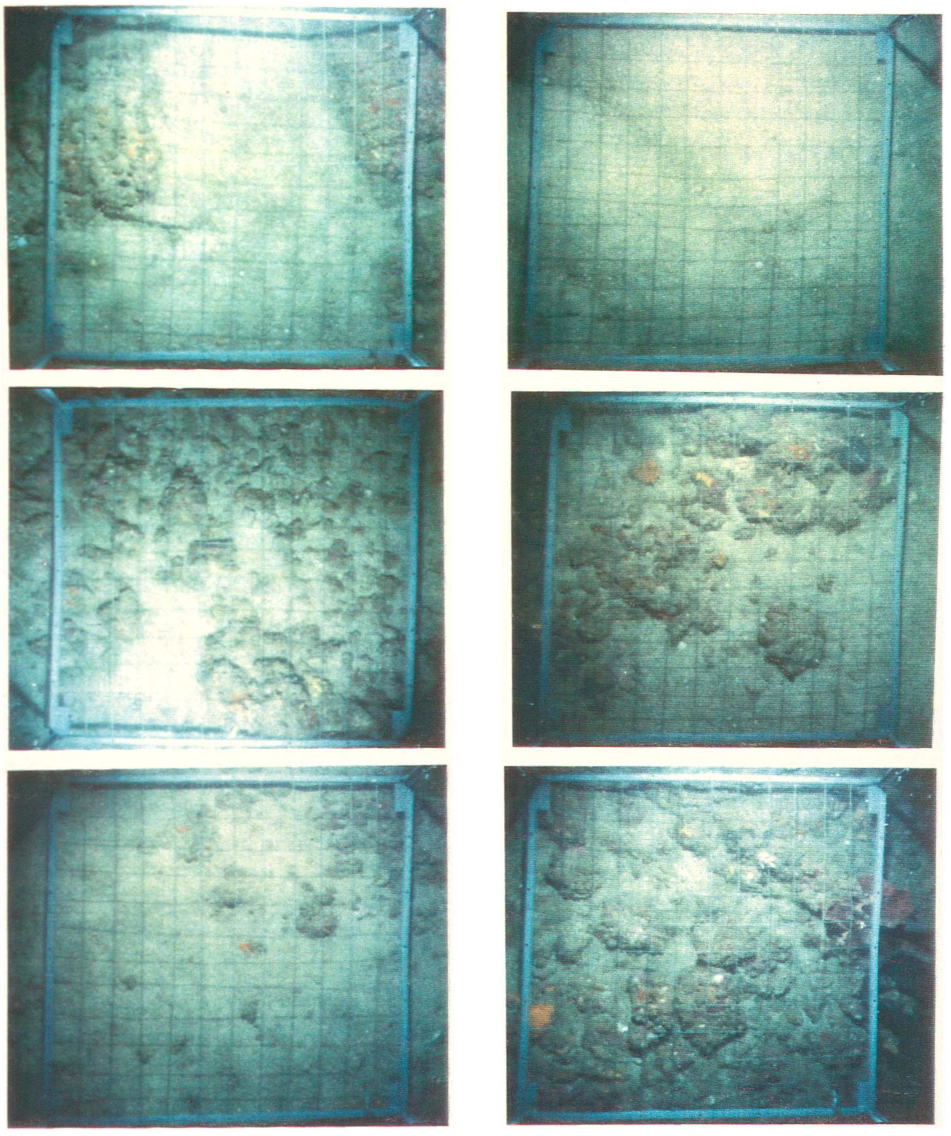
2 Muddy fine sand

3 Medium sand

4 Gravelly muddy sand

5 Slightly sandy mud

Figure 9A.1: Distribution of five facies defined in Chapter 7 in the outer Hauraki Gulf.



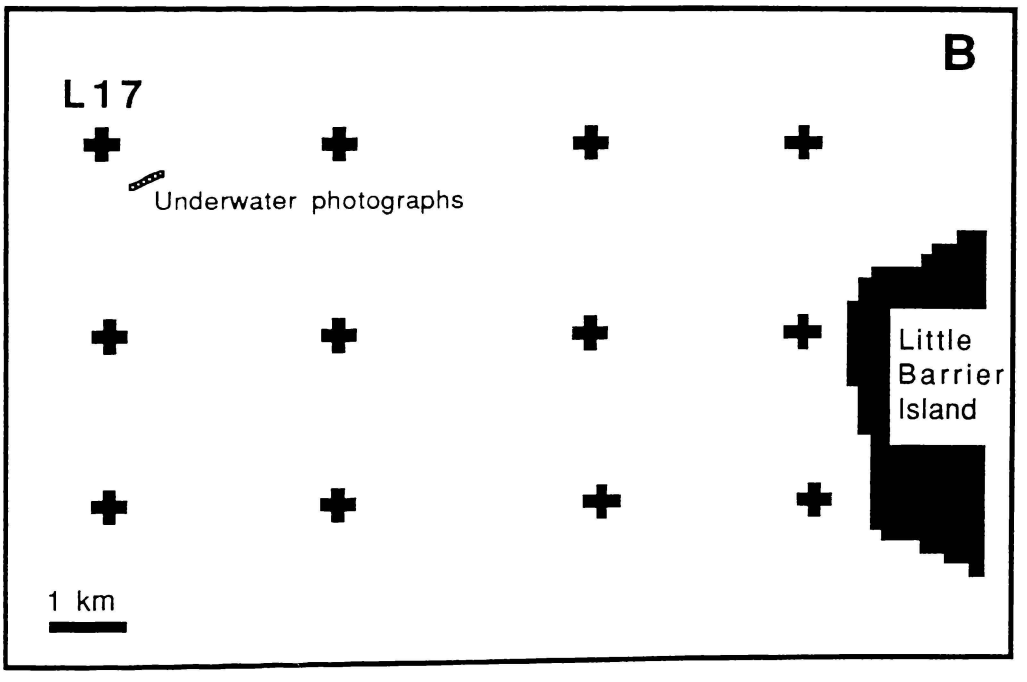


Figure 9A.2: Photographs of the sea floor west of Little Barrier Island, showing variability over very short distances. (A) Six photos taken in 44 m water depth, about 8 m apart. Grid spacing is 10 cm. (B) Location of photos. Crosses indicate sediment sample locations (e.g., L17). See Figure 9B.1 for larger map of area.

Table 9A.1: Hauraki Gulf facies, as defined by this study, Thompson (1975), Greig (1982), and Hilton (1990).

Facies (this study)	Textural group (Chapter 7)	Thompson (1975)	Greig (1982)	Hilton (1990)
High-carbonate gravel	1	Central zone gravelly carbonates	Colville Channel Facies	
Muddy sand	2 and 4	Mid-shelf muddy fine sand	Central Gulf Facies	
Sand	3			Pakiri Beach sand wedge
Mud	5		Inner Gulf Facies	

Groups 2 and 4 (muddy sand facies) are similar to Greig's (1982) Central Gulf Facies (CGF), and Thompson's (1975) mid-shelf muddy fine sands. In fact the main difference between the two is the gravel content, group 4 being a slightly coarser version of group 2 (see Figure 7C.2). This muddy sand facies occurs throughout the central Gulf, west of Cape Colville, east of Kawau Island, and northwest of Little Barrier Island. This distribution is similar to Carter and Eade's (1980) mapping of terrigenous sand (see Figure 5D.3).

The sand facies (group 3) is described by Hilton (1990) as a Pakiri Beach sand wedge. A similar sand wedge has been described by Bradshaw (1991) off the eastern coast of Coromandel Peninsula. Carter and Eade (1980) make no differentiation between different sizes of sand, nor in regard to sorting, thus their map shows this facies as the same as other sandy sediments. It is found northeast of Cape Rodney and southwest of Great Barrier Island.

Group 5, the mud facies, is like Greig's (1982) Inner Gulf Facies (IGF) and the Firth of Thames muds described by Naish (1990). Found in the outer Gulf only south of Kawau Island and surrounding Tiritiri Matangi Island, this facies is dominant in the inner regions of the Gulf. Carter and Eade (1980) show it blanketing the inner Gulf, and also in the far north, seaward of the present study.

Four facies (high-carbonate gravel, muddy sand, sand, and mud) are the final result of having explored the relationship between the sedimentary groups found in this study and facies defined in the literature (see Table 9A.1). Interpretation of Greig's (1982) sedimentary facies map, of Carter and Eade's (1980) NZOI Sediments map, and of RNZN maps 522, 532, and 5321 allows compilation of a generalized surficial sediment map for the outer Hauraki Gulf (Figure 9A.3). The distribution of the four facies defined above is delimited, and boundaries smoothed.

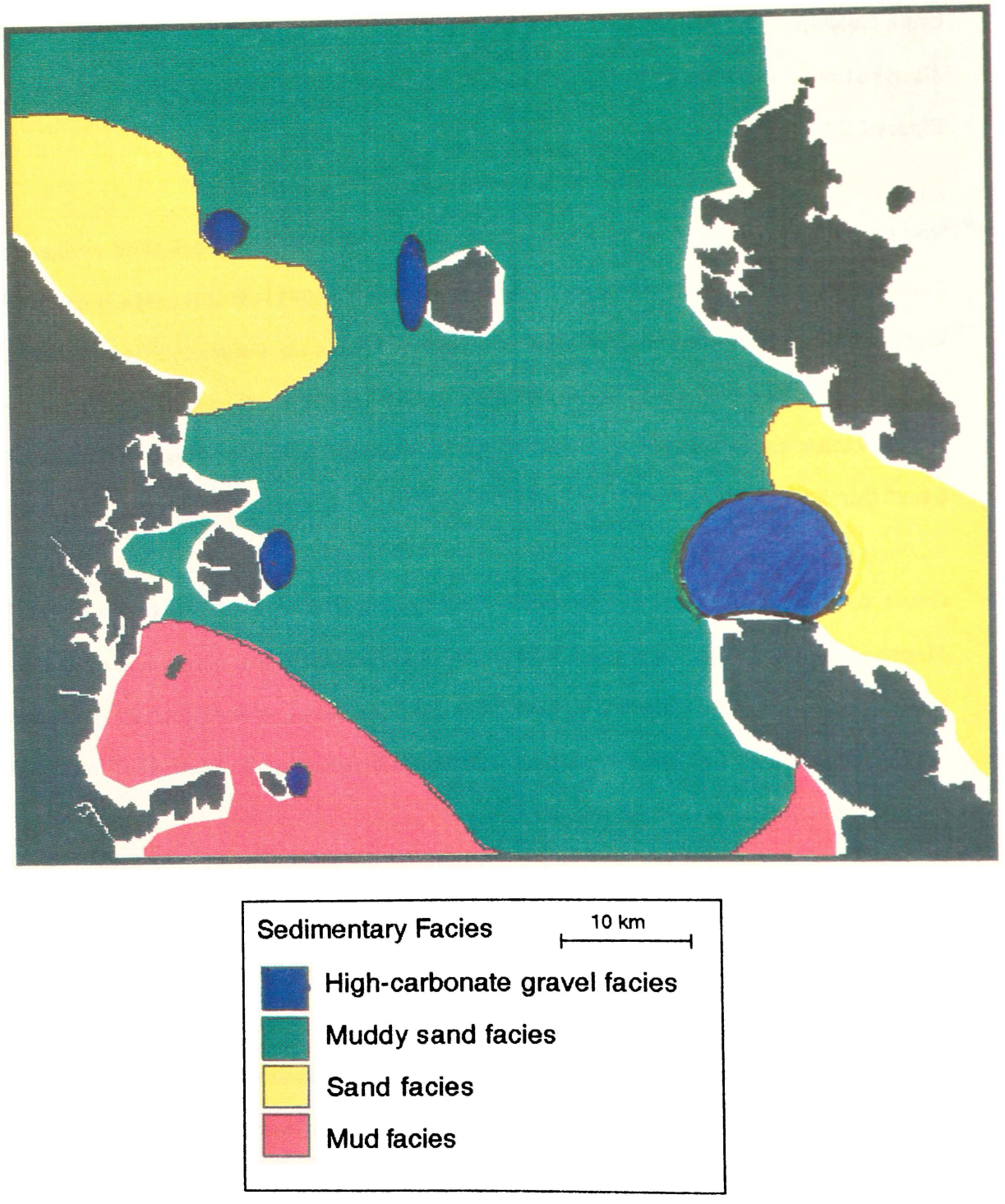


Figure 9A.3: Map of sedimentary facies in the outer Hauraki Gulf.

B. CORES

Two piston core descriptions from NZOI archives are available for the outer Gulf, H482 and H491, located east of Kawau Island (42 m water depth) and north of Cape Colville (40 m), respectively (Figure 9B.1). A further core from the western Gulf near Kawau Island in 35 m water depth is described by Pocknall et al. (1989). The sedimentary types described in the cores correspond closely to the surficial sediment facies described here, except for a peaty mud (Figure 9B.2).

H482 is muddy up to 130 cm downcore, where it becomes muddy sand. From 77 cm to the surface, sediment is shelly and may represent another localized high-carbonate patch. In an older high-carbonate patch, H491 consists of high-carbonate gravel overlain from 36 cm downcore to the top by sand. H488 has fine sand with scattered shells overlying overlying peat with root structures, with an unconformable contact at 60 cm downcore. The peat is dated at >40,000 y (Pocknall et al., 1989).

In order to interpret these cores, a brief account of late Quaternary sea-level history will be given.

C. LATE QUATERNARY HISTORY OF THE HAURAKI GULF

The history of the Hauraki Gulf began in the Miocene (c. 10 my BP), when the Kaikoura Orogeny (an ongoing uplift event dating from 24 my BP) created incipient tensional rifting in the back-arc of the Coromandel Volcanic Zone (Hochstein and Ballance, in prep.). By 5 my BP, sediment was accumulating in the Hauraki Rift, both volcanic and fluvial. Seismic studies of the modern Gulf show up to about 1 km of quasi-consolidated Tertiary sediments (Miocene to Pliocene) overlying the faulted half-grabens of greywacke basement. Overlying these sediments are unconsolidated Quaternary sediments of variable thickness (Thrasher, 1986; Hochstein and Ballance, in prep.).

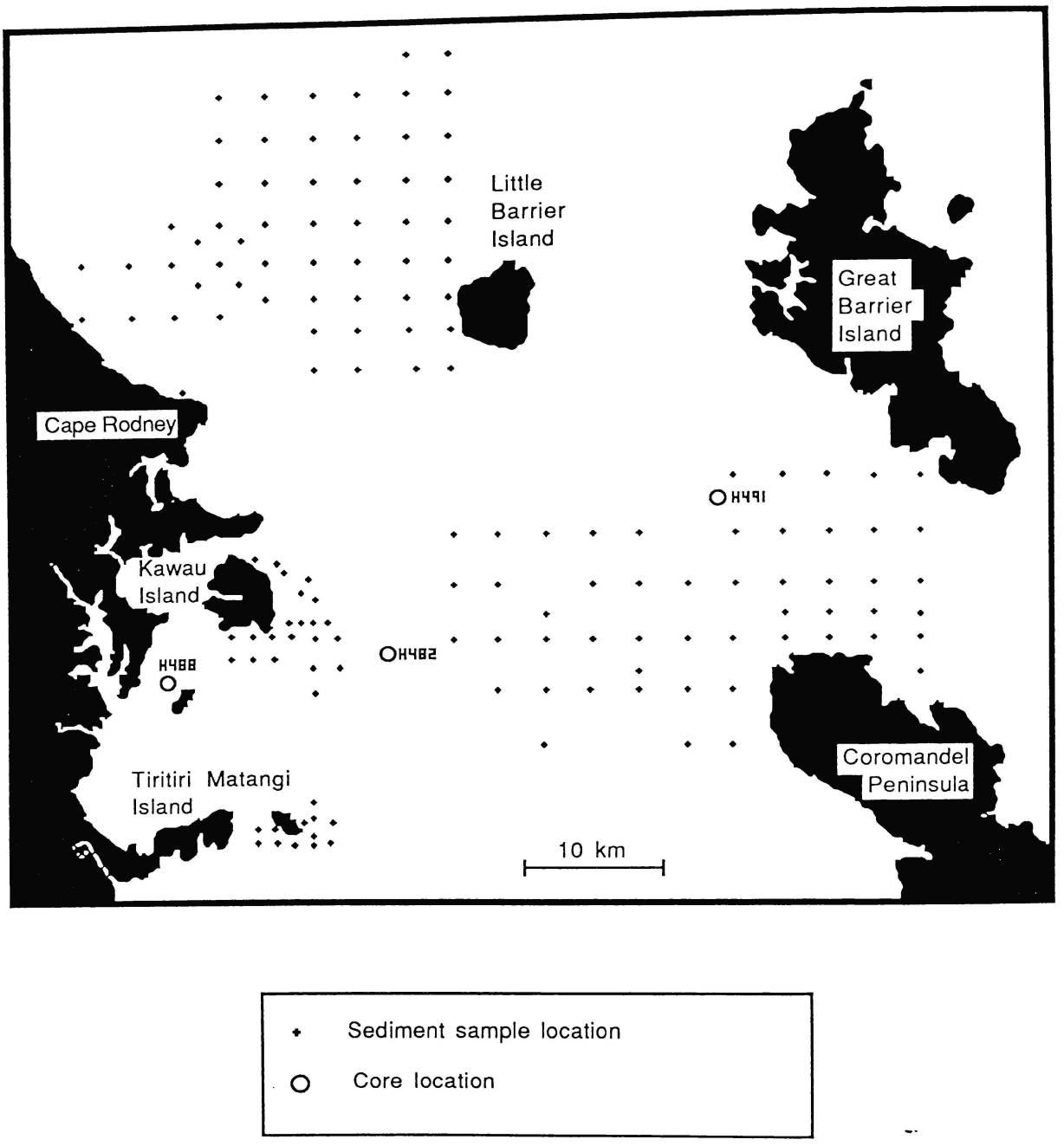


Figure 9B.1: Locations of cores described in the text from the outer Hauraki Gulf (details in Appendix Table A6.1).

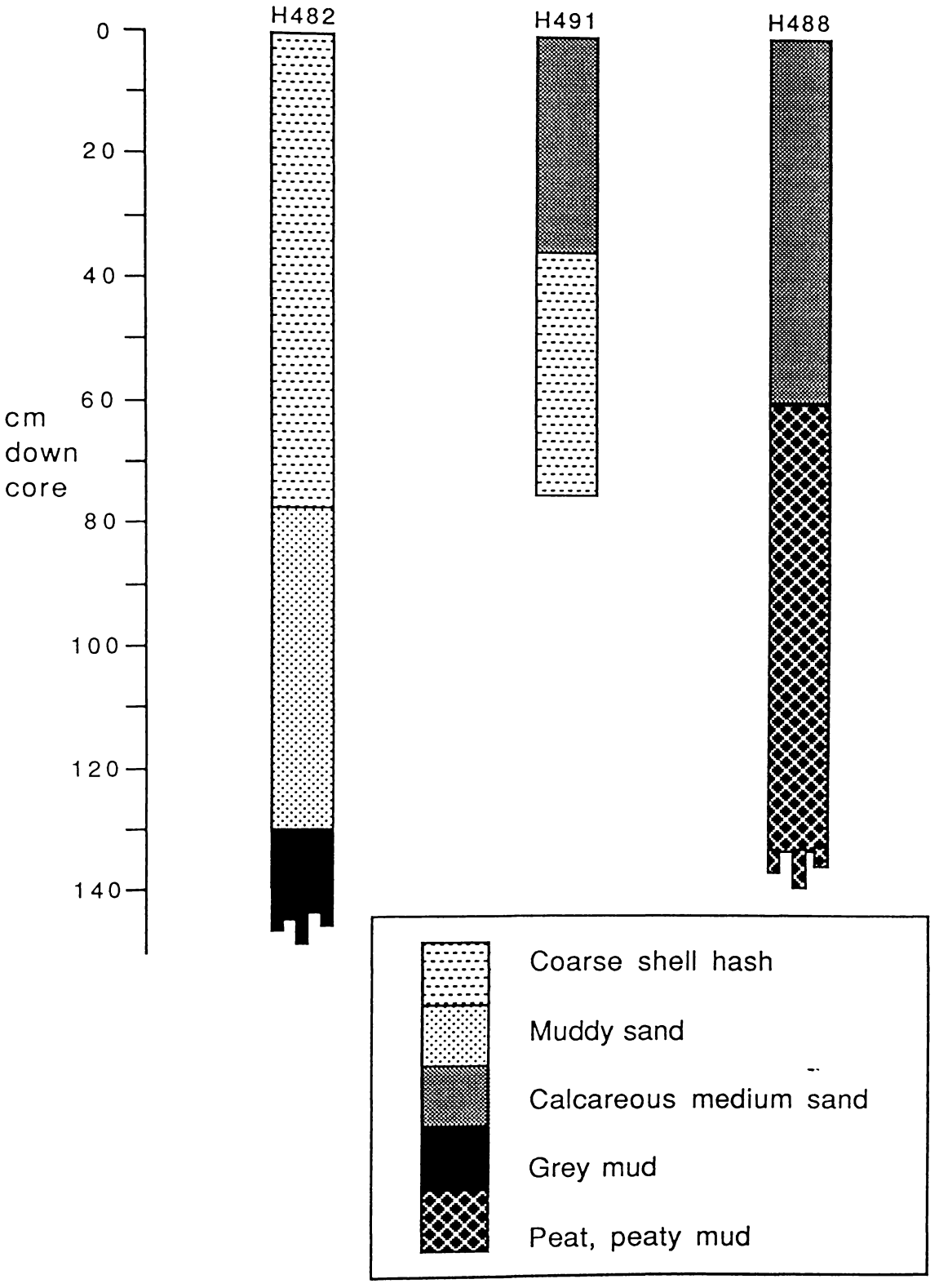


Figure 9B.2: Descriptions of cores H482 and H491 (New Zealand Oceanographic Institute archives) and H488 (Pocknall et al., 1989) in the outer Hauraki Gulf.

The last glacial maximum occurred during the late Quaternary Otiran stage in New Zealand, about 20 ky BP. The accompanying lowering of sea level has been estimated, in Australia, to be 150 m below modern sea level at 18 ky BP (Chappell, 1987); and terraces in New Guinea give a similar figure for the glacial maximum (Chappell and Shackleton, 1986). In New Zealand, sea level at 18 ky BP is estimated to have been 113 m below present sea level (Carter et al., 1986; Proctor and Carter, 1989). Following the last glacial maximum was the post-glacial or Holocene (Aranuian in New Zealand) marine transgression, punctuated by fairly brief stillstands (Figure 9C.1). At about 6500y BP, present sea level (+/- 1m) was reached and maintained until modern times (Gibb, 1986; Pillans, 1990).

Gibb's (1986) sea-level curve is derived from New Zealand data, and includes several locations in the Hauraki Gulf. Earlier data are available for New Zealand (Carter et al., 1986) and have been applied to other locations about New Zealand (e.g., Proctor and Carter, 1989). These curves have had the tectonic component removed, so a regional tectonic component must be taken into account. According to Gibb, uplift in the region of the Hauraki Gulf is low (0 to 0.1 mm/y). Pillans (1990) considers uplift to be zero in the Hauraki Gulf. Thus a tectonic component is not required, and shoreline changes can be derived solely from sea-level curves. The New Zealand curves are generally similar to others derived for the south Pacific region (e.g., Chappell and Shackleton, 1986).

In the Hauraki Gulf, the last glacial lowstand of about -113 m (at 18 ky BP) would have exposed the entire area (Figure 9C.2). A landscape rather like the modern Hauraki Lowland to the south may have been the result, dominated by the high volcanoes of what are now Little Barrier and Great Barrier Islands. The Firth of Thames would have hosted coastal forests and mangrove swamps (Pocknall et al., 1989). Marine transgression into the outer Gulf would have begun at about -75 m sea level, corresponding to a stillstand at about 15 ky BP (Carter et al., 1986). At -56 m (about 12 ky BP), a major stillstand (Proctor and Carter, 1989), about half of the outer Gulf would have been submerged, as a north-facing bay with tidal inlets in the modern channels. A

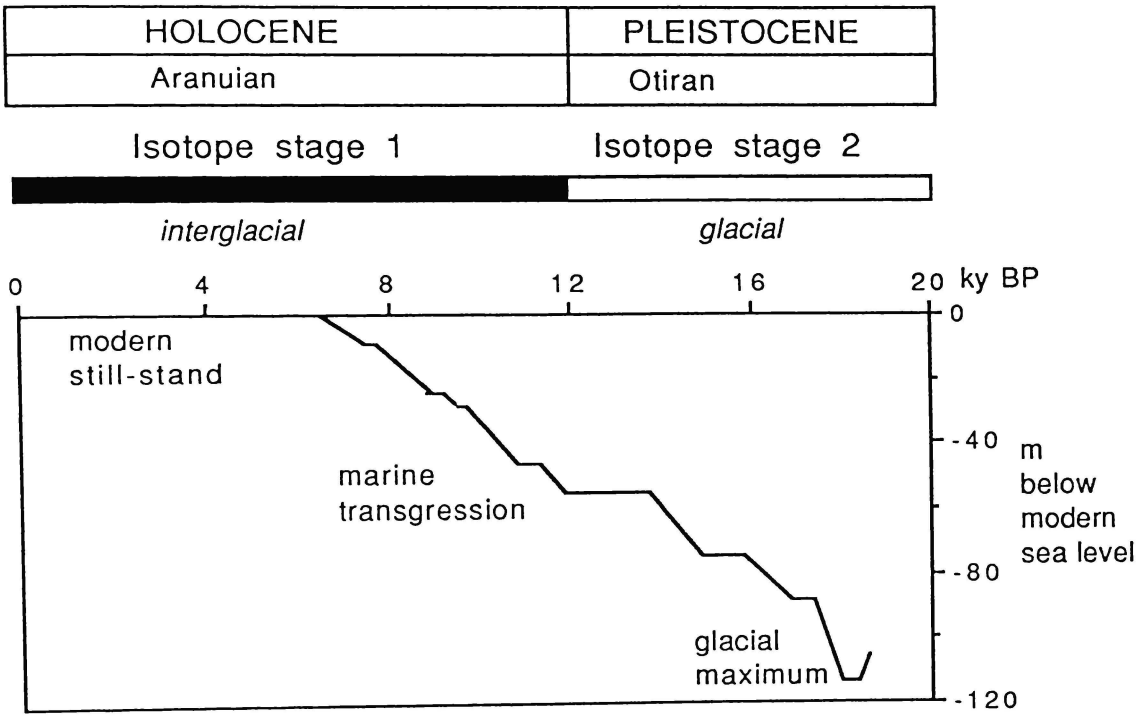


Figure 9C.1: Late Quaternary sea-level history of Hauraki Gulf. Isotope stages of Shackleton and Opdyke (1976). New Zealand sea-level curve from Carter et al. (1986) and Gibbs (1986).

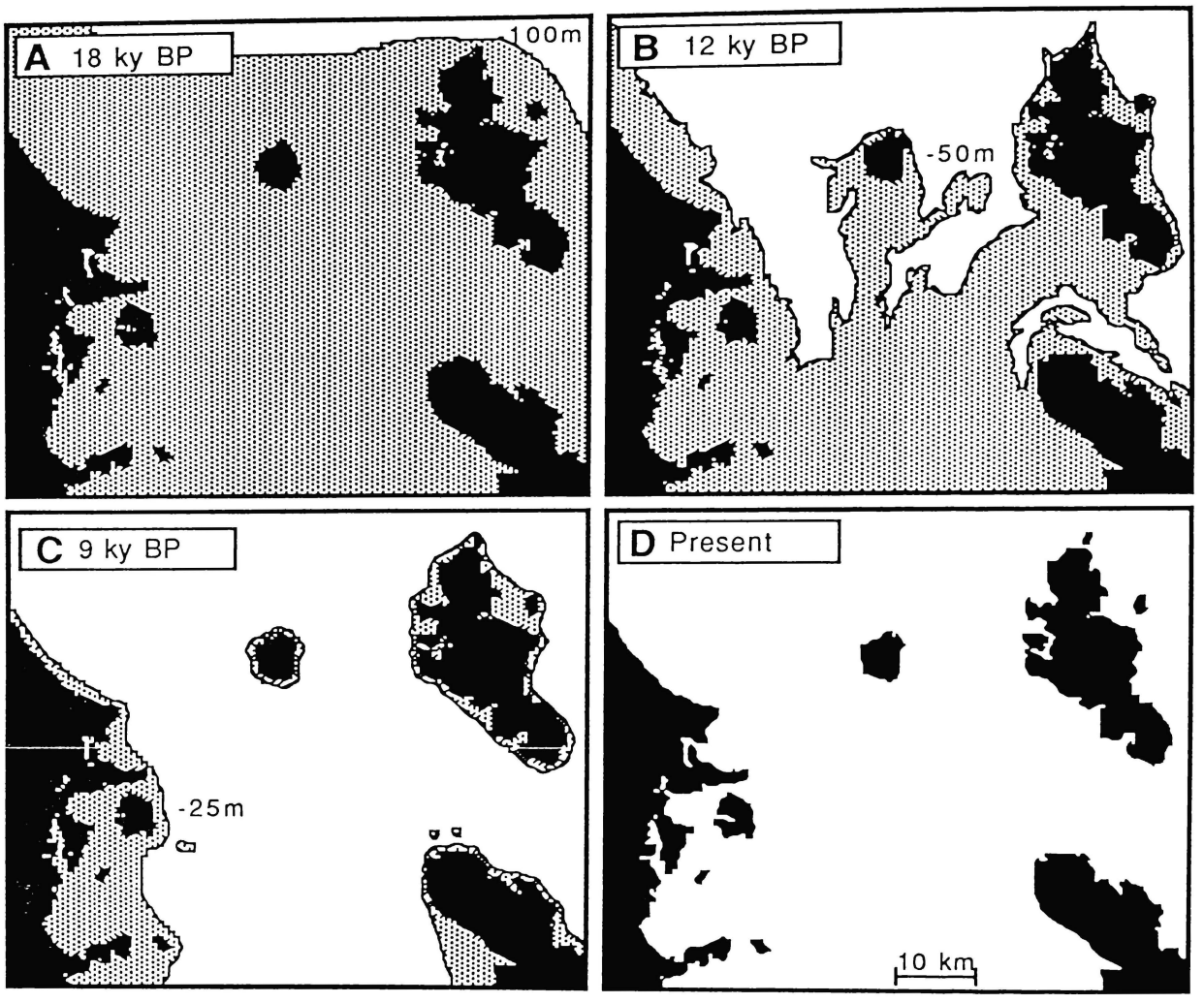


Figure 9C.2: Physiography of possible past shorelines (shaded) for outer Hauraki Gulf at different times during the post-glacial transgression, based on present-day bathymetry. (A) 100 m below present sea-level, soon after 18 ky BP. (B) 50 m below present sea-level, about 12 ky BP. (C) 25 m below present sea-level, about 9 ky BP. (D) Present shoreline.

further rise in sea level to -25 m (the still-stand of 9200 to 8400 y BP, according to Gibb, 1986) would have seen the outer Gulf substantially the shape it is now, although the innermost Gulf would have remained a terrestrial plain or estuary for some time. Modern sea-level position was reached at about 6500 y BP (Gibb, 1986). Figure 9C.2 shows these paleo-shorelines.

The huge volumes of fluvial and volcanic sediments delivered to the Gulf from the interior of the North Island (e.g., see Hochstein and Ballance, in prep.), have been reworked throughout the marine transgression. During the transgression, nearshore areas would perhaps have been estuarine, gradually becoming truly marine as shorelines receded, allowing for the precipitation of carbonate by marine organisms. By 9000 y BP, conditions were substantially the same as they are now in the outer Gulf. Radiocarbon dates for surface sediments in the Gulf postdate the establishment of the modern regime (see Table 6F.1).

The four facies defined in Section A and shown in Figure 9A.3 fit simply into this scenario. The widespread muddy sand facies is a palimpsest combination of re-worked fluvial/terrigenous sediment from the marine transgression (Greig, 1982) with modern and relict biogenic carbonates. Local concentrations of these latter coarse shell carbonates, discussed below, make up the high-carbonate gravel facies. A coastal wedge of clean sand lies on the exposed east coasts. The mud facies originates in the Firth of Thames and may have been prograding northwards since sea level stabilized (Greig, 1982; Naish, 1990). The mud blanket is thus fairly young, and may interfinger with the muddy sand facies (Greig, 1982). The mosaic-like pattern of sedimentation is related to the complex interaction of the various Holocene stillstands with the heterogeneity of the transgressed fluvial sediment substrates. The mixing of autochthonous carbonate with allochthonous terrigenous sediment further complicates facies distribution patterns.

D. CONTROLS ON FACIES DISTRIBUTION

Sedimentary facies may be affected by sedimentary processes, sediment supply, climate, tectonics, sea-level change, biota, water chemistry, and volcanism (Reading, 1986). Of these, three sedimentary and biological processes will be discussed below.

1. Water depth

Water depth is an obvious possible control, and zonation of facies by water depth is commonly observed (Figure 9D.1). The shallowest facies (< 40 m) is the mud facies, reflecting its distribution principally in the inner Gulf. The other three facies all have similar depths (mainly 30 to 70m), although all the deepest (>70m water depth) samples are in the muddy sand facies. Thus the high-carbonate gravel facies and the sand facies are primarily found at inner shelf depths, but the muddy sand facies extends into the deepest parts of the Gulf.

2. Water energy

There are several ways in which the motion of water has affected the distribution of facies in the outer Gulf. Waves have reworked the sand facies into coastal/nearshore wedges (Bradshaw, 1991). Tidal currents may be active in transporting mud and extending the mud blanket from the Firth of Thames north into the outer Gulf (Naish, 1990). In addition, tidal currents may winnow out fine terrigenous material from patches of the muddy sand facies, resulting in local skeletal carbonate patches (high-carbonate gravel facies). The fine material may perhaps be transported to deeper water and ultimately lost to the shelf (e.g., Kidwell, 1989). Greig and Proctor's (1988) model of tidal currents in the Gulf show that in Colville Channel, west of Little Barrier Island, and east of Kawau Island, high current velocities occur at the sea floor (Figure 9D.2). These are all areas of the high-carbonate gravel facies, thus supporting the idea that it is essentially a winnowed lag of the muddy sand facies. Dominantly- terrigenous mud and sand are removed, leaving the dominantly-carbonate gravel.

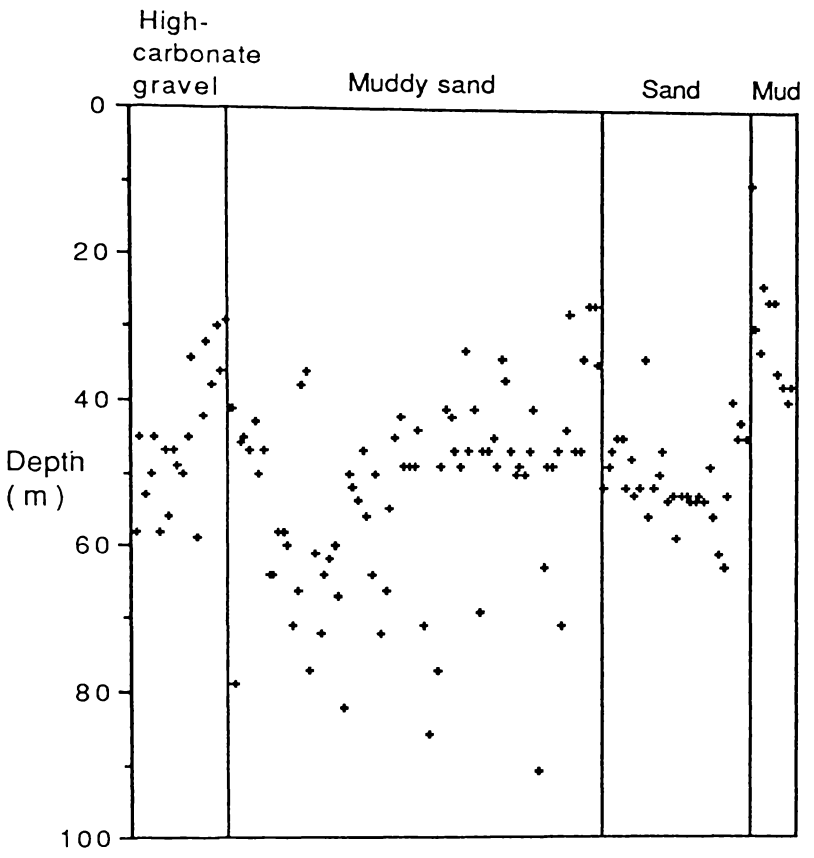


Figure 9D.1: Water depths for Hauraki Gulf sediments within four facies.

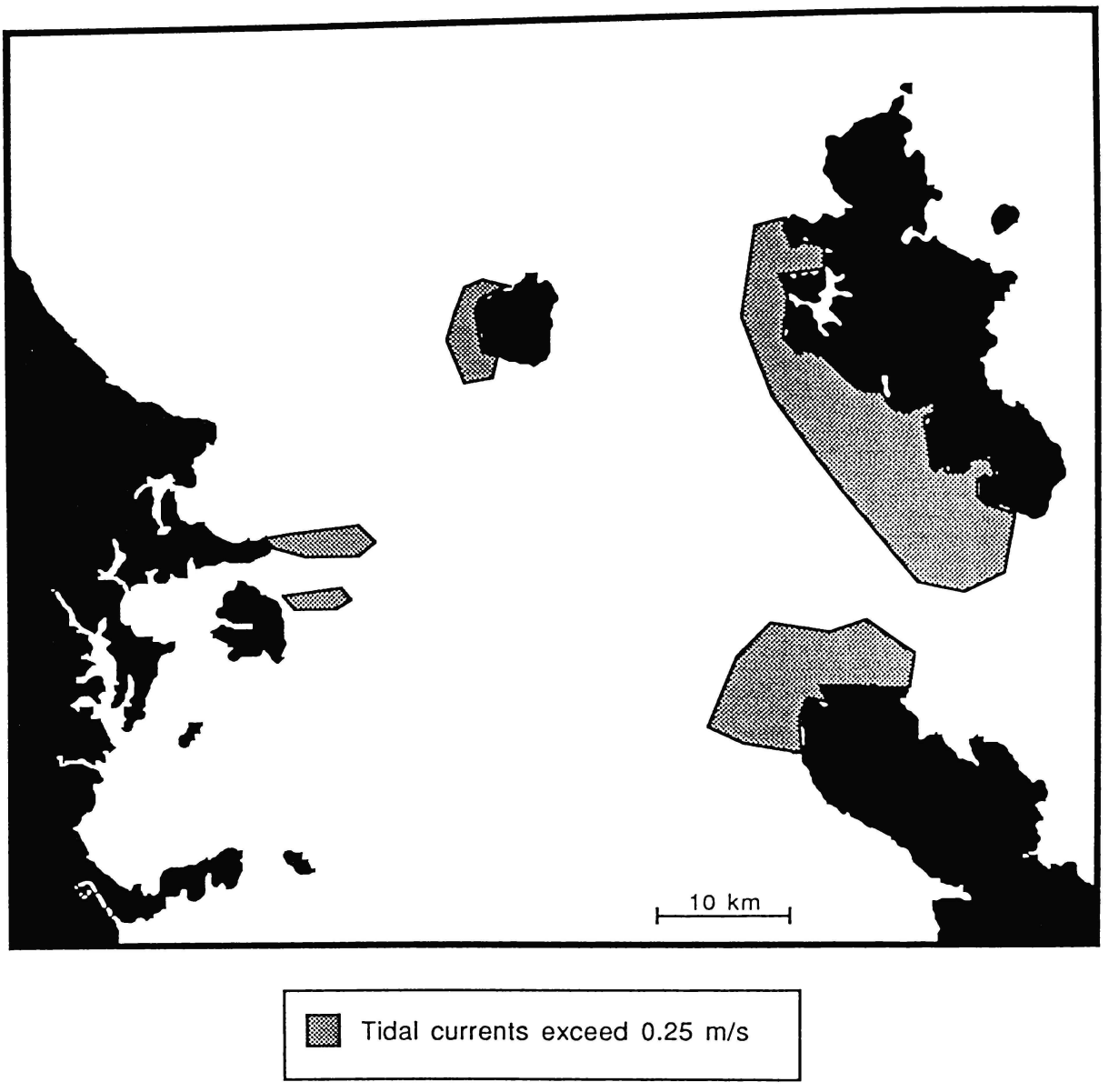


Figure 9D.2: Locations of high-velocity tidal currents (>0.25 m/s) in the Hauraki Gulf (after a model devised by Greig and Proctor, 1988). Compare Figure 9A.3.

3. Substrates

Epifaunal marine organisms are dependent on hard substrates for attachment. Two important groups (bryozoans and barnacles) are almost entirely made up of attached species. Rocky areas of rough topography are best-suited for settlement, and dead shells are often highly populated by attached organisms. The two groups of skeletal composition (A and B described in Chapter 7, Section E) are different due to the lack of attached organisms in Group A, which is about 80% bivalves with gastropods subdominant. The mollusc shells do not provide extensive substrate due to their predominantly infaunal nature. In contrast, Group B is less bivalve-rich (65%) and has as subdominant components barnacles, bryozoans, and gastropods. Samples with Group B assemblages must have local hard substrates. And indeed, this appears to be the case. The lowest diversity is found in the mud facies, where a specialized infaunal community (the heart urchin *Echinocardium*, some infaunal bivalves) produces very little carbonate (mean for samples in this study is 16% $CaCO_3$) and there are few firm sites for attachment. The muddy sand facies includes dominantly skeletal Group A; there are very few attached organisms. It is in the coarser sand and high-carbonate gravel facies that attached organisms contribute a considerable amount of the carbonate fraction.

E. EARLY SEA-FLOOR DIAGENESIS OF CARBONATE

Visual examination of Hauraki Gulf shells shows that bioerosion is a major process of shell destruction. It may be quite slow, as 8000 y old shells have been found at the sediment-sea water interface. Some species (e.g., *Pecten novaezelandiae*) may be completely bioeroded in less than 500 y. In the process, shells subject to bioerosion lose strength and gradually become smaller. Biological dissolution reduces solid carbonate, and mud chips may be excavated. The high-carbonate facies would be the most strongly affected by bioerosion of carbonate, perhaps becoming over time lower in carbonate and finer in texture. The result could ultimately be rather like the muddy sand facies.

F. RESULTING ROCK RECORD

Ideally, the description of modern-day sediments gives geologists a tool for helping with the interpretation of the ancient rock record. Sedimentary depositional models have been described in both modern and ancient settings, using this extrapolation over time. In carbonate sediments, the majority of depositional models are tropical (e.g., reef flat and coastal lagoons) and are not applicable to temperate environments. Most temperate shelf depositional models refer to open shelves, not semi-enclosed seas, and they tend to focus on the siliciclastic sediments (e.g., Johnson and Baldwin, 1986). For these reasons, an existing model which fits the Hauraki Gulf is not readily available.

The Gulf is similar to a tide-dominated (Figure 5C.3), palimpsest (Table 6F.1) shelf (after Swift, 1974). The main way in which the Hauraki Gulf differs from the typical terrigenous shelf models (e.g., Reading, 1986) is that the modern mud blanket is not on the outer shelf, but in fact lies in the shallowest parts of the Gulf. This is mainly due to the semi-enclosed, low-energy nature of the Gulf and high mud supply (Naish, 1990).

If the Hauraki Gulf sediments were lithified now, the deposit would be indicative of a dominantly siliciclastic, tide-dominated, semi-enclosed sea. The modern situation, with coastal sands, central Gulf muddy sands, patchy high-carbonate areas, and inner Gulf muds, might be repeated at other sea-level highstands. Fluctuations of sea level could be evident over time, with erosion and/or fluvial terrigenous deposition occurring at sea-level lowstands. Carbonates in this deposit could persist as shelly lenses among the muddy sands. Their position in areas of high-energy or local topographic highs might not be clear. After burial, carbonate could dissolve and re-crystallize as cement, resulting in a calcareous muddy sandstone. No evidence as to the species producing the carbonate nor the patchy nature of carbonate deposition would necessarily be retained. Other temperate shelf carbonate deposits, particularly mixed terrigenous-biogenic deposits, will be discussed and compared with the Hauraki Gulf in Chapter 12.

Part Three Temperate Carbonate Sediment Model

The purpose of Part Three of the thesis is to discuss the implications of the different studies and results described in the first two Parts. Both bryozoans and the Hauraki Gulf are used to refine and expand the current model of temperate shelf carbonates.

Chapter 10 contains a literature review and description of the model. In Chapter 11, bryozoans are discussed from an overall sedimentological viewpoint. A budget for bryozoan carbonate is suggested, and the paleoenvironmental interpretation and taphonomy of bryozoans are discussed. Chapter 12 describes carbonate-clastic mixtures in shelf sediments, particularly the *in situ* type of mixtures (*sensu* Mount, 1984). The Hauraki Gulf and other New Zealand sediments are used as examples to discuss the implications of mixed sediments. The consequences for the rock record are also considered. In Chapter 13, early marine diagenetic processes in temperate carbonates are discussed, synthesized, and modelled.

Chapter 10 Temperate Shelf Carbonate Model

"As if thought plunged into a sea of words and came up dripping."
V. Woolf, The Common Reader, 1925

A. INTRODUCTION

Temperate shelf carbonate sediments have been known to exist for over 60 years, and described in well over 50 papers from all over the world, although they remain poorly known by non-specialists. A descriptive model has been under construction for over 20 years, trying to define what makes temperate carbonates separate and different from tropical ones. Tropical carbonate sedimentation is well-understood and extensively documented, particularly from some key localities such as the Bahamas (e.g., Hardie, 1977). Temperate carbonates are considered "atypical" (see Milliman, 1974) and therefore their attributes are less generally well-known.

Temperate is used here to refer to the regions between 30 and 60° (N or S) latitude. There are a few studies of polar carbonates (> 60°) (e.g., Domack, 1988), but so few that a "polar shelf carbonate model" cannot yet be constructed (e.g., see Brookfield, 1988). Nor can one assume that the temperate model will apply in polar regions. The continental shelf, that is, the sea floor beneath the neritic zone, generally in less than 200 m water depth, is the location for the carbonates under discussion. Deep-sea carbonates are excluded. Carbonate sediments are taken to be those with > 50% $CaCO_3$, although it will become clear that on many temperate shelves carbonates are often very patchily distributed amongst terrigenous sediments, forming mixed siliciclastic-carbonate deposits (e.g., Roberts, 1987).

A diagrammatic model for the formation of skeletal limestone, the eventual end-product of carbonate sedimentation, is given in Figure 10A.1. Carbonate is formed by living organisms from sea water, death or damage results in skeletons becoming sediment through early sea floor diagenesis (as defined in Chapter 4), deposited sediments are further modified by "true" diagenesis, and limestones of various kinds are the end

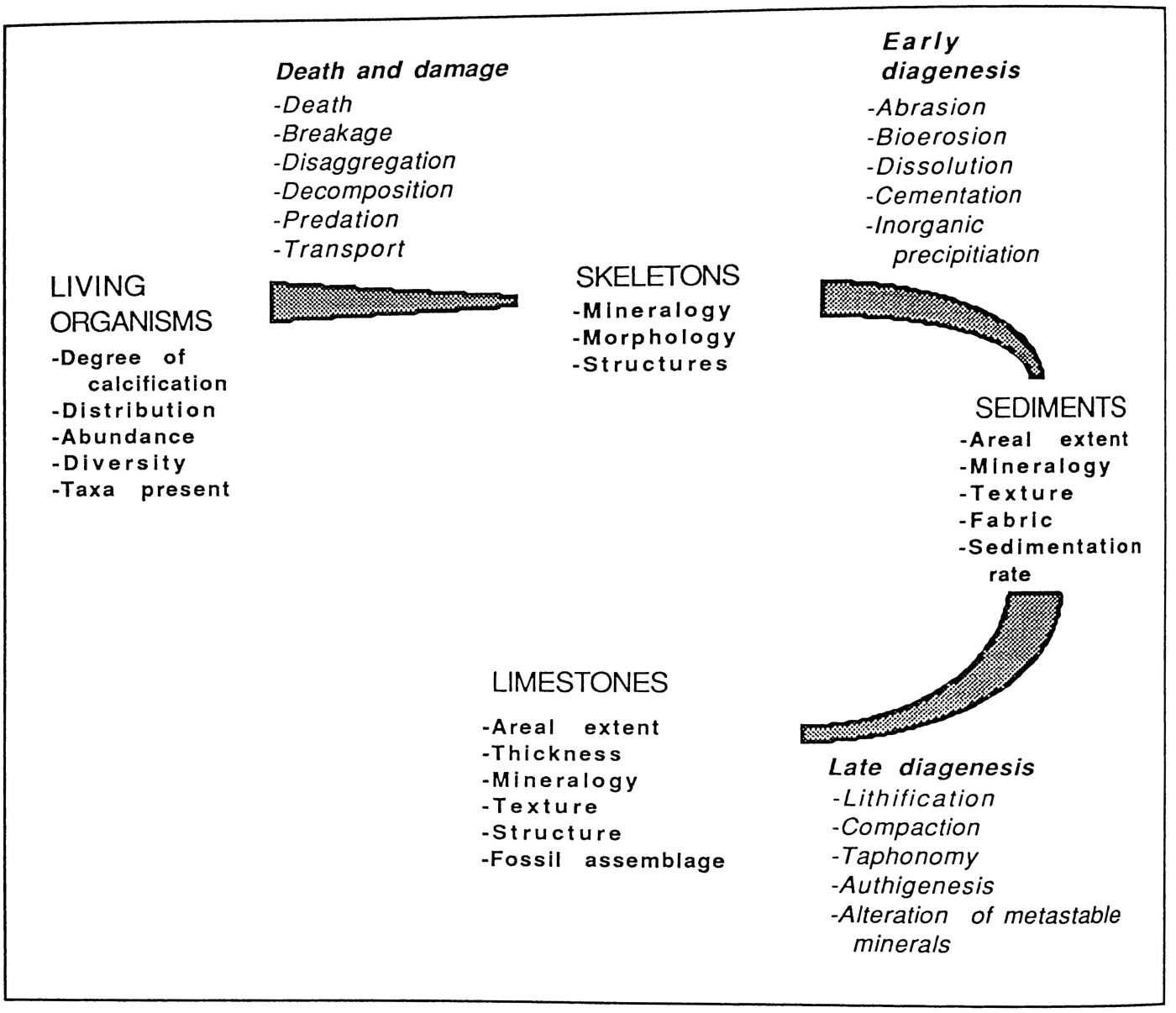


Figure 10A.1: Stages in the development of a limestone. Processes are in italics, whereas aspects of each stage are in bold face. After Chave (1960) and Morse and Mackenzie (1990).

result. The many processes and aspects of the various stages in the development of a limestone do not all affect every carbonate.

The purpose of this chapter is to discuss the different stages and processes of limestone formation within the context of the differences between temperate and tropical carbonates. It will become clear that there are significant gaps in our knowledge of the subject.

B. LITERATURE REVIEW

There were some early descriptions of temperate shelf and nearshore carbonates (e.g., Raymond and Hutchins, 1932), however, most geologists felt that tropical carbonates were the norm and that only under extremely unusual circumstances would carbonate be deposited in cold water. It was the prevailing view that high temperatures were required for formation of carbonate deposits, and that such deposits were limited to the tropical and subtropical regions (Rodgers, 1957).

It was an enormous step forward when Chave (1967) pointed out that carbonate was forming quite universally, but that in many temperate zones it was being diluted by abundant terrigenous material. He argued against temperature being a primary control on carbonate distribution, proposing instead dilution by clastics. This critical paper was really the beginning of temperate carbonate sedimentology.

Through the seventies and eighties, many regional descriptions of temperate carbonates were published (see Appendix Table A10.1). Most were from the north Atlantic, primarily British (e.g., Farrow et al., 1978) and Canadian (e.g., Slatt, 1977) shelves, although many were from the south Pacific (e.g., Rao, 1981a, b; Nelson and Hancock, 1984, Nelson et al., 1988b). Most temperate shelves were found to have some carbonate areas (Figure 10B.1). These descriptions provided the data from which subsequent models were developed.

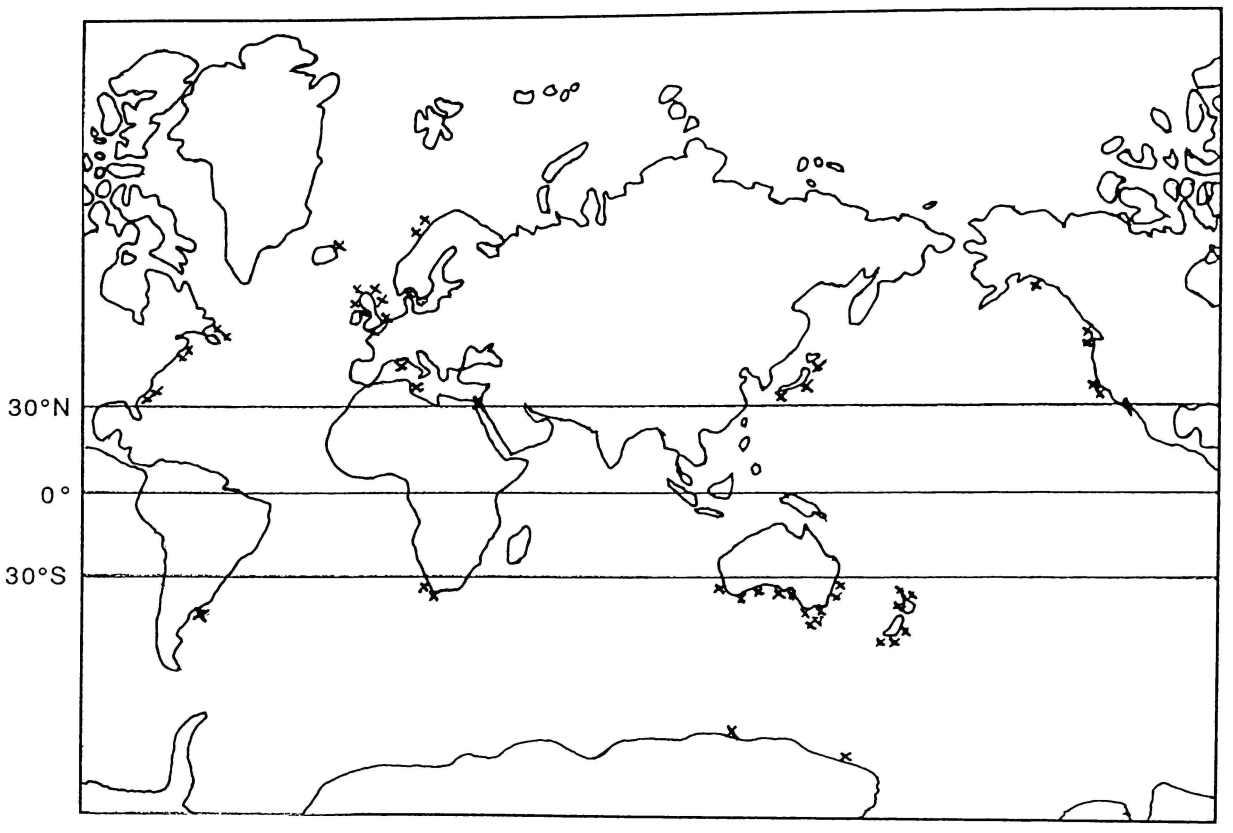


Figure 10B.1: World-wide distribution of temperate shelf carbonate sediments. Crosses mark locations of temperate shelf carbonate studies listed in Appendix Table A10.1.

The first real models of temperate shelf carbonates investigated the effects of temperature and salinity on carbonate type (Lees and Buller, 1972; Lees, 1975). The terms "foramol" and "chlorozoan" were coined to describe the very different skeletal assemblages that occur in temperate and tropical waters, respectively. "Bryomol" was later added by Nelson et al. (1988b) to describe the bryozoan- dominated sediments typical of Australasia. Nelson (1978) summarized many of the differences between temperate and tropical carbonates, most recently updated by Nelson (1988b). Leonard et al. (1981) evaluated the potential of the tropical/temperate differences in paleoenvironmental interpretations. The 1988 *Sedimentary Geology* Special Volume on non-tropical carbonates was another critical step forward (Nelson,1988a).

The models developed thus far have been comparative in nature. That is, they take the standard tropical carbonate system and compare the temperate one to it (e.g., Brookfield, 1988). This has the result of highlighting differences rather than pointing out similarities. The fundamental assumption, however, of this comparative method is that the overall process (biogenic and inorganic carbonates combine in sediments which are acted upon by various diagenetic forces and may become limestones) is the same in both situations.

It is implicit in such a model that tropical carbonates are better studied, better understood, and more common than temperate ones. The result appears to be one of describing exceptions to the rule. The approach is quite an appropriate one when little is known about the younger subject, and much about the older. There is, however, now quite a range of literature on the subject of temperate carbonates. It is clear that they occupy sectors of many of the world's shelves (Figure 10B.1) and have some fairly uniform characteristics. It is time for a descriptive model of temperate carbonates that is independent of tropical models.

It is a feature of most publications on temperate carbonates that they begin by justifying their existence. Many who do not work in temperate areas still do not realize

the extent or importance of temperate carbonates. For example, in their recent text on diagenesis of carbonate sediments, Morse and Mackenzie (1990) make no reference to latitudinal variation in carbonates. In their chapter on carbonate shelves, they state that "shoal-water carbonates are commonly associated with reefs," which is only true in warm waters. All their examples are apparently tropical. Yet there is no acknowledgement that the assertions made may apply only to tropical carbonates.

In the published literature there are two clear biases. A five-year survey of four international sedimentological journals shows that there is a strong bias toward tropical research, and another bias toward the northern hemisphere (Figure 10B.2). Only in 1988, with the publication of the *Sedimentary Geology* special volume (Nelson, 1988a), were temperate carbonates well-represented.

The study of temperate carbonates is thus at a rather unusual stage. On the one hand, we have a great deal of information available from a wide range of locations, which should enable the development of a widely-applicable model for the formation of temperate limestones. On the other hand, quite a large body of geoscientists may not be aware that there is any need for such a model, either assuming that the tropical model is globally applicable, or that temperate carbonates are rather small aberrations.

C. TROPICAL AND TEMPERATE CARBONATES CONTRASTED

The current model, then, is one in which temperate and tropical carbonates are compared. A summary of the main aspects of carbonates listed in Figure 10A.1 is given in Table 10C.1.

The most obvious difference in tropical and temperate sediments is in their composition. The fauna and flora are different in the two climatic zones, the degree of

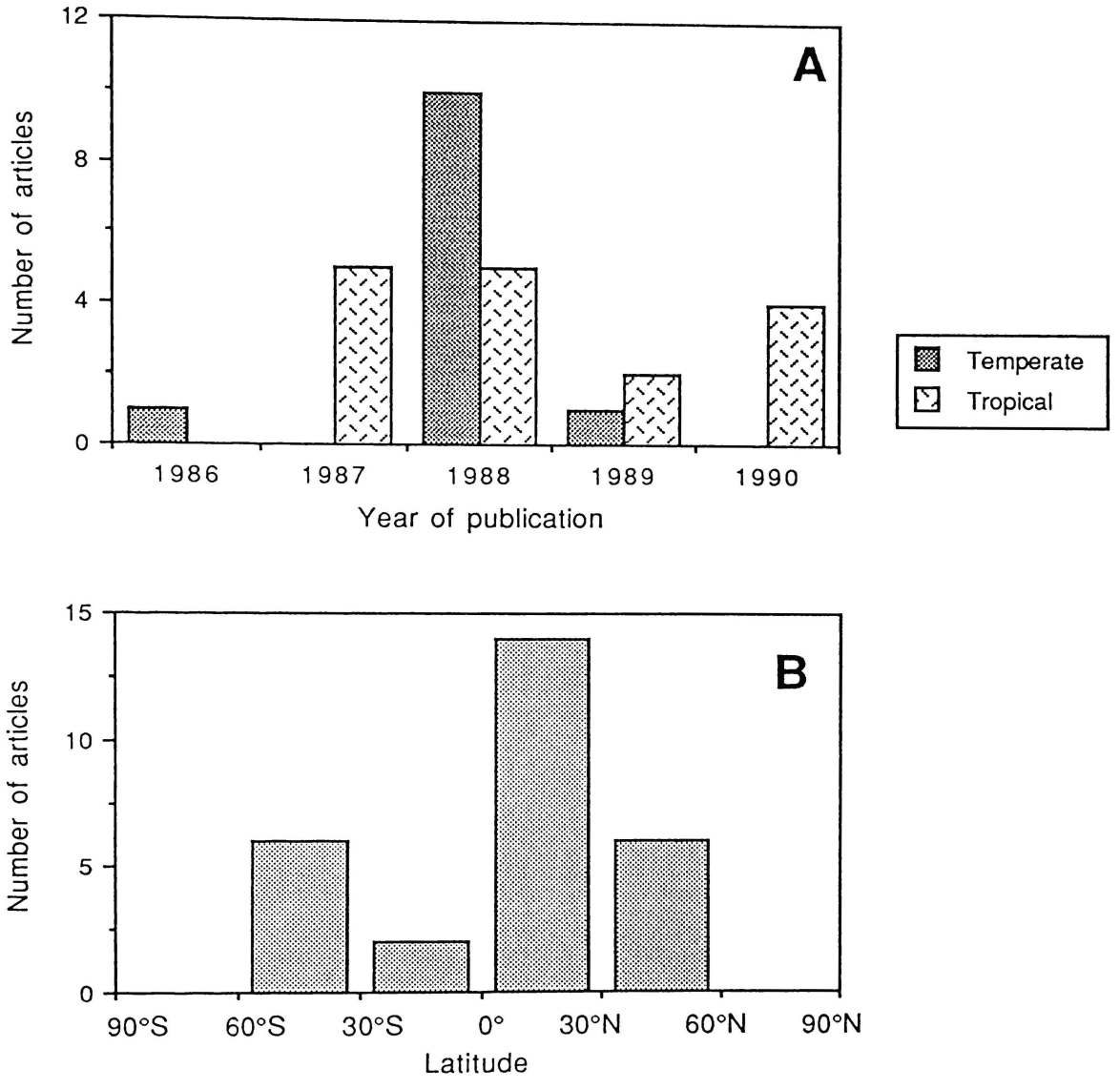


Figure 10B.2: Results of a literature search for modern shelf carbonate studies over five years in major sedimentological journals *(Sedimentology, Marine Geology, Sedimentary Geology, Journal of Sedimentary Petrology).* (A) Temperate and tropical studies over time. (B) Studies for each latitudinal zone.

Table 10C.1: Comparison of aspects of temperate and tropical shelf carbonates (after Nelson, 1978, 1988b; Nelson and Bornhold, 1984; Nelson et al., 1988b). Aspects illustrated in Figure 10A.1. Blank spaces indicate little or no information is available on the subject.

Aspect	Tropical	Temperate
Living organisms		
Degree of calcification	thick shells, high production	thin shells, lower production?
Distribution	discrete zones (depth)	often patchy
Abundance		
Diversity	high	mainly lower?
Taxa present-dominant	green algae, corals, molluscs	molluscs, barnacles, bryozoans
Taxa present-subdom.	foraminifera, red algae	serpulids, echinoids, forams
Sedimentation		
Death		
Breakage		
Decomposition		
Predation	fish, chitons documented	
Skeletons		
Mineralogy	aragonite dominant	low to high-Mg calcite dominant
Morphology	corals form reefs	corals solitary
Structures	reefs, algal mats	oyster reefs
		bryozoan mounds (rare)
Early diagenesis	constructive	strongly destructive
Disaggregation	floral produces mud	
Abrasion		produces mud
Sorting		
Bioerosion	common	dominant - produces mud
Dissolution	absent	rare to common
Cementation	common, early, arag common	late, calcite (sometimes Fe)
Inorganic precipitation	ooids, aggregates, peloids, mud	from intergranular dissolution
Sediments		
Areal extent		
Mineralogy	arag>calcite, evaporites	calcite>arag, mixed terrig.
	95-100% $CaCO_3$	50-100% $CaCO_3$
Texture	mud, sand, gravel	sand, gravel
Fabric		
True diagenesis		
Lithification	submarine, subaerial	
Taphonomy		shallow subsurface
Sedimentation rate	rapid (>10 cm/ky)	strong bias due to destruction
Authigenesis	rare	slow (<10 cm/ky)
Alteration (metastable)	subaerial	glauconite
Limestones	mudstone, wackestone, packstone, grainstone, boundstone	?submarine
		grainstone, packstone
Extent/thickness		
Mineralogy	dolomite,evaporites common	no dolomite, <100% $CaCO_3$
	aragonite>calcite	calcite>aragonite
Texture	matrix, cement	
Structures	reefs, algal mats	
Fossil assemblage	chlorozoan	rare
		bryomol or foramol

inorganic contribution is very different, and the dilution by terrigenous sediments is often different. A "typical" tropical carbonate is made up mainly of corals and green algae, contains various inorganic grains such as ooids and peloids, and has little or no terrigenous material. Temperate sediments commonly are dominated by molluscs, barnacles, or bryozoans, have no inorganic constituents, but may be up to 50% terrigenous (beyond which point it is not technically a carbonate sediment).

The compositional differences result in other differences. Mineralogy, for example, varies depending on the mineralogy of the constituent species. Texture is also dependent on composition, in that some organisms disaggregate to form mud (e.g., green algae in the tropics) and some are broken or disarticulated to form sands and gravels (e.g., bryozoans). Structures are another variable that arises from biotic composition (e.g., reefs, mats).

Another very important difference is in the processes of diagenesis. The entire diagenetic regime is different: dominantly constructive in the tropics (cementation, preservation), and dominantly destructive in temperate zones (dissolution, bioerosion). Temperate carbonates may be subject to early marine diagenesis much longer than are tropical ones, because residence time at the sediment surface is usually longer due to lower sedimentation rates.

Resulting limestones obviously have quite different characters. A tropical limestone might show biogenic structures like reefs, and would be (initially) mainly aragonite. It would be strongly cemented and would have the "chlorozoan" assemblage (of Lees and Buller, 1972). Temperate limestones, in contrast, may have a terrigenous component, would be mainly calcite, and the skeletal grains ("foramol" of Lees and Buller, 1972 or "bryomol" of Nelson et al., 1988b) may be badly bioeroded.

There is obviously much to be gained by a comparative model such as this one (based on work by Nelson, 1978, 1988b; Nelson and Bornhold, 1984; Nelson et al., 1988b; and

Smith, 1988). Another model, in which tropical sediments and processes play no part, may also be of use, and is developed below.

D. DEVELOPING A TEMPERATE CARBONATE MODEL

1. Introduction and the temperate setting

A number of important papers on temperate carbonates have been used, together with Appendix Table A10.1, to determine if global trends are present in temperate carbonates. The following descriptions are based on work from both sides of the North Atlantic (Boillot, 1965; Slatt, 1977) and the North Pacific (Schlanger and Konishi, 1975; Nelson and Bornhold, 1983). The southern oceans are also represented, including South Africa (Siesser, 1971), Australia (Wass et al., 1970; Marshall and Davies, 1978; Rao, 1981a,b), and New Zealand (Nelson et al., 1988b). World-wide surveys were also examined (Chave, 1967; Hayes, 1967; Lees, 1975; Leonard et al., 1981).

Temperate-water carbonates studied in the above literature tend to be found between 30 and 50° latitude. In the higher latitudes very few studies have been made, exceptions being Askelsson (1974) and Domack (1988). The climatic setting, therefore, is generally warm to cool temperate. As Hayes (1967) demonstrated, coastal climate and sediments are closely interrelated. In cool temperatures weathering is not so destructive as in warm temperatures, thus limiting the supply of terrigenous material. Many temperate shelves, however, have been glaciated, which provides terrigenous material. Leonard et al. (1981) pointed out that glaciated coasts also provide the hard substrate needed for many carbonate-producing organisms, allowing rapid production of carbonate (e.g., Smith, 1970; Smith, 1988). Active tectonic uplift also provides high relief for erosion, irrespective of climate. Production rates may also be influenced by solar radiation, which becomes less with higher latitude (Schlanger and Konishi, 1975).

The temperature of sea water in the temperate zones generally falls in the range of 5 to 20°C. Salinity varies depending on environment, but low to normal ranges are

common: 29 to 30‰ (Nelson and Bornhold, 1983) on the Scott shelf near Vancouver Island, 34 to 36 ppt in south Australia (Wass et al., 1970). Several studies reported sea water carbonate levels to be at or below saturation with respect to $CaCO_3$. The only one to quote experimental data, however, found supersaturated waters to 100m water depth in the Labrador Sea and the Gulf of Maine, off the coast of California and near Bermuda (Chave, 1967). This suggests that undersaturation with respect to $CaCO_3$ may be less common than is often expressed.

No particular trend in shelf morphology emerges from the studies done. Circulation tends to be open to the ocean, with storm surges and tidal ranges important (e.g., Nelson et al., 1988b). Tectonic regime varies from stable to unstable, and topography may be steep or rather shallow.

One of the most obvious features of the global distribution of temperate carbonates is that the distribution is bipolar. The northern temperate zone is separated from the southern temperate zone by well over 6000 km. That sediments from such widely separated areas have many features in common is rather surprising, and requires explanation.

2. Living organisms and skeletons

It has been claimed by several studies that calcification rates in cold waters are relatively slow (e.g., Schlanger and Konishi, 1975; Leonard et al., 1981). According to Leonard et al. (1981), temperate shells are thin, and both individuals and whole taxa are smaller than in the tropics. On the other hand, Chave (1967) convincingly argues using several lines of reasoning that calcification rates in the tropics and in temperate zones are similar. Smith (1970) reached the conclusion that $CaCO_3$ production in temperate shallow rocky areas is comparable to tropical non-reef production (about 500 $g/m^2/y$). Smith (1988) reached a similar conclusion in the temperate rocky intertidal of Maine. There is thus no consensus as to overall calcification rates in temperate waters. The location of carbonate production in temperate waters tends to be on the shelf (to

100m), rather than in the intertidal and shallowest subtidal zones (Schlanger and Konishi, 1975).

The distribution of carbonate-producing organisms is controlled by several factors. On a large scale, the boundary between temperate and tropical assemblages is primarily due to temperature (Lees, 1975; Marshall and Davies, 1978). Salinity is a secondary control; in waters of low salinity, a more temperate-like assemblage is often found irrespective of temperature (Lees, 1975). Substrate is another important factor: on the Atlantic coast of the USA, the more northerly glacial morphology provides more rocky substrate and therefore hosts more carbonate-producing organisms than the sandy barrier beaches of the southern coast. Distribution of organisms that make up temperate carbonates is also strongly dependent on substrate, as well as water energy, turbidity, and depth (Schlanger and Konishi, 1975; Leonard et al., 1981; Nelson et al., 1988a).

In some cases, equitability (that is, the relative abundance of organisms among species) tends to increase in higher latitudes. Diversity (the number of different species) tends to decrease (Leonard et al., 1981). If this is generally the case, temperate assemblages should be characterized by few species, each of which is well-represented.

The major carbonate producers in temperate waters are molluscs, bryozoans, barnacles, and foraminifera. Usually less important are serpulid worms, echinoids, red algae, and brachiopods. Very minor constituents which are often reported are sponges, ahermatypic corals, asteroids, and ophiuroids. It has been said that the most important characteristic of temperate carbonates is the lack of hermatypic corals and codiacean green algae (Lees, 1975; Schlanger and Konishi, 1975). Although this lack is true of temperate carbonates, a more positive definition is also possible. Commonly, temperate carbonates are dominated by bivalves or bryozoans (thus "bryomol" sediments). Benthic foraminifera and barnacles make up the majority of the remainder, with gastropods, worm tubes, and echinoids locally common.

Turnover rates and causes of death are not well-known. Mechanical dislodgement and breakage are certainly possible on the open shelf; predation is often important (Nelson et al., 1988b). The disaggregation found in tropical flora shows no sign of being important in temperate waters.

Mineralogy of the skeletons of the temperate carbonate-producing taxa is rather mixed. Dominant components (bivalves, bryozoans) can be aragonite or calcite or Mg-calcite (Milliman, 1974). Foraminifera, red algae, serpulid worms, and ahermatypic corals can be aragonite or Mg-calcite, whereas barnacles and brachiopods are generally calcitic. Sponges and echinoids are generally Mg-calcite. Thus temperate assemblages are often a mixture of mineralogies.

Most taxa have fairly fixed morphologies, that is, a temperate bivalve looks rather like a tropical bivalve. Bryozoans, however, have many possible colonial growth forms, and it would be interesting to know if certain ones were dominant in temperate sediments. Erect, delicate branching and erect flexible forms appear to be the most common in temperate sediments. Erect fenestrate forms and encrusting forms and locally free-living forms are also important (Boillot, 1965; Wass et al., 1970; Schlanger and Konishi, 1975; Bradstock and Gordon, 1983; Nelson and Bornhold, 1983; Nelson et al., 1988a). Occasionally, bryozoans and bivalves form clumps or "reefs" that have clear structure. Oyster banks and bryozoan clumps have been reported in New Zealand (Nelson et al., 1988b), and rhodoliths have been found (Nelson et al., 1988b). Australian bryozoan build-ups are also known (Rao, 1981b; Bone and Wass, 1990).

3. Sediments

It was Chave (1967) who first commented that the main control over distribution of carbonate sediments was rivers. The absence of terrigenous dilution (from any source, not just fluvial) is now recognized as the major reason for shelf carbonate deposits. In fact, a lack of terrigenous material actually promotes calcification, in that water is clearer (Nelson et al., 1988b). Active circulation can achieve the same effect.

Generally, the benthic organisms that are most important in temperate carbonates prefer hard substrates, which means there are often localized "carbonate factories" in areas of rough or rocky topography (e.g., Nelson and Bornhold, 1983). The best environment for temperate carbonate production is one with clear, well-circulated water, low terrigenous input, and rocky substrate. Temperature and depth do not appear to be so important.

Temperate carbonate sediments tend not to be pure carbonates. Mixing with terrigenous material is common, as is a patchy distribution among terrigenous sediments. Most temperate carbonates reach a maximum of 100% $CaCO_3$, but mean values are typically much lower (around 60%) (e.g., Siesser, 1971; Slatt, 1977; Nelson et al., 1988b). Within the carbonate material, calcite and Mg-calcite are generally more common than aragonite; this is controlled by the taxa present (Nelson et al., 1988b).

Most temperate carbonates are sandy gravels or gravelly sands; mud is not so common. Hayes (1967) found gravels to predominate on temperate shelves. Nelson et al. (1988b) suggested that mud was probably not produced in great quantities, and the little mud that was produced was possibly not deposited due to water circulation. Whether swept away or dissolved, pure carbonate mud is not common in most modern temperate carbonates. There are, however, instances of temperate muds that are 10 to 20% $CaCO_3$, for example, east of Scotland in the North Sea (Farrow and Fyfe, 1988). The mixed provenance of many temperate sediments means that sorting and textural grading may be rather complex (as noted by Slatt, 1977).

Despite possibly rapid production rates, sedimentation in temperate carbonates is slow (Smith, 1988). Nelson et al. (1988b) have interpreted relict and palimpsest sediments as indicating low sedimentation rates. Rao (1981b) cited extensive boring to mean the same thing. Given the potentially high rates of bioerosion discussed by Nelson and Bornhold (1983) (see below), Rao's interpretation may not hold. There is thus some question as to whether a generalization about sedimentation rate of temperate

carbonate sediments is appropriate. Certainly some temperate sediments accumulate very slowly compared to their production rate (Smith, 1988); the difference may be due to diagenetic processes.

4. Diagenetic processes

The single most important point about early diagenesis in temperate carbonates is that the overall regime is destructive. Dissolution and bioerosion may account for much of the destruction; abrasion is of less importance. Bioerosion in particular is commonly reported, both macroscopic drilling or breakage, and microscopic boring and pitting (e.g., Young and Nelson, 1988). Leonard et al. (1981) noted that the many algal borings found are generally not infilled with micrite, thus they weaken the substrate. According to Nelson and Bornhold (1983), a large bivalve could be destroyed by bioerosion very rapidly, in 1000 to 2000 y. Dissolution is usually inferred from the state of sediment grains rather than being directly observed. Chalky, corroded grains with little surface ornamentation are described as having been subject to dissolution (Nelson et al., 1988b). Pitting and etching (Rao, 1981b) are also symptoms of dissolution.

This is not to say that constructive processes never occur. Cementation has been described in some temperate carbonates, usually as a late diagenetic process. Cement is usually calcite (Nelson et al., 1988b) although it can be aragonite (Leonard et al., 1981) or ferroan calcite. It can be fibrous spherulitic in texture, or rhombohedral (Rao, 1981a). Lithification cement appears to be formed mainly from intergranular shell dissolution and reprecipitation of carbonate, rather late in diagenetic history, and typically under burial, submarine, or subsurface conditions (Rao, 1981a; Nelson et al., 1988b).

Sea-floor lithification forming hardgrounds is rather rare in temperate carbonates (e.g., see Scoffin, 1987), but does occur under particular conditions. Marine cementation requires large volumes of sea water in continuous motion through the upper layers of sediment and exposure of the sea floor for some period of time, either through lack of

sedimentation or biological stabilization (e.g., bacterial mats). In the tropical setting, hardgrounds may form in only a few months (Moore, 1989). Temperate waters may be less saturated with respect to $CaCO_3$, and thus require longer term exposure. Some temperate carbonates do have such very low sedimentation rates that cementation may occur in the upper few cm of sediment, producing thin hardground beds associated with erosional surfaces (Reeckmann, 1988; James and Bone, 1991). Little is known about the rates and detailed mechanisms of lithification in temperate carbonates.

Otherwise, inorganic precipitation is generally rare in temperate waters. Ooids, peloids, and grapestone are absent to rare; evaporite minerals are seldom found, and micrite is unusual. Submarine cementation may occur, but is rarely extensive (e.g., James and Bone, 1991). There is no evidence of inorganically precipitated carbonate mud - the carbonate mud found in temperate carbonates is of skeletal origin (Farrow and Fyfe, 1988). Authigenesis, on the other hand, may be common. Glauconite is commonly found in skeletal chambers in New Zealand carbonates (Nelson et al., 1988b).

Metastable carbonate minerals eventually alter to stable forms. In temperate carbonates, some cements have been interpreted to be inverted from vaterite (Rao, 1981a); Mg has been reported to be leached from Mg-calcite in both the submarine (Nelson et al., 1988b) and the subaerial (Siesser, 1971) environments. Dolomitization, however, is not recorded.

5. Limestones

Some ancient limestones are clearly temperate in origin (e.g., see Brookfield, 1988; Kamp et al., 1988; Rao, 1988b). As expected, they have some of the characteristics of modern temperate carbonate sediments. In mineralogy, for example, New Zealand Cenozoic shelf limestones are more calcitic than aragonitic, and have locally high terrigenous content. They have the typical temperate assemblage of fossils (bryozoans, bivalves, foraminifera), and no non-skeletal grains. Cement is calcitic (often ferroan) and is mainly the result of intergranular dissolution. In texture they are mainly coarse,

although locally there is carbonate mud matrix; there are rare oyster "reefs" (Nelson, 1978). Another temperate limestone, this time from Ryukyu Islands, Japan, shows similar patterns (Schlanger and Konishi, 1975). Mud is rare; red algal balls occur, as well as foraminifera, bryozoans, and molluscs. Calcite is the dominant mineral in these Pliocene to Holocene sediments.

A temperate carbonate model may well be more appropriate than a tropical one for interpretation of ancient calcitic limestones (James and Bone, 1989). Many early and middle Paleozoic sediments comprise assemblages much like those typical of modern temperate carbonates, and may have had similar calcite-dominated mineralogies. Whatever the paleolatitude of these ancient sediments, modern temperate carbonates are useful analogues (James and Bone, 1989; Rao and Nelson, 1992).

Although there are temperate limestones, most modern temperate carbonates have low preservation potential. The degree of mixing with terrigenous material is one factor: temperate carbonates are likely to be small local deposits (perhaps lenses) within mainly terrigenous deposits. Another problem is the destructive diagenetic regime coupled with low sedimentation rates. The long residence time of sediment grains in contact with possibly periodically undersaturated sea water and exposed to colonization by boring organisms leads to loss of skeletal material and fossil information. It is possible that a temperate carbonate sediment may be formed at a fairly high production rate but not be preserved as more that a thin veneer or small lens, due to such destruction.

Similarly, there is very likely to be some sort of selection in dissolution and bioerosion. Some skeletal grains may withstand diagenesis better than others. This would lead to a distorted fossil record, if any carbonate survives. It is thus that interpretation of ancient rocks may be quite inaccurate. A mainly terrigenous rock may have been the site of considerable production of carbonate at one time. There may be few clues left in the eventual deposit.

6. Summary: the model

Figure 10D.1 summarizes some of the above points. Among the most important criteria for recognition of a temperate carbonate deposit are:

1. Composition: the fauna and flora are diagnostic (bryomol or foramol assemblage), along with the absence of non-skeletal grains.
2. Carbonate content: the deposit may not be pure carbonate. Terrigenous material may be mixed with carbonate, or surround carbonate-rich patches.
3. Mineralogy: carbonate mineralogy is mixed, with skeletons of aragonite, calcite, and Mg-calcite. Of the three, aragonite may be least common.
4. Texture: sand and gravel will be common, carbonate mud less so.
5. Early diagenetic processes: there may be evidence of bioerosion and/or dissolution. Older grains will have a "moth-eaten" appearance. Cementation will be rare; glauconite may be common.
6. Structures: coral reefs and algal mats will be absent, but bivalve or bryozoan "reefs" and/or algal balls may occur, although not commonly.
7. Disparity between production and sedimentation rates: although plenty of organisms appear to be available for calcification, and their turnover rates may be high, sedimentation rates may be low (as evidenced by relict grains or thin veneer deposits). This difference may be due to destructive diagenetic processes.

E. MISSING PIECES

Although a sensible and orderly model of temperate carbonate sedimentation has been described, there are serious gaps in our knowledge. Some questions that have arisen in the course of assembling this model are listed below.

What are the patterns of saturation with respect to $CaCO_3$ on temperate shelves? Is there any seasonal variation? What happens at the sea floor?

Are shells really thinner in cold water? Is growth slower? Is calcification slower?

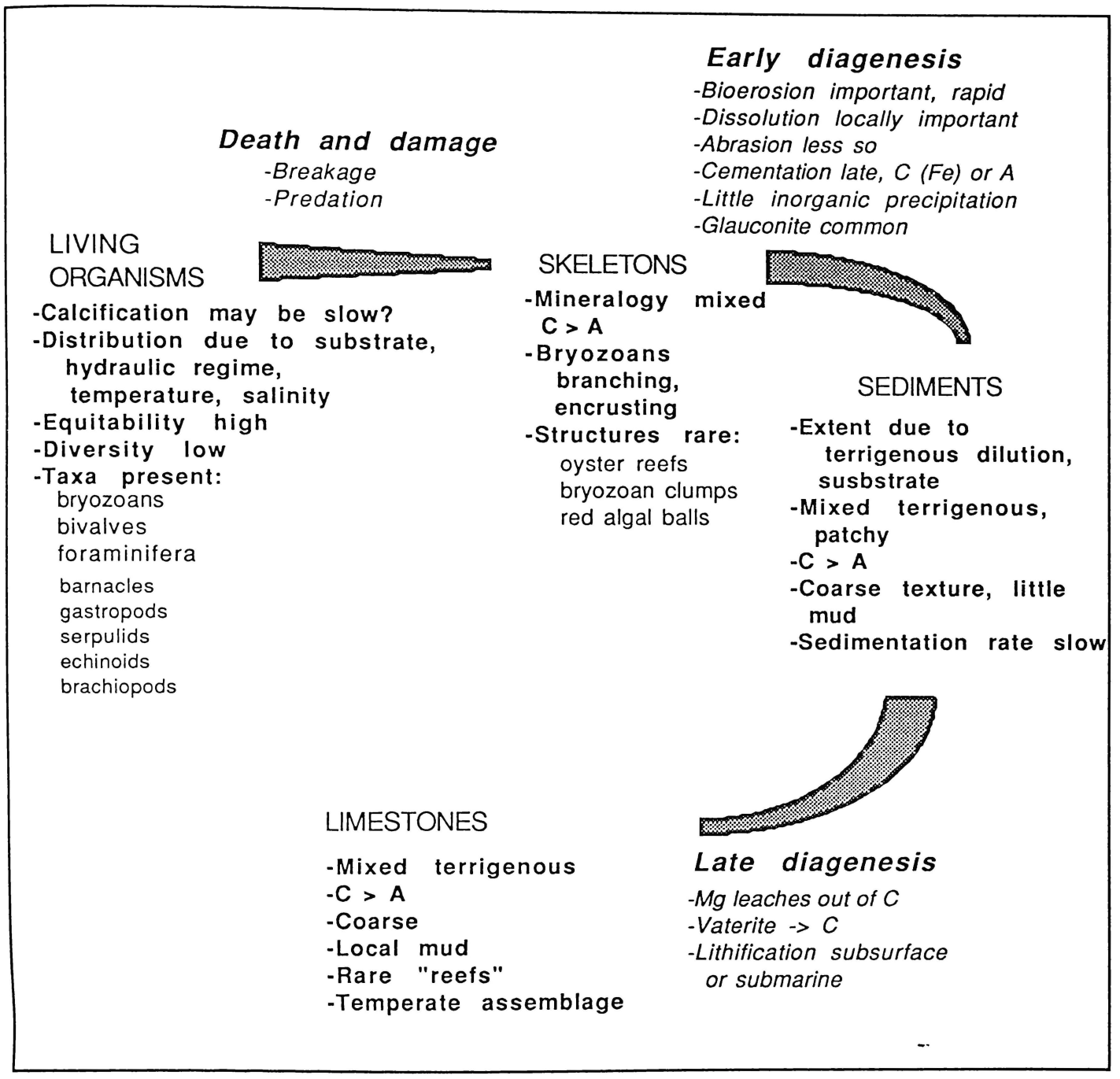


Figure 10D.1: Stages in the development of limestones in temperate settings (cf. Figure 10A.1). Processes in italics, aspects of each stage in bold. A = aragonite, C = calcite.

Is diversity really lower in cold water? Is equitability higher? Does it vary depending on environment? Does it vary among taxa?

What are the mechanisms of death, damage, decomposition, and predation in temperate water? At what rates do they occur?

Does mineralogy vary with water temperature within taxa?

Is carbonate mud produced by abrasion or bioerosion? What happens to it?

At what rates do diagenetic processes occur? Which processes are most important? How long does it take before Mg-calcite starts leaching Mg? How long does it take for aragonite to alter to calcite? How long does glauconite take to form? How fast is cementation?

Can the difference between production rate and sedimentation rate be accounted for by known diagenetic processes? Does the budget balance?

What about polar carbonates? Should they be considered temperate carbonates or are they yet another regime (as suggested by Brookfield, 1988)?

These, then, are some of the areas of uncertainty in the temperate shelf carbonate model. Although much has been accomplished in temperate carbonate description, many processes have yet to be quantified, and much remains to be done. Only a few of these will be addressed in the following chapters.

Chapter 11 Bryozoans and Temperate Carbonates

"Every animal leaves traces of what it was..."

J. Bronowski, Ascent of Man, 1973

A. INTRODUCTION

Numerous biological studies of bryozoans have explored their physiology, ecology, and evolution. Geological studies have typically concentrated on fossil bryozoans (e.g., Brown, 1952), although the importance of bryozoans as components of modern carbonate sediments has received attention recently (e.g., Wass et al., 1970; Marshall and Davies, 1978; Nelson and Hancock, 1984; Nelson et al., 1988a, b; Bone and Wass, 1990). Bryozoans play several roles in sediments, described below and in Table 11A.1.

Probably the most important sedimentary role for bryozoans is as producers of skeletal carbonate sediment. Bryozoan sediment is present in both tropical and temperate carbonates, but is probably more widespread and certainly relatively more abundant in temperate carbonates (e.g., Wass et al., 1970; Lees and Buller, 1972; Marshall and Davies, 1978; Nelson et al., 1988b). Another important and global role for bryozoans is as encrusters (Cuffey, 1974). Bryozoans encrust nearly every submarine surface available, including rocks, shells, glass, piles, boats, algae, sand, and dead coral reefs (Ryland, 1970). Encrusters add structure and volume to substrates, perhaps enhancing preservation.

On coral reefs, bryozoans may be principal frame-builders, but more often they live in and fill cavities (Cuffey, 1972, 1973, 1974). Meadows of erect flexible bryozoans may act as baffles, trapping fine sediment. In fact, the weak currents (0.4 cm/s) set up by filter feeding appear to enhance the sediment-trapping effect in quiet waters, and may have fossil analogues in Paleozoic bryozoan-associated mudmounds (McKinney et al., 1987). As filter feeders, bryozoans produce fecal pellets, packaging fine particles and organic material. A few bryozoans are active in bioerosion, living within skeletal carbonate.

Table 11A.1: Active sedimentological roles of modern marine calcifying bryozoans (after Cuffey, 1974).

	Role	Importance
Structures		
	Frame builders	Occasional
	Encrusters	Major
	Cavity fillers	Minor
Sediments		
	Producers	Major
	Binders	Minor
	Trappers	Minor
Diagenesis		
	Borers	Occasional

These active sedimentological roles have only begun to be explored by geologists (particularly Cuffey, 1972, 1973, 1974). This thesis has investigated only one of these: the role of bryozoans as sediment-producers.

Bryozoans are of great importance in temperate carbonates. They are dominant producers of carbonate on the Australian (e.g., Wass et al., 1970) and New Zealand (e.g., Nelson et al., 1988b) shelves. Northern Pacific sediments also contain bryozoan carbonate (e.g., Smith, 1970; Nelson and Bornhold, 1984). In the north Atlantic, both the North American (e.g, Slatt, 1977) and the European (e.g., Dobson et al., 1971; Bouysse et al., 1979; Scoffin et al., 1980) shelves include bryozoan-rich carbonates. Even in the Antarctic (Domack, 1988), bryozoans are sub-dominant producers of carbonate.

Production, sedimentation, composition, and early marine diagenesis of bryozoan carbonate have been discussed in earlier Chapters, using New Zealand examples. They will be summarized and discussed in Section B.

One purpose of studying modern bryozoans is to allow interpretation of fossils and ancient limestones. A discussion of the use of bryozoans in paleoenvironmental analysis is given in Section C, and the effect of diagenesis on the bryozoan fossil record is considered in Section D.

B. A BRYOZOAN BUDGET

Carbonate production rates of bryozoans are poorly known. Research described in Chapter 1 (e.g., see Table 1D.3) shows that, although most individual bryozoans produce carbonate fairly slowly (less than 1 g $CaCO_3$/y), populations of bryozoans may produce sediment at rates from 25 to 250 g/m^2/y, or in favorable circumstances even higher (over 8000 g/m^2/y).

In temperate carbonates, bioerosion is considered the most active form of destructive diagenesis. Bryozoans do not appear to be as susceptible to bioerosion and encrustation as are molluscs. A comparison of Figure 4C.1 with Figure 8C.2 shows little or no weight change over a year in a bryozoan, whereas molluscs showed weight gain and loss over the same period. This may be primarily due to the small size and porous microstructure of bryozoan skeletons. Certainly, in Hauraki Gulf sediments containing many badly bioeroded molluscs, bryozoans may be fairly fresh (personal observation). This either reflects a greater resistance to bioerosion on the part of bryozoans, or a shorter overall residence time at the sea floor. A preliminary study of bioerosion from radiocarbon dating indicates that bioerosion in temperate waters is a long-term process, perhaps taking 100s to 1000s of years to destroy a large mollusc shell. Rates of bioerosion of bryozoans may be even slower.

The relative importance of abrasion is determined primarily by hydraulic regime. On a turbulent, exposed, or storm-dominated coast, bryozoans might be expected to be broken and abraded. Because of the modular nature of bryozoan colonies, even small fragments can be relatively easily identified (e.g., Lagaaij and Gautier, 1965). This may make evidence of abrasion accessible. No absolute rates of abrasion in nature are available, although the tumbling experiment in Chapter 4, Section B gives relative resistance (Figure 4B.6).

Temperate shelf dissolution is, in some situations, more important than cementation. Dissolution affects bryozoans strongly, particularly small delicate forms (Figure 4D.4). In the longer term, aragonite skeletons may also be dissolved. No rates of bryozoan dissolution on the continental shelf are available.

Accumulation of sediment in temperate carbonates in usually quite slow (1 to 10 cm/ky), considerably slower than many tropical carbonates (100 to 1000 cm/ky according to James and Bone, 1991). In some cases this is due to destructive diagenetic

processes such that sedimentation rates are less than production rates, perhaps considerably so (Smith, 1970; Smith, 1988). Is this the case for bryozoans?

If bryozoan carbonate production is on the order of 25 to 250 g/m^2/y (as discussed in Chapter 1, see Table 1D.3), carbonate would be accumulating at a rate of 4 to 40 cm/ky (assuming a density of 0.6 g/cm^3) in areas of bryozoan production. Production can be locally much higher, for example, over 200 cm/ky in sheltered areas of south Australia (Gostin et al., 1988), and about 1400 cm/ky in Bermuda (Pestana, 1985). Rates of sedimentation, however, tend to be about 1 to 10 cm/ky (James and Bone, 1991). There are two possible explanations for this wide difference between production and accumulation: regional production areas, and destructive diagenesis.

At Three Kings Platform, north of New Zealand, the area of active carbonate production ("carbonate factories") covers about 1.5% of the total 10,000 km^2 platform (Nelson et al., 1988b). Thus bryozoan carbonate production of 250 g/m^2/y averaged over the entire area comes to about 0.6 cm/ky. As bryozoans form about 30% of the overall carbonate, this is certainly consistent with the sedimentation rate estimated at 1 to 2 cm/ky (Nelson et al., 1988b).

Carbonate production of 250 g/m^2/y is, however, a very conservative minimum, and if production approached that of Bermudan bryozoans (over 8000 g/m^2/y according to Pestana, 1985), it could be as high as 14 cm/ky averaged over the whole plateau. Even that is low, compared with accumulation rates in south Australia of 100 cm/ky. Active and strong destructive diagenesis would be required to account for the two orders of magnitude difference between production and accumulation.

Although there is a real lack of information regarding the rates of major processes in temperate carbonate bryozoan sedimentation, a qualitative budget may be proposed (Figure 11B.1).

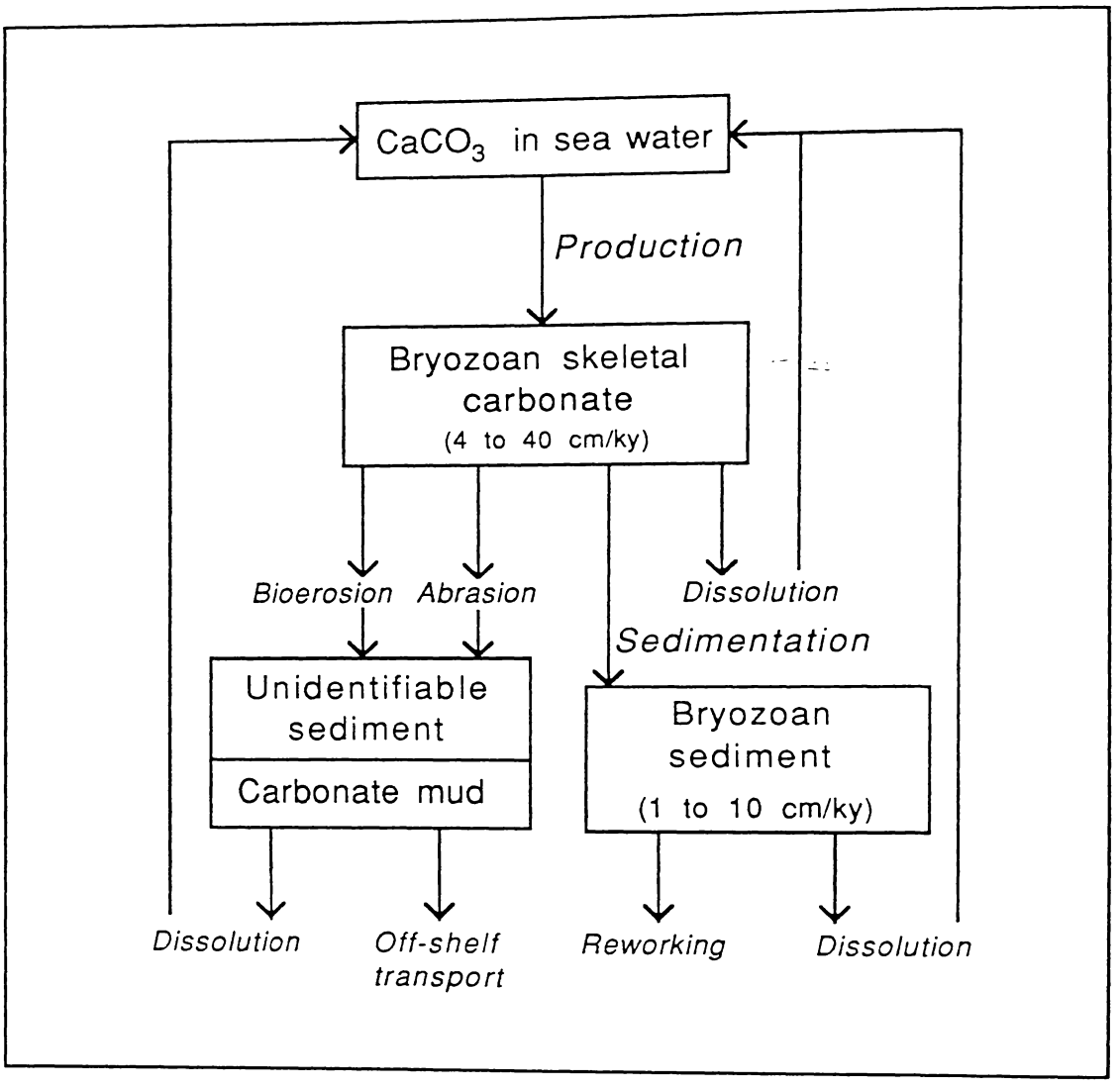


Figure 11B.1: A budget of bryozoan carbonate sedimentation in temperate shelf sediments.

C. PALEOENVIRONMENTAL INTERPRETATION OF BRYOZOANS

1. Introduction

Bryozoans have been producing calcified skeletons in the marine environment since the Lower Ordovician (or possibly the Upper Cambrian), and are an important group of fossils. Most Paleozoic groups are extinct, but the cyclostomes have persisted from the Upper Ordovician to the present, dominating bryozoan faunas in the Upper Mesozoic. Cheilostomes arose in the Cretaceous, and became dominant in the Cenozoic (Figure 11C.2).

Interpretation of fossil bryozoans has been based on studies of modern species, with the acknowledged danger of applying uniformitarianism to a system in which evolution has occurred. The ecology, morphology, and associations of living bryozoans, nevertheless, are the only systems comparable to fossil bryozoans available for study. Cheilostomes are best used in studying Cenozoic faunas, cyclostomes are more useful in the Mesozoic, and, unfortunately, no extant group is directly related to Paleozoic bryozoans, so cyclostomes are generally applied.

Modern bryozoans occupy a great variety of environments. Some species can tolerate estuarine conditions, but truly marine species are found in salinities ranging from 32 to 37‰ (Ryland, 1970). They are tolerant of temperatures up to 30°C, and most abundant on the continental shelf (although found down to 6000 m water depth).

Some aspects of bryozoans that have been studied with paleoenvironmental interpretation in view have been: the presence or absence of taxa and species, zooid size and shape, growth position of colony, and relative abundance of colonial growth forms. The latter method has proved to be particularly useful, as geologists without specialist knowledge of bryozoans have been able to quantify growth forms to make paleoenvironmental interpretations.

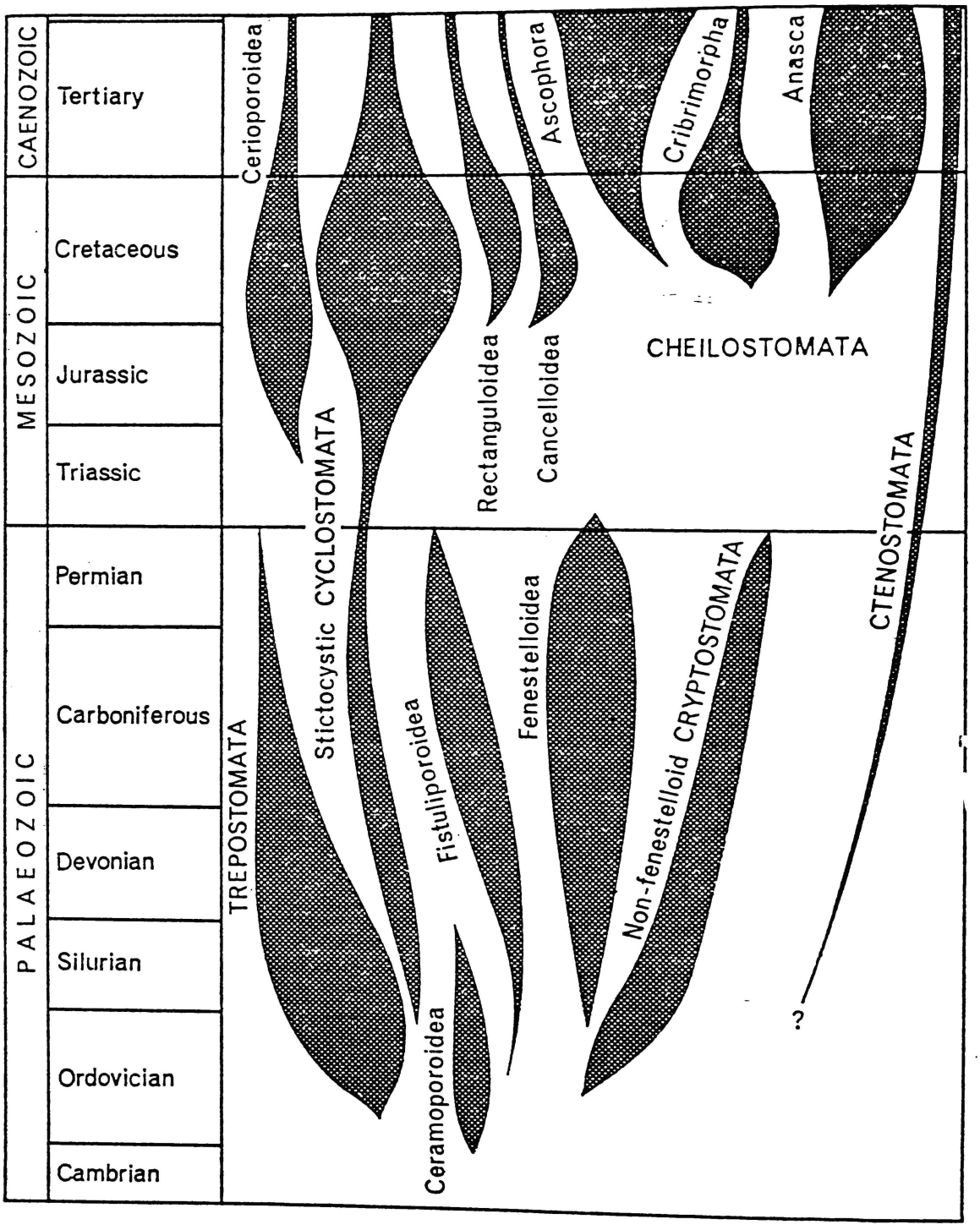


Figure 11C.1: Geological history of the bryozoans (Ryland, 1970, figure 20).

Stach (1936, 1937) first pointed out the association of living bryozoans with such environmental parameters as depth, hydraulic energy, and substrate. Lagaaij and Gautier (1965) modified this approach, including sedimentation rate as an important control on bryozoan distribution in their application of growth form analysis to the Rhone delta sediments. Schopf (1969) summarized growth form analyses to that time, as did Kelly and Horowitz (1987) much later. Growth forms have been correlated with water depth (e.g., Harmelin, 1988), water energy (e.g., Harmelin, 1975), substrate (e.g., McKinney and Jackson, 1989), and sedimentation rate (e.g., Lagaaij and Gautier, 1965).

In New Zealand, bryozoans from Tertiary limestones have been studied by Brown (1952), Leitch et al. (1969), Crabb (1971), Hyden (1979), Leask (1980), Hancock (1980), and Nelson et al. (1988a, b), among others. Modern bryozoan faunas have been studied by Cook and Chimonides (1981), Grace (1983), Gordon (1967, 1972, 1984, 1986, 1987, 1989), Probert et al. (1979), and Whitten (1979).

2. Bryozoans and paleoenvironmental interpretation

Perhaps the simplest aspect of fossil bryozoans to determine is their presence or absence. The presence of bryozoans does not give a narrow climatic or latitudinal range (as would, for example, the presence of hermatypic corals). A diverse and abundant bryozoan fauna does, however, argue for normal salinity (Ryland, 1970), and perhaps for a non-tropical setting (e.g., Marshall and Davies, 1978). Bryozoans are most abundant on the continental shelf, often below wave base but in areas of strong currents (Ryland, 1970) which provide continuous food supply and sweep away small particles. In New Zealand, species numbers decrease with depth, varying from over 100 species in a sample on the shelf to less than 10 in the deep sea (Head, 1985; Gordon, 1987). A total absence of bryozoans may indicate smothering by suspended sediment (Lagaaij and Gautier, 1965), low salinity (Ryland, 1970), or lack of acceptable substrate.

Sessile organisms are limited in their possible responses to environment by their lack of mobility. In order to find a favorable environment, attached species must either select their environment while in a motile larval stage, or grow towards a better environment (Buss, 1979). Colonial organisms are best able to use this second tactic, as partial mortality of the colony need not affect new growth. Bryozoans use both tactics. Bryozoan larvae have been shown to choose particular substrates for settlement, to settle near adults of the same species, and to find refuges, particularly by a photonegative larval response (Ryland, 1960). Certainly in the zone available to divers, bryozoans are generally noted in caves, on overhangs, and on undersides of rocks. With depth, and with decreasing competition from photosynthetic organisms, bryozoans begin to colonize open surfaces. Schopf et al. (1980) suggested that, in the fossil record, bryozoans on all sides of a boulder or pebble indicates deeper water, whereas bryozoans only on one side (presumably the underside) suggests shallower water.

Aspects of the physiology of individual bryozoan colonies may indicate environment. Size and shape of zooids and of colonies have been shown to vary bathymetrically (Flor, 1973; Schopf et al., 1980), decreasing with depth in *Heteropora pacifica*. Temperature, both in culture and in natural populations, may also affect size; zooids are larger in cooler water, whether temperature variation is seasonal, temporal, or geographic (Okamura and Bishop, 1988). In some species, formation of specialized heterozooids is temperature-controlled (Morris, 1976); in others heterozooids appear in response to competition, predation, or substrate irregularities (Silen, 1977). Temperature is thought to affect rate of calcification and growth rather than overall form (Schopf, 1969).

3. Growth forms and paleoenvironmental interpretation

As mentioned above, colonial organisms have the potential to change their environment by directional growth (Buss, 1979). Non-ascophoran colonies may add zooids in a preferred direction, perhaps in response to substrate (e.g., the direction of growth of an algal substrate), or to food availability. In some ascophorans, frontal budding is also

possible, resulting in multilaminar colony forms. Experimental culture of *Conopeum tenuissimum* showed that colonial growth form (see Figures 11C.2 and IB.3 for definitions) is a unilaminar sheet if the location is favorable, but uniserial if the colony is "hunting" for a better location (Winston, 1976). Thus, in "plastic" species, growth form may vary intraspecifically with habitat (Harmelin, 1975). The two most common intraspecific growth form variations are encrusting unilaminar to uniserial (e.g., Winston, 1976), and erect rigid delicate branching to foliose. In an extreme case, *Caleschara denticulata* is unilaminar in the littoral zone, erect foliose in deep active water, and delicate branching in deep sheltered water (Stach, 1937). Growth form is a reflection of genotype and environment, with some species more environmentally sensitive than others.

In addition to affecting intraspecific variation, environment may determine overall composition of a bryozoan population. Some growth forms may not be suited to a particular environment, and therefore will not be found in abundance under those conditions. This is the basis for Stach's (1936) method of environmental correlation with dominant growth forms. Most growth forms are found in most habitats, so overall relative abundance of growth forms is the measure used. As many workers have refined this method over the years, Table 11C.1 summarizes their work. The primary controls on growth form distribution appear to be water depth, water energy, sedimentation rate, and substrate.

Water depth has indirect effects on bryozoan distribution, through primary depth-related controls such as temperature, light, salinity, sedimentation rate, and hydrology (Harmelin, 1988). Intertidal (0 to 5 m) environments are subject to drying, wave action, and periodic lowered salinity; algal substrates are abundant. Subtidal environments are similar but without the drying and with less salinity variation. Shelf environments may be rocky, sandy, or muddy; either calm or subject to currents; below the photic zone algal substrates become unavailable. Deep-sea environments are dark, cold, and often muddy.

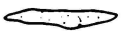
Life habit	Zooid arrangement	Abbrev.	New Zealand example	Schematic diagram
ENCRUSTING	unilaminar	ENul	*Chaperia acanthina*	
	multilaminar	ENml	*Celleporaria agglutinans*	
ERECT FLEXIBLE	articulated	EFar	*Cellaria immersa*	
	delicate branching	EFde	*Bugula dentata*	
	foliose	EFfo	*Beania sp.*	
	rooted	EFrt	*Steginoporella neozelanica*	
ERECT RIGID	delicate branching	ERde	*Galeopsis porcellanicus*	
	robust branching	ERro	*Adeonellopsis sp.*	
	foliose	ERfo	*Arachnopusia unicornis*	
	fenestrate	ERfe	*Hippellozoon novaezelandiae*	
	massive	ERma	*Celleporina grandis*	
	radiate	ERra	*Telopora buski*	
FREE-LIVING	motile	FLmo	*Otionella squamosa*	
	rooted	FLrt	*Conescharellina angulopora*	

Figure 11C.2: Common colonial growth forms among New Zealand bryozoans (presented in more detail in Figures IB.2 and IB.3).

Table 11C.1: Environmental associations of bryozoan growth forms (based on Stach, 1936, 1937; Lagaaij and Gautier, 1965; Schopf, 1969; Ryland, 1970; Harmelin, 1975, 1988; Pedley, 1976; Kelly and Horowitz, 1978; Nelson et al., 1988a; McKinney and Jackson, 1989; Reguant et al., 1991). Terms relating to controls defined in text (Section C, Part 3).

CONTROLS ON GROWTH FORM			Substrate			
			Short-life Fairly stable Flexible	Moderate-life Unstable Particulate	Moderate-life Fairly stable Hard	Long-life Stable Hard
Water depth	Hydraulic regime	Sedimentation rate				
Intertidal 0 to 5 m	Strong wave action Turbulent	Moderate to high	EFde ENul EFar	EFar EFfo ENml	ENul	ENul
Subtidal 5 to 10 m	Strong wave action Turbulent	Moderate to high	EFar ENul EFde	ERfe ENul	ENul	ENul
	Weak wave action Sheltered	Moderate to high	ENml	ENml	ENul	ENul
Inner shelf 10 to 50 m	Moderate strength Tidal currents Storm waves	Low to moderate	EFar ENul EFde	ERfo FLmo FLrt	ENul	ENul
Mid to outer shelf 50 to 200 m	Low to moderate strength Tidal currents Geostrophic currents	Low		ERfo FLmo FLrt	ERde	ERde
Slope, rise, abyss > 200 m	Low strength Geostrophic currents	Low		ERfo FLmo FLrt	ERde EFde	ERde EFde
	High energy currents	Low		FLmo	ERfe ERro	ERfe ERro

Hydraulic energy may affect bryozoans in one of two ways. Waves are turbulent, bidirectional, and unpredictable. In general they are stressful to bryozoans. Currents, on the other hand, are usually unidirectional and often fairly consistent. Low velocity currents (less than 20 cm/s) predominate in deep water; moderate-velocity currents, such as tidal currents (20 to 100 cm/s) are often found on the shelf; and high-velocity currents (more than 100 cm/s) are usually episodic (Schopf, 1969). Currents may cause abrasion and damage, but they also provide a constant food supply and may remove settling sediments (Ryland, 1970). Large colonies are subject to more stress than small ones; erect colonies more than encrusting ones. In modern large erect robust colonies, breakage occurs at about 100 cm/s (Cheetham and Thomsen, 1981); thus in high-velocity currents, encrusting species should be more common.

Sedimentation rate of terrigenous material also tends to vary with distance offshore. High sedimentation (100 to 1000 cm/ky) is found in enclosed bays, the nearshore zone, and some parts of the inner shelf. Even higher sedimentation rates are unusual and associated with particular features (e.g., a delta). Moderate sedimentation (10 to 100 cm/ky) may take place on the inner shelf, near estuaries and deltas. Low sedimentation (1 to 10 cm/ky) is typical of the mid to outer shelf, continental slope, and abyssal plain. The majority of bryozoan habitats are found in areas of low sedimentation; in fact, when sedimentation rates are greater than 100 cm/ky, bryozoans are generally absent (Lagaaij and Gautier, 1965).

Substrate is another important factor in determining growth form abundance. Many bryozoans live on flexible, rather short-lived substrates such as algal fronds. These substrates are, of course, limited to the photic zone. Hard substrates, moderately long-lived and fairly stable, such as mollusc shells, glass bottles, or cobbles, attract other bryozoans. Very long-lived, stable, hard substrates such as rock walls, reefs, boulders, and pilings are also important. On these long-lived substrates, competition becomes important, and bryozoans often lose space to other organisms such as sponges, ascidians, or algae (McKinney and Jackson, 1989). Particulate (sandy or muddy)

substrates pose special problems. Organisms living among the unstable, moving sand grains need to be able to regain the surface after burial (either by growth or by moving), to clean their surfaces of debris, and to stay in a stable position (or to be able to live despite not staying in a stable position). The two bryozoan solutions to these problems involve flexible but rooted colonies, and motile, conical-shaped colonies. To some degree, the grain size of the particulate substrate is another controlling factor.

These environmental conditions have been related to the occurrence of bryozoan growth forms (Table 11C.1). A few useful generalizations may be made. Encrusters abound on hard and flexible substrates in depths less than 50 m, but in deeper waters erect rigid forms may dominate. Free-living growth forms are most important on particulate substrates, usually in mid-shelf depths. Rooted erect forms are more important in shallower water. Erect flexible forms flourish in strong wave action, where erect rigid forms prefer quiet water. There is some disagreement about erect rigid fenestrate (ERfe) growth forms. On the one hand, the strong rigid structure is thought to be able to withstand strong currents (Stach, 1936); on the other hand, fenestrate forms have been found to be larger in calmer waters (Whitten, 1979).

Much of the information summarized above has been discovered and tested in the northern hemisphere. Associations may not be the same in southern oceans, as noted by Crabb (1971) and Wass and Yoo (1976). Some New Zealand examples, particularly the Hauraki Gulf, may be instructive.

4. Bryozoan growth forms in New Zealand shelf sediments

As bryozoans are dominant carbonate producers in New Zealand shelf carbonates, it is not surprising that several studies have considered their growth form distribution in these sediments. A limitation common to these studies is that early sea-floor diagenesis, transport, and mixing with relict sediments may have distorted the environmental "signature" of the growth forms present. Distribution of bryozoan growth forms, however, has been broadly correlated with environment at Three Kings

Plateau (Hancock, 1980; Nelson and Hancock, 1984), Hauraki Gulf (Whitten, 1979), Otago Shelf (Probert et al., 1979), Snares Platform (Head, 1985), and in the deep sea (Gordon, 1987) (see Figure 1D.4 for map).

Depth zonation of growth forms has been recorded at Three Kings (Table 11C.2), where encrusting forms dominate in water shallower than 50 m, but delicate and robust branching forms increase with depth, reaching dominance at 85 m and 150 m, respectively (Hancock, 1980). Distribution of growth forms is more complex at Snares Platform (Table 11C.3), and on the Otago Peninsula (Table 11C.4) where substrate type is more important than depth.

In New Zealand sediments, as elsewhere, rooted (EFrt, EFde, EFar) and free-living (FLmo, FLrt) forms are found on soft bottoms, whereas encrusting forms (ENus, ENul, ENml) are more common on hard bottoms (Gordon, 1987). A more detailed study of substrates carried out in the inner Hauraki Gulf by Gordon (1967) reveals the same trend (Table 11C.5). In general, though, New Zealand bryozoans are most abundant on coarse-textured gravelly sediments, particularly erect delicate branching forms such as ERde, EFar, and ERro (Probert et al., 1979; Whitten, 1979; Head, 1985).

Sedimentation on the New Zealand shelf is generally too slow to affect bryozoan distribution (Probert et al., 1979). There is a possible temperature-related change in bryozoan fauna with latitude, and the relative abundance of growth forms reflects this change. Carbonate sediments at Snares Platform, off southern New Zealand, are often dominated by multilaminar forms, also common on the Otago shelf (Head, 1985). Farther north, ENml is seldom found in the Hauraki Gulf, and dominant only from 10 to 50 m at Three Kings (Hancock, 1980). Robust branching forms have far more importance at Snares than at Three Kings, mainly due to the presence of the subantarctic *Cinctipora elegans*.

Table 11C.2: Bathymetric distribution of bryozoan colonial growth forms at South Maria Ridge, northern New Zealand (Nelson et al., 1988a, Table 2). Bold X indicates dominant; small x indicates present.

Water depth (m)	Colonial growth form					
	ENul	ENml	ERde	ERro	ERfe	EF
Intertidal	**X**					
0 - 10	**X**	x				x
10 - 25	x	**X**	x	x	x	
25 - 50	x	**X**	x	x	x	
50 - 75	x	x	**X**	x	x	
75 - 100	x	x	**X**	x	x	
100 - 125	x	x	**X**	x	x	
125 - 150	x	x	**X**	x	x	
150 - 175	x	x	**X**	**X**	x	
175 - 200	x	x	x	**X**	x	

Table 11C.3: Distribution of bryozoan colonial growth forms at Snares Platform, New Zealand (Head, 1985).

Water depth (m)	Substrate	Dominant taxon	Growth forms present
50-100	Fine-medium sand	Bivalves	EFar, FLmo, FLrt
100-150	Coarse gravel	Bryozoans	ERde, EFar, ERro
150-200	Very coarse sand	Bryozoans, foraminifera	ENml, ERro
>200	Very fine sand	Foraminifera	None-few

Table 11C.4: Distribution of bryozoan colonial growth forms on the Otago shelf (Probert et al., 1979, Nelson et al., 1988a).

Water depth (m)	Zone	Substrate	Growth forms present
0-70	Inner shelf	Sand	Few bryozoans
30 - 80	Middle shelf	Gravel, pebbles	ERro, ERra, ERde, ERfo
30-120	Outer shelf	Gravelly muddy sand	ERfo, EFar, ENml, ERro
50-150	Upper slope	Muddy sand	ENml, ERfo, ERde

Table 11C.5: Substrate associations of bryozoans in the Hauraki Gulf (after Gordon, 1967). C - common; x - present.

Colonial growth form	Solid substrate					Flexible substrate	
	Stones	Shells	Piles	Glass	Bryozoans	Algae	Soft-bodied animals
EFar			x		x		
EFde	C	C	C	x	x	C	x
EFrt	x						x
ENml						x	
ENra	x				x	C	x
ENul	C	C	C	x	x	C	x
ENus	x	x	x		x	x	x

Table 11C.6: Bryozoan growth form distribution in the Hauraki Gulf. Depth zones after Whitten (1979) and Grace (1983). Data from Whitten (1979) and the author (see Appendix Table A11.1).

Zone	Depth	Substrates	Growth forms present
Shallow mixed weed zone wave action dessication freshwater mixing	0-6 m	Algae Rock	ENul, EFde (few) ENul, EFde (few)
Rock flats zone wave action	6-12 m	Algae Rock, shell	ENul, EFfo ERde, ERro
Kelp forest zone storm waves may be turbid	12-25 m	Algae Rock (undersides)	ENul, ERde ENul, EFrt, ERra
Nearshore zone tidal currents	25-50 m	Rock (open surfaces) Gravel Sand Mud	EFar, ENul ERfe, ERde, ENul, FLmo FLmo, ERfo ENml (few)
Quiet shelf zone low velocity currents	50-200 m	Rock Gravel Sand	ERde ERde FLmo, FLrt
Channels moderate velocity currents	50-200 m	Gravel	ERro, ERfe, ENul

A study of growth forms in the Hauraki Gulf (see Figure 5A.1 for map) provides more information (incorporating the work of Whitten, 1979 and the author). The Gulf is fairly sheltered; current velocities are generally low (<10 cm/s). Sedimentation is also low (<10 cm/ky), particularly in the outer Gulf. Salinity is lowered in harbors and at river mouths (e.g., Whangateau Harbour according to Whitten, 1979). The main controls on bryozoan distribution, then, are substrate, hydraulic energy, and depth (particularly in regard to zonation of algal substrate).

The intertidal zone generally has fairly few bryozoans, and these are mainly encrusting unilaminar (ENul) forms (Table 11C.6). Wave action and the associated turbidity, freshwater input, and periodic desiccation are all hostile to most bryozoans (Whitten, 1979). The subtidal shallows provide algal support for ENul, and space among the holdfasts of the brown alga *Ecklonia radiata* for erect delicate branching (ERde) colonies. Whitten (1979) noted that ERde colonies, when found in active water, have secondary skeletal thickening or anastomosing branches, perhaps providing additional strength. As noted by Whitten (1979), this abundance of ERde, normally considered a deep, quiet-water form (e.g., Schopf, 1969), is unusual and may reflect a difference in southern hemisphere distribution of this growth form, or the influence of microhabitat.

Nearshore and shelf zones have different growth forms depending on substrate and water energy, much as predicted by the published literature (and summarized in Table 11C.1). One exception is the presence of erect flexible articulate (EFar) forms on rocky substrates of the inner shelf. EFar forms are traditionally interpreted to indicate agitated, turbid, shallow water (e.g., Lagaaij and Gautier, 1965). In the Hauraki Gulf, on the Otago shelf, and on Snares Platform, EFar are common at inner- to mid-shelf depths. This may reflect a wide depth range for the dominant genus (*Cellaria*).

A greater variety of forms is noted in the Hauraki Gulf on particulate substrates than in published associations, particularly on gravel substrates, which may include large shells and therefore be more stable than many particulate substrates. It would

probably be of help if future workers defined loose sediments according to grain size, as different grain sizes clearly support different bryozoan faunas. Bryozoans are notably absent in Hauraki samples with greater than 90% mud (muddy facies, defined in Chapter 9, Section 1).

The Hauraki Gulf and other New Zealand carbonates have provided good tests of Stach's (1936) growth form interpretation model. The occurrence of delicate branching forms in algal holdfasts under high-energy conditions is one interesting exception to the model, reflecting the baffling effect of kelp fronds. Another exception is the abundant growth of articulated erect flexible forms on rocky substrate in inner- to mid-shelf depths. Further studies are needed to establish the environmental distribution limits of common bryozoan species, to determine occurrences of living bryozoans on the New Zealand shelf, and to ascertain the relationship between living faunas and shelf sediments.

D. BRYOZOAN TAPHONOMY

1. Introduction

Bryozoans that occur in living faunas may die and become part of the sediment, and bryozoan skeletons in sediment may be preserved in limestones, to be interpreted by paleontologists. There are, however, a number of taphonomic processes that damage or destroy bryozoan skeletons such that they do not become preserved. Taphonomic processes may be thought of as a filter, which allows only a subset of the original fauna to be preserved. The sum of taphonomic filters to which a fauna is subject will determine to what extent it is represented as fossils in a limestone (Figure 11D.1).

The first major transition is from living bryozoans to dead skeletons. Individuals may be so damaged by their mode of death (e.g., consumed, chewed, and digested by a fish) that they are unidentifiable as bryozoans. Species may be relatively rare or patchily distributed, such that chance determines whether they are present in a given sample.

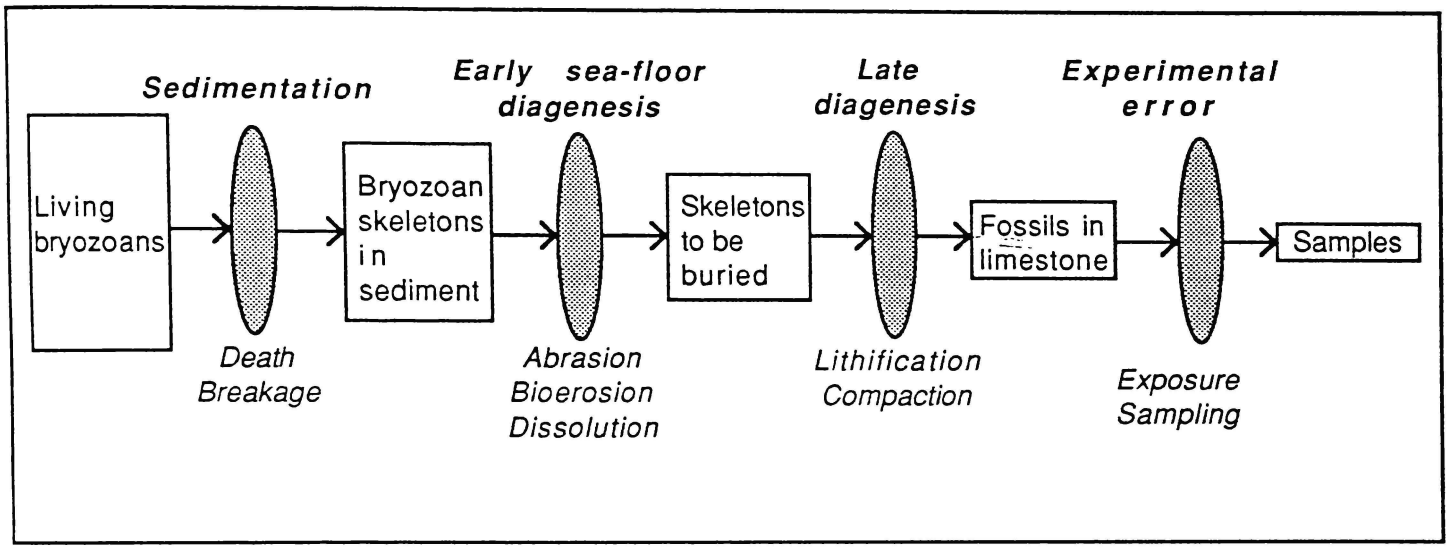


Figure 11D.1: Taphonomic filters affecting the fossil record of bryozoans. Processes in italics. Based in part on concept of Bosence (1979).

Some organisms may become abundant or absent despite a relatively constant environment, others may be relics of a previous environment (Bosence, 1979).

Bryozoans that do become sediments are then subject to a variety of potentially destructive processes, including abrasion, dissolution, and bioerosion. Skeletons may be removed from sediments, damaged beyond recognition, or reduced in size to mud. Early sea-floor diagenesis thus limits the skeletons available for lithification; and the later diagenetic processes of cementation, compaction, and neomorphism further limit the information available in the final product.

A limestone, being studied by a geologist, may retain few clues as to its original bryozoan fauna. Interpretation is further limited by sampling and exposure.

It is critical, in applying the paleoenvironmental correlations discussed in Section C, to realize that taphonomic filters will have been operating, and a limestone or even a sediment sample will almost certainly not represent the full living community. If taphonomic processes acted similarly for all species and all growth forms, the fossil record would be simpler to interpret. It is far more likely, as discussed below, that taphonomic processes are selective, not only reducing the fossil record but in fact biasing it.

A preliminary study of the representation of living fauna in recently dead sediment was discussed in Chapter 1, Section D.5. Bryozoans currently living on the wreck of the vessel *Rainbow Warrior* are poorly represented in carbonate sediments immediately below the wreck. This may reflect the short time that the wreck has been on the bottom (4 years), or perhaps some other more fundamental filter preventing bryozoan debris from accumulating. A similar experiment in several years time would help to address the problem. Any study in which living and dead bryozoan assemblages were compared would be useful in determining the extent of this early taphonomic filter.

2. Effects of early sea-floor diagenesis on bryozoans

Abrasion

Bryozoans as a whole are not particularly resistant to breakage and physical damage. Very strong bryozoans are still only about one third as strong as molluscan nacre (Cheetham and Thomsen, 1981). Many bryozoans live in high-energy habitats, so abrasion is likely to be a major source of destruction for them.

Different growth forms within the bryozoans have differing degrees of resistance to physical diagenesis (see Figure 4B.6). Least resistant forms include the lightly calcified forms (EFde, EFfo), which are quite resistant when alive but disintegrate without organic material, and encrusting multilaminar forms (ENml), which for some reason are the most likely to disintegrate to form mud (see Chapter 4, Section B). Articulated flexible forms (EFar) tend to disarticulate, but the resulting individual cylindrical pieces are quite resistant. Encrusting unilaminar (ENul) and most erect forms (ERra, ERde, ERro, ERfo) are moderately resistant to abrasion. The most resistant forms are the very compact free-living (FLmo, FLrt) and secondarily-thickened fenestrate erect (ERfe) ones.

In nature, a whole variety of complicating factors may obscure the simple associations outlined above. There is some variation within growth forms. Cheetham and Thomsen (1981) found an order of magnitude range of strengths within adeoniform (ERro) bryozoans (modulus of rupture ranges from 15 to 105 MPa), perhaps due to patterns of branching. Small bryozoans living close to a large surface (a rock, the sea floor) are subject to far lower current velocities than ones that project into the water column, due to a viscous sublayer effect (Caldwell and Chriss, 1979).

Abrasion affects individual bryozoan grains, as well as whole communities. The stages observed in the experimentally abraded skeletons (see Figure 4B.8) were as follows. When abrasion is weak, grains may lose fine surface structure (e.g., spines), and become polished. In moderate abrasion, surface ornamentation is lost, even to the extent of

losing the frontal wall altogether. Strong abrasion reduces the side walls of zooids too, leaving an unidentifiable shape. In addition, abrasion produces mud, which is additional evidence of its action.

Abrasion is a complex process, depending mainly on hydraulic energy, but also producing different degrees of change in grains subject to it. A preliminary model has been constructed (Figure 11D.2), combining the typical energy levels of the habitats of various growth forms (as shown in Figure 11C.1) with their susceptibility to abrasion (described above and given in Figure 4B.6).

In a high-energy environment, the erect flexible and encrusting forms predominate. EFde and EFfo forms are too weakly calcified to survive into the fossil record in a recognizable form. ENml is likely to disintegrate into carbonate mud, which will be transported away and lost from a high-energy environment. EFar and ENul forms, being only moderately resistant, might survive only as fragments. These fragments may be unidentifiable, missing frontal and side walls.

A moderate-energy environment would have a similar effect on EFar, EFde, and ENml forms. Erect fenestrate forms (ERfe) and ENul might stay fairly large, even whole, in the lowered abrasion of this habitat. Carbonate mud, produced by ENml abrasion, might remain in this environment, perhaps in hollows or wherever currents are reduced. Although frontal walls may be lost in some specimens, stronger bryozoans would only show damaged surface structure and polishing.

The low-energy bryozoan fauna comprises mainly erect forms (ERde, ERfo, ERfe, and ERro) along with free-living ones (FLmo, FLrt). All of these are moderately to strongly resistant to abrasion, and would be likely to survive intact or in large fragments in the fossil record. Little carbonate mud would be produced by abrasion. Some minor polishing might remove some fine surface structure.

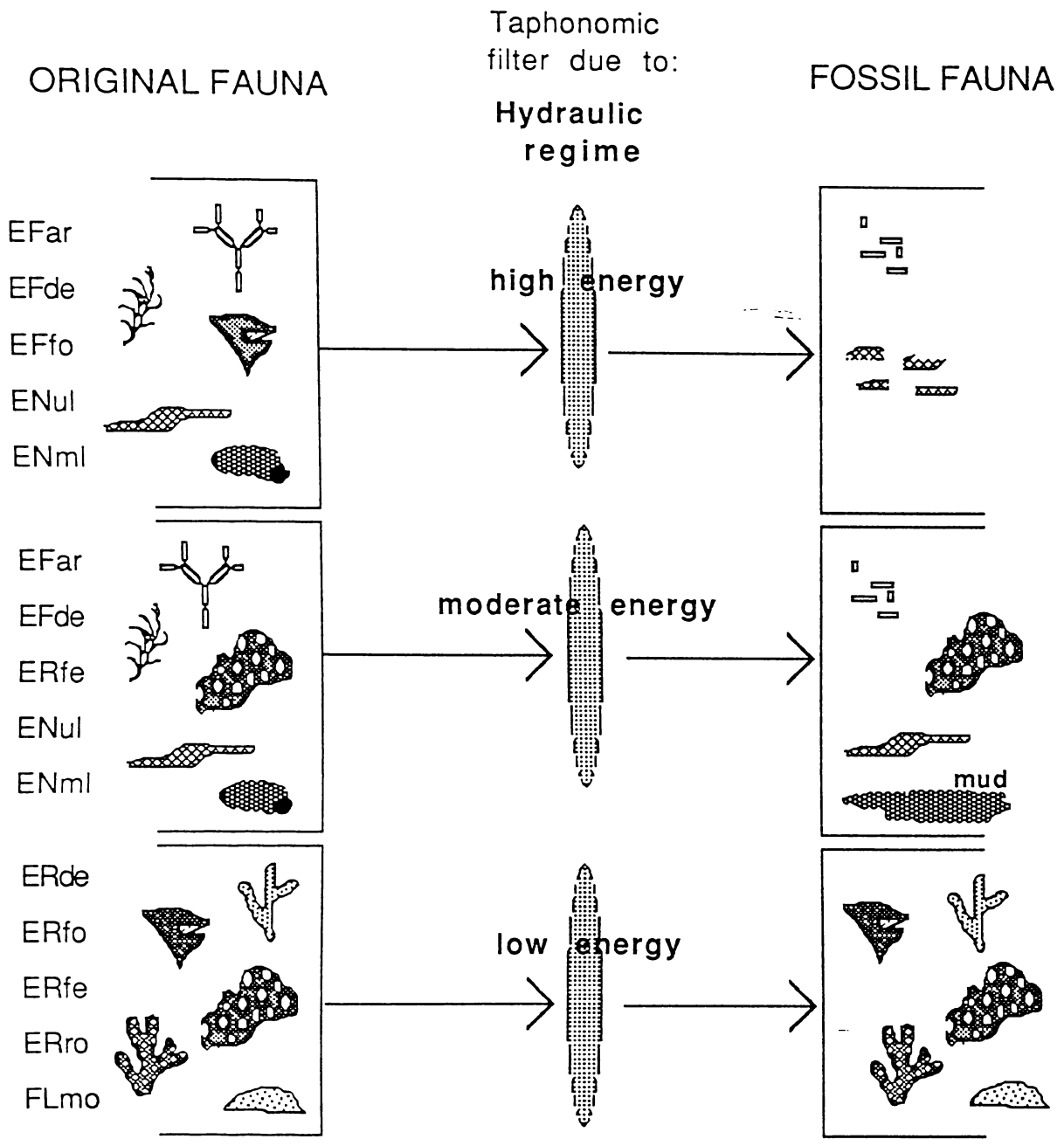


Figure 11D.2: A possible model for the taphonomy of abrasion and the effect of hydraulic regime on bryozoan sediments. Growth form abbreviations as in Figure 11C.2.

Paleointerpretation of faunas with obvious abrasion features should take into account the loss of growth forms with low resistance to abrasion (e.g., ENml). Particularly in high-energy environments, evidence of a thriving and diverse bryozoan community might be almost entirely missing due to abrasion.

Bioerosion

Biological diagenesis may be constructive (encrustation) or destructive (bioerosion), but in the long term bioerosion outweighs encrustation in overall importance (see Figure 8D.2). Bryozoans show evidence of both encrustation and bioerosion, but no evidence is available as to the effect of different bryozoan substrates (e.g., different growth forms, surface morphologies). There is a suggestion that bryozoans are not as "attractive" to bioeroders as are molluscs (Perkins and Halsey, 1971; personal observations), perhaps due to palatability of organic matrix. Experimental evidence indicates that bioeroded shells are more susceptible to other forms of destruction, including abrasion (Young and Nelson, 1988). This appears to be true of bryozoans as well (compare abrasion of old and new samples in Figure 4B.6). Abraded or previously bioeroded shells are also more susceptible to continued boring (see Figure 8D.5). In the absence of more information on bioerosion of bryozoans, it can at least be noted as a synergistic effect, increasing the destruction brought on by abrasion or dissolution.

Dissolution

Bryozoan sediments, like some other carbonate skeletons (Flessa and Brown, 1983), may dissolve differentially due to a combination of mineralogy and morphology (as shown in Chapter 4, Section D). It is traditional in carbonate sedimentology to describe differential dissolution as a mineralogical response (e.g., Morse and Mackenzie, 1990). Aragonite is more likely to dissolve than calcite, and high-Mg calcite may also dissolve, though it is more likely that it will leach Mg into solution.

Reactive surface area must also be important, and this is where bryozoan growth forms are of interest. A qualitative scale of compactness, adopted in Chapter 4, Section D,

groups the growth forms in terms of surface area exposed to sea water. The adaptation of an erect branching form means more surface area is available for feeding in the water column; it also means that dissolution is more effective in removing erect branching skeletons from the sedimentary record. Small size as well as a branching habit increase the effect of dissolution, as noted by Lagaaij and Gautier (1965) in regard to the small internodes of catenicellid bryozoans which are only preserved in areas of rapid sedimentation and thus rapid burial.

Dissolution due to morphology requires exposure on all surfaces to undersaturated fluid, a situation that occurs in sea water on some temperate shelves, if only periodically. Dissolution due to mineralogy may possibly be a subaerial or subsurface phenomenon; at least it is a longer-term one.

Bryozoans that have undergone dissolution have a characteristic appearance (see Figure 4D.5). Fragments tend to thin rather than break. Surface structure is removed, and the surface looks pitted or corroded. Sometimes layers delaminate, and after longer exposure bryozoans crumble and become unrecognizable.

A fossil fauna that has been subject to dissolution (Figure 11D.3) would exhibit the characteristic pitted and thinned appearance. It might be composed entirely of low-Mg calcite, implying that dissolution has removed or modified other mineralogies. It might also show a depletion in delicate forms (ERra, ERde) relative to robust forms, indicating that surface area has been important, and perhaps that the bryozoan sediment was exposed to undersaturated sea water.

Interaction of destructive diagenetic processes

No marine diagenetic process operates in isolation. In fact the cumulative effects of abrasion, dissolution, and bioerosion are likely to be synergistic, as each process appears to increase vulnerability to the others. The interaction of these processes, in total, finally determines the preservation potential of bryozoan grains.

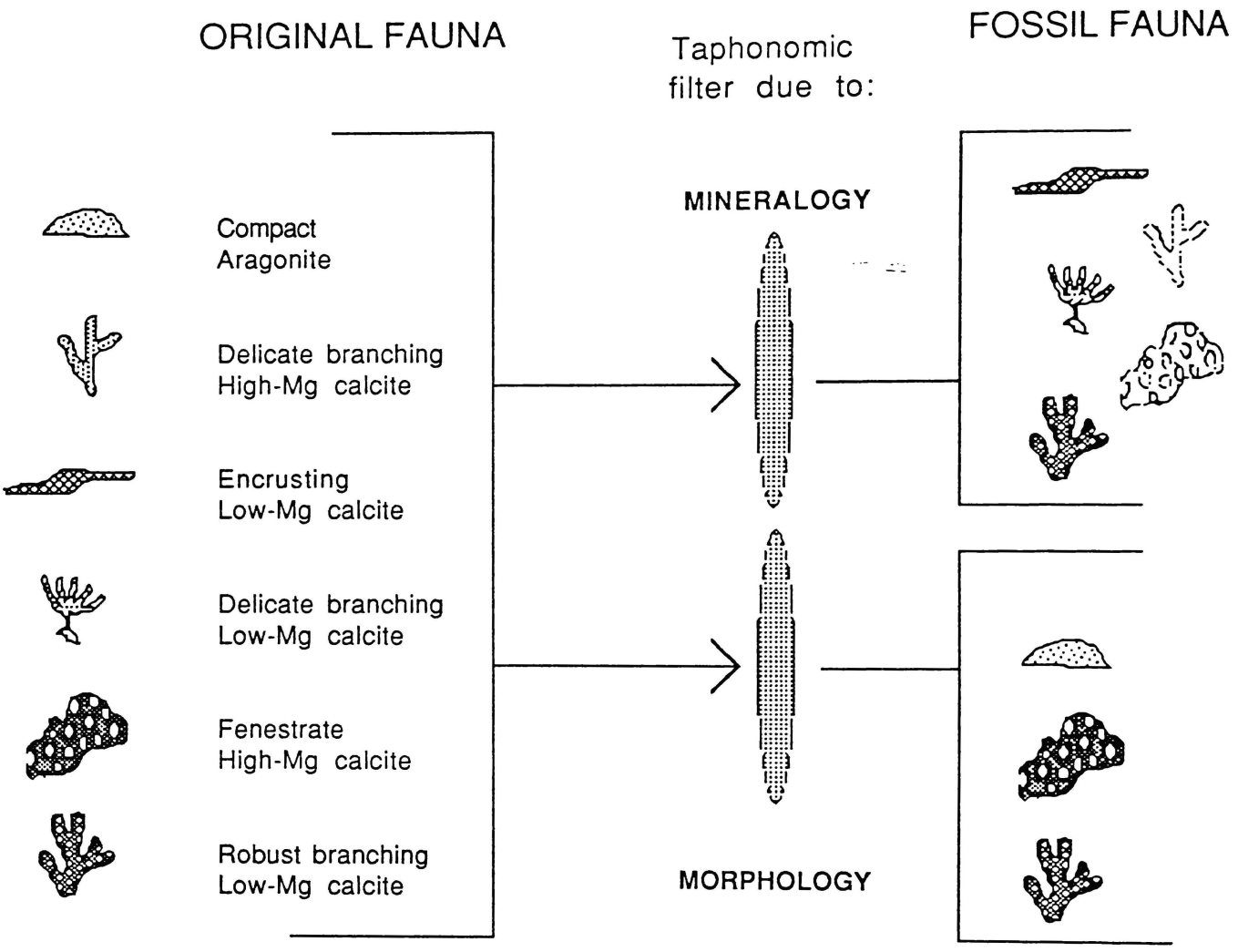


Figure 11D.3: Dissolution taphonomy. A theoretical fauna is preserved differently depending on the relative importance of mineralogy or morphology as a filter. Dashed outlines indicate Mg leached.

Table 11D.1: Factors influencing the preservation potential of bryozoan colonial growth forms.

Colonial growth form (Figure 1B.2)	Mineralogy (Figure 2B.34)	Morphology (Table 4D.1)	Energy of habitat (Figure 11D.2)	Resistance to abrasion (Figure 4B.6)
ENul	full range	planar	mod-high	mod
ENml	mod- to high-Mg C	compact	mod-high	low
EFde	high-Mg C	delicate	mod-high	low
EFar	mod-Mg C	delicate	mod-high	mod
EFrt	low- to mod-Mg C	robust	mod-high	mod
EFfo	high-Mg C	delicate	mod-high	low
FLmo	bimin, A	compact	low	high
FLrt	bimin, C	compact	low	high
ERra	low Mg C	delicate	?	low
ERde	low- to high-Mg C	delicate	low	mod
ERro	full range	robust	low	mod
ERfo	high-Mg C	planar	low	mod
ERma	low-Mg C	compact	?	mod
ERfe	low- to high-Mg C	robust	low-mod	high

Abbreviations: C - calcite; A - aragonite; bimin - bimineral; mod - moderate.

Aspects of the grains themselves determine the resistance to diagenetic factors (Table 11D.1). Mineralogy and morphology affect response to dissolution, whereas energy of habitat and physical strength affect response to abrasion. Habitat choice, age, and possibly morphology may play a role in response to bioerosion (although no experimental evidence is available for bryozoans).

Growth forms with the greatest resistance to abrasion (ERfe, FLmo) are not the most resistant to dissolution (ERma). Least resistant to dissolution are the aragonite or high-Mg calcite delicate forms (EFde, EFfo, ERde), whereas the least resistant to abrasion are erect flexible or multilaminar encrusting (ENml, EFde, EFfo). As different growth forms have different degrees of resistance to different diagenetic processes (and it seems reasonable to assume that bioerosion would affect assemblages in still another pattern, as yet unknown), the ultimate fossil assemblage will be different depending on which processes occur and their relative importance.

It is possible to model the effects of a highly destructive diagenetic regime on bryozoan faunas (Figure 11D.4). Abrasion, depending on level of hydraulic energy, would eliminate the least resistant forms (ENml, EFde, EFfo), and reduce articulated forms to fragments (EFar, EFrt). A high-energy environment would reduce all forms to fragments.

Dissolution of the abrasion-survivors has been divided into two parts. Sea-floor dissolution, taking place in (periodically) undersaturated sea water, is modelled here as being most affected by morphology; mineralogy affects longer-term diagenesis. This is a conscious simplification. The results are that most of the original fauna is destroyed. Low-energy environments retain the most, with ERfe and ERro forms retained, although reduced in Mg. Moderate-energy environments also keep ERfe, along with EFrt fragments. High-energy environments may retain very few fragments of EFrt.

Hydraulic regime	Low-energy (outer shelf, deep sea)	Moderate-energy (inner shelf)	High-energy (waves, strong currents)
Bryozoan assemblage	ERde ERfo ERfe ERro FLmo	EFde EFar EFrt ERfe ENul ENml	EFde EFfo EFar EFrt ENul ENml
Effect of abrasion	little	EFde lost EFar, EFrt fragments ENml -> mud	EFde, EFfo lost EFar, EFrt-> fragments ENml -> mud, lost ENul -> fragments
Assemblage after abrasion	ERde ERfo ERfe ERro FLmo	EFar, EFrt fragments ERfe ENul carbonate mud	EFar, EFrt fragments ENul fragments
Effect of sea-floor dissolution	ERde, ERfo lost	EFar fragments lost ENul lost carbonate mud lost	EFar, ENul fragments lost small fragments lost
Assemblage after sea-floor dissolution	ERfe ERro FLmo	EFrt fragments ERfe	large EFrt fragments
Effect of long-term dissolution	ERfe leached of Mg some ERro lost FLmo lost	ERfe leached of Mg	little effect
Assemblage available for lithification	ERfe ERro all low-Mg calcite	EFrt fragments ERfe	large EFrt fragments

Figure 11D.4: Interaction of dissolution and abrasion and their effects on preservation of bryozoan growth form assemblages.

One can look at fossil assemblages and make interpretations as to past environments based on relative depletion of certain growth forms. Conversely, the relative abundance of particular growth forms may argue against the grains having been subject to certain diagenetic processes. This paleoenvironemental interpretation is complex, especially since bioerosion is an important process in temperate carbonates, yet its effect on bryozoans is not well known.

3. Bryozoans in limestone

Are the taphonomic processes described above actually operating in real limestones? Is there any evidence of the sort of fossil assemblages predicted by simple models? Numerous bryozoan fossil faunas have been described, and some of these will be used as examples in beginning to answer these questions.

There are some overall trends in growth-form abundances over time. The fossil record does not correlate particularly well with modern assemblages (Figure 11D.5). Some changes may be due to evolution of forms over time. Other differences are more abrupt: the dominantly encrusting bryozoan faunas of the Cenozoic contrast sharply with earlier faunas which were dominantly erect forms (McKinney and Jackson, 1989).

Uniserial encrusting growth forms occur far less commonly in fossil assemblages than in living ones, an observation attributed by McKinney and Jackson (1989, p. 89) to "problems of preservation of their weakly calcified skeletons." No doubt a similar effect is seen with other weakly calcified forms (EFde and EFfo). Modern living faunas tend to be about 70% encrusting species, irrespective of depth (Gordon, 1987). In contrast, encrusters make up only about 50% of Mesozoic fossil bryozoans, and generally less than 20% of Paleozoic bryozoan faunas. Some of this variability is due to evolutionary change in bryozoans over time (e.g., Lidgard and Jackson, 1989), and some perhaps to living distribution (Lidgard, 1990). How much is due to these biological factors and how much to diagenesis is impossible to determine.

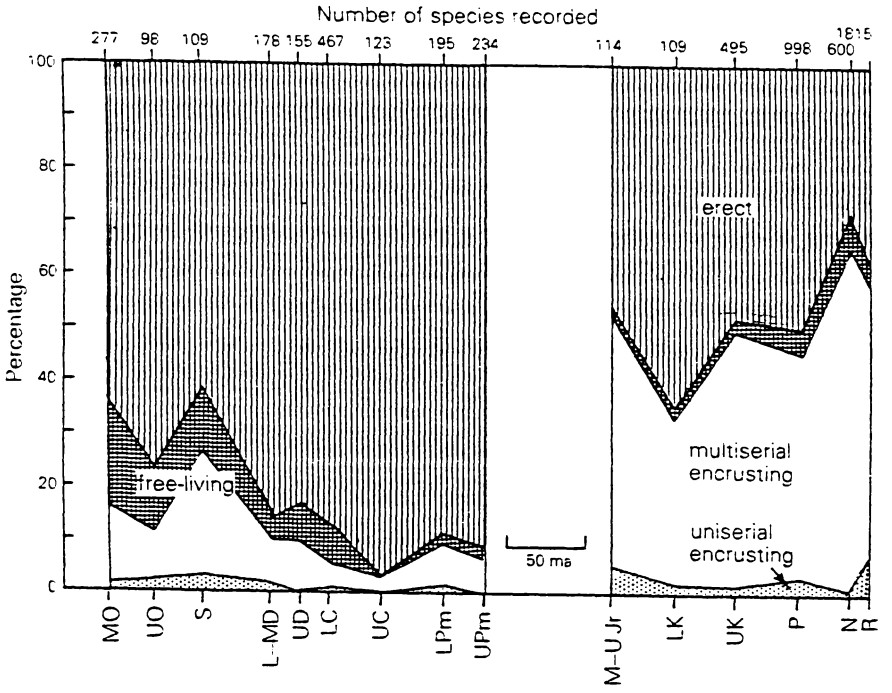


Figure 11D.5: Abundance of growth forms in fossil and Recent faunas (McKinney and Jackson, 1989, figure 4.18).

Abbreviations (in order of age) :
O - Ordovician; S - Silurian; D - Devonian; C - Carboniferous; Pm - Permian; Jr - Jurassic; K - Cretaceous; P - Paleogene; N - Neogene; R - Recent. L - Lower; M - Middle; U - Upper.

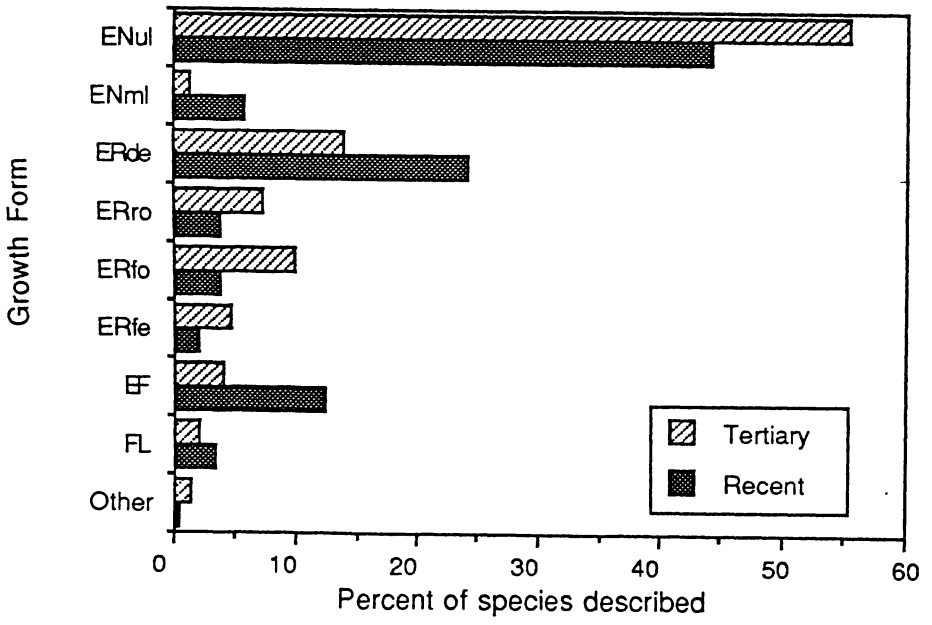


Figure 11D.6: Comparison of growth forms described in Recent (Gordon, 1984, 1986, 1989) and Tertiary (Brown, 1952) New Zealand bryozoan faunas.

Comparing bryozoan species from New Zealand Recent and Tertiary collections is instructive (Figure 11D.6). Unilaminar encrusting forms are the most common in both Recent and Tertiary faunas, but they are proportionately rather less abundant in the Recent examples. Other growth forms that show this pattern are erect robust, foliose, and fenestrate. In contrast, erect delicate forms are much less common in the Tertiary fauna, as are erect flexible and, to a lesser degree, multilaminar and free-living forms. This may indicate that in New Zealand some delicate branching species in particular are disappearing from the fossil record, whereas encrusting species generally are not. While evolutionary or environmental controls may be involved, it is also possible that these changes are due to dissolution.

The abundant bryozoan component in the nontropical Oligocene-Miocene bryomol limestones from New Zealand (Nelson, 1978) provides some further evidence of possible faunal filtering. First, the huge dominance of encrusting unilaminar forms recorded in Recent and Tertiary collections generally (Figure 11D.6; see also Gordon, 1987) is not reflected in any of these limestones (Nelson et al., 1988a), possibly because of preferential abrasive or bioerosive destruction of such growth forms. Second, in the typical bryozoan-dominated limestones, exemplified by the Takaka Limestone of northern South Island, New Zealand, or the Otorohanga and Orahiri Limestones of western North Island, New Zealand, erect delicate branching species are seldom the overall dominant growth form as they are in their modern counterpart carbonate deposits off northern and southern New Zealand (Nelson et al., 1988a). Original environmental differences may again explain the situation, but selective dissolution of more delicate species also remains a possibility. Other evidence of dissolution (e.g., absence of aragonitic skeletons, including free-living bryozoans) is found in the western North Island Te Kuiti Group (Nelson et al., 1988a).

A mid-Miocene limestone from North Cape, New Zealand, also may contain evidence of dissolution. Interpretation of fauna indicates a shallow subtidal (20-30m), high-energy environment. Encrusting forms are most common, followed by erect flexible, while

erect rigid faunas are least common (Leitch et al., 1969). This is what one would expect in a high-energy, abraded faunal assemblage (e.g., Figure 11D.4). The presence of delicate forms implies that sea-floor dissolution is unlikely, but the absence of any aragonitic species (intepreted from modern species of the same genera or families) may indicate longer-term diagenesis did occur. The lack of free-living forms has been interpreted to mean that the environment was in shallow water (Leitch et al., 1969). Modern free-living forms may be found in great abundance (over 15,000 colonies/m^2 according to McKinney and Jackson, 1989) below 20 m, so an equally plausible explanation may be the selective dissolution of the aragonitic FL growth forms.

In contrast, the bryozoan fauna of the Tertiary southern Australian Abrakurrie limestone is dominantly erect rigid delicate forms, with subdominant occurrences of multilaminar encrusters and other erect rigid forms (James and Bone, 1991). ERde forms vastly outnumber other forms in three different lithologic units, varying in inferred water depth from 70 to 200 m. The unit from which ERde is absent is considered a high-energy one, and contains ERfo, ERfe, and ERro forms. What explains this huge dominance of erect forms over encrusting forms? Part of the answer is clearly the paleo-depth; ENul is not common on the deep shelf. Abrasion has been proposed to be important during low-stands of sea level, and dissolution may be indicated by the rare occurrence of free-living forms. Perhaps aragonitic species have been dissolved during subaerial diagenesis.

A rather cursory examination of the fossil record indeed provides some evidence for early sea-floor diagenetic processes destroying some part of the original bryozoan fauna. The taphonomic selectivity of abrasion and dissolution is different, and each has discernibly different effects on the fossil record. Fossil bryozoan faunas can be interpreted to indicate what diagenetic processes have been most active, and to some extent this provides insight into what the original bryozoan fauna may have been.

Chapter 12 Mixed Carbonate-Clastic Sediments

"The seas roll over but the rocks remain."

A.P. Herbert, Tough at the Top, 1949

A. INTRODUCTION

It has long been sedimentological dogma that siliciclastic terrigenous sedimentation is incompatible with marine carbonate sedimentation. Texts discussing sedimentary environments (e.g., Reading, 1986) traditionally separate siliciclastic shelf sediments from carbonate shelves, as do sedimentologists. At first this appears sensible, as many carbonate-producing organisms are highly sensitive to particulate matter in the water column.

In the 1980s, however, it became increasingly clear that some mixing of clastic and carbonate sediments has occurred in the past and is occurring now. Symposia on the subject (McIlreath and Ginsburg, 1982; Doyle and Roberts, 1983) led to a very useful synthesis of world-wide evidence (Mount, 1984), followed by increased interest in carbonate-clastic mixtures, leading to publication of two important volumes on the subject (Doyle and Roberts, 1988; Budd and Harris, 1990). There is thus a considerable body of information available on carbonate-clastic mixtures or transitions, as Doyle and Roberts (1988) refer to them.

It is important to note that terrigenous siliciclastic sediments are fundamentally different in nearly every aspect from biogenic carbonate sediments (Table 12A.1). The physical attributes of the sediments differ, including density and chemical composition. The mode of delivery to the sea is very different; terrigenous sediments are mainly delivered by fresh-water rivers to single point sources into the shelf system while biogenic sediments are precipitated *in situ* across their whole deposit. Biogenic sediment supply and distribution are controlled mainly by the productivity and distribution of precipitating organisms, and environment of deposition is a secondary

Table 12A.1: Comparison of clastic and carbonate shelf sediments.
(Compiled from: Johnson and Baldwin, 1986; Sellwood, 1986; Hay et al., 1988).

Aspect	Clastic shelf sediments	Carbonate shelf sediments
Composition of sediment	Highly varied Mainly silicates	Very little variation Almost always $CaCO_3$
Controls on composition	Source rock	Sea-water chemistry Organisms present
Mechanism of entry into sea	Fluvial transport	In situ precipitation from solution in sea water
Location of entry in sea	Point sources along shelf	Deposited simultaneously over entire area
Controls on sediment supply	Elevation of source area Continental climate	Organisms present Sea-water temperature
Controls on sediment distribution	Shelf hydraulic regime Sea-level fluctuations Bioturbation	Organisms present Sea-water chemistry Sea-water temperature Depth (light)
Typical facies	Shelf relict sand Nearshore modern sand Modern shelf mud blanket	Chlorozoan Foramol Bryomol
Typical rate of accumulation	Relatively rapid at point source	Relatively slow 1 mm/y

factor (Sellwood, 1986). Terrigenous sediment supply is controlled by the regional climate (erosion rate) and by land elevation. Terrigenous sediment distribution is determined mainly by hydraulic regime (Johnson and Baldwin, 1986). The source of supply and distribution controls are so different between the two types of sediment that their distribution may be almost unrelated. Sediments made up of both may have misleading characteristics (e.g., mean grain size) because of this mixing of quite unrelated materials (e.g., Nelson, 1977).

Each type of sediment, however, may limit the possibility of accumulation of the other type. Terrigenous sediment inhibits carbonate production in four ways. Fresh-water input at river mouths, large volumes of sediment in suspension, turbulence, and episodic high mechanical abrasion (floods) are all likely to limit the productivity of carbonate-producing organisms (Santisteban and Taberner, 1988). Carbonate shelves, in turn, may limit terrigenous deposition by a build-up shallowing the shelf; or channels in the carbonate may allow terrigenous sediment to bypass the shelf (Hay et al., 1988). In some cases, terrigenous and biogenic sediments may be incompatible, or at least would have sharp facies transitions.

How then do we explain the many examples of mixed clastic and carbonate deposits found in the rock record and in modern sediments? Living reefs have been found in areas of active terrigenous sedimentation (e.g., Friedman, 1988). Neogene siliciclastic deposits may contain oyster banks (Friedman, 1988). Some deltaic sediments appear to have reefs as integral components (Santisteban and Taberner, 1988). Well over 150 carbonate-clastic mixtures have been described (Mount, 1984). Since they obviously exist, explanations for carbonate-clastic mixtures are required.

Mount (1984) devised four mechanisms by which carbonate-clastic mixing could occur on shelves (Figure 12A.1): facies mixing, source mixing, punctuated mixing, and *in situ* mixing.

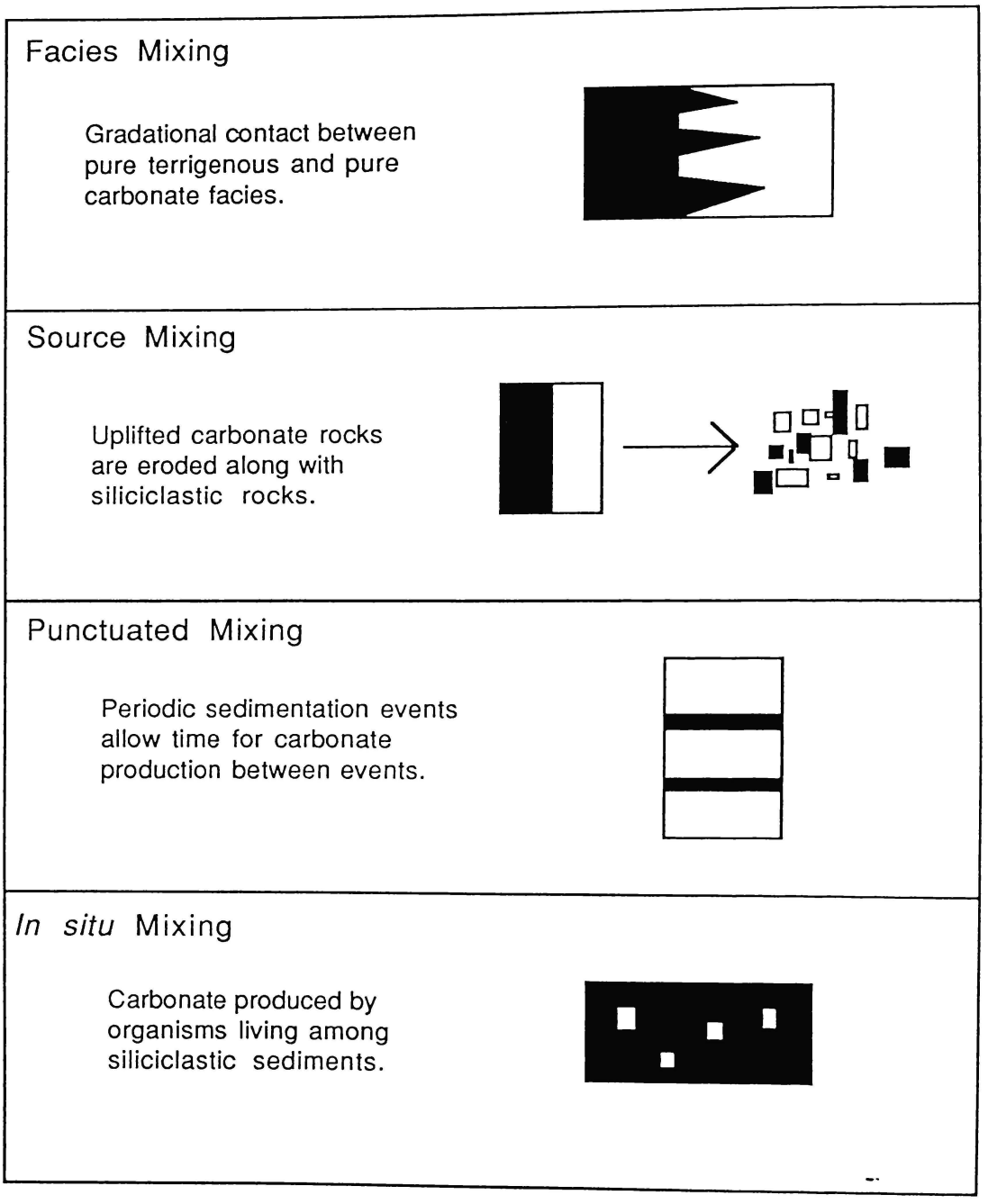


Figure 12A.1: Four mechanisms for producing clastic-carbonate mixtures in shelf sediments (after Mount, 1984). Black indicates terrigenous sediment, white indicates biogenic carbonate.

Facies mixing (a gradational contact between purely carbonate and purely clastic deposits) is rare, as generally these contacts are sharp (Mount, 1984). Source mixing, in which uplifted carbonate rocks are eroded along with silicate rocks, is another possible mechanism, requiring tectonic activity and appropriate source rocks.

In some environments, terrigenous sedimentation is periodic (e.g., linked to storms) and the intervals between sedimentation events are long enough to allow carbonate production to develop. Rapid recovery after each event is possible because the organisms involved are normally healthy and non-stressed by sediment. This is defined by Mount (1984) as punctuated mixing. The reefs developing in terrigenous environments referred to above are all contributing to this mixing mechanism - they only survive among the clastic material because it is episodic.

Related to this is what may be termed "bypass mixing," in which carbonate sediments are produced only where the local hydraulic regime removes or diverts terrigenous sediment supply (e.g., Java Sea, Friedman, 1988).

The mixture of allochthonous (modern, palimpsest, or relict) terrigenous material with autochthonous biogenic carbonate is called *in situ* mixing. It occurs in subtidal muds and, according to Mount (1984), most often includes the foramol carbonate-producing assemblage. It is this type of carbonate-clastic mixing that predominates in New Zealand shelf sediments (including the Hauraki Gulf) and thus will be mainly discussed below.

B. *IN SITU* MIXING

Facies mixing, source mixing, and punctuated mixing all result in carbonate-clastic deposits due to some spatial or temporal offsetting of the two modes of sedimentation. None of them involve carbonate sediments and clastic sediments accumulating in the same place at the same time. Only *in situ* mixing involves true syndepositional mixing.

It is commonly argued that terrigenous sedimentation inhibits carbonate production (e.g., Chafetz et al., 1986). Certainly this makes sense ecologically. Photosynthetic organisms (algae, zooxanthellae in corals) function less well under turbid conditions in which light may be limited. Consumers of primary producers (including foraminifera and some molluscs) will then have a reduced food supply. Filter-feeding organisms (corals, bryozoans, many molluscs, barnacles) may experience clogging or starvation due to feeding on nutrient-free suspended sediment. The effect of destroying lower trophic levels will eventually be felt by carnivores (crabs, fish). Deposit feeders may be less sensitive to sedimentation, but in general they are not major carbonate producers (e.g., holothurians).

Despite this intuitively reasonable scenario, carbonate is being produced in terrigenous settings all over the world. From a selection of *in situ* mixtures (Table 12B.1), generalizations can be drawn.

There are two ways in which carbonate production is overcoming the effect of terrigenous sedimentation: a sufficiently low rate of terrigenous supply, and disequilibrium. Low sedimentation rates may be due to local bathymetry (i.e., a trough between the shelf area and land collects sediment, as in Scoffin and Bowes, 1988), or terrigenous sediment may be removed from suspension rapidly by sediment baffles such as sea grass beds (Weiss et al., 1978), or sediment input may be small due to climate (Nittrouer et al., 1988).

Shelves may be in disequilibrium. Coral reefs may be remnants of a past regime with lower terrigenous input, and be in the process of dying off (Morelock et al., 1983). Conversely, terrigenous sediment may be relict and modern carbonate production will eventually swamp the palimpsest terrigenous sediments (Collins, 1988).

Thus the conflict between a geological observation, that carbonates may form in terrigenous settings, and a basic biological fact, that fine sediments may kill carbonate-

Table 12B.1: Several examples of *in situ* mixing in modern sediments.

Source	Location	Environment	Carbonate sediments	Clastic sediments	Comments
Scoffin and Bowes 1988	W. Ireland Atlantic 52°N	cold temperate bank	5-90% foramol	boulders, sand or mud relict glacial	physiography prevents modern terrigenous sedimentation
Nittrouer et al. 1988	E. Spain Mediterranean 40°N	warm temperate sheltered	40% foramol high productivity	60% sandy mud low input	
Frey and Pinet 1978	Georgia, USA Atlantic 31°N	warm temperate low energy	bryomol high production	coarse sand low/episodic	some reworking
Morelock et al. 1983	W. Puerto Rico Caribbean 18°N	tropical	coral reefs chlorozoan on bathymetric highs	mud and sandy mud low input	modern agricultural practices increasing terrigenous runoff reefs becoming smothered
Weiss et al. 1978	E. Venezuela Atlantic 11°N	tropical well circulated clear water	20-90% chlorozoan	sandy mud alluvial in bathymetric lows	trapping by seagrass beds means little in suspension
Collins 1988	W. Australia Indian 32°S	warm temperate wave-dominated shelf	25-95% bryomol with rhodophytes	relict silicates 5 cm/ky	rapid transgression
Fleming 1977	E. South Africa Atlantic 33°S	arid subtropical tidal flat low energy	5-40% foramol	eroded dunes very low input	

producing organisms, is explained by sufficiently low terrigenous supply, or by a shelf in the process of adjusting to modern conditions.

"An overall impression we have is that the *carbonate factory* was always ready to produce the instant the *sand machine* ran down a little, but commonly the two fought to a stand off and produced mixed lithologies" (Dott and Byers, 1981, p. 330).

In situ mixing has been reported from tropical and temperate shelf sediments, with carbonate contents ranging from 5 to 95%. Tropical mixing is less common in the literature, and tends to be in disequilibrium. This is not surprising, as corals making up tropical carbonates are particularly sensitive to turbidity, being both filter-feeders and photosynthetic (symbiotically). Many temperate carbonates, however, are mixed. Indeed it is one of the common aspects of temperate carbonate deposits that they are seldom 100% $CaCO_3$ (Nelson, 1988b). This may reflect higher tolerance of low levels of terrigenous sedimentation on the part of temperate organisms.

A simple model of shelf sedimentation, then, might be a line with terrigenous and carbonate sediments as its two end members. The addition of carbonate assemblages to the carbonate end would result in a triangular pyramid, the apex representing purely terrigenous sediments and the triangular base representing different carbonate assemblages (Figure 12B.1). One vertex of the base represents the common tropical chlorozoan assemblage, while the opposite edge contains the temperate assemblages of foramol and bryomol. Thus any shelf sediment can be placed within this shape based on its skeletal carbonate assemblage and the relative proportion of clastic to carbonate material.

It was Lees and Buller (1972) who first proposed the chlorozoan (corals and green algae dominant) and foramol (foraminifera and molluscs dominant) categories as being the major carbonate assemblages in marine shelf sediments. Nelson et al. (1988b) added bryomol (bryozoans and molluscs dominant) to this nomenclature, noting that many

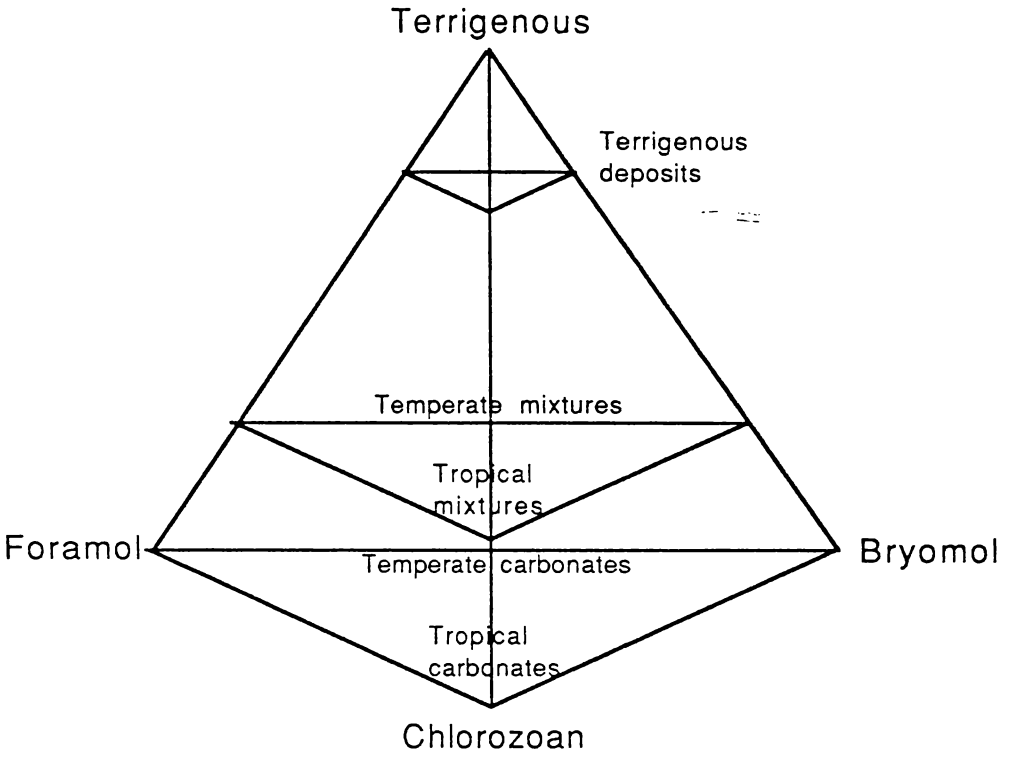


Figure 12B.1: Conceptual framework for the carbonate-clastic transition in temperate and tropical climates.

temperate carbonates were bryozoan-dominated. A survey of the literature (see Appendix Table A10.1) shows that in some cases, molluscs alone dominate the carbonate fraction (e.g., Askelsson, 1974). Thus temperate carbonates have three possible assemblages (Figure 12B.2). Although temperature (as approximated by latitude) appears not to be a factor in determining carbonate assemblage (as it is in chlorozoan sediments), degree of terrigenous input does (Figure 12B.3). Foramol and mollusc sediments occur in deposits with relatively high proportions of terrigenous material (20-80%), whereas bryomol sediments are limited to the high carbonate sediments (less than 20% terrigenous). This may indicate a higher tolerance to particulates on the part of foraminifera and molluscs than bryozoans.

C. NEW ZEALAND CARBONATE SEDIMENTS

The New Zealand shelf is dominantly terrigenous, not surprising given the land's youthful topography and wet climate (Carter, 1975). Fluvial sediment input on the New Zealand shelf totals some 300 million m^3/y (Kamp and Nelson, 1988). In some areas, however, where terrigenous supply is lowest (mainly located in a backarc setting) carbonate does accumulate. There are five main locations of carbonate deposition on the New Zealand shelf (Figure 12C.1, Table 12C.1). The extensive carbonates in the north (Three Kings and Wanganui) are mainly bryomol, but in the southern deposits (Snares and Otago), a mixed foramol-bryomol assemblage is found. Hauraki Gulf is mainly mollusc (Figure 12C.2).

Analysis of data from Head (1985) shows foramol sediments at Snares to be more characteristic of low carbonate areas than bryomol sediments (Figure 12C.3). This supports the more general finding in the literature, that bryomol sediments are associated with higher carbonate deposits. In fact, a highly terrigenous New Zealand carbonate (5 to 60% $CaCO_3$) deposit on the Kaipara shelf is wholly foramol (Keane, 1986).

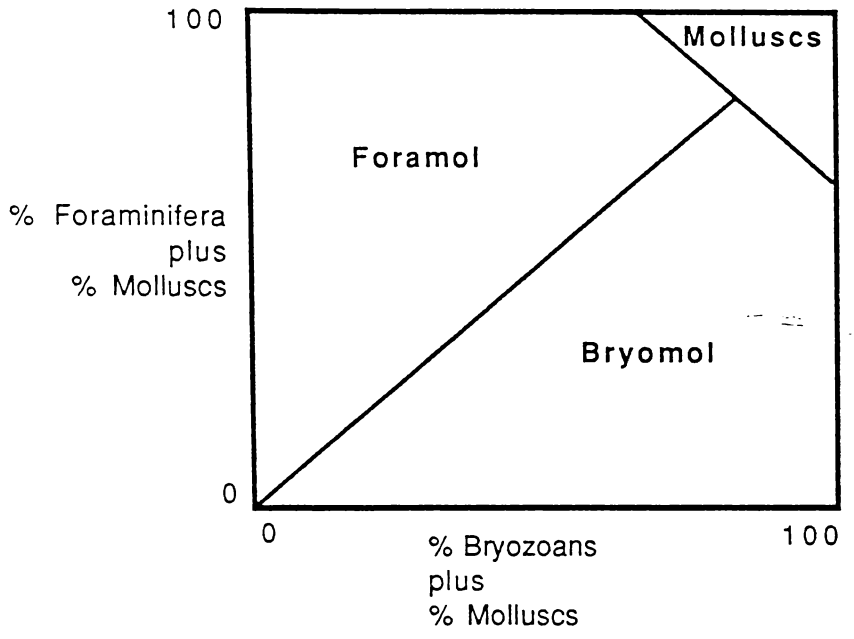


Figure 12B.2: Temperate skeletal carbonate assemblages.

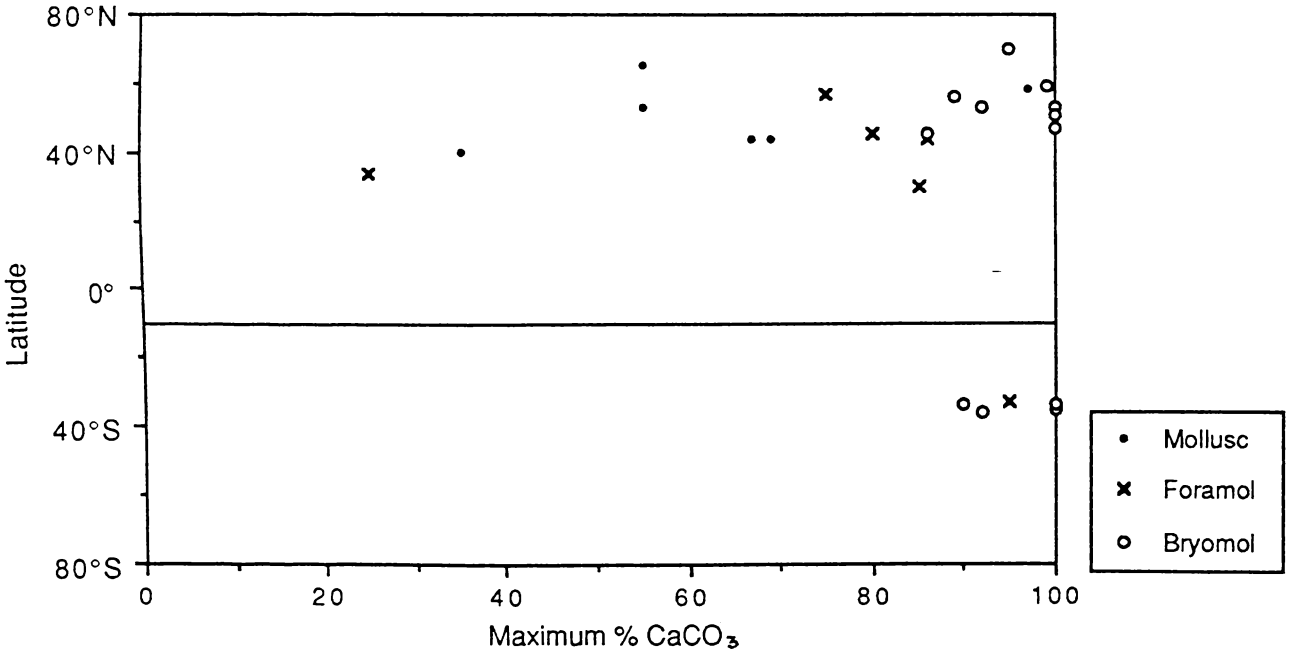


Figure 12B.3: Latitude and % carbonate of temperate assemblages. Data from literature summarized in Appendix Table A10.1.

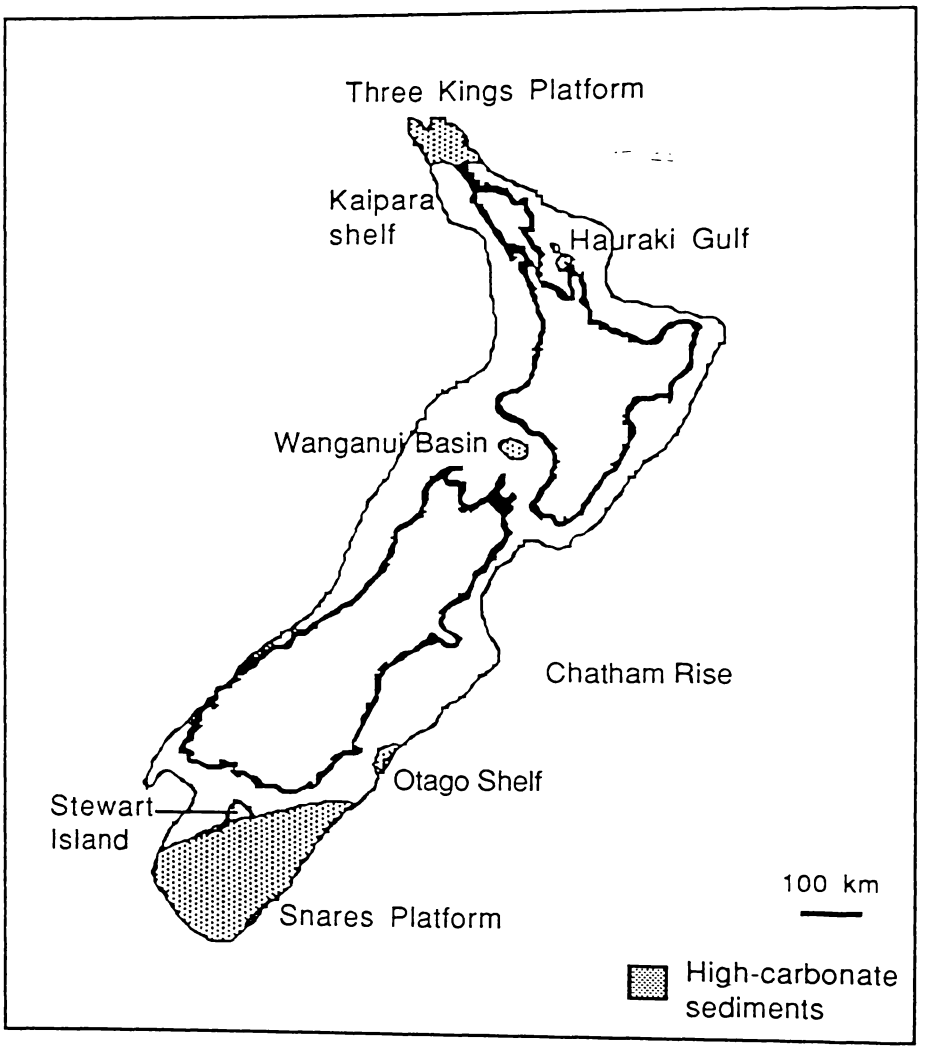


Figure 12C.1: New Zealand shelf areas (after Nelson et al., 1988b, figure 1). Shelf break is shown at about 200 m water depth.

Table 12C.1: Examples of New Zealand carbonate sediments.

Source	Location	Environment	Carbonate sediments	Clastic sediments	Comments
Nelson et al. 1988b	Three Kings Platform 34°S	cool temperate platform	50-100% bryomol	mainly lithic clasts very low input	terrigenous sediments excluded by bathymetry
This study	Hauraki Gulf 36°S	cool temperate sheltered gulf	11-93% bryomol patchy	muddy sand local erosion	carbonate may be hydraulically winnowed
Gillespie in prep.	Wanganui Basin 40°S	cool temperate open shelf	5-90% bryomol	volcanogenic clasts muddy sand	mid shelf receives little terrigenous input
Andrews 1973	outer Otago Shelf 46°S	cold temperate open shelf	40-95% bryomol, foramol many relict	muddy sand local erosion	carbonates concentrated on outer shelf, away from terrigenous source
Head 1985	Snares Platform 48°S	cold temperate platform	40-90% bryomol, foramol	local erosion silicates	platform receives little terrigenous input

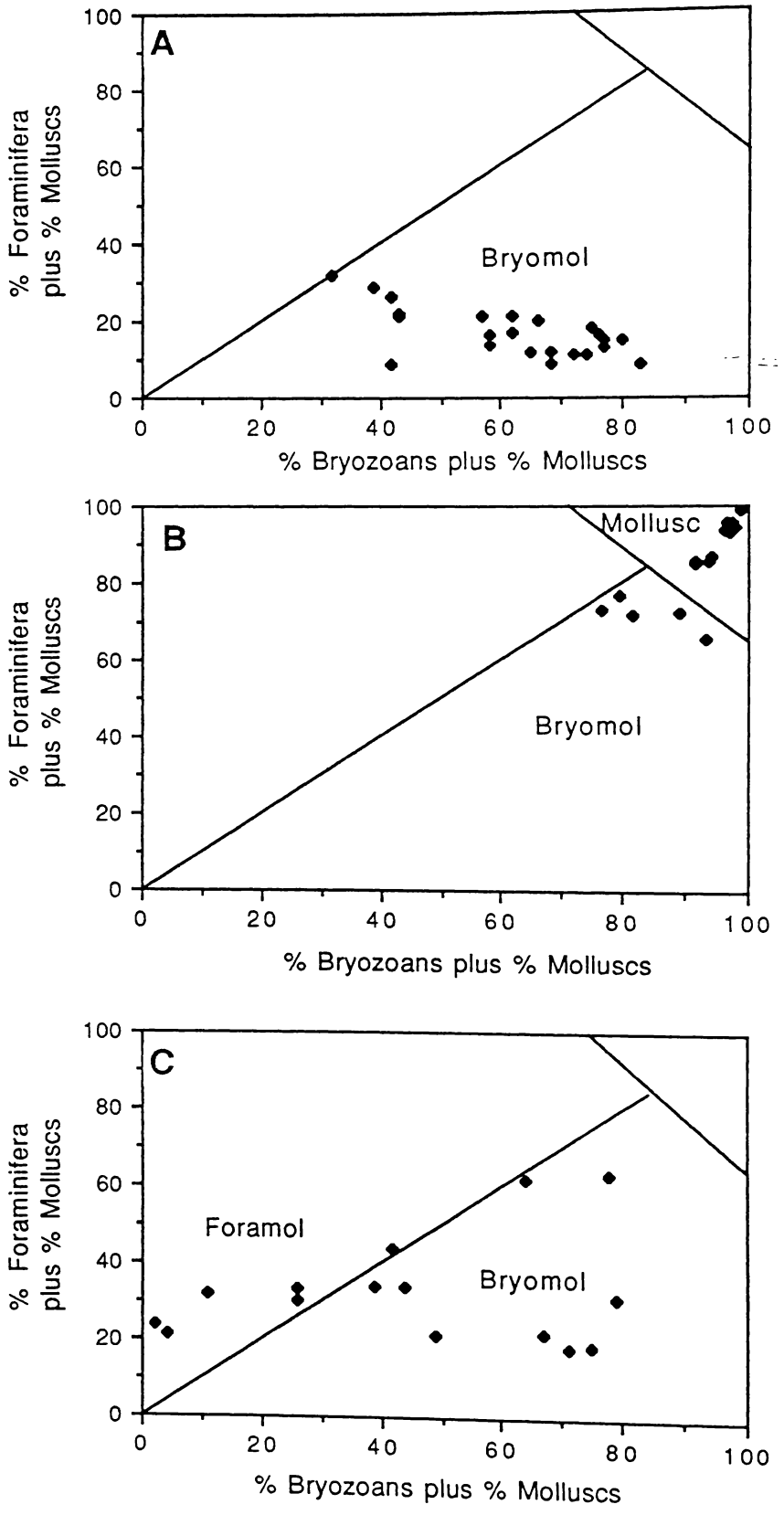


Figure 12C.2: Carbonate assemblages in some New Zealand sediments. A - South Maria Ridge, Three Kings Platform. B - High-carbonate patches, Hauraki Gulf. C - Western Stewart Island, Snares Platform.

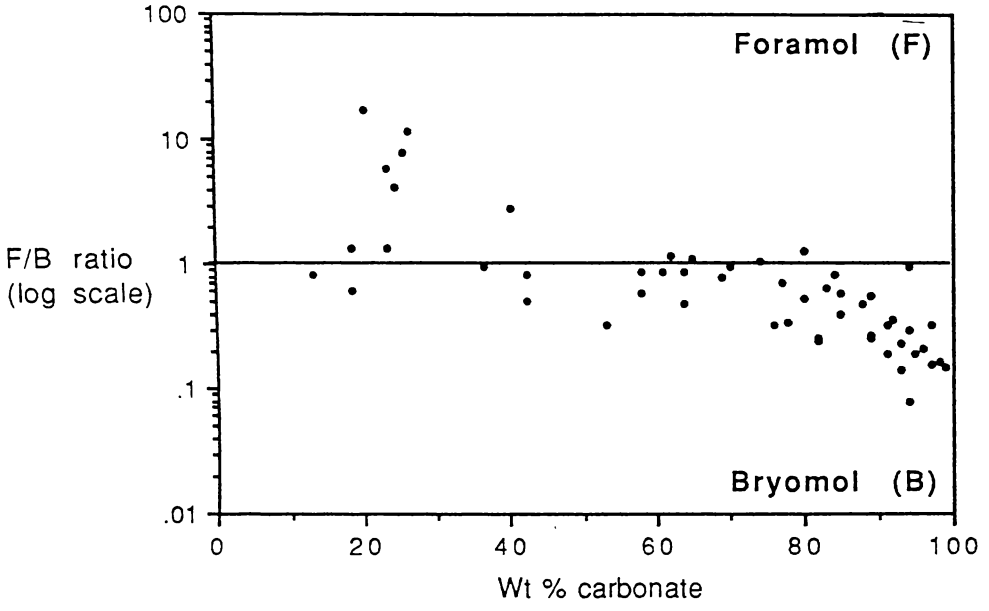


Figure 12C.3: Association between carbonate assemblage and degree of terrigenous mixing in sediments from Snares Platform (data from Head, 1985). F/B ratio is wt% foraminifera/wt% bryozoans.

Two possible reasons may be put forward for this association of carbonate assemblage with terrigenous input. Carbonate-producing organisms in the foramol assemblage may be more tolerant of terrigenous sedimentation than those in the bryomol. Bryozoans are suspension-feeders, thus rather vulnerable to suspended load, whereas foraminifera are either bottom-grazers or predators of plankton. Alternatively, carbonate production by foraminifera may be slower than that of bryozoans, and therefore the foraminiferal assemblage would not keep pace with terrigenous sedimentation as effectively as the bryomol assemblage. Bryozoan carbonate production is poorly known (cf. Chapter 1, Section D) but thought to be rather slow. Foraminiferal production depends in large part on the density of the population, and thus the productivity of the water column. This theory is a difficult one to test.

New Zealand shelf carbonate sediments are typical of temperate carbonates in that they are often mixed with terrigenous material, and show typical temperate carbonate assemblages. They have quite a variety of assemblages, including the foramol, the bryomol, and the mollusc assemblages. Assemblage may be related to the degree of terrigenous dilution. In contrast, terrigenous content depends on the source rock being eroded on land. New Zealand shelf sediments all plot on the temperate side of the triangular pyramid (Figure 12C.4).

D. *IN SITU* MIXING IN THE ROCK RECORD

The recognition of a process or facies in modern sediments does not necessarily mean that it is found in the rock record, nor if it is, that it is due to processes similar to modern ones. The application of the modern to the ancient, nevertheless, is the primary goal of sedimentologists describing modern processes. Are there examples of *in situ* mixing in ancient sediments?

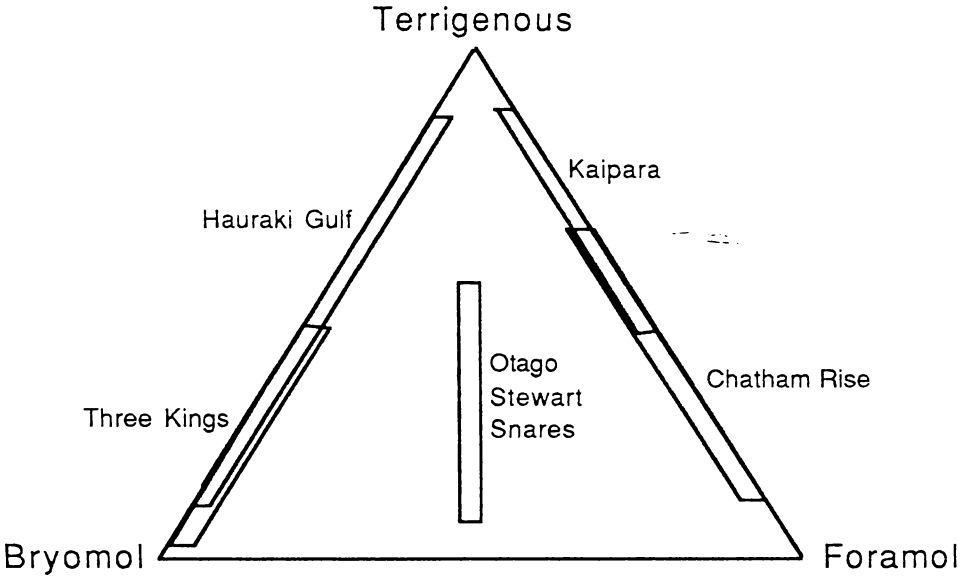


Figure 12C.4: Distribution of New Zealand shelf carbonate sediments on one face of the pyramid given in Figure 12B.1.

Certainly there are carbonate-clastic mixtures. In Table 12D.1, several examples of what may be *in situ* mixtures have been listed from the Proterozoic to the Neogene. As in modern sediments, low terrigenous supply (Brookfield, 1988) or disequilibrium (Beukes, 1977; Button and Vos, 1977) seems to be associated with *in situ* mixing.

New Zealand limestones (Nelson, 1978; Kamp et al., 1988; Nelson and Kamp, 1988) have a wide range of carbonate contents. The terrigenous muds, sands, and gravels are derived from local erosion. Carbonate is mainly skeletal and dominantly of the bryomol assemblage. Hauraki Gulf sediments, if lithified, might be similar to some of the more terrigenous units of the New Zealand Cenozoic. If a sufficient sea-level rise were to occur to limit terrigenous input, the imagined Hauraki Deposit would grade upward into a true limestone, possibly with more and more bryozoans in the assemblages as water depth increased and terrigenous input decreased. It would then strongly resemble some of the Oligocene limestones described by Nelson (1978).

In a different scenario, in which carbonate sedimentation continues to be of minor importance, with terrigenous input high, the Hauraki Deposit would be more like the Redwater Shale in the Sundance Formation of Wyoming and Montana, U.S.A. (Brenner and Davis, 1973; Specht and Brenner, 1979). The Redwater Shale represents the transition between dominantly carbonate deposition and dominantly terrigenous deposition in North America (Specht and Brenner, 1979). Although the Upper Jurassic epicontinental sea was less enclosed than the Hauraki Gulf is, it had similar features (Table 12D.2), being normally of low energy, but occasionally subject to strong storms. Bivalves are by far the most common skeletal component.

In both the Redwater Shale and in the modern Hauraki Gulf, terrigenous muddy sands are deposited at the same time that sediment-tolerant bivalves are precipitating carbonate. Post-depositional winnowing by tidal currents or storm waves results in coarse shell deposits, particularly on topographic highs. The distribution of these shell deposits is highly variable. They are patchy, almost random, in distribution, sometimes

Table 12D.1: Examples of carbonate-clastic mixtures in ancient sediments.

Source	Location	Age	Carbonate deposits	Clastic deposits	Comments
Beukes 1977	Schmidtsdrift Fmn Pretoria Group	Lower Proterozoic	stromatolites algae	quartz arenites mudstones	macrotidal rapid transgression
Button and Vos 1977	Transvaal Supergroup South Africa		up to 75% carbonate		slow regression
Brookfield 1988	Black River and Trenton Limestones S. Ontario, Canada	Ordovician 15°S paleolatitude	bryozoans, brachiopods crinoids (rare inorganic)	4-40% clay	sed rate <0.015 mm/y boring, cementation, carbonate mud
Sadd 1991	Buckhorn Asphalt Deese Group Oklahoma, USA	Mid Carboniferous 10°S paleolatitude	thin, discontinuous molluscs dominant otherwise chlorozoan	coastal lagoon alluvial	low energy shallow marine
Draper 1988	Bowen Basin limestones E. Australia	Permian 60°S paleolatitude	crinoids, bryozoans, bivalves, brachiopods no non skeletals	rare to common marine siliciclastic silt-mud stones	boring, encrustation, loss of aragonite, micritization
Brenner and Davis 1973 Specht and Brenner 1979	Sundance Fmn Wyoming, USA	Upper Jurassic	bivalve, crinoid found on topographic highs (winnowed)	mud matrix quartzose sands	bioerosion important aragonite dissolved out storm-generated lags
Nelson 1978	Cenozoic limestones New Zealand	Oligocene 45°S paleolatitude	bryomol wide range of carb. content	mud and sand stones nearshore or slope	bioerosion, cementation 0.1 - 0.2 mm/y
Kamp et al. 1988	Te Aute Limestone E. North Island New Zealand	Pliocene 38°S paleolatitude	barnacle, mollusc, bryozoan (no non-skeletal) on tops of anticlines	mudstones, matrix lithic clasts	abrasion, transport strong tidal currents up to 1 mm/y

Table 12D.2: Comparison of Hauraki Gulf sediments with New Zealand Cenozoic limestones, and with the Redwater Shale of Wyoming and Montana, U.S.A.

Aspect	Hauraki Gulf, Modern (This study)	New Zealand, Cenozoic (Nelson, 1978)	Redwater Shale, Upper Jurassic (Specht and Brenner, 1979)
Location	N. New Zealand	New Zealand	Wyoming and Montana, USA
Climate	Cool temperate	Cool to warm temperate	
Environment	Semi-enclosed sea	Shallow marine	Shallow epicontinental sea
Hydraulic Regime	Strong tidal currents	Open sea	Open, low energy, strong storms
Latitude	36°S	35°S - 60°S	
Terrigenous sediments			
Composition	Clay minerals, quartz sands	Variable	Quartz, clay minerals
Texture	Muds, sands	Muds, sands, gravels	Muds, sands
Structures			Bars
Source	Local erosion, fluvial transport	Local erosion, fluvial tranport	
Carbonate sediments	10-95%	50-100%	30-100%
Dominant skeletal	Bivalves	Bryozoans, bivalves	Bivalves
Subdominant skeletal	Gastropods, bryozoans, barnacles	Barnacles, brachiopods, forams	Crinoids, brachiopods, belemnites
Non-skeletal grains	None	Few pellets	Some ooids, pellets
Texture	Gravels, sands	Gravels, sands, muds	Coarse
Structures	None	Rare oyster banks	
Mineralogy	Mixed low-Mg calcite/aragonite	Mainly high-Mg calcite	
Diagenesis			
Abrasion	No evidence	Evidence present	Little evidence
Bioerosion	Extensive	Evidence present	Common to extensive
Dissolution	No evidence	Skeletal aragonite dissolved	Skeletal aragonite dissolved
Cementation	None	Intergranular solution	Some
Cement mineralogy		Calcite or ferroan calcite	Ferroan calcite
Authigenesis	None	Glauconite common	Glauconite very common
Rate of Sedimentation		0.01-0.02 mm/y	Slow
Comments	Carbonates on topographic highs, may have been winnowed		Carbonates in sheets or shoestrings Storm, swell or channel lag deposits

with abrupt contacts. They may be quite thin, or up to 10s of cm thick, forming shoestring or sheet-like deposits. At times when shell material is exposed at the surface, bioerosion takes place. The resulting rock unit is thus dominantly terrigenous, and indeed the Redwater Shale has been mainly studied as a siliciclastic deposit. The carbonate shoestrings or sheets seem to be aberrations until one considers the importance of *in situ* mixing, and subsequent redistribution by strong hydraulic elements.

It appears, then, that sediments in the Hauraki Gulf could become progressively more calcareous, until they resemble a typical New Zealand limestone (as in Nelson, 1978). Alternatively, they could continue to be dominantly terrigenous deposits, lithifying as a siliciclastic rock with carbonate stringers or lenses, like the Redwater Shale (as in Specht and Brenner, 1979). A third possibility is that the modern sediments may be completely reworked in a new regime (e.g., major regression) and evidence of the modern sedimentary deposits of the Hauraki Gulf would never be fully realized as part of the rock record.

Chapter 13 Early Marine Diagenesis in Temperate Carbonates

"From so simple a beginning endless forms most beautiful and most wonderful have been and are being evolved."

C. Darwin, On the Origin of Species, 1859

A. INTRODUCTION

Temperate carbonates are fundamentally different from tropical carbonates (Table 10C.1); it follows that diagenetic processes may have fundamentally different effects. Further, temperate processes themselves may be different from tropical ones, or their relative importance may vary. Even very recent publications regarding carbonate diagenesis (e.g., Tucker and Bathurst, 1990) overlook temperate carbonates and the rather different style of diagenesis operating outside the tropics. The overwhelming majority of published diagenetic studies, models, and theories apply only to tropical carbonates. A discussion of diagenetic processes and their effects that are important in temperate carbonates follows.

Morse and Mackenzie (1990) divide diagenesis into three parts: early marine, early non-marine, and burial. Early marine diagenesis takes place at or near the sediment-seawater interface, whose effects may sometimes be extended several centimeters below the surface by bioturbation and bioirrigation. Physical (abrasion), biological (bioerosion and micritization), and chemical (dissolution and cementation) processes act on sediments while they are resident at or near the surface, within the medium of sea water.

Early non-marine diagenesis occurs if carbonates are transported or uplifted or left behind by sea-level fall, into the subaerial environment. Authigenesis, neomorphism (inversion, recrystallization, and replacement), and lithification are all important non-marine processes. Weathering and dissolution can destroy carbonates in the non-marine environment.

Burial diagenesis begins when carbonates cease to be affected by near-surface processes. With time and depth, burial diagenesis grades into metamorphism, and the boundary between them is not sharply defined. Compaction, both physical and chemical, is important; neomorphism, cementation, and decarbonation may also occur.

Clearly, then, environment of diagenesis is an important control on the processes occurring. Pressure, temperature, ambient fluid chemistry, and climate are the main components of the diagenetic environment (Tucker and Bathurst, 1990). Aspects of the carbonate undergoing change are also critical in determining response to diagenetic process, such as the mineralogy, porosity and permeability, and shape and size of grains.

Much study of diagenesis is carried out by analysis of ancient rocks, in which it is impossible to be certain of the exact nature of the original sediment. Modern diagenetic processes are studied and the results applied to ancient environments. At least two major controls on diagenesis are not necessarily uniform over time: climate and sea-water chemistry. Mineralogy of skeletal carbonates may have changed over time as different types of organisms entered and left the fossil record. It is not easy to determine the original mineralogy of skeletons that were precipitated millions of years ago by organisms that are now extinct, especially when they are found only in altered rocks. Thus the study of modern carbonates, while providing some basis for interpretation of ancient limestones, is limited by the changes in world climate and the evolution of organisms over time.

This chapter will discuss early marine diagenesis, particularly as it affects temperate carbonates. Results of experiments described elsewhere (Chapters 4 and 8) will be used to help build up a more complete picture of diagenesis in temperate carbonates.

Diagenetic regimes have been characterized as being destructive to constructive in nature (Alexandersson, 1979). Although the meaning of these terms is fairly self-

evident, a definition may prove useful. A destructive diagenetic process, at its most extreme, removes sediment grains from the sedimentary record. When less drastic, a destructive process may result in loss of structure (for example bioturbation destroys bedding), decrease in grain size, or dissociation of $CaCO_3$. Conversely, constructive diagenetic processes add new grains, add structure (e.g., binding grains together), increase grain size, and increase overall solid $CaCO_3$ content.

B. PHYSICAL DIAGENESIS

Abrasion is a comprehensive term incorporating all the effects of physical (usually hydraulic) energy on sediments. Breakage, smoothing, and grain-size reduction are major effects of abrasion. In general, sediment grains become less distinctive (that is, it becomes more difficult to identify their source) with increasing abrasion. Abrasion is thus a wholly destructive diagenetic process.

Hydraulic energy (e.g., movement of water by currents, waves, and storms) is the primary control on the intensity of abrasion. In a very sheltered environment, occasional strong storms may be the only source of abrasion. Alternatively, in an active intertidal zone, strongly abrasive waves may be a twice-daily phenomenon. This energy is partly related to depth, as waves are most important in shallow water, tidal currents on some shelves, and geostrophic currents in deep water (Collins, 1988; Reeckmann, 1988).

Response to abrasion by carbonate sediment grains varies according to the state of the grain (Young and Nelson, 1988). A highly bioeroded grain is far more likely to crumble in moving water than a fresh one. The morphology of grains is another variable in response to abrasion. As shown in Figures 4B.6 and 4B.9, different bryozoan growth forms respond quite differently to the same degree of abrasion. Shape, size, and microstructure of grains are all likely to be important parts of this morphological response. Carbonate is not a particularly robust material; certainly most siliciclastic

materials are far harder and more resistant to abrasion. The result is that in a mixture of siliciclastic and carbonate sediments, the carbonate will become more heavily abraded in its contacts with the harder material (e.g., Chave, 1964). Thus, degree of terrigenous mixing is a third control on sediment response to abrasion.

At first it would appear that there can be no latitudinal or climatic control on abrasion. Surely, for example, sheltered bays in the Bahamas and in Antarctica having similar hydraulic regimes would impose a similar degree of grain abrasion. Several of the major controls on abrasion and response, however, are related to climate, such that abrasion also becomes indirectly affected by climate.

There is to some degree a climatic control on hydraulic energy on shelves. Tropical carbonate shelves are often shallow, built-up, and rimmed, due to the growth of corals (e.g., Heckel, 1972). This may offer protection to inner shelf areas from strong storms, limiting abrasion. Usually reefs reach as high as the intertidal zone, thus being exposed to more wave energy than deeper carbonates.

Temperate carbonates are often found in open exposed areas, and many, including the New Zealand carbonates described in this thesis, show clear signs of winnowing by strong currents or waves. On the other hand, they tend to be found in the deeper shelf, untouched by fair-weather waves (e.g., Collins, 1988).

The occurrence of coral reefs in tropical carbonate environments also provides a degree of resistance to abrasion (Bathurst, 1975). The structure of a reef is rigid and stable, and can protect interstitial sediments from abrasion. Another typical tropical environment, the seagrass bed, protects sediment as the grass blades act as a baffle and promote settlement of fine sediment. Cementation in tropical environments may also protect sediments from abrasion, immobilizing them.

Temperate shelves seldom show any of these protective features. Build-ups and hardgrounds are rare, and there are only rare temperate equivalents to sediment-baffling seagrass beds (e.g., McKinney et al., 1987). Temperate carbonate sediments may reside at the sediment-sea water interface for years, incurring regular if periodic abrasion, depending on hydraulic regime.

As has been shown earlier (e.g., Table 12B.1), many temperate carbonates are mixed with terrigenous material, in contrast with the common tropical carbonate model which is wholly $CaCO_3$. As abrasion of carbonate is far more effective when a harder substance is introduced, temperate carbonate-clastic mixtures are likely to show far more abrasion effects than a pure carbonate deposit would under the same hydraulic conditions.

To summarize, abrasion is controlled mainly by hydraulic regime. Sediment response to abrasion is dictated by preservation state and morphology of the carbonate grains, and by their degree of mixing with terrigenous sediment. Although abrasion itself is not related to climate, some of its controls are. Temperate carbonates are more strongly affected by abrasion than their tropical counterparts for three reasons: temperate carbonates are often found on exposed, unrimmed shelves; temperate environments generally lack protective structures (reefs) and sediment baffles which reduce water energy (grass beds); and temperate carbonates are often mixed with terrigenous material which, being generally harder than carbonate, enhances the effect of abrasion.

C. BIOLOGICAL DIAGENESIS

Unlike physical diagenesis, which is entirely destructive, biological agents may be destructive or constructive in carbonate diagenesis. The major biological processes are bioturbation (including bioirrigation), bioerosion, micritization, and encrustation.

The major control on all biological processes is the distribution, density, and population of organisms responsible. Climate, environment, micro-environment, and season all affect marine organisms, and thus indirectly affect biological diagenesis. One would expect the difference between tropical and temperate processes to be considerable, given the wide differences between their faunal and floral assemblages. In some processes, however, it appears that although the niches are filled with different organisms, the overall effect is much the same irrespective of latitude.

Bioturbation may be destructive of structures such as bedding planes and sorting. It may simultaneously create structures such as burrows, or bind grains together in pellets. These effects occur irrespective of the chemistry of the sediment; bioturbation is as likely to occur in terrigenous mud as in carbonate sediments. The main control on the intensity of bioturbation is the infaunal population. This is in turn controlled by climate, sediment texture, nutrient availability, and probably other environmental factors. Bioturbation is widespread and important, particularly in providing trace fossils and destroying bedding planes. Because it is dependent on so many variables, generalizations about the extent of bioturbation on a world-wide scale are meaningless. Most shelf sediments show some bioturbation.

Bioerosion is entirely destructive. Borings weaken grains and hasten disintegration. Many borers dissolve $CaCO_3$ while others excavate tiny chips (Young and Nelson, 1988). Again, the main factor in determining the extent of bioerosion is the bioeroding fauna. The intensity of bioerosion has been shown to be seasonal (Figure 8D.3), and environmental factors play an undoubted role, particularly in the case of photosynthetic borers, which must live in the photic zone (Perkins and Halsey, 1971). A rather qualitative control is the "appeal" of substrate. It is apparent on observation of New Zealand shelf sediment samples that the bivalves *Glycymeris* and *Pecten* are more susceptible to bioerosion than other bivalves. Barnacles and echinoids seldom show any sign of bioerosion. It is possible that this reflects shell chemistry (but not, apparently, mineralogy, see Figure 8D.4), availability and type of shell matrix proteins, or perhaps

some other unknown factor. Bioeroding organisms must attach, germinate, grow, and bore; some degree of "choice" may be built in to these processes. Bioerosion is widespread and common in tropical and temperate sediments. The effect of bioerosion is often more catastrophic in temperate sediments because they may reside at the sediment-sea water interface for a very long time, and can be subject to intensive bioerosion throughout (see Figure 8D.2). Nevertheless, tropical bioerosion has been shown to be as rapid as 2 wt%/y (Tudhope and Risk, 1985). In some places, this may outstrip burial and cementation. Bioerosion continues to destroy carbonate after cementation and indeed after lithification, so burial or removal from the marine environment is the only way for carbonate sediments to avoid continued bioerosion.

Micritization is one way in which the destructive effect of bioerosion is counteracted. Bioeroders may dissolve $CaCO_3$ but, in supersaturated waters, $CaCO_3$ will tend to precipitate out of solution (Morse and MacKenzie, 1990). The result is micrite, a cryptocrystalline precipitate, infilling the borings left by microorganisms. There is a loss of structure, and eventually micritized grains may become unidentifiable. In terms of overall carbonate, micritization is constructive. New $CaCO_3$ is added, and grains are strengthened. Micritization appears to be controlled by sea-water chemistry and therefore climate. It is common in tropical sediments but seldom evident in temperate ones.

Wherever there are hard surfaces (rocks, shells, pilings, or sunken vessels), there are colonizers of those surfaces. In much of the marine environment, competition for space is a primary control on distribution. Encrustation is a major biological process, entirely constructive in nature. New carbonate is added, grains are strengthened and may be bound together, and structures may be formed. Again the primary control is the encrusting biota, and again climate, environment, and season will play a part in determining distribution and intensity of encrustation. Substrate suitability is also critical, perhaps including surface texture and ornamentation, strength, and mobility of

substrate. Encrustation occurs in most marine shelf sediments, depending mainly on substrate availability.

Biological diagenesis is both constructive and destructive in temperate and tropical environments. Bioturbation removes existing sedimentary structure, but adds trace fossils and pellets. Bioerosion is destructive, and encrustation is constructive, both controlled strongly by substrate. Micritization is constructive of solid carbonate but destructive of skeletal structure. Bioturbation, bioerosion, and encrustation appear to be equally prevalent in temperate and tropical shelf sediments. Micritization is the only biological diagenetic process with an obvious climate control; it is most common in tropical sediments, where supersaturation with respect to $CaCO_3$ is constant and high.

D. CARBONATE MUD

Carbonate mud, while not a diagenetic process, is a diagenetic product and as such evidence for diagenesis. A non-diagenetic origin for carbonate mud is the settling of calcareous nannoplankton (e.g., coccoliths). Coccoliths are calcitic (Milliman, 1974). In some very highly supersaturated waters, $CaCO_3$ may precipitate out of solution as flakes of mud (whitings). These would most likely be aragonite (Scoffin, 1987). A major source of carbonate mud in many tropical environments is the disaggregation of the codiacean green algae into their component aragonite shards. Abrasion and bioerosion (particularly by clionid sponges, which excavate chips) of existing carbonates is another postulated source of carbonate mud (e.g., Farrow et al., 1978; Scoffin et al., 1980). This third type of carbonate mud would most likely reflect the mineralogy of the local carbonate assemblage (see Figure 4B.7).

It thus seems that one should be able to determine the source of carbonate mud, in part, by its mineralogy. Comparison of mud mineralogy to that of the bulk sediment would be an important tool. Wholly low-Mg calcite mud may be coccoliths, easily tested by scanning electron microscopy (SEM). Aragonite mud can be attributed to inorganic

precipitation or to algal disaggregation. Mud of a mixed mineralogy, similar to the bulk mineralogy of surrounding sediments, may be a product of abrasion or bioerosion. Clionid sponges excavate chips with a diagnostic morphology, and microfossils may remain recognizable in the mud fraction. Electron microscopy will thus be useful in determining the origin of carbonate mud (Figure 13D.1).

In temperate shelf sediments, carbonate mud is often missing (e.g., Hauraki Gulf, see Figure 6C.4), possibly due to the winnowing action of tidal currents on the exposed shelf. Where present in the Gulf, carbonate mud is clearly nannofossil in origin. In some temperate deposits, carbonate mud is abundant, up to 50% of the sediment (e.g., Kukal, 1970; Brookfield, 1988). In general, particularly on shallow shelves, temperate mud is Mg calcite, not aragonite (e.g., Farrow et al., 1978). Aragonitic algae are not found outside the tropics, and it appears that sea water is not sufficiently supersaturated with respect to $CaCO_3$ to allow for inorganic precipitation of mud.

Temperate carbonate assemblages certainly can generate mud under conditions of sufficiently strong abrasion. In one experiment, almost half the originally gravel-sized bryozoan sample was abraded to mud in 127 h of tumbling (see Chapter 4, Section B4). Mud produced by abrasion of skeletons reflects the mineralogy of the original components (Figure 4B.7), and the clay-sized equant grains are rather irregular (Figure 13D.1). Chips excavated by clionid sponges have been found in temperate sediments (Nelson and Bornhold, 1983), indicating that bioerosion also produces mud. Under the destructive force of abrasion and bioerosion, sediments decrease in size, becoming mud. Temperate muds, being either calcite or of mixed mineralogies, may have a better chance of preservation than tropical aragonite mud, which may dissolve over time or reprecipitate as the more stable calcite.

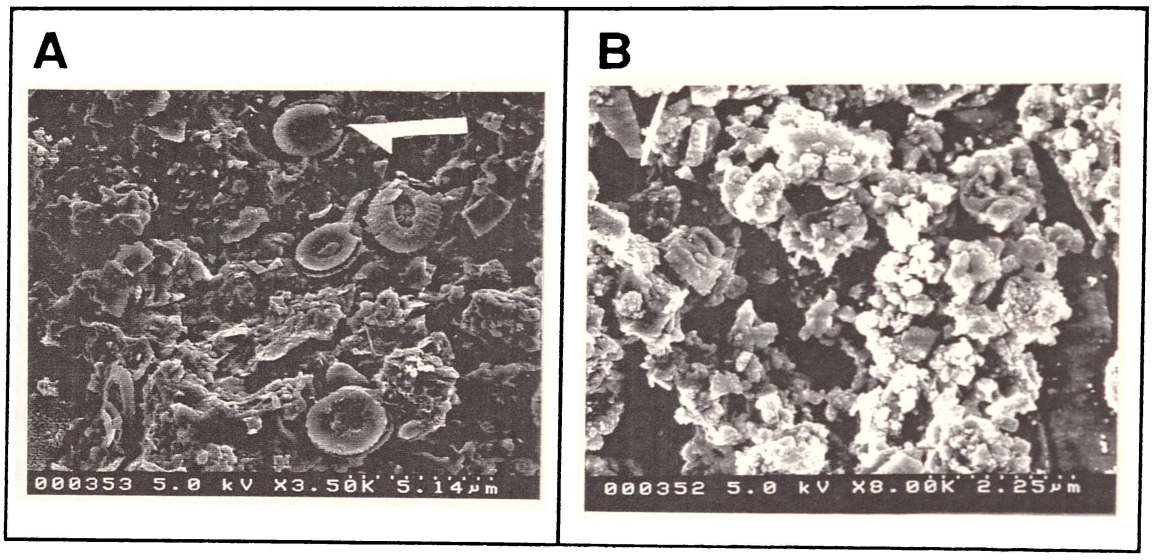


Figure 13D.1: Carbonate mud (A) from the Hauraki Gulf (sample K17, see Figures 6C.4 to 6C.6) showing nannofossils (arrow); and (B) from abrasion experiment (ENml, after 127 h, see Figure 4B.5), showing irregular nature of clay-sized particles.

E. CHEMICAL DIAGENESIS

Chemical diagenesis is unlike physical diagenesis, which is solely destructive, and biological diagenesis, of which some aspects are destructive and some constructive. Chemical diagenesis occupies a true spectrum, with dissolution and precipitation as end members. In any conditions, some dissolution and some precipitation are occurring. The overall effect is determined by their relative importance.

The primary control over this spectrum is sea-water chemistry. In water supersaturated with respect to $CaCO_3$, precipitation will dominate; in undersaturated water, dissolution will dominate. Factors affecting sea-water chemistry include temperature, salinity, pH, and hydraulic energy. Apparently there is some variation over geologic time in sea-water chemistry related to sea level change (Sandberg, 1983). Sea water globally has been characterized as calcite during sea-level highstands, while aragonite seas characterize lowstands, possibly due to changes in pCO_2 and the ratio of Mg/Ca (Sandberg, 1983). Response to chemical changes are controlled by mineralogy, morphology, and porosity of sediment.

In general, it is thought that tropical shelf sediments are subject to constructive chemical diagenetic processes, and temperate shelf sediments to destructive processes (e.g., Brookfield, 1988). Temperate carbonates, however, sometimes are well-cemented; and tropical carbonates can show obvious signs of dissolution.

Cementation occurs when there is a sufficiently large source of $CaCO_3$ in solution, and an appropriate environment for precipitation. Cement is generally precipitated in pores and interstices, though it may form external envelopes around grains. Pore fluid must be supersaturated with respect to $CaCO_3$, and must be constantly replenished. Tremendous throughput of sea water and very low or no sedimentation are required for extensive sea-floor cementation. Currents, waves, bioturbation, and bioirrigation are some of the sources of fluid flow. Interestingly, cementation is inhibited by water

agitation (Bathurst, 1975), and possibly by the presence of organic material (Morse and Mackenzie, 1990).

Incomplete cementation results in a few grains bound together in clumps, called grapestone. Intertidal cementation results in beachrock; submarine cementation produces hardgrounds. All three types of cemented carbonate are widespread in tropical shallow marine sediments. Temperate cements may be intertidal in origin (Reeckmann and Gill, 1981; Reeckmann, 1988), while submarine hardgrounds have been found by James and Bone (1991) in Oligocene-Miocene temperate limestones from southern Australia.

It has been common in textbooks to refer to all submarine Recent and Tertiary cements as either aragonite or high-Mg calcite (e.g., Bathurst, 1975). Certainly reef cements are formed of these less stable mineralogies. This fits with Sandberg's (1983) idea that Cenozoic seas have been disposed to precipitate aragonite. Unfortunately, temperate-water cements do not bear this out, often being composed of low-Mg calcite (e.g., Draper, 1988). According to Brookfield (1988), the critical temperature for switching from aragonite cementation to calcite is 5°C. Many temperate limestones are cemented with ferroan calcite. This may be a burial cement, precipitated in reducing conditions that allowed Fe^{2+} to substitute for Ca^{2+} in the crystal lattice.

Cementation is only one form of the major constructive chemical process of inorganic precipitation. Sometimes nucleated and sometimes independent, precipitation requires supersaturation with respect to $CaCO_3$. A great deal has been written about the origins of ooids, aggregates, peloids, and other non-skeletal grains; the main point to make about them here is that they are seldom if ever reported in temperate carbonates (Brookfield, 1988; Nelson et al., 1988b).

In supersaturated environments, then, highly constructive chemical diagenesis occurs. New grains are precipitated, older grains are enlarged or bound together, and structure

and strength are added to sediments. All of this is in considerable contrast to the situation commonly found among many temperate carbonates.

There are few measurements of the saturation state with respect to $CaCO_3$ of modern temperate shelf sea water, and most evidence for undersaturation is inferred from the state of sediment (e.g., Alexandersson, 1978b). Chronic undersaturation, such as occurs in the deep sea, is not likely to occur at shelf depths (Morse and MacKenzie, 1990). Periodic undersaturation, perhaps brought about by the large seasonal temperature changes experienced in the temperate climate, may occur locally (e.g., Long Island Sound, NW Atlantic, as reported by Aller, 1982). More likely, perhaps, is a "neutral" state, where dissolution is fairly minor, but so is precipitation.

Dissolution is controlled by sea-water chemistry and climate. It is also strongly controlled by the chemistry of microenvironment. Even in actively precipitating tropical reefs, localized tidal pools may become acid due to the photosynthetic cycle and dissolve the surrounding beachrock (Revelle and Emery, 1957). Organic decay adds CO_2 to surrounding water and, if concentrated, may dissolve locally. In Connecticut, high organic activity in summer provides abundant iron sulfides which, in winter, oxidize to form undersaturated sea water (Reaves, 1986). Sulfate reactions may also cause local undersaturation. Extensive bioturbation may bring sulfuric acid to the surface and cause local dissolution (Morse and Mackenzie, 1990).

Shelf dissolution is by no means the norm in temperate waters. The presence of carbonate mud argues convincingly that dissolution cannot be universal. Very small particles of carbonate may become "supersoluble" (Chave and Schmalz, 1966), so their presence must indicate neutral or saturated conditions. In addition, extensive regional dissolution must result in re-saturating sea water with respect to $CaCO_3$, such that dissolution would decrease.

Sediment response to dissolution has been shown to vary depending on the mineralogy and morphology of grains. Aragonite and high-Mg calcite are the first to dissolve, even in tropical reefs (Miller, 1986). In addition, surface area available for dissolution (i.e., microarchitecture, overall shape, porosity, and size), has considerable influence on rate of dissolution (see Figures 4D.6 and 4D.8).

Maceration, a term devised by Alexandersson (1978a,b) to explain the total disintegration of carbonates in the Skaggerak, involves dissolution followed by structural collapse. Scoffin (1988) invokes the decay of organic matrix in maceration, which could well involve very localized dissolution if oxidation produced CO_2.

Chemical diagenesis is a two-way phenomenon. Precipitation outweighs dissolution in most tropical environments; temperate carbonates often display dissolution features. Nevertheless, both processes occur in both climates, and a simple relationship does not exist.

F. EFFECT OF ASSEMBLAGE

As has been shown above, different processes are important in the tropical and temperate zones. Equally important, however, is the response of the sediments to these processes. One of the most obvious and clear-cut differences between tropical and temperate carbonates is the skeletal assemblage. Given the variation in mineralogy and morphology associated with assemblage, it would be surprising if the chlorozoan assemblage (corals, algae, non-skeletal grains) did not react differently from the bryomol/foramol assemblages (bryozoans, molluscs, foraminifera) to diagenetic processes.

In Figure 13F.1, the major sedimentary carbonate components are characterized as to mineralogy and morphology. The relative susceptibility of each to important destructive diagenetic processes is estimated. It will be noted that, as bryozoans are

TEMPERATE ASSEMBLAGE	Mineralogy	Morphology	Susceptibility to temperate diagenesis		
			Abrasion	Bioerosion	Dissolution
Bivalves	A (C)	mainly convex shells quite robust	o	XXX	o
Bryozoans	C M (A)	varies from branching to compact solid	o to XXX	o to X	X to XXX
Foraminifera	C (A)	tiny and fragile, but compact	X	o	X
Barnacles	C	triangular, robust	o	X	o
Gastropods	A (C)	coiled or convex	X	XXX	X
Serpulids	C (A)	tubes	X	X	X

TROPICAL ASSEMBLAGE	Mineralogy	Morphology	Susceptibility to tropical diagenesis		
			Abrasion	Bioerosion	Dissolution
Corals	A	fairly solid reefs	o	XXX	o
Codiacean green algae	A	delicate, branching fragile	XXX	X	o
Non-skeletal grains	A (M)	usually rounded fairly robust	o	X	o

Figure 13F.1 Destructive diagenesis and its effect on tropical and temperate assemblages.

Mineralogy: A - aragonite; C - calcite; M - high-Mg calcite.
Susceptibility: o - low ; X - moderate; XXX - high.

remarkably variable in both morphology and mineralogy, their response is also the most variable (see Chapter 11, Section D). In both the temperate and tropical environments, bioerosion seems to be the most active destructive process. The additional presence of local or periodic dissolution in temperate sediments makes temperate carbonates as a whole more likely to be destroyed.

G. OVERALL EFFECT OF TEMPERATE DIAGENESIS

There are eight major early marine diagenetic processes, some constructive, some destructive, and some both (Figure 13G.1).

When Alexandersson (1979) referred to diagenesis as occupying a spectrum between destructive and constructive, he really was only referring to chemical diagenesis. Abrasion is wholly destructive, no matter where or when it occurs; the only variable is its intensity. Similarly, bioerosion is destructive; encrustation is constructive. For these processes, there is no spectrum with two end members, just extent. Abrasion, bioerosion, and encrustation are unidirectional, and cumulative over time. In contrast, chemical diagenesis is a spectrum, where precipitation and dissolution are concurrent, and the balance between them varies with climate, microenvironment, and season (Figure 13G.2). It is thus inappropriate to refer to temperate diagenesis as solely destructive. Encrustation and sometimes bioturbation are two constructive processes that occur in many temperate carbonates; cementation may be locally important (Figure 13G.3).

The most important controls on early marine carbonate diagenetic processes are climate and sea-water chemistry (Table 13G.1). Directly or indirectly they are related to every process. Local biota are much less important. Skeletal assemblage to some degree determines response to diagenetic processes.

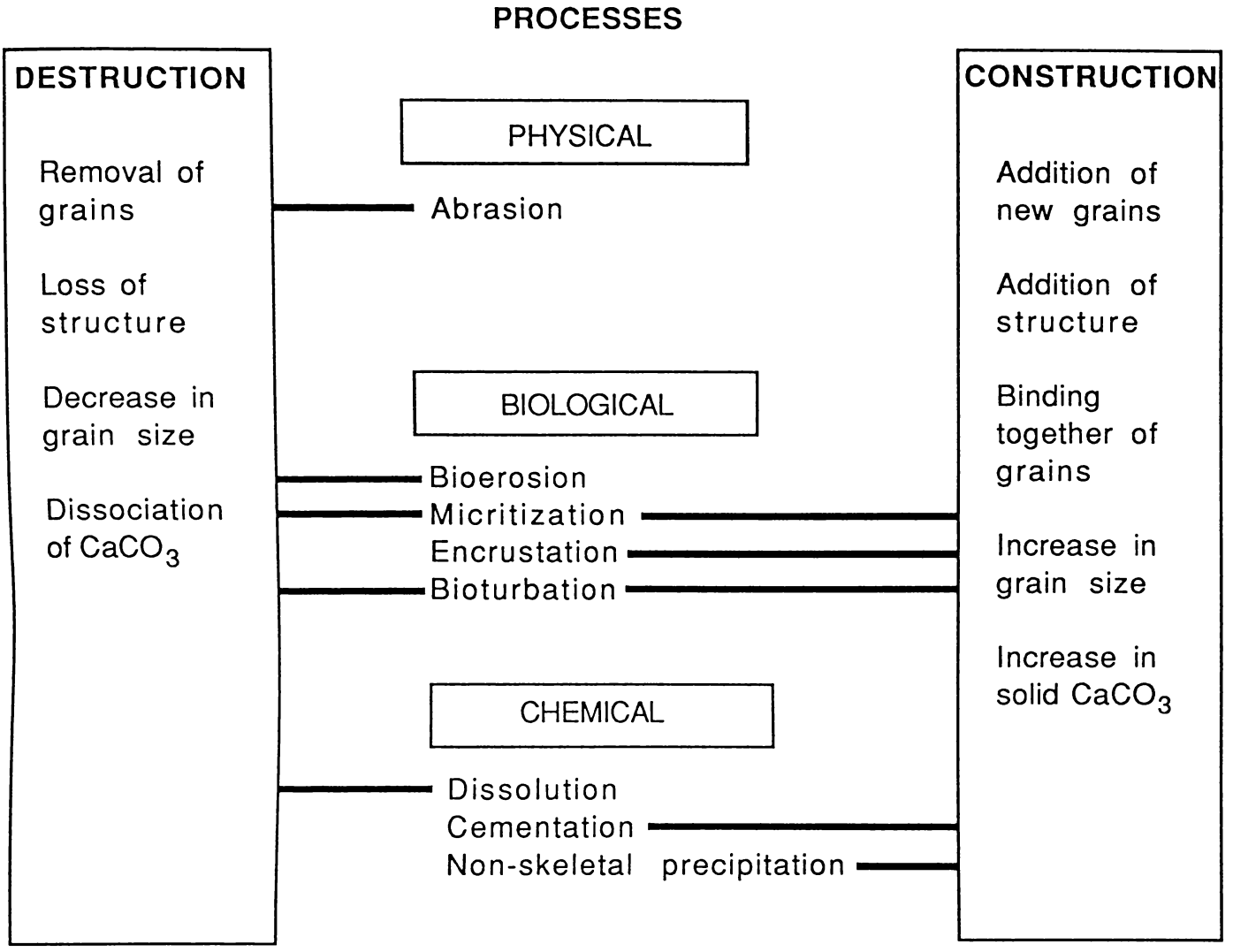


Figure 13G.1: Early marine diagenesis of carbonate sediments generally. Constructive and destructive nature of each process is indicated.

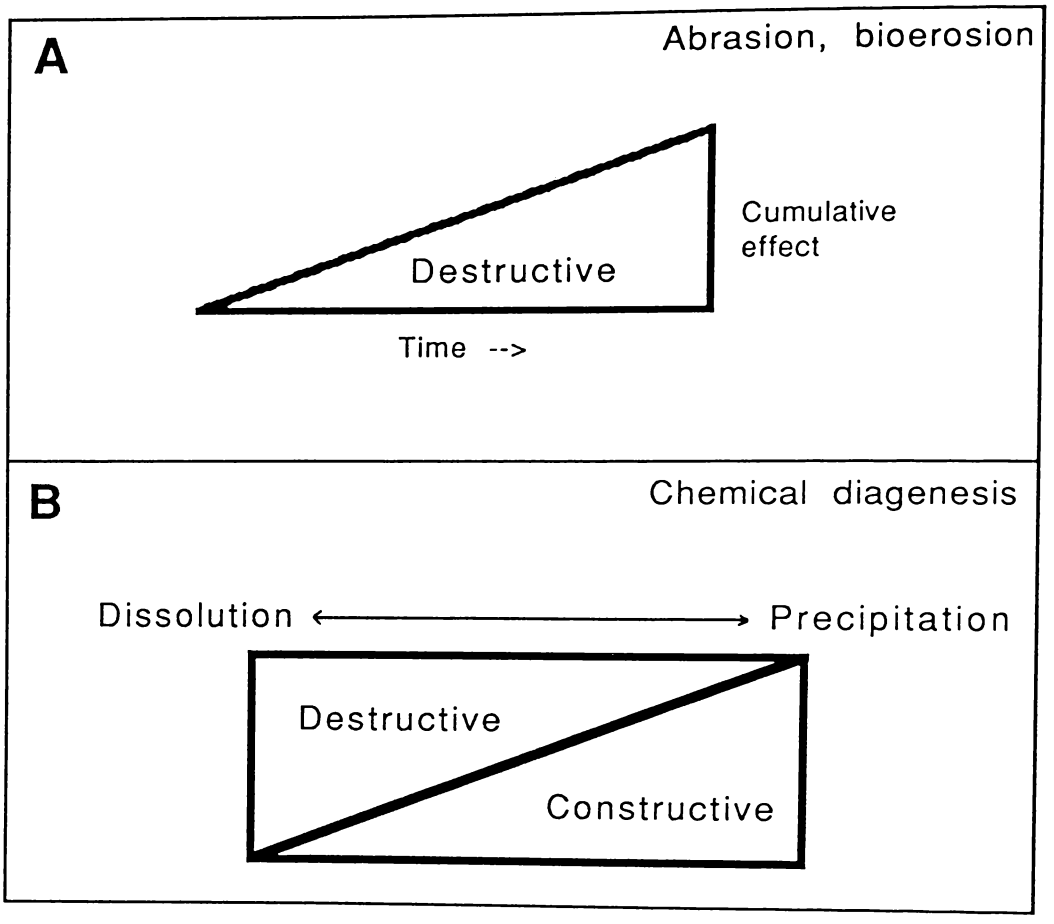


Figure 13G.2: Conceptual models for a cumulative, one-way diagenetic process (A), and a continuous spectrum diagenetic process (B).

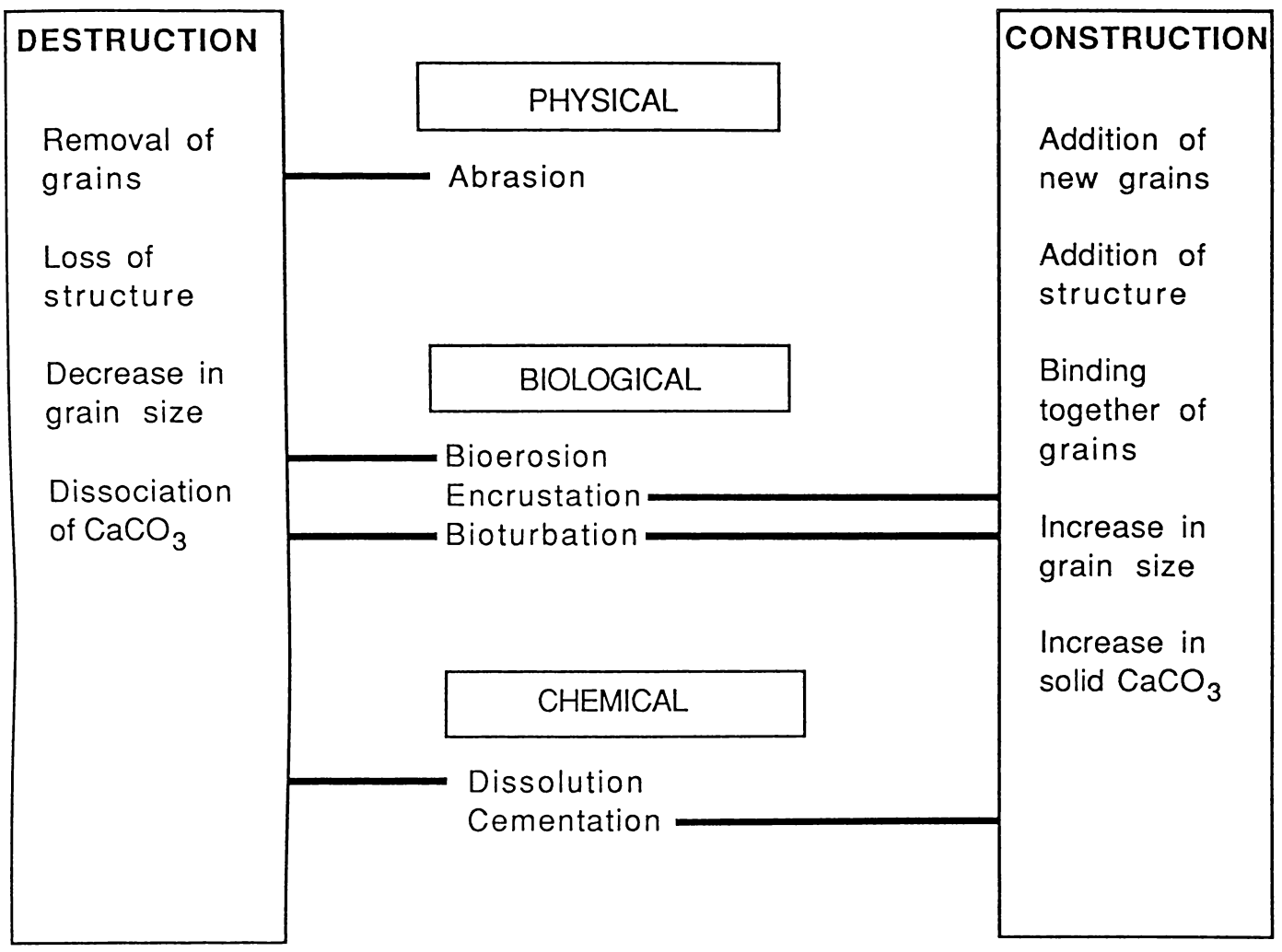


Figure 13G.3: Early marine temperate carbonate shelf diagenesis (cf. Figure 13G.1).

Table 13G.1: Controls on early marine diagenesis of carbonate sediments.

Process	Control on process	Control on substrate response
PHYSICAL		
Abrasion	Hydraulic regime Physiography Climate	Morphology of grain State of grain (strength) Terrigenous content Residence time
BIOLOGICAL		
Bioerosion	Bioeroding fauna/flora Season, environment, climate	Substrate "appeal" to fauna State of grain (already bored) Residence time
Micritization	Sea-water chemistry Climate	
Encrustation	Encrusting fauna/flora Season, environment, climate	Substrate suitability Residence time
Bioturbation	Infauna Sediment texture	
CHEMICAL		
Dissolution	Sea-water chemistry Climate	Morphology of grain Mineralogy of grain
Cementation	Sea-water chemistry Fluid flow regime CaCO3 source	Porosity
Non-skeletal precipitation	Sea-water chemistry CaCO3 source	

An important factor in diagenesis is time. The length of time a grain is exposed to diagenetic processes is fundamental in determining the degree of response. Sedimentation and lithification remove sediments from the sediment-sea water interface and thus from exposure to early marine diagenesis. Where sedimentation rate is low and lithification slow, as in most temperate carbonates (Nelson, 1988b), exposure to diagenetic processes is longer and they therefore have the potential to be more effective.

Temperate carbonates are exposed to more destructive processes than tropical carbonates. They are often more vulnerable to destructive processes, and are subjected to them for longer periods of time (Table 13G.2). The overall result is that temperate carbonates generally have a lower preservation potential than tropical carbonates. Consequently, temperate carbonate production may not always be represented in the limestone record.

Table 13G.2: Differences in diagenesis between shelf carbonate sediments (modified from Nelson, 1988b).

Aspect	Tropical/subtropical	Temperate/polar
Carbonate minerals	aragonite dominant	low- to high-Mg calcite dominant
Degree of saturation (with respect to $CaCO_3$)	supersaturated to saturated	saturated to undersaturated
Diagenetic regime	constructive	destructive
Dominant processes	precipitation bioerosion encrustation bioturbation abrasion	dissolution bioerosion encrustation bioturbation abrasion
Shell preservation	generally good	poor to good
Carbonate mud	common to abundant	rare, locally abundant
Source of carbonate mud	floral disaggregation inorganic precipitation	skeletal abrasion bioerosion
Evaporites	locally common	mainly absent
Sea-bed lithification	common	uncommon

Conclusions and Suggestions for Future Research

"Come now, and let us reason together..."
Isaiah 11:18, Old Testament, King James Version, 1611

A. BRYOZOANS

Recalculated growth rates for most bryozoans yield calcifications rates of less than 1 g $CaCO_3$/y, although under ideal conditions individuals may produce up to 46 g $CaCO_3$/y. An *in situ* study gives even slower rates: most species produce less than 0.05 g $CaCO_3$/y, with a mean of 0.007 g $CaCO_3$/y. The highest rate of production determined was 0.77 g $CaCO_3$/y. In general, bryozoans are not particularly rapid producers of carbonate, compared to other carbonate-producing organisms..

Over the area of an *in situ* experiment near Cape Rodney, total bryozoans produced carbonate at a rate of 24 g $CaCO_3/m^2/y$. This is much less than other published sediment production rates for bryozoans (100 to 8000 $g/m^2/y$), and may reflect the limited area available for settlement. A comparison of a living fauna on the submerged wreck *Rainbow Warrior* with bryozoans in sediments around the wreck indicates that in the four years since its sinking, little bryozoan sediment from the wreck has been deposited. Presumably carbonate sedimentation takes some time to establish. Bryozoans die and become sediment through senility, predation, competition, abrasion, or environmental change.

New Zealand bryozoans may have low (0-3 wt% $MgCO_3$), moderate (3-5 wt% $MgCO_3$), or high (5-9 wt% $MgCO_3$) Mg contents in calcite. Many are 100% calcite, while fewer are aragonitic or bimineralic. Mainly calcitic bimineralic species have a primary skeleton of calcite with secondary thickenings of aragonite; mainly aragonitic ones were originally all aragonite but that metastable mineral alters to calcite over time. There are thus two causes for bimineralic skeletons: developmental and diagenetic.

Mineralogical variation within colonies and within populations is small. There is more variation among populations, but no systematic trend (for example, with latitude) was found. Mineralogy is linked to major bryozoan taxa. Cyclostomes are low to moderate-Mg calcite. Cheilostomes are more variable, with anascans having an overall lower Mg content than ascophorans. Some colonial growth forms have fairly consistent mineralogies, others are more variable (particularly encrusting forms). State of preservation was not found to have an effect on mineralogy.

Mineralogy, taxon, and degree of terrigenous mixing in sediments were found to influence co-precipitation of Mg, Sr, Fe, and Mn. Bryozoans secrete $CaCO_3$ close to isotopic equilibrium with sea water, therefore $\delta^{18}O$ and $\delta^{13}C$ in New Zealand bryozoans reflect their temperate climate. Mineralogy and water depth were shown to affect isotopic ratios.

In a tumbling experiment, different growth forms were found to respond differently to abrasion. Encrusting multilaminar forms were least resistant, while erect rigid fenestrate and free living motile forms were most resistant. Erect rigid branching, encrusting unilaminar, and erect flexible forms were intermediate in resistance to abrasion. Preservation state was also found to be important. This limits the use of bryozoans as indicators of transport or age, and may bias the fossil record. Bryozoans subject to abrasion may produce large quantities of carbonate mud; almost 50% of multilaminar encrusting forms were converted to mud in 127 h tumbling.

Bryozoans may be agents of biological diagenesis as encrusters or as borers. They may be encrusted or overgrown, and may also be subject to bioerosion, although little was observed in *Otionella* sp. over the course of a year's sea-water immersion in the western Hauraki Gulf.

Morphology, mineralogy, and initial size were found to be important predictors of experimental dissolution behavior. Bryozoans that were small, delicate, and aragonitic

dissolved faster than large, compact, calcitic ones. The traditional assumption that mineralogy solely affects dissolution rate must be widened in bryozoans to include morphology.

Bryozoans are important as producers of carbonate, stabilizers of sediment, encrusters and bioeroders, subjects of diagenesis, and eventual fossils. A qualitative budget for bryozoans as sediment-formers indicates that carbonate produced is often greater than that deposited, and that diagenetic processes may account for the disparity. Bioerosion, abrasion, and dissolution are all important in reducing bryozoan carbonate available for lithification.

A study of Hauraki Gulf bryozoan faunas shows that depth, hydraulic energy, and substrate are important controls on distribution of bryozoans. The effect of diagenesis in temperate waters is mainly to remove potential information from the fossil record. Bryozoans are not particularly strong, and are susceptible to abrasion. The interaction of habitat choice and resistance to abrasion results in distinctive faunas in areas of different degrees of hydraulic energy. Low-energy faunas may be retained intact, but high-energy faunas may be represented only by fragments of the strongest forms. The extent of bioerosion of bryozoans is unknown, but is likely to enhance the destructive effects of abrasion and dissolution. Mineralogy and morphology both affect dissolution history, both early sea-floor dissolution and later diagenetic dissolution. Theoretical resultant faunas are found in New Zealand Tertiary limestones, and the combination of paleoenvironmental interpretation with diagenetic change can be used to explain fossil faunas.

B. TEMPERATE CARBONATE SEDIMENTS

Four major facies are recognized in the Hauraki Gulf on the northeastern shelf of New Zealand. The majority of the area of the Gulf is blanketed by a muddy sand, containing about 30% carbonate. In several small patches, a high-carbonate (mean 64% $CaCO_3$)

gravel facies is found. These patches coincide with both submarine topographic highs and high-velocity tidal currents, suggesting that fine terrigenous material is winnowed out. A terrigenous sand facies occurs near shore, and a mud facies to the south. Substrate availability appears to be a primary control on biota, in which bivalves are dominant, but bryozoans, barnacles, and gastropods may be subdominant to some degree. Skeletal sediments range in age from 1750 to 8250 years old, perhaps indicating the palimpsest or relic nature of at least part of the carbonate sediment.

Biological diagenesis is important in Hauraki Gulf mollusc shells. Experimental immersion in sea water at Cape Rodney showed that within one year, encrustation was more important than bioerosion. Bioerosion is a longer-term process than encrustation, and outweighs it after 100s to 1000s of years. Four bioeroders were identified and described: clionid sponges, green algae, fungi, and some prokaryotes. Substrate species and to a lesser extent season affected bioerosion rate, while mineralogy of substrate appeared to make little difference.

In situ mixing, where allochthonous terrigenous material is mixed with autochthonous skeletal carbonate, occurs in the Hauraki Gulf, and in other New Zealand carbonate occurrences. Locally low rates of terrigenous supply allow this to occur, as does disequilibrium. Rate of terrigenous supply appears to affect temperate assemblages, with foramol and mollusc sediments occurring in sediments high in terrigenous material, and bryomol sediments requiring lower terrigenous input. Mixing also increases abrasion rate. Terrigenous material also occurs in New Zealand Tertiary limestones. From these and other mixed lithologies, two possibilities for a hypothetical future Hauraki Gulf formation are proposed. In one case, sea-level rise would result in an upward increase in $CaCO_3$, until the deposit became a typical New Zealand bryomol limestone. If terrigenous material remained dominant, the Hauraki Gulf deposit would more likely resemble the Upper Jurassic Redwater Shale of Wyoming, USA, a fine terrigenous deposit with shoestrings and lenses of bivalve carbonate.

C. TEMPERATE DIAGENESIS

Abrasion, whether in tropical or temperate environments, is wholly destructive and controlled by hydraulic energy, which is only indirectly influenced by climate. Temperate shelf sediments are lacking some of the protective features of tropical ones (e.g., reefs, seagrass beds, rimmed shelves). The addition of terrigenous sediment increases the effect of abrasion on the weaker carbonate grains.

Biological diagenesis is controlled by biota, which is affected by season, environment, and climate. Substrate "appeal" is another important factor, seen in New Zealand sediments as preferential boring of certain bivalves. Biological processes may be destructive (bioerosion) or constructive (encrustation) or both (bioturbation).

Abrasion and bioerosion both have been invoked as producers of carbonate mud in temperate carbonates, particularly in the absence of the typical tropical sources (codiacean green algae and inorganic precipitation). Coccolithophores may also form carbonate mud; they are found in small quantities in Hauraki Gulf sediments. The difference between these sources may be indicated by their mineralogy, and by SEM examination of particle morphology.

Chemical diagenesis is a spectrum, with dissolution and precipitation as end-members. In temperate carbonates, dissolution often predominates. Sea-water chemistry is the primary control, and temperature, pH, salinity, and hydraulic energy all affect it. Mineralogy, morphology, and porosity of sediment control response to dissolution. Cementation is rare in temperate carbonates, but examples of intertidal and sea-floor cementation have been found, although not in New Zealand, both requiring strong water flow and little or no sedimentation.

The temperate skeletal assemblage plays a role in temperate diagenesis. Bryozoans occupy a particularly wide range of mineralogies and morphologies, and consequently

have a diversity of responses to diagenetic processes. Overall, temperate carbonates, particularly bryozoan carbonates, are exposed to mainly destructive processes. They are quite vulnerable to these processes, and may be exposed at the sediment-sea water interface for a long time. In general, temperate carbonates have a lower preservation potential than tropical carbonates, and are therefore probably under-represented in the fossil record.

D. FUTURE RESEARCH

Despite the gains made here, much remains to be discovered about temperate carbonates. Of particular interest, and following on from aspects of this study, are the following questions.

What are the ranges of carbonate production rates among bryozoans? Do they vary with taxon, with mineralogy, with latitude? How do they relate to production rates of other organisms at the same location? Is it true that a species calcifies less rapidly and makes a thinner skeleton in colder water? What are typical gross rates of production for all bryozoans in an area?

How well are different carbonate-producing taxa represented in sediments? What causes sedimentary assemblages to be different from nearby living ones? Can rates of death and damage be ascertained?

What is the cause of mineralogical variation within a single colony? How does one explain variation among populations? Is growth form related to mineralogy? Can one use the concentration of co-precipitates to ascertain diagenetic change in mineralogy?

What are the rates of diagenetic processes in nature? What determines their relative importance? On what time-scale do the different processes operate?

How widespread is abrasion and what degree of water agitation is required to cause considerable abrasion?

At what rate can bioeroders remove shell material? Does it vary among bioeroders? What causes a particular shell to "appeal" to bioeroders and encrusters?

How does the source of carbonate mud vary with location, depth, climate, or other environmental factors? What happens to carbonate mud over time in temperate seas?

How widespread is dissolution on the continental shelf? Is it related to undersaturation of sea water with respect to $CaCO_3$?

If rates of production, diagenesis, and sedimentation do become known, does the budget balance?

How applicable is bryozoan paleoenvironmental analysis without an understanding of taphonomic processes?

Questions such as these must be addressed using a multidisciplinary effort. Geochemists, sedimentologists, benthic ecologists, oceanographers, and invertebrate paleontologists must all cooperate to fully understand the interaction of oceanographic, biologic, and geologic factors that combine to produce temperate carbonate sediments.

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Appendix Figures

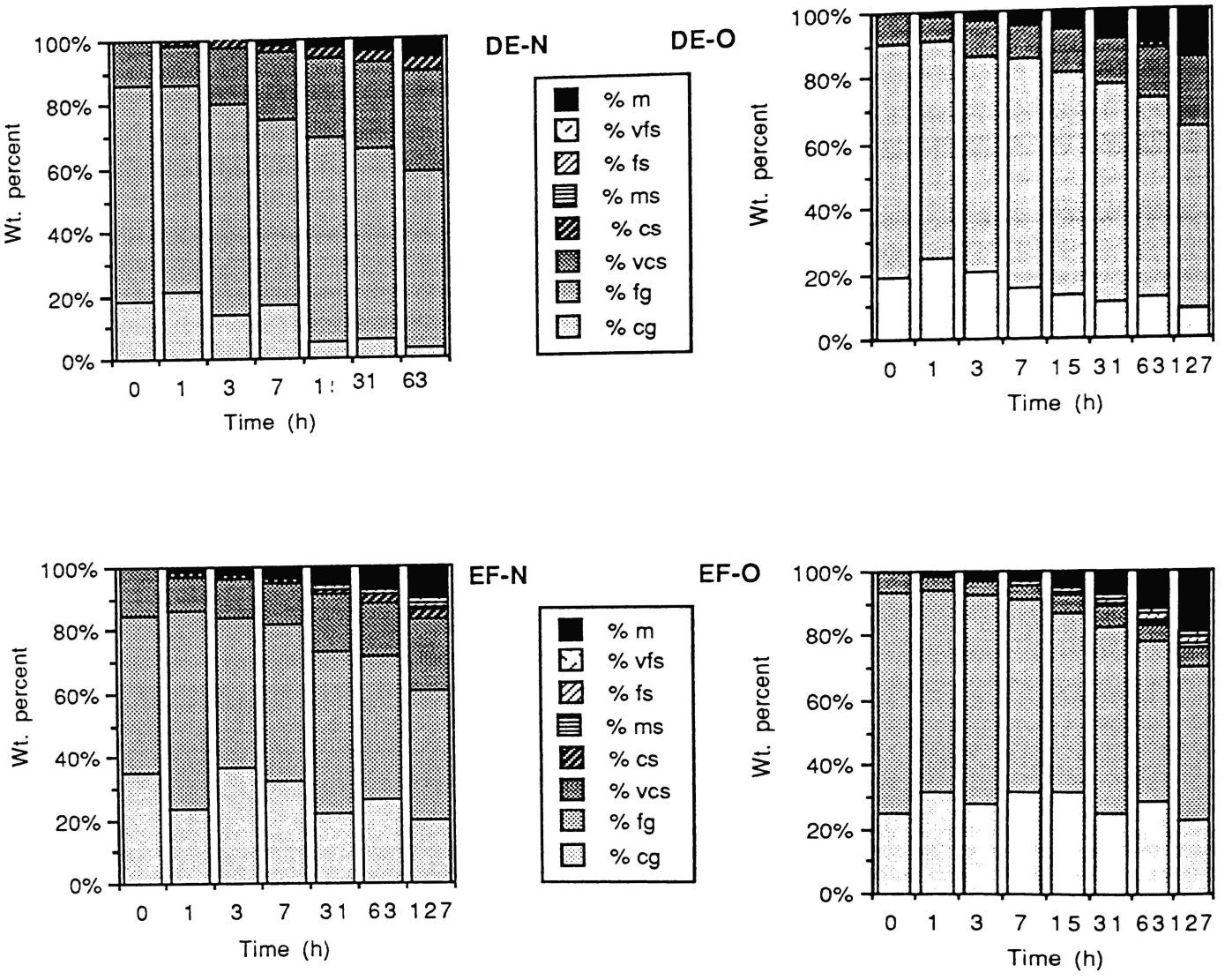
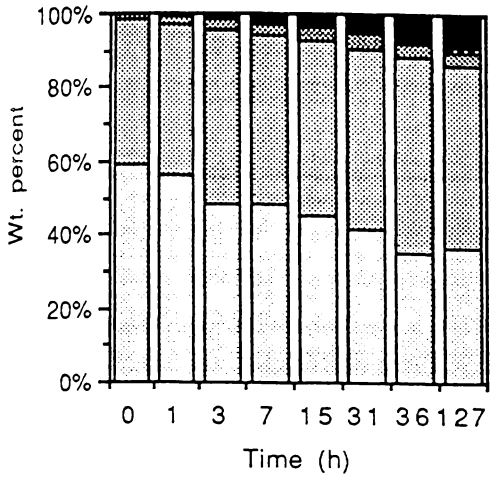
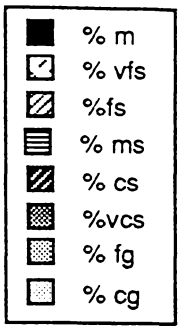


Figure A4.1: Changes in size fractions over time for 16 samples subjected to tumbling.

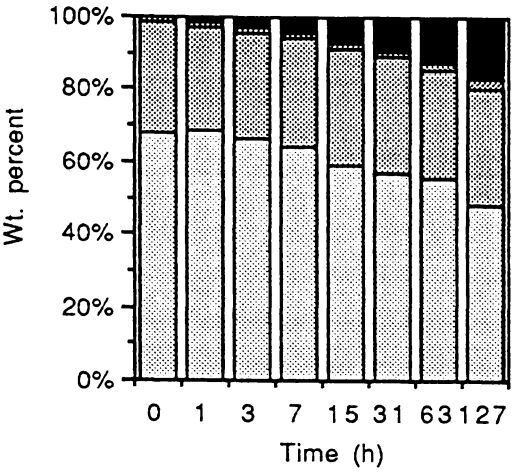
Size fractions: m - mud (<0.063mm); vfs - very fine sand (0.063-0.125mm); fs - fine sand (0.125-0.25mm); ms - medium sand (0.25-0.5mm); cs - coarse sand (0.5-1mm); vcs - very coarse sand (1-2mm); fg - fine gravel (2-4mm); cg - coarse gravel (>4 mm).

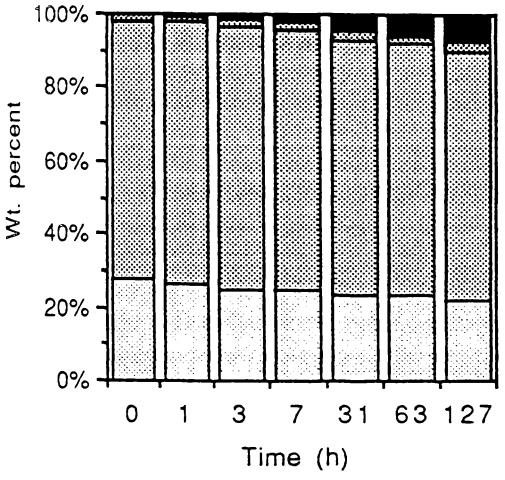


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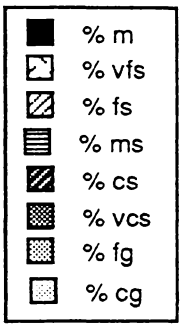


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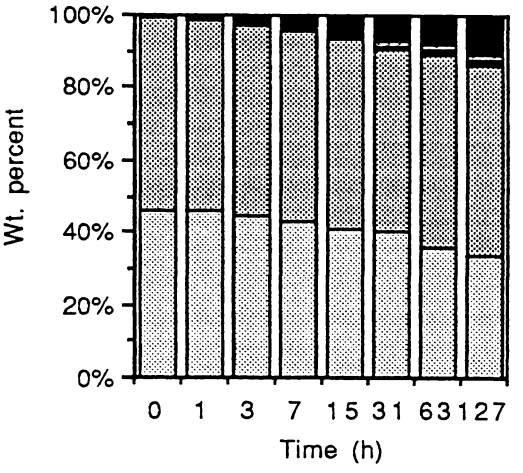


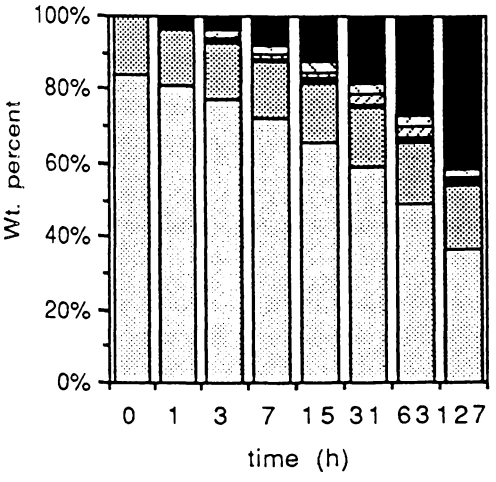


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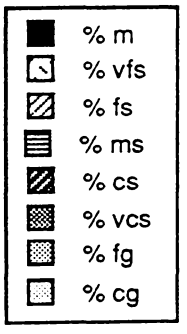


FL-O

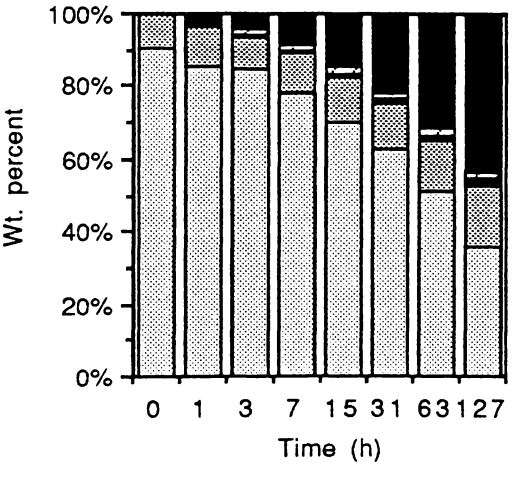


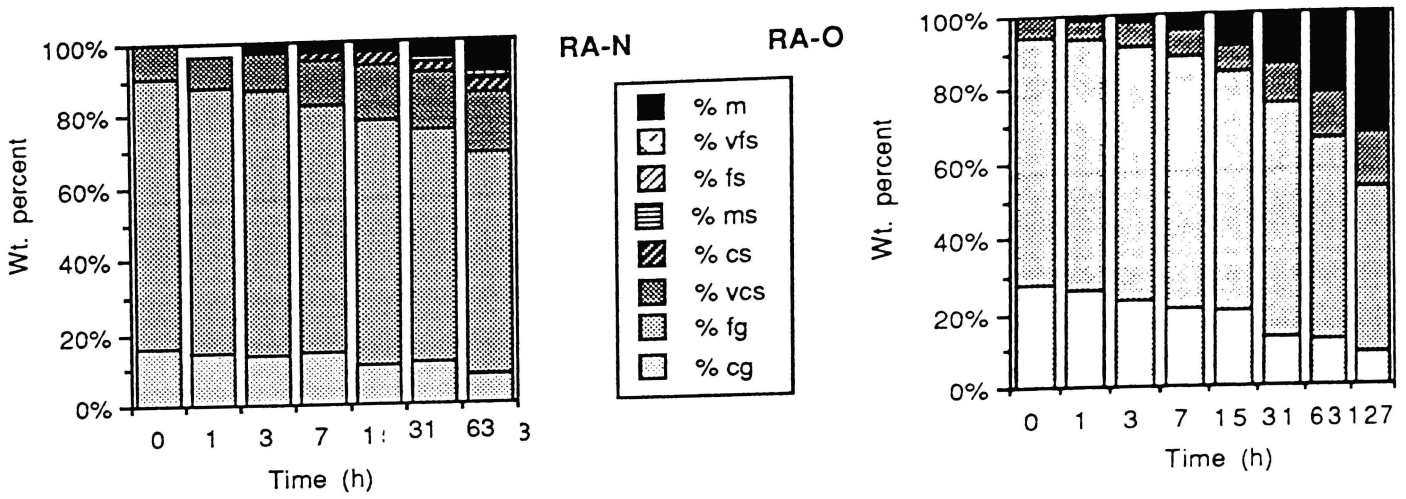


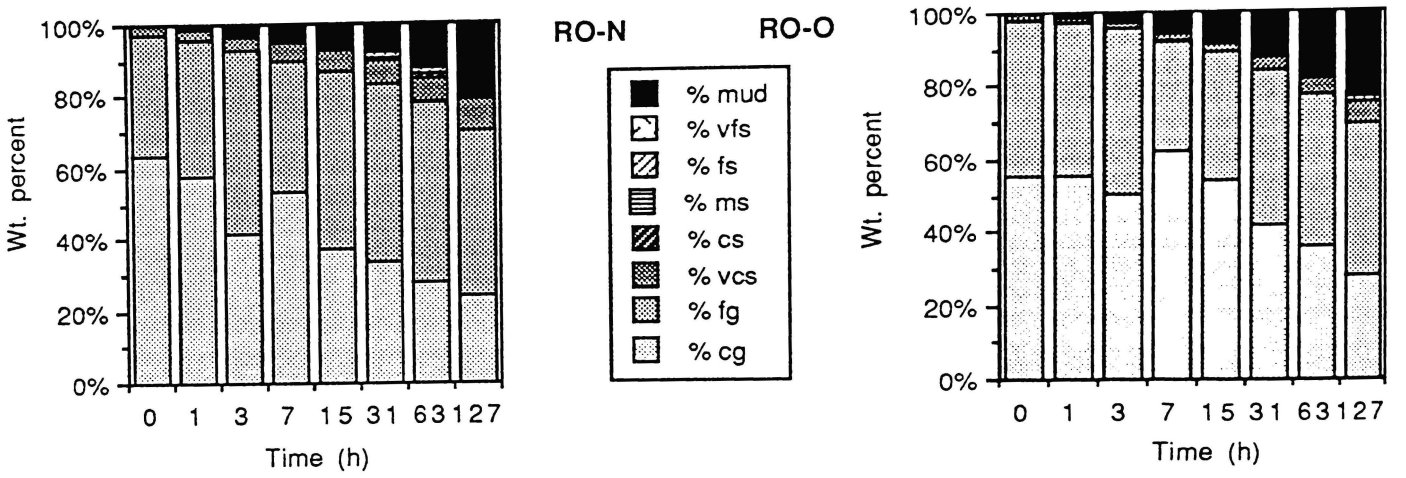
ML-N

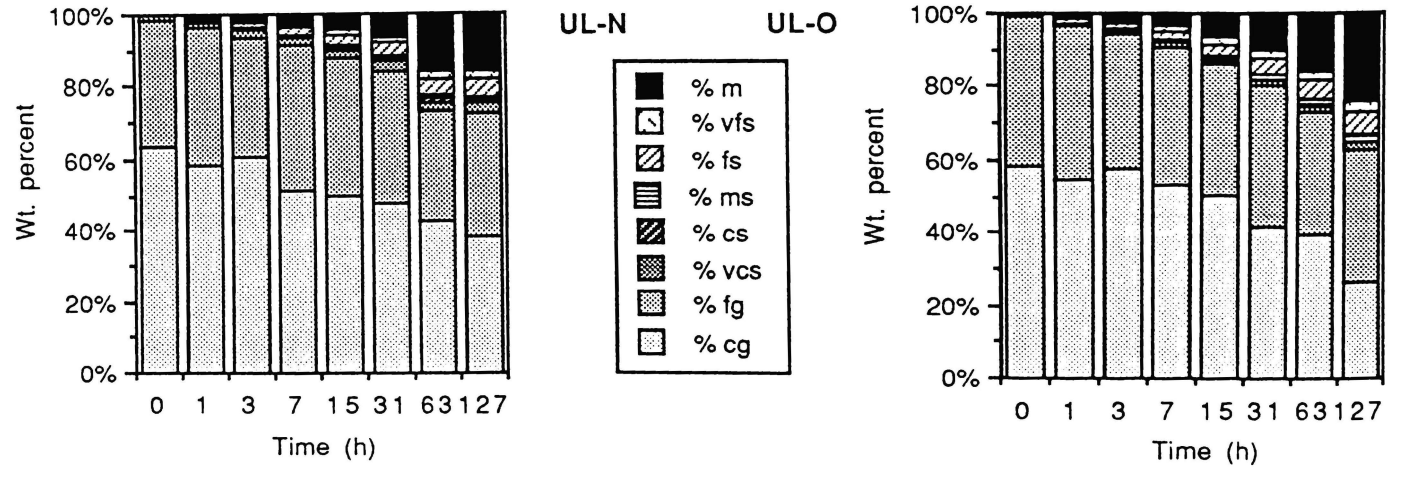


ML-O




RA-N
RA-O
% m
% vfs
% fs
% ms
% cs
% vcs
% fg
% cg
Wt. percent
100%
80%
60%
40%
20%
0%
0 1 3 7 15 31 63 127
Time (h)


RO-N
RO-O
% mud
% vfs
% fs
% ms
% cs
% vcs
% fg
% cg
Wt. percent
100%
80%
60%
40%
20%
0%
0 1 3 7 15 31 63 127
Time (h)


UL-N
UL-O
% m
% vfs
% fs
% ms
% cs
% vcs
% fg
% cg
Wt. percent
100%
80%
60%
40%
20%
0%
0 1 3 7 15 31 63 127
Time (h)

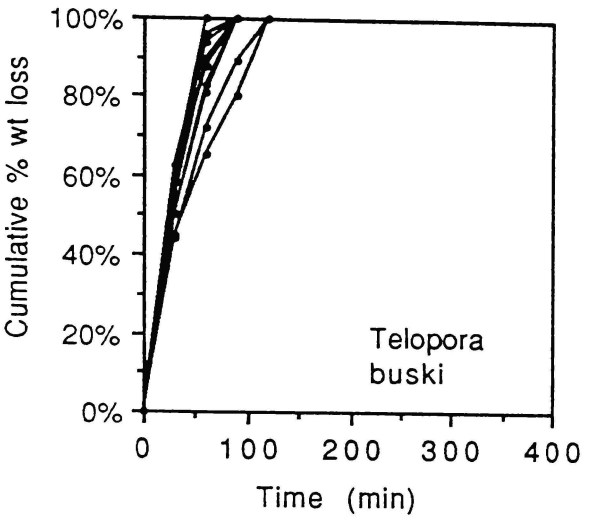
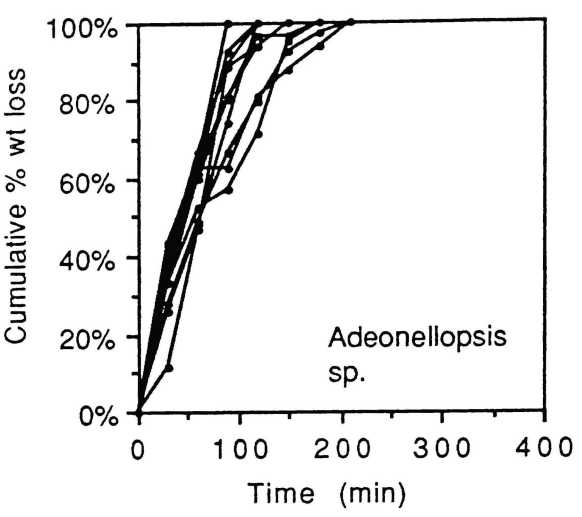
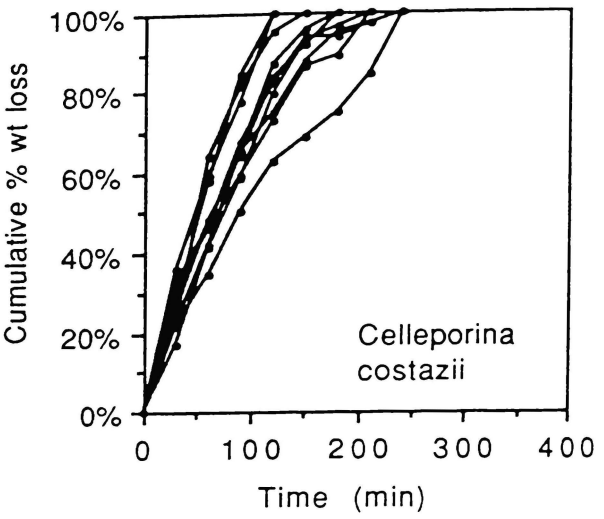
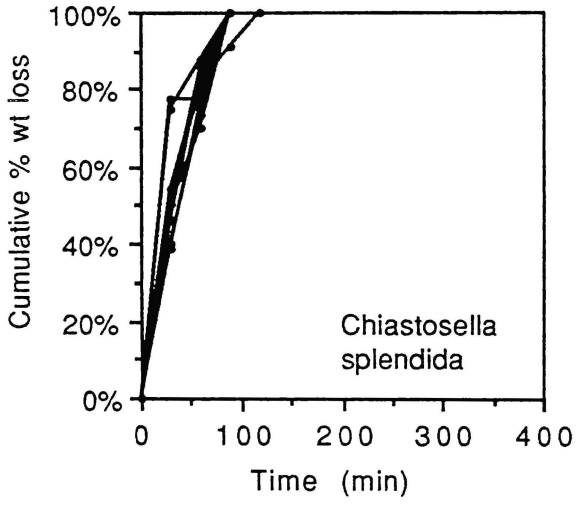
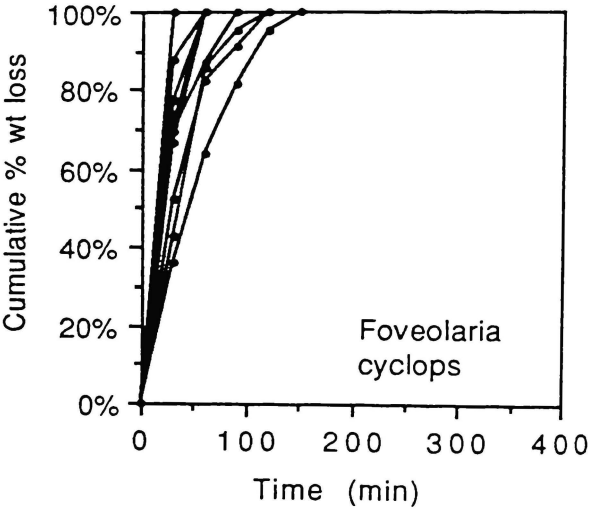


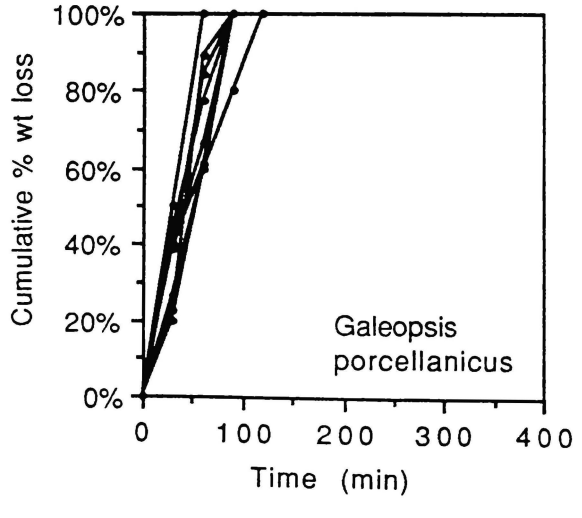
Figure A4.2: Cumulative percent weight loss curves for each of 10 replicate specimens of each of 13 species of New Zealand bryozoans subjected to dissolution by experimental acid bath.

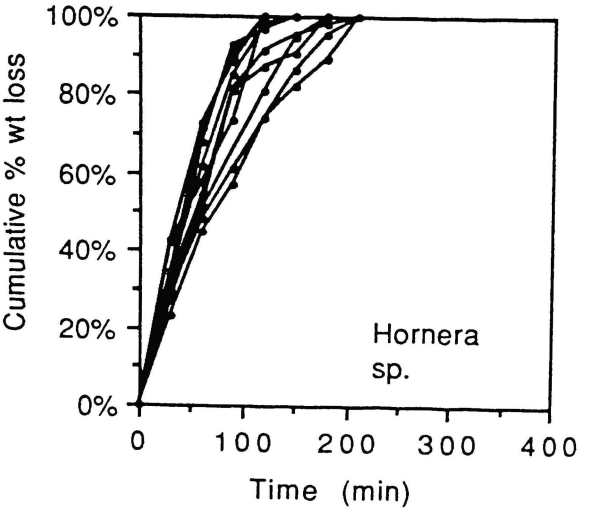

100%
80%
60%
40%
20%
0%
Cumulative % wt loss
Adeonellopsis
sp.
0
100
200
300
400
Time (min)

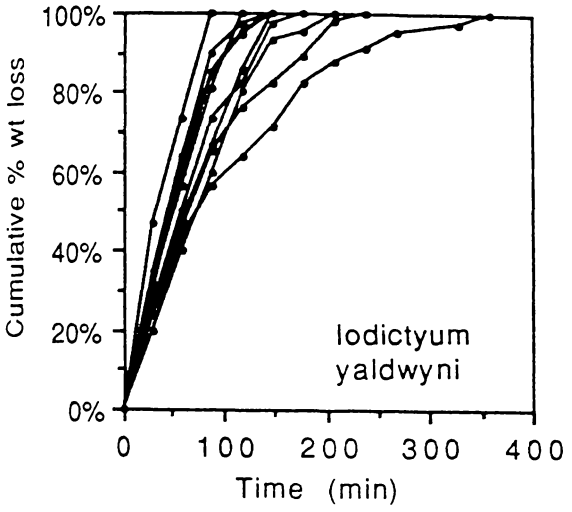

100%
80%
60%
40%
20%
0%
Cumulative % wt loss
Celleporina
costazii
0
100
200
300
400
Time (min)

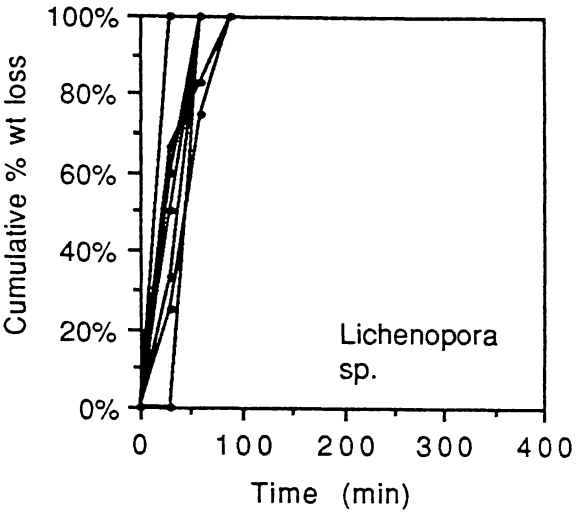

100%
80%
60%
40%
20%
0%
Cumulative % wt loss
Chiastosella
splendida
0
100
200
300
400
Time (min)

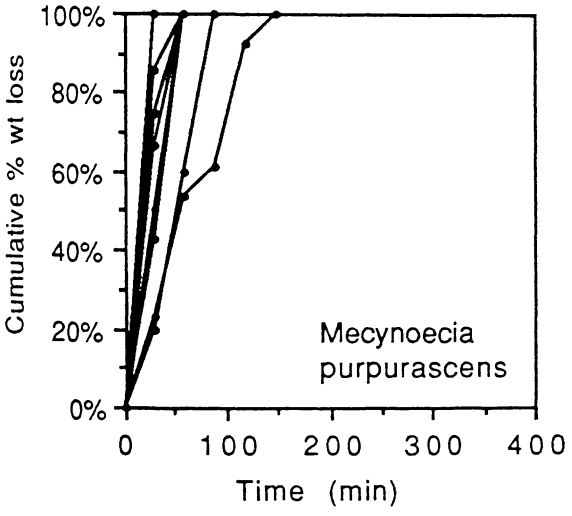

100%
80%
60%
40%
20%
0%
Cumulative % wt loss
Foveolaria
cyclops
0
100
200
300
400
Time (min)

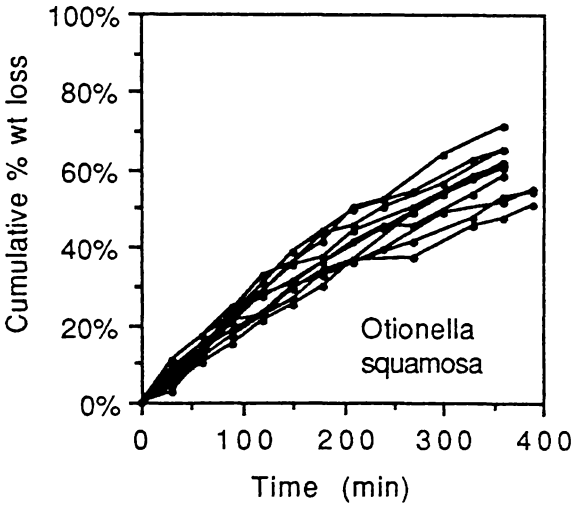

100%
80%
60%
40%
20%
0%
Cumulative % wt loss
Galeopsis
porcellanicus
0
100
200
300
400
Time (min)

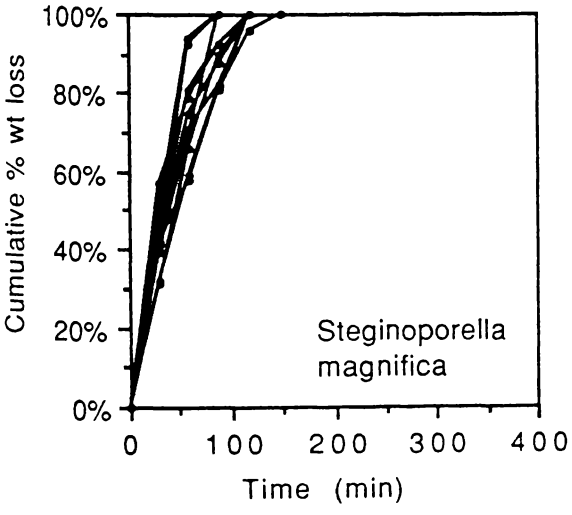

100%
80%
60%
40%
20%
0%
Cumulative % wt loss
Hornera
sp.
0
100
200
300
400
Time (min)

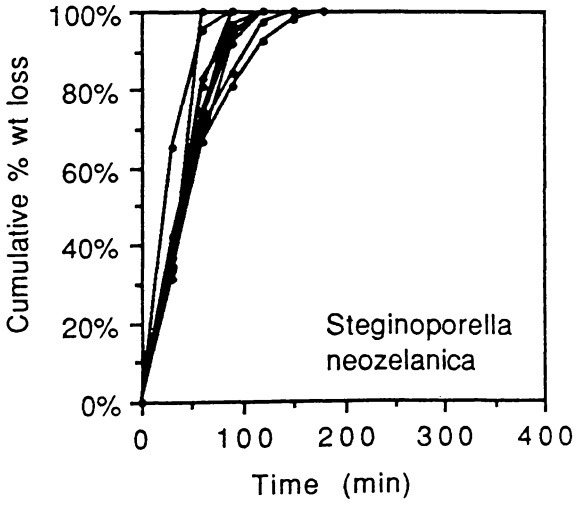

Cumulative % wt loss
100%
80%
60%
40%
20%
0%
0
100
200
300
400
Time (min)
Iodictyum
yaldwyni

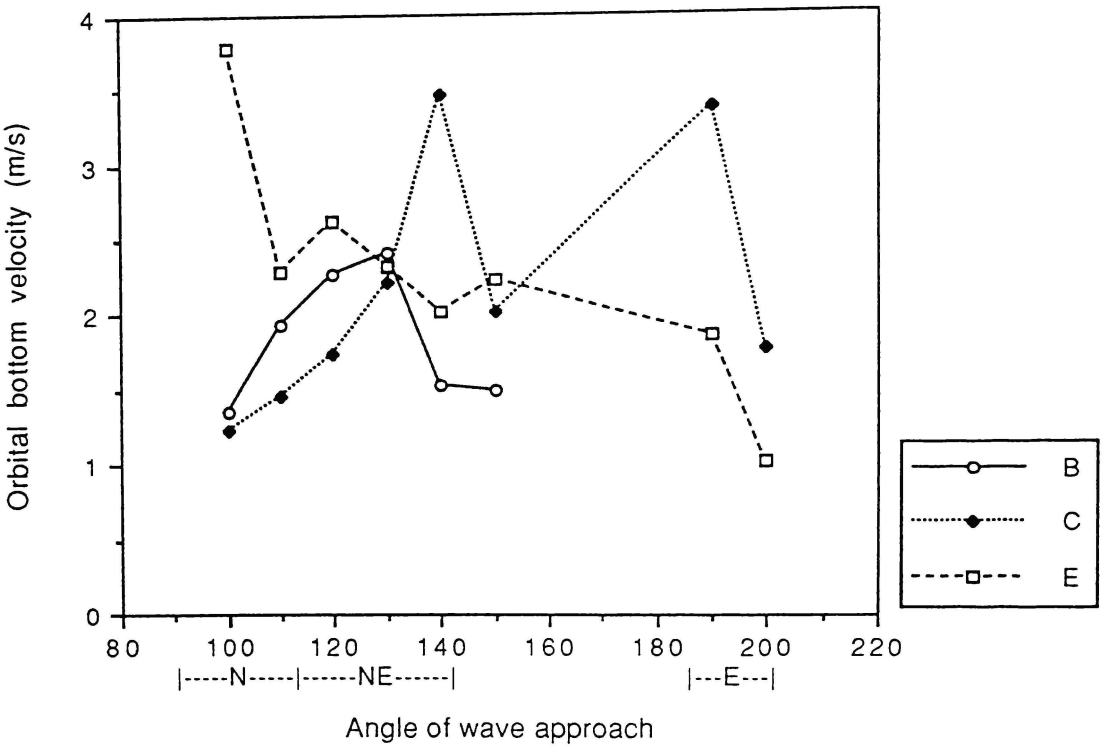

Cumulative % wt loss
100%
80%
60%
40%
20%
0%
0
100
200
300
400
Time (min)
Lichenopora
sp.


Cumulative % wt loss
100%
80%
60%
40%
20%
0%
0
100
200
300
400
Time (min)
Mecynoecia
purpurascens


Cumulative % wt loss
100%
80%
60%
40%
20%
0%
0
100
200
300
400
Time (min)
Otionella
squamosa


Cumulative % wt loss
100%
80%
60%
40%
20%
0%
0
100
200
300
400
Time (min)
Steginoporella
magnifica


Cumulative % wt loss
100%
80%
60%
40%
20%
0%
0
100
200
300
400
Time (min)
Steginoporella
neozelanica



Design wave
Height: 9.08 m Period: 13.9 m Based on a storm in July, 1978.

Appendix Figure 5A.1: Results from computer simulation of wave refraction (Black and Healy, 1981) carried out at three sites at Goat Island Bay, Leigh.

Site B at 15 m water depth and moderately exposed; site C at 8 m and sheltered; site E at 21 m and exposed.

Appendix Tables

Table AI.1 Classification of New Zealand bryozoans mentioned in this thesis (after Ryland, 1970; and Gordon, 1984, 1986, 1989).

Class Stenolaemata
Order Cyclostomida
Suborder Tubuliporina
Superfamily Tubuliporoidea
Family Plagioeciidae
Plagioecia sarniensis (Norman)
Family Tubuliporidae
Platonea sp.
Tubulipora anderssoni
Tubulipora sp.
Hemipustulopora harmeri Brood
Family Theonoidae
Telopora buski d'Hondt
Family Multiparsidae
"Idmonea" sp.
Family Hastingsiidae
Hastingsia irregularis Borg
Family Mecynoeciidae
Mecynoecia purpurascens (Hutton)
Mecynoecia sp.
Family Annectocymidae
Annectocyma sp.
Family Cinctiporidae
Cinctipora elegans (Hutton)
Suborder Articulina
Superfamily Crisioidea
Suborder Cancellina
Superfamily Horneroidea
Family Horneridae
Hornera foliacea MacGillivray
Hornera sp.
Suborder Rectangulina
Superfamily Lichenoporoidea
Family Lichenoporidae
Disporella gordoni Taylor, Schembri and Cook

Disporella n. sp.

Lichenopora cf *novaezelandiae*

Lichenopora sp.

Class Gymnolaemata

Order Ctenostomida

Suborder Stoloniferina

Superfamily Penetrantioidea

Family Penetrantiidae

Immergentia atypica

Penetrantia parva

Penetrantia irregularis Silen

Penetrantia spp. indet.

Spathipora sp.

Terebripora sp.

Order Cheilostomida

Suborder Scrupariina

Superfamily Scruparoidea

Suborder Malacostegina

Superfamily Membraniporoidea

Family Membraniporidae

Membranipora tuberculata (Bosc)

Family Electridae

Suborder Neocheilostomina

Superfamily Calloporoidea

Family Flustridae

Family Calloporidae

Foveolaria (Odontionella) cyclops (Busk)

Family Chaperiidae

Chaperia acanthina (Lamouroux)

Chaperiopsis tintinnabula Hayward and Thorpe

Patsyella flemingi Brown

Superfamily Buguloidea

Family Bugulidae

Bugula dentata Lamouroux

Bugula flabellata (Thompson in Gray)

Bugula neritina (Linnaeus)

Family Cabereidae

Caberea zelandica (Gray)

Menipea zelandica Hastings

Superfamily Microporoidea

Family Selenariidae

Otionella squamosa (Tenison-Woods)

Otionella sp.

Family Steginoporellidae

Steginoporella magnifica Harmer

Steginoporella neozelanica (Busk)

Steginoporella perplexa Livingstone

Family Macroporidae

Macropora grandis (Hutton)

Family Microporidae

Manzonella lepida (Hincks)

Superfamily Cellarioidea

Family Cellariidae

Cellaria immersa (Tenison-Woods)

Cellaria tenuirostris (Busk)

Melicerita chathamensis Uttley & Bullivant

Suborder Ascophorina

Infraorder Cribriomorpha

Superfamily Cribrilinoidea

Family Euthyroididae

Euthyroides episcopalis (Busk)

Euthyroides jellyae Levinsen

Superfamily Catenicelloidea

Family Eurystomellidae

Eurystomella foraminigera (Hincks)

Family Catenicellidae

Cornuticella taurina (Busk)

Infraorder Hippothoomorpha

Superfamily Hippothooidea

Family Hippothoidae

Celleporella cancer (Hutton)

Family Pasytheidae

Gemellipora eburnea Smitt

Infraorder Umbonulomorpha

Superfamily Arachnopusioidea

Family Arachnopusiidae

Arachnopusia unicornis (Hutton)

Superfamily Umbonuloidea

Family Exochellidae

Escharoides angela (Hutton)

Escharoides excavata (MacGillivray)

Family Celleporariidae

Celleporaria agglutinans (Hutton)

Superfamily Adeonoidea

Family Adeonidae

Adeonellopsis sp.

Infraorder Lepraliomorpha

Superfamily Schizoporelloidea

Family Hippoporinidae

Metroperiella mucronifera (Powell)

Family Gigantoporidae

Gigantopora pupa (Jullien)

Family Cryptosulidae

Cryptosula pallasiana (Moll)

Family Watersiporidae

Watersipora arcuata Banta

Watersipora subtorquata (d'Orbigny)

Family Schizoporellidae

Schizoporella unicornis

Chiastosella splendida Livingstone

Escharina waiparaensis Brown

Hippomenella vellicata (Hutton)

Family Smittinidae

Hippomonavella flexuosa (Hutton)

Parasmittina sp.

Smittoidea maunganuiensis (Waters)

Family Microporellidae

Fenestrulina sp.

Family Margarettidae

Margaretta barbata (Lamarck)

Superfamily Celleporoidea

Family Hippoporidridae

Odontoporella adpressa (Busk)

Family Celleporidae

Celleporina costazii (Audouin)

Celleporina grandis Gordon

Celleporina sp.

Galeopsis polyporus (Brown)

Galeopsis porcellanicus (Hutton)

Family Philodoporidae

Hippellozoon novaezelandiae (Waters)

Iodictyum yaldwyni Powell

Superfamily Consecharellinoidea

Family Conescharellinidae

Conescharellina angulopora (Tenison-Woods)

Table AI.2: List of Abbreviations used in this thesis.

Common abbreviations (used throughout)	
SCUBA	Self-contained underwater breathing apparatus
SEM	Scanning electron microscope
T	Temperature
Wt	Weight
XRD	X-ray diffraction
Bryozoan zoarial growth forms: (Defined in Introduction, Figure IB.2)	
EFar	Erect flexible, articulated
EFde	Erect flexible, delicate branching
EFfo	Erect flexible, foliose
EFrt	Erect flexible, rooted
ENml	Encrusting, multilaminar
ENra	Encrusting, radiate
ENul	Encrusting, unilaminar
ENus	Encrusting, uniserial
ERde	Erect rigid, delicate branching
ERfe	Erect rigid, fenestrate
ERfo	Erect rigid, foliose
ERma	Erect rigid, massive
ERra	Erect rigid, radiate
ERro	Erect rigid, robust branching
FLmo	Free-living, motile
FLrt	Free-living, rooted
Measurements of carbonate production (Defined in Chapter 1, Section A)	
APR	Areal production rate
GPR	Gross production rate
ICP	Individual carbonate production
ICPR	Individual carbonate production rate
NPR	Net production rate
Mineralogy of bryozoans (Defined in Chapter 2, Section A, figure 2A.6)	
A	Aragonite
Bi	Bimineralic
C	Calcite
M	High-Mg calcite
Mo	Monomineralic
Mineralogical classes of New Zealand bryozoans (Defined in Chapter 2, Section B, Table 2B.4)	
B/A	Bimineralic or aragonite
B/C	Bimineralic or calcite
hi C	High-Mg calcite
lo C	Low-Mg calcite
mod C	Moderalte-Mg calcite

Taxonomy of bryozoans
(Defined in Chapter 2, Section A, Table 2A.1)

Anas	Anascans
Asco	Ascophorans
Ch	Cheilostomes
Cy	Cyclostomes

Sources of sediment samples
(Defined in Chapter 2, Section B, Table 2B.1)

AMS	the author
CSN	C. S. Nelson
DPG	D. P. Gordon
JG	J. Gillespie
NZOI	New Zealand Oceanographic Institute
UW	University of Waikato Archives

Locations
(Defined in Chapter 2, Appendix table A2.4)

BOP	Bay of Plenty, Coromandel
CKS	Cook Strait
CNT	Canterbury Shelf
HKG	Hauraki Gulf
NLD	Northland
NZ	New Zealand
OTG	Otago Shelf
SAI	Sub-Antarctic Islands
SFL	South Fiordland
STP	Subtropical Pacific
STS	Stewart Island, Snares Islands
Tas	Tasmania, Australia
TKP	Three Kings Plateau
WNG	Wanganui Basin

Dissolution parameters
(Defined in Chapter 4, Section D2)

DHL	Dissolution half-life
TTD	Total time to dissolve
W30	% weight lost after 30 minutes

Sediment textural groups
(Defined in Chapter 4, Figure 4B.2)

cg	Coarse gravel
fg	Fine gravel
vcs	Very coarse sand
cs	Coarse sand
ms	Medium sand
fs	Fine sand
vfs	Very fine sand
m	Mud
s	Sand
g	Gravel

Abrasion samples	
(Defined in Chapter 4, Table 4B.2)	
-N	"New" = fresh-looking
-O	"Old" = degraded looking
Degree of resistance to abrasion	
(Defined in Chapter 4, Figure 4B.4)	
l	Low
m or mod	Moderate
h	High
Species used in dissolution experiment	
(Defined in Chapter 4, Table 4D.2)	
Fc	Foveolaria cyclops
Ls	Lichenopora sp.
Tb	Telopora buski
Cs	Chiastosella splendida
Mp	Mecynoecia purpurascens
Sm	Steginoporella magnifica
Sn	Steginoporella neozelanica
Gp	Galeopsis porcellanicus
As	Adeonellopsis sp.
Hs	Hornera sp.
Iy	Iodictyum yaldwyni
Cc	Celleporina costazii
Os	Otionella squamosa
Sedimentary facies of the Hauraki Gulf (Greig, 1982)	
(Defined in Chapter 5, Figure 5D.3)	
CCF	Colville Channel Facies
CGF	Central Gulf Facies
IGF	Inner Gulf Facies
Textural classifications (Folk, 1974)	
(Defined in Chapter 6, Figure 6D.1)	
msG	Muddy sandy gravel
sG	Sandy gravel
gS	Gravelly sand
gmS	Gravelly muddy sand
gM	Gravelly mud
M	Mud
sM	Sandy mud
mS	Muddy sand
S	Sand
Subdominant skeletal components	
(Defined in Chapter 6, Figure 6E.3)	
B	Bryozoans
G	Gastropods
C	Cirripedes (barnacles)

Abundance	
(Defined in Chapter 11, Table 11C.5)	
C	Common
x	Present
Geological time periods	
(Defined in Chapter 11, Figure 11D.5)	
O	Ordovician
S	Silurian
D	Devonian
C	Carboniferous
Pm	Permian
Tr	Triassic
Jr	Jurassic
K	Cretaceous
P	Paleogene
N	Neogene
R	Recent
L	Lower
M	Middle
U	Upper
Susceptibility to diagenesis	
(Defined in Chapter 13, Figure 13F.1)	
o	Low
X	Moderate
XXX	High

Table AI.3: Details of some methodologies used in this thesis.

X-ray diffractometry

Equipment:	Philips Compact Analyzer System 1840 PW1729 x-ray generator P1840 goniometer PM8203A one line recorder	
Settings:	generator	20 kv 20 mA
	goniometer	From 25.0 to 32.5 °2Θ Speed 0.02 °2Θ/s Chart 50 mm/°2Θ Range 2000 c/s TC 1.0 s Slit 0.2 mm
	recorder	Chartdrive 10 mm/s

Sample preparation:
pick clean specimens, record species and sample
soak in dilute bleach
rinse with distilled water
probe ultrasonically 5 to 20 seconds
dry
add halite
crush to powder
sieve powder through 200 μm mesh
backfill dry powder mount

Analysis of charts:
label halite peak 31.72 °2Θ
find aragonite peaks if any at 26.2 and 27.2 °2Θ
find exact position of calcite peak (between 29.4 and 30.0 °2Θ)
measure peak heights
find wt% $MgCO_3$ using curve from Chave (1952)
find % aragonite using calibration curve (Figure 2B.4)

Underwater photography

Equipment:	Nikonos V camera Nikonos SB4 Flash Microframer and extension tubes 50 ASA Fujichrome film	
Settings:	Camera	minimum focal length F-stop 16 or 22 Speed 1/125 sec 50 ASA
	Flash	1/4 strength

Calculation of temperature from stable isotopes in carbonate
(using method of Morse and Mackenzie, 1990)

Given	$\delta^{18}O$ of water measured relative to SMOW (Standard mean ocean water) (SMOW = 0.002) $\delta^{18}O$ of skeleton measured relative to PDB (Cretaceous belemnite)
Calculate x	$x = \delta SMOW - \delta SKEL$
Calculate T (°C)	$T=16.0 - 4.14x + 0.13x^2$

Table A1.1: Maximum growth rates of marine calcareous bryozoans reported in the published world-wide literature.

Source	Species	Growth rate (as published)
Skerman, 1958	*Cryptosula pallasiana*	12 cm^2 /6 mo
Schneider 1963	*Bugula avicularia*	7 mm high/2 mo 5 bifurc/2 mo
Bushnell, 1966	*Cryptosula pallasiana*	5-9 d/double in size
	Bugula turrita	2-4.5 d/double in size
Gordon, 1968	*Eurystomella foraminigera*	+56-310 zooids/17 wk
	Eurystomella foraminigera	790mm^2 /4y
	Eurystomella foraminigera	4400 zooids/4y
	Fenestrulina sp.	380mm^2 /2y
	Fenestrulina sp.	1280 zooids/2y
Smith and Haderlie, 1969	*Crisulipora occidentalis*	60 mm/9 mo
	Tubulipora pacifica	15 mm/12 mo
	Bugula californica	25 mm/9 mo
	Bugula neritina	40 mm/9 mo
	Holoporella brunnea	40 mm/6 mo
Stebbing, 1971	*Flustra foliacea*	1.5 cm/y
Humphries, 1973	*Microporella ciliata*	7.5 mm^2 /63 d
	Microporella ciliata	49 zooids/63 d
	Conopeum tenuissimum	2.5 -130 mm^2 /21 d
	Conopeum tenuissimum	14 - 700 zooids/21 d
Hayward and Ryland, 1975	*Bugula neritina*	1500 zooids/30 d
	Bugula simplex	10,000 zooids/28 d
	Watersipora subtorquata	150 zooids/28 d
Vail and Wass, 1981	*Tubulipora sp.*	4 mm^2 /2wk
	Rhynchozoon sp.	44 mm^2 /5wk
	Schizoporella unicornis	11,847 mm^2 /22 wk
	Valdemunitella valdemunita	151 mm^2 /wk
	Celleporaria fusca	1548 mm^2 /5 wk
	Bugula neritina	476 mm^2 /2 wk
	Scrupocellaria scrupea	3439 mm^2 /12 wk
	Watersipora arcuata	20 mm^2 /2 wk
	Beania magellanica	859 mm^2 /9 wk
	Cyclicopora longipora	352 mm^2 /9 wk
	Bugula avicularia	196 mm^2 /4 wk
Yashioka, 1982	*Membranipora membranacea*	0.194 cm/d

Source	Species	Growth rate (as published)
Winston, 1983	*Melicerita obliqua*	10 cm high/10 y
	Cellarinella margueritae	5-6 mm/y
Palumbi and Jackson, 1983	*Steginoporella sp.*	regen .274 mm^2 /d
Harvell, 1984	*Membranipora membranacea*	58 zooids/d
Winston and Jackson, 1984	*Cleidochasma porcellanum*	1.9 mm^2 /d
	Coleopora sp.	0.5 mm^2 /d
	Cribrilaria radiata	0.3 mm^2 /d
	Cigclisula aviculifera	0.44 mm^2 /d
	Cigclisula turrita	0.04 mm^2 /d
	Drepanophora tuberculatum	1.6 mm^2 /d
	Gephyrophora rubra	3.5 mm^2 /d
	Microporella umbracula	1.4 mm^2 /d
	Parasmittina sp.	5.8 mm^2 /d
	Parellisina curvirostris	0.31 mm^2 /d
	Reptadeonella "plagiopora"	1.5 mm^2 /d
	Smittipora levinseni	4.2 mm^2 /d
	Steginoporella sp. nov.	14 mm^2 /d
	Stylopoma spongites	2.5 mm^2 /d
	Trypostega venusta	8.7 mm^2 /d
Keough, 1986	*Bugula neritina*	6 bifurc/28 d
	Bugula neritina	11 bif/100 d
Patzold et al., 1987	*Pentapora foliacea*	2 cm/y
	Pentapora foliacea	20 cm diam, 10 cm hi
	Pentapora foliacea	in 3 y
Swami and Karande, 1987	*Electra bengalensis*	15 cm/90 d
	Membranipora annae	15 cm/90 d
	Membranipora tenuis	13 cm/90 d
	Acanthodesia sp.	9.5 cm/90 d
	Hippoporina indica	4 cm/90 d
McKinney and Jackson, 1989	*Bugula neritina*	8 cm tall in 6 mo
	Drepanophora tuberculatum	2-3 cm^2 in 6 mo
	Disporella fimbriata	1 cm^2 in 3-6 mo
	Membranipora savartii	10 cm across
Udhayakumar and Karande, 1989	*Electra bengalensis*	71.8 cm^2 /80 d
	Membranipora annae	42.2 cm^2 /80 d
	Membranipora tenuis	15.6 cm^2 /60 d
	Membranipora savartii	7.3 cm^2 /60 d
	Acanthodesia sp.	3 cm^2 /60 d
	Hippoporina indica	1.3 cm^2 /60 d
Bone, 1991	*Membranipora aciculata*	6 cm diam, unilam/3 mo
	Membranipora aciculata	2mm/day

Table A1.2: Lifespans and turnovers of marine calcareous bryozoans in the published world-wide literature.

Source	Species	Lifespan (as published)	Turnover (1/y)
Gordon, 1968	*Eurystomella foraminigera*	zooid 135 d	2.70
Smith and Haderlie, 1969	*Crisulipora occidentalis*	6 mo	2.00
	Tubulipora pacifica	2 mo	6.00
	Bugula californica	7 mo	1.71
	Bugula neritina	3 mo	4.00
	Holoporella brunnea	6 mo	2.00
Smith, 1970	*Diaperoecia californica*	3 y	0.33
	Philodopora pacifica	2 y	0.50
	Membranipora sp.	6 mo	2.00
	Antropora sp.	6 mo	2.00
	Scrupocellaria sp.	6 mo	2.00
Stebbing, 1971	*Flustra foliacea*	up to 12 y	0.08
Osman, 1977	*Schizoporella errata*	10 y	0.10
Winston and Heimberg, 1986	*Flustra thysanica*	6-12 y	0.17 to 0.08
Patzold et al., 1987	*Pentapora foliacea*	3 y	0.33
McKinney and Jackson, 1989	*Membranipora membranacea*	6 mo	2.00
	Bugula neritina	6 mo	2.00
	Drepanophora tuberculatum	6 mo	2.00
	Disporella fimbriata	4 mo to 3 y	3 to 0.33
	Membranipora savartii	3 mo	4.00

Table A1.3: Size data for several New Zealand bryozoans used in growth rate calculations.

Strongly calcified encrusting species	Zooids	Area (mm^2)	Height (mm)	$CaCO_3$ (g)	Density ($\mu g/mm^3$)	$CaCO_3$ /zooid (g/z)	$CaCO_3$ /area (g/mm^2)
Chaperia acanthina	50	8.0	0.6	0.003	0.62500	0.00006	0.00038
Chaperiopsis tintinnabula	75	18.0	0.7	0.010	0.79365	0.00013	0.00056
Escharoides angela	16	9.5	0.9	0.004	0.46685	0.00025	0.00042
Escharoides excavata	49	17.2	0.7	0.009	0.74969	0.00018	0.00052
Escharoides excavata	37	13.8	0.7	0.009	0.93168	0.00024	0.00065
Hippellozoon novaezelandiae	120	22.0	0.6	0.016	1.21212	0.00013	0.00073
Hippomenella vellicata	57	40.1	0.7	0.011	0.39237	0.00019	0.00027
Hippomonavella flexuosa	260	44.9	0.4	0.013	0.72464	0.00005	0.00029
Lichenopora cf novaezelandiae	800	47.8	1.2	0.005	0.08720	0.00001	0.00010
Lichenopora cf novaezelandiae	600	34.2	0.8	0.003	0.10961	0.00001	0.00009
Lichenopora cf novaezelandiae	600	26.4	0.7	0.002	0.10814	0.00000	0.00008
Smittoidea maunganuiensis	85	25.7	0.5	0.014	1.09162	0.00016	0.00055
Smittoidea maunganuiensis	280	48.9	0.2	0.008	0.81833	0.00003	0.00016
Steginoporella perplexa	172	59.7	1.2	0.053	0.74018	0.00031	0.00089
Mean					0.63222	0.00013	0.00041

Weakly calcified erect species	Zooids	Bifurc-ations	Height (mm)	$CaCO_3$ (g)	$CaCO_3$ /zooid	$CaCO_3$ /bifurc	$CaCO_3$ /ht
Bugula dentata	1000	7	25.5	0.008	0.00001	0.00114	0.00031
Bugula dentata	1200	8	27.9	0.015	0.00001	0.00188	0.00054
Caberea zelandica	1500	8	19.9	0.046	0.00003	0.00575	0.00231
Caberea zelandica	220	5	10.0	0.020	0.00009	0.00400	0.00200
Mean					0.00004	0.00319	0.00129

Strongly calcified erect species	Zooids	Bifurc-ations	Height (mm)	$CaCO_3$ (g)	$CaCO_3$ /zooid	$CaCO_3$ /bifurc	$CaCO_3$ /ht
Galeopsis porcellanicus			19.4	1.518			0.07825
Mecynoecia purpurascens			22.7	1.886			0.08308
Mecynoecia purpurascens			17.8	1.591			0.08938
Mecynoecia purpurascens			16.4	1.020			0.06220
Melicerita chathamensis	706		18.2	0.030	0.00004		0.00165
Mean					0.00004		0.06291

Table A1.4: Calculation of individual carbonate production rates of bryozoans from published growth rates.

Species	Maximum growth rate (as published)	Standardized growth rates				Factor used in conversion	Calculated production rate (g $CaCO_3$ /y)
		mm high/y	bifurc/y	zooids/y	mm^2 /y		
Bugula avicularia	7 mm high/2 mo	43				0.00129	0.055
Bugula avicularia	5 bifurc/2 mo		30			0.00319	0.097
Bugula californica	25 mm/9 mo	33				0.00129	0.043
Bugula neritina	40 mm/9 mo	53				0.00129	0.069
Bugula neritina	1500 zooids/30 d			18250		0.00004	0.730
Bugula neritina	2 zooids/4 d			183		0.00004	0.007
Bugula neritina	6 bifurc/28 d		78			0.00319	0.250
Bugula neritina	11 bif/100 d		40			0.00319	0.128
Bugula neritina	8 cm tall in 6 mo	160				0.00129	0.206
Bugula simplex	10,000 zooids/28 d			130357		0.00004	5.214
Cellarinella margueritae	6mm/y	6				0.00129	0.008
Celleporaria fusca	1548 mm^2 /5 wk				113004	0.00041	46.332
Cigclisula aviculifera	0.44 mm^2 /d				161	0.00041	0.066
Cigclisula turrita	0.04 mm^2 /d				15	0.00041	0.006
Cleidochasma porcellanum	1.9 mm^2 /d				694	0.00041	0.284
Coleopora sp.	0.5 mm^2 /d				183	0.00041	0.075
Conopeum tenuissimum	130 mm^2 /21 d				2260		
Conopeum tenuissimum	700 zooids/21 d			12167		0.00004	0.487
Cribrilaria radiata	0.3 mm^2 /d				110	0.00041	0.045
Crisulipora occidentalis	60 mm/9 mo	80				0.00129	0.103
Cryptosula pallasiana	12 cm^2 /6 mo				2400	0.00041	0.984
Cyclicopora longipora	352 mm^2 /9 wk				2034	0.00041	0.834
Disporella fimbriata	1 cm^2 in 3-6 mo				400	0.00041	0.164
Drepanophora tuberculatum	1.6 mm^2 /d				584	0.00041	0.239
Drepanophora tuberculatum	3 cm^2 in 6 mo				600	0.00041	0.246
Electra bengalensis	15 cm/90 d	608				0.00129	0.785
Electra bengalensis	71.8 cm^2 /80d				32759		

Species	Maximum growth rate (as published)	Standardized growth rates				Factor used in conversion	Calculated production rate (g $CaCO_3$ /y)
		mm high/y	bifurc/y	zooids/y	mm^2 /y		
Eurystomella foraminigera	310 zooids/17 wk			948		0.00004	0.038
Eurystomella foraminigera	4400 zooids/4y			1100		0.00004	0.044
Fenestrulina sp.	1280 zooids/2y			640		0.00004	0.026
Flustra foliacea	1.5 cm/y	15				0.00129	0.019
Gephyrophora rubra	3.5 mm^2 /d				1278	0.00041	0.524
Hippoporina indica	4 cm/90 d				20612	0.00041	8.451
Hippoporina indica	1.3 cm^2 /60 d				791	0.00041	0.324
Melicerita obliqua	10 cm high/10 y	10				0.06291	0.629
Microporella ciliata	7.5 mm^2 /63 d				43	0.00041	0.018
Microporella ciliata	49 zooids/63 d			284		0.00013	0.037
Microporella umbracula	1.4 mm^2 /d				511	0.00041	0.210
Parasmittina sp.	5.8 mm^2 /d				2117	0.00041	0.868
Parellisina curvirostris	0.31 mm^2 /d				113	0.00041	0.046
Pentapora foliacea	2 cm/y				314	0.00041	0.129
Pentapora foliacea	20 cm diam/3y				38	0.00041	0.016
Pentapora foliacea	10 cm hi/3 y	3				0.06291	0.210
Rhynchozoon sp.	44 mm^2 /5wk				458	0.00041	0.188
Schizoporella unicornis	11,847 mm^2 /22 wk				28002	0.00041	11.481
Scrupocellaria scrupea	3439 mm^2 /12 wk				14902	0.00041	6.110
Smittipora levinseni	4.2 mm^2 /d				1533	0.00041	0.629
Steginoporella sp.	regen .274 mm^2 /d				100	0.00041	0.041
Steginoporella sp.nov.	14 mm^2 /d				5110	0.00041	2.095
Stylopoma spongites	2.5 mm^2 /d				913	0.00041	0.374
Trypostega venusta	8.7 mm^2 /d				3176	0.00041	1.302
Tubulipora pacifica	15 mm/12 mo				177	0.00041	0.072
Tubulipora sp.	4 mm^2 /2wk				104	0.00041	0.043
Valdemunitella valdemunita	151 mm^2 /wk				7852	0.00041	3.219
Watersipora arcuata	20 mm^2 /2 wk				520	0.00041	0.213
Watersipora subtorquata	150 zooids/28 d			1955		0.00013	0.254
mean		101	50	18432	7172		1.760

Table A1.5: Weight of carbonate in bryozoans grown for specified intervals at Cape Rodney in 14 m water depth. Sample numbers consist of species (letter), time in months, and an individual sample number.

THREE MONTHS IMMERSION

Lichenopora cf. novaezelandiae

Sample	Weight (g)
A 3 1	0.004
A 3 2	0.004
A 3 3	0.004
A 3 4	0.004
A 3 5	0.004
A 3 6	0.004
A 3 7	0.004
A 3 8	0.010
A 3 9	0.010
A 3 10	0.010
A 3 11	0.010
A 3 12	0.006
A 3 13	0.006
A 3 14	0.006
A 3 15	0.006
A 3 16	0.006
A 3 17	0.003
A 3 18	0.003
A 3 19	0.003
A 3 20	0.003
mean	0.006
annual rate	0.021 g/y

Disporella n.sp.

Sample	Weight (g)
F 3 1	0.002
F 3 2	0.002
F 3 3	0.002
F 3 4	0.002
F 3 5	0.020
F 3 6	0.017
F 3 7	0.017
F 3 8	0.017
F 3 9	0.010
F 3 10	0.010
F 3 11	0.010
F 3 12	0.010
F 3 13	0.010
F 3 14	0.010
F 3 15	0.010
F 3 16	0.010
F 3 17	0.010
F 3 18	0.010
mean	0.010
annual rate	0.037 g/y

Tubulipora anderssoni

Sample	Weight (g)
N 3 1	0.010
N 3 2	0.050
N 3 3	0.010
N 3 4	0.015
N 3 5	0.015
mean	0.020
annual rate	0.075 g/y

Mecynoecia purpurascens

Sample	Weight (g)
B 3 1	0.037
B 3 2	0.007
mean	0.022
annual rate	0.090 g/y

Manzonella lepida

Sample	Weight (g)
P 3 1	0.010
mean	0.010
annual rate	0.038 g/y

NINE MONTHS IMMERSION

Lichenopora cf. novaezelandiae

Sample	Weight (g)
A 9 1	0.003
A 9 2	0.001
A 9 3	0.001
A 9 4	0.001
A 9 5	0.005
mean	0.002
annual rate	0.003 g/y

Galeopsis porcellanicus

Sample	Weight (g)
J 9 1	0.262
J 9 2	0.265
J 9 3	0.015
J 9 4	0.030
mean	0.143
annual rate	0.181 g/y

Mecynoecia sp.

Sample	Weight (g)
B 9 1	0.022
B 9 2	0.015
B 9 3	0.014
B 9 4	0.006
mean	0.014
annual rate	0.018 g/y

Smittoidea maunganuiensis

Sample	Weight (g)
K 9 1	0.040
K 9 2	0.033
mean	0.037
annual rate	0.046 g/y

Telopora buski

Sample	Weight (g)
C 9 1	0.019
C 9 2	0.020
C 9 3	0.005
C 9 4	0.003
mean	0.012
annual rate	0.015 g/y

Escharoides angela

Sample	Weight (g)
L 9 1	0.076
L 9 2	0.009
mean	0.043
annual rate	0.054 g/y

Disporella gordoni

Sample	Weight (g)
E 9 1	0.281
E 9 2	0.156
E 9 3	0.581
E 9 4	0.216
E 9 5	0.062
E 9 6	0.166
E 9 7	0.068
E 9 8	0.395
E 9 9	0.057
E 9 10	0.023
E 9 11	0.103
E 9 12	0.148
E 9 13	0.098
E 9 14	0.112
E 9 15	0.024
E 9 16	0.184
E 9 17	0.138
E 9 18	0.121
E 9 19	0.237
E 9 20	0.027
mean	0.160
annual rate	0.203 g/y

Caberea zelandica

Sample	Weight (g)
G 9 1	0.026
G 9 2	0.012
G 9 3	0.048
G 9 4	0.006
G 9 5	0.026
G 9 6	0.009
G 9 7	0.018
G 9 8	0.016
G 9 9	0.051
mean	0.024
annual rate	0.030 g/y

Arachnopusia unicornis

Sample	Weight (g)
H 9 1	0.032
M 9 1	0.031
M 9 2	0.293
M 9 3	0.034
M 9 4	0.315
M 9 5	0.178
M 9 6	0.014
M 9 7	0.053
M 9 8	0.006
M 9 9	0.035

Arachnopusia unicornis

Sample	Weight (g)
M 9 10	0.010
M 9 11	0.012
M 9 12	0.265
M 9 13	0.028
M 9 14	0.062
M 9 15	0.242
M 9 16	0.001
M 9 17	0.236
M 9 18	0.132
M 9 19	0.109
M 9 20	0.023
M 9 21	0.018
M 9 22	0.129
M 9 23	0.089
M 9 24	0.235
M 9 25	0.028
M 9 26	0.039
M 9 27	0.054
M 9 28	0.030
mean	0.000
annual rate	0.000 g/y

TWELVE MONTHS IMMERSION

Hastingsia ?irregularis

Sample	Weight (g)
D 12 1	0.194
mean	0.194
annual	0.188
rate	g/y

Plagioecia sarniensis

Sample	Weight (g)
U 12 1	0.001
mean	0.001
annual	0.001
rate	g/y

Escharoides angela

Sample	Weight (g)
L 12 1	0.144
mean	0.144
annual	0.139
rate	g/y

Disporella gordoni

Sample	Weight (g)
E 12 1	0.131
E 12 2	0.039
E 12 3	0.031
E 12 4	0.044
E 12 5	0.066
E 12 6	0.483
E 12 7	0.115
E 12 8	0.078
E 12 9	0.082
E 12 10	0.066
E 12 11	0.027
E 12 12	0.087
E 12 13	0.125
E 12 14	0.061
E 12 15	0.096
E 12 16	0.014
mean	0.097
annual	0.093
rate	g/y

Galeopsis porcellanicus

Sample	Weight (g)
J 12 1	0.036
J 12 2	0.028
J 12 3	0.228
J 12 4	0.193
J 12 5	0.181
J 12 6	0.010
J 12 7	0.029
J 12 8	0.026
J 12 9	0.124
mean	0.095
annual	0.092
rate	g/y

Annectocyma sp.

Sample	Weight (g)
Q 12 1	0.012
Q 12 2	0.071
Q 12 4	0.024
mean	0.036
annual	0.035
rate	g/y

Smittoidea maunganuiensis

Sample	Weight (g)
K 12 1	0.092
K 12 2	0.078
K 12 3	0.015
K 12 4	0.007
K 12 5	0.013
K 12 6	0.055
K 12 7	0.039
K 12 8	0.040
K 12 9	0.029
K 12 10	0.016
K 12 11	0.007
K 12 12	0.041
K 12 13	0.006
mean	0.034
annual	0.033
rate	g/y

Arachnopusia unicornis

Sample	Weight (g)
M 12 1	0.188
M 12 2	0.165
M 12 3	0.127
M 12 4	0.090
M 12 5	0.227
M 12 6	0.039
M 12 7	0.218
M 12 8	0.004
M 12 9	0.064
M 12 10	0.128
M 12 11	0.043
M 12 12	0.030
mean	0.110
annual	0.107
rate	g/y

Tubulipora anderssoni

Sample	Weight (g)
N 12 1	0.003
N 12 2	0.018
mean	0.011
annual	0.010
rate	g/y

Tubulipora sp.

Sample	Weight (g)
R 12 1	0.026
Q 12 3	0.009
mean	0.018
annual	0.017
rate	g/y

Hornera sp.

Sample	Weight (g)
S 12 1	0.074
mean	0.074
annual	0.072
rate	g/y

Celleporina sp.

Sample	Weight (g)
T 12 1	0.116
mean	0.116
annual	0.112
rate	g/y

Table A1.6: Some published calcification rates for marine organisms.

Source	Organism	Location	Production rate (g $CaCO_3$ /m^2/y)
	Algae		
Neumann and Land, 1975	Green calcareous	Bahamas	90
Stockman et al., 1967	Penicillus	Florida Bay	3 - 25
Littler, 1971	Red coralline	Hawaii	500 - 2500
Adey and Vassar, 1975	Red coralline	St. Croix	0 - 7
Cucci, 1979	Red calcareous	Iona	30
Smith, 1970	Red algae	S. California	159
	Foraminifera		
Muller, 1974	Benthic	Hawaii	260
Hallock, 1981	Benthic	Hawaii	40 - 150
Hallock, 1981	Benthic	Palau	50 - 2800
	Invertebrates		
Chave et al., 1972	Coral	Indo-Pacific	24000 - 31000
Cucci, 1979	Barnacles	Iona	30
Smith, 1970	Bryozoans	California	170
Smith (this study)	Bryozoans	New Zealand	24
	Communities		
Moore, 1972	Macrobenthos	Florida	400 - 1000
Broeker and Takahashi, 1966	Carbonate bank	Bahamas	500
Smith, 1970	Shallow rocky	California	70 - 4000

Table A2.1: Mineralogical data for bryozoans taken from published literature.

Genus	Species	Order	Suborder	Location	Cond	Growth Form	Wt % Calc.	Wt % $MgCO_3$	Source
Entalophora	*proboscidea*	Cyclo	?	Strait of Sicily	F		100.0	2.5	P&S 73
Entalophora	*proboscidea*	Cyclo	?	Strait of Sicily		ERde	100.0	2.0	P&S 74
Entalophora	*sp.*	Cyclo	?	Ionian Sea		ERde	100.0	3.0	P&S 74
Filicrisia	*sp.*	Cyclo	?	Tyrrhenian Sea		EF	100.0	3.0	P&S 74
Tervia	*irregularis*	Cyclo	?	Adriatic Sea		ERde	100.0	1.0	P&S 74
Crisia	*eburnea*	Cyclo	Artic	Martha's Vineyard	F			5.1	S&M 67
Crisia	*elongata*	Cyclo	Artic	Strait of Sicily		EF	100.0	4.0	P&S 74
Hornera	*striata*	Cyclo	Canc	Strait of Sicily	F	ERde	100.0	4.2	P&S 73
Hornera	*striata*	Cyclo	Canc	Strait of Sicily	F	ERde	100.0	1.7	P&S 73
Hornera	*striata*	Cyclo	Canc	Strait of Sicily	F	ERde	100.0	1.7	P&S 73
Hornera	*striata*	Cyclo	Canc	Strait of Sicily		ERde	100.0	4.0	P&S 74
Hornera	*striata*	Cyclo	Canc	Strait of Sicily		ERde	100.0	1.0	P&S 74
Hornera	*striata*	Cyclo	Canc	Strait of Sicily		ERde	100.0	1.0	P&S 74
Frondipora	*verrucosa*	Cyclo	Fasc	Naples	F			0.2	C&W 22
Frondipora	*verrucosa*	Cyclo	Fasc	Ligurian Sea		ERfe	100.0	7.0	P&S 74
Frondipora	*verrucosa*	Cyclo	Fasc	Ligurian Sea		ERfe	100.0	5.0	P&S 74
Lichenopora	*radiata*	Cyclo	Rectang	Strait of Sicily	F		100.0	5.9	P&S 73
Lichenopora	*radiata*	Cyclo	Rectang	Strait of Sicily		ENul	100.0	6.0	P&S 74
Lichenopora	*verrucaria*	Cyclo	Rectang	Strait of Otranto		ENul	100.0	6.0	P&S 74
Idmonea	*serpens*	Cyclo	Tubul	Strait of Sicily		ERde	100.0	6.0	P&S 74
Berenicea	*patina*	Cyclo	Tubul	Strait of Sicily	F		100.0	6.3	P&S 73
Berenicea	*patina*	Cyclo	Tubul	Strait of Sicily		ENul	100.0	7.0	P&S 74
Diaperoecia	*sp.*	Cyclo	Tubul	Three Kings	S	ERro	100.0	2.8	SJK 86
Diaperoecia	*californica*	Cyclo	Tubul	So. Calif.		ERro	100.0	6.0	S70
Diplosolen	*obelium*	Cyclo	Tubul	Strait of Sicily	F		100.0	7.6	P&S 73
Diplosolen	*obelium*	Cyclo	Tubul	Strait of Sicily		ENul	100.0	8.0	P&S 74
Idmidronea	*atlantica*	Cyclo	Tubul	Strait of Sicily	F		100.0	5.1	P&S 73
Idmidronea	*atlantica*	Cyclo	Tubul	Strait of Sicily		ERde	100.0	5.0	P&S 74
Idmonea	*aff petri*	Cyclo	Tubul	Adriatic Sea		ERde	100.0	1.0	P&S 74

Genus	Species	Order	Suborder	Location	Cond	Growth Form	Wt % Calc.	Wt % $MgCO_3$	Source
Mecynoecia	*purpurascens*	Cyclo	Tubul	Three Kings	S	ERde	100.0	1.0	SJK 86
Tubulipora	*flabellaris*	Cyclo	Tubul	Strait of Sicily	F		100.0	1.7	P&S 73
Tubulipora	*liliacea*	Cyclo	Tubul	Vineyard Sound	F		100.0	4.3	S&M 67
Tubulipora	*flabellaris*	Cyclo	Tubul	Strait of Sicily		ENul	100.0	1.0	P&S 74
Tubulipora	*aff phalangea*	Cyclo	Tubul	Ionian Sea		ENul	100.0	2.0	P&S 74
Idmonea	*atlantica*	Cyclo	Tubul	Grand Manan Island	F			4.7	S&M 67
Idmonea	*atlantica*	Cyclo	Tubul	Gulf of Maine	F		100.0	5.0	S&M 67
Idmonea	*serpens*	Cyclo	Tubul	Strait of Sicily	F		100.0	5.9	P&S 73
Cribrilaria	*radiata*	Cheilo	Acanth				100.0	?4-8	R&C 69
Alderina	*solidula*	Cheilo	Anasca	Strait of Sicily		ENul	8.0	10.0	P&S 74
Aplousina	*gigantea*	Cheilo	Anasca				100.0	4-8	R&C 69
Aplousina	*filum*	Cheilo	Anasca	Ionian Sea		ENul	4.0		P&S 74
Beania	*hirtissima*	Cheilo	Anasca	Ionian Sea			100.0	6.0	P&S 74
Beania	*robusta*	Cheilo	Anasca	Adriatic Sea			100.0	6.0	P&S 74
Beania	*robusta*	Cheilo	Anasca	Strait of Sicily			100.0	7.0	P&S 74
Biflustra	*savartii*	Cheilo	Anasca				100.0	4-8	R&C 69
Biflustra	*savartii*	Cheilo	Anasca				100.0	4-8	R&C 69
Bugula	*californica*	Cheilo	Anasca				100.0	4-8	R&C 69
Bugula	*neritina*	Cheilo	Anasca				100.0	4-8	R&C 69
Bugula	*neritina*	Cheilo	Anasca	Florida				13.2	S&M 67
Bugula	*simplex*	Cheilo	Anasca				100.0	4-8	R&C 69
Bugula	*simplex*	Cheilo	Anasca	Woods Hole			100.0	10.2	S&M 67
Bugula	*simplex*	Cheilo	Anasca	Woods Hole			100.0	8.7	S&M 67
Bugula	*simplex*	Cheilo	Anasca	Woods Hole			100.0	8.9	S&M 67
Bugula	*simplex*	Cheilo	Anasca	Woods Hole			100.0	7.0	S&M 67
Bugula	*turrita*	Cheilo	Anasca	George's Bank				12.7	S&M 67
Bugula	*turrita*	Cheilo	Anasca	Woods Hole				9.9	S&M 67
Bugula	*spicata*	Cheilo	Anasca	Ionian Sea			100.0	7.0	P&S 74
Cabera	*boryl*	Cheilo	Anasca	Strait of Sicily		EF	100.0	6.0	P&S 74
Caberea	*ellisi*	Cheilo	Anasca				100.0	4-8	R&C 69

Genus	Species	Order	Suborder	Location	Cond	Growth Form	Wt % Calc.	Wt % $MgCO_3$	Source
Calpensia	*nobilis*	Cheilo	Anasca	Strait of Otranto		ENul	90.0	4.0	P&S 74
Calpensia	*nobilis*	Cheilo	Anasca	Ligurian Sea		ENul	84.0	4.0	P&S 74
Calpensia	*nobilis*	Cheilo	Anasca	Ionian Sea		ENul	89.0	5.0	P&S 74
Calpensia	*nobilis*	Cheilo	Anasca	Adriatic Sea		ENul	73.0	4.0	P&S 74
Calpensia	*nobilis*	Cheilo	Anasca	Strait of Otranto		ENul	84.0	4.0	P&S 74
Calpensia	*nobilis*	Cheilo	Anasca	Strait of Sicily		ENul	74.0	5.0	P&S 74
Canda	*retiformis*	Cheilo	Anasca				80.0	4-8	R&C 69
Cellaria	*bassleri*	Cheilo	Anasca			EF	100.0	4-8	R&C 69
Cellaria	*sp.*	Cheilo	Anasca	Three Kings	F	EF	100.0	5.5	SJK 86
Cellaria	*salicornia*	Cheilo	Anasca	Adriatic Sea		EF	100.0	5.0	P&S 74
Cellaria	*salicornioides*	Cheilo	Anasca	Strait of Sicily		EF	100.0	5.0	P&S 74
Chaperia	*condylata*	Cheilo	Anasca				100.0	4-8	R&C 69
Conopeum	*seurati*	Cheilo	Anasca	Adriatic Sea		ENul	100.0	6.0	P&S 74
Coronellina	*fagei*	Cheilo	Anasca	Strait of Sicily		ENul	5.0	8.0	P&S 74
Cribrilaria	*radiata*	Cheilo	Anasca	Strait of Sicily		ENul	100.0	9.0	P&S 74
Cupuladria	*canariensis*	Cheilo	Anasca						R&C 69
Cupuladria	*canariensis*	Cheilo	Anasca						R&C 69
Dendrobeania	*murrayana*	Cheilo	Anasca				100.0	4-8	R&C 69
Discoporella	*doma*	Cheilo	Anasca				11.0	4-8	R&C 69
Discoporella	*umbellata*	Cheilo	Anasca				4.0	4-8	R&C 69
Discoporella	*umbellata*	Cheilo	Anasca				3.0	4-8	R&C 69
Electra	*anomala*	Cheilo	Anasca				100.0	0-4	R&C 69
Electra	*pilosa*	Cheilo	Anasca				100.0	4-8	R&C 69
Electra	*tenella*	Cheilo	Anasca				100.0	4-8	R&C 69
Eucratea	*loricata*	Cheilo	Anasca				100.0	0-4	R&C 69
Eucratea	*loricata*	Cheilo	Anasca	Crowe Neck Maine				10.3	S&M 67
Eucratea	*loricata*	Cheilo	Anasca	Crowe Neck Maine			100.0	8.0	S&M 67
Eucratea	*loricata*	Cheilo	Anasca	Nantucket Shoals			100.0	8.1	S&M 67
Flustra	*foliacea*	Cheilo	Anasca				100.0	4-8	R&C 69
Flustra	*foliacea*	Cheilo	Anasca	St Johns New Brunswick			100.0	6.8	S&M 67

Genus	Species	Order	Suborder	Location	Cond	Growth Form	Wt % Calc.	Wt % $MgCO_3$	Source
Flustra	*foliacea*	Cheilo	Anasca	St Johns New Brunswick			100.0	6.0	S&M 67
Flustra	*membranacea truncata*	Cheilo	Anasca	St. Paul Is. Pribilof Group				7.2	C&W 17
Lunulites	*capulus*	Cheilo	Anasca			FL	60.0	4-8	R&C 69
Lunulites	*jacksonensis*	Cheilo	Anasca		R	FL	50.0	4-8	R&C 69
Lunulites	*jacksonensis*	Cheilo	Anasca		R	FL	45.0	4-8	R&C 69
Melicerita	*chathamensis*	Cheilo	Anasca	Three Kings	F	ERro	100.0	8.0	SJK 86
Membranipora	*aciculata*	Cheilo	Anasca	Australia		ENul	100.0	8.0	B&W 90
Membranipora	*aurita*	Cheilo	Anasca				100.0	0-4	R&C 69
Membranipora	*lacroixi*	Cheilo	Anasca	Falmouth Mass				8.5	S&M 67
Membranipora	*lacroixi*	Cheilo	Anasca	Falmouth Mass				11.0	S&M 67
Membranipora	*membranacea*	Cheilo	Anasca	Australia		ENul			B&W 90
Membranipora	*tuberculata*	Cheilo	Anasca			ENul	100.0	>12	R&C 69
Membranipora	*tuberculata*	Cheilo	Anasca			ENul	100.0	8-12	R&C 69
Membranipora	*tuberculata*	Cheilo	Anasca			ENul	100.0	>12	R&C 69
Membranipora	*tuberculata*	Cheilo	Anasca			ENul	100.0	>12	R&C 69
Membranipora	*unicornis*	Cheilo	Anasca				100.0	4-8	R&C 69
Membranipora	*unicornis*	Cheilo	Anasca				100.0	4-8	R&C 69
Membranipora	*unicornis*	Cheilo	Anasca				100.0	0-4	R&C 69
Membranipora	*hastingsae*	Cheilo	Anasca				100.0	4-8	R&C 69
Membranipora	*sp.*	Cheilo	Anasca	So. California		ENul	100.0	10.0	S70
Mollia	*patellaria*	Cheilo	Anasca	Strait of Sicily			100.0	7.0	P&S 74
Mollia	*patellaria*	Cheilo	Anasca	Strait of Sicily			100.0	8.0	P&S 74
Monoporella	*venusta*	Cheilo	Anasca	Strait of Sicily		ENul	4.0		P&S 74
Nellia	*tenella*	Cheilo	Anasca				100.0	8-12	R&C 69
Onchyocella	*antiqua*	Cheilo	Anasca	Strait of Otranto		ENul	100.0	9.0	P&S 74
Onchyocella	*antiqua*	Cheilo	Anasca	Ionian Sea		ENul	100.0	9.0	P&S 74
Onchyocella	*antiqua*	Cheilo	Anasca	Strait of Sicily		ENul	100.0	9.0	P&S 74
Otionella	*sp.*	Cheilo	Anasca	Three Kings	F	FL			SJK 86
Otionella	*sp.*	Cheilo	Anasca	Three Kings	S				SJK 86
Puellina	*gattyae*	Cheilo	Anasca	Strait of Sicily		ENul	100.0	8.0	P&S 74

Genus	Species	Order	Suborder	Location	Cond	Growth Form	Wt % Calc.	Wt % $MgCO_3$	Source
Rosseliana	*rosselii*	Cheilo	Anasca	Strait of Sicily		ENul	97.0	8.0	P&S 74
Scrupocellaria	*maderensis*	Cheilo	Anasca				100.0	4-8	R&C 69
Scrupocellaria	*regularis*	Cheilo	Anasca				100.0	4-8	R&C 69
Scrupocellaria	*scrupea*	Cheilo	Anasca	Adriatic Sea		EF	100.0	7.0	P&S 74
Securiflustra	*securifrons*	Cheilo	Anasca	Ionian Sea			100.0		P&S 74
Setosella	*vulnerata*	Cheilo	Anasca	Tyrrhenian Sea					P&S 74
Setosellina	*goesi*	Cheilo	Anasca						R&C 69
Setosellina	*roulei*	Cheilo	Anasca	Strait of Sicily			100.0	7.0	P&S 74
Spiralaria	*gregaria*	Cheilo	Anasca	Adriatic Sea		ENul	100.0	7.0	P&S 74
Steginoporella	*magnilabris*	Cheilo	Anasca				100.0	4-8	R&C 69
Steginoporella	*magnilabris*	Cheilo	Anasca				100.0	4-8	R&C 69
Steginoporella	*neozelanica*	Cheilo	Anasca	Three Kings	F	EF	100.0	4.5	SJK 86
Steginoporella	*neozelanica*	Cheilo	Anasca	Three Kings	S		100.0	3.8	SJK 86
Thalamoporella	*distorta*	Cheilo	Anasca				100.0	0-4	R&C 69
Thalamoporella	*falcifera*	Cheilo	Anasca				100.0	4-8	R&C 69
Thalamoporella	*falcifera*	Cheilo	Anasca				93.0	4-8	R&C 69
Thalamoporella	*granulata*	Cheilo	Anasca				100.0	4-8	R&C 69
Catenicella	*margaritacea*	Cheilo	Anasca?	Australia				9.1	S&M 67
"Cellepora"	*pumicosa*	Cheilo	Ascoph	Ionian Sea		ENml	100.0	6.0	P&S 74
"Hippodiplosia"	*foliacea*	Cheilo	Ascoph	Adriatic Sea		ENul	12.0	7.0	P&S 74
"Hippodiplosia"	*foliacea*	Cheilo	Ascoph	Ionian Sea		ERfo	28.0	7.0	P&S 74
"Hippodiplosia"	*foliacea*	Cheilo	Ascoph	Strait of Sicily		ERfo	33.0	7.0	P&S 74
"Hippodiplosia"	*ottomulleriana*	Cheilo	Ascoph	Strait of Sicily		ENul	48.0	6.0	P&S 74
Adeona	*cellulosa*	Cheilo	Ascoph				16.0	8-12	R&C 69
Adeonella	*polystomella*	Cheilo	Ascoph	Strait of Sicily		ERro	100.0	7.0	P&S 74
Adeonellopsis	*distoma*	Cheilo	Ascoph	Tyrrhenian Sea		ERro			P&S 74
Antropora	*sp.*			So. Calif			100.0	10.0	S70
Buchneria	*fayalensis*	Cheilo	Ascoph	Strait of Sicily		Erde	100.0	8.0	P&S 74
Cellepora	*incrassata*	Cheilo	Ascoph	Grand Banks				6.1	S&M 67
Celleporaria	*albirostris*	Cheilo	Ascoph				16.0	4-8	R&C 69

Genus	Species	Order	Suborder	Location	Cond	Growth Form	Wt % Calc.	Wt % $MgCO_3$	Source
Celleporaria	*aperta*	Cheilo	Ascoph				67.0	4-8	R&C 69
Celleporaria	*cristata*	Cheilo	Ascoph	Australia		ENml	100.0		B&W 90
Celleporaria	*tridenticulata*	Cheilo	Ascoph	Three Kings	F	ENml	100.0	7.5	SJK 86
Celleporaria	*vagans*	Cheilo	Ascoph						R&C 69
Celleporaria	*vagans*	Cheilo	Ascoph				63.0	4-8	R&C 69
Celleporaria	*vagans*	Cheilo	Ascoph				16.0	4-8	R&C 69
Celleporaria	*granulosa*	Cheilo	Ascoph						R&C 69
Celleporaria	*sardonica*	Cheilo	Ascoph	Strait of Sicily		ENml	8.0	8.0	P&S 74
Celleporina	*costazii*	Cheilo	Ascoph	Three Kings	F	ENml	100.0	7.5	SJK 86
Celleporina	*sp.*	Cheilo	Ascoph	Three Kings	F	ENml	100.0	8.3	SJK 86
Celleporina	*costazii*	Cheilo	Ascoph				100.0	8-12	R&C 69
Celleporina	*caminata*	Cheilo	Ascoph	Strait of Sicily		ENml	100.0	7.0	P&S 74
Celleporina	*hassallii*	Cheilo	Ascoph	Strait of Sicily		ENml	100.0	8.0	P&S 74
Chorizopora	*brongniartii*	Cheilo	Ascoph	Strait of Sicily		ENul	100.0	6.0	P&S 74
Codonellina	*montferrandii*	Cheilo	Ascoph				100.0	4-8	R&C 69
Cribellopora	*trichotoma*	Cheilo	Ascoph	Strait of Sicily		ENul	100.0	7.0	P&S 74
Cryptosula	*pallasiana*	Cheilo	Ascoph				100.0	0-4	R&C 69
Cryptosula	*pallasiana*	Cheilo	Ascoph				100.0	4-8	R&C 69
Cryptosula	*pallasiana*	Cheilo	Ascoph				100.0	4-8	R&C 69
Cryptosula	*pallasiana*	Cheilo	Ascoph				100.0	4-8	R&C 69
Cryptosula	*pallasiana*	Cheilo	Ascoph				100.0	4-8	R&C 69
Cryptosula	*pallasiana*	Cheilo	Ascoph				100.0	4-8	R&C 69
Cryptosula	*pallasiana*	Cheilo	Ascoph				100.0	4-8	R&C 69
Cryptosula	*pallasiana*	Cheilo	Ascoph				100.0	4-8	R&C 69
Cryptosula	*pallasiana*	Cheilo	Ascoph				100.0	4-8	R&C 69
Cryptosula	*pallasiana*	Cheilo	Ascoph				50.0	4-8	R&C 69
Cryptosula	*pallasiana*	Cheilo	Ascoph				100.0	0-4	R&C 69
Cryptosula	*pallasiana*	Cheilo	Ascoph	Gloucester Mass				5.9	C&W 17
Cryptosula	*pallasiana*	Cheilo	Ascoph	Falmouth Mass			<100	6.8	S&M 67
Cryptosula	*pallasiana*	Cheilo	Ascoph	Falmouth Mass				8.0	S&M 67

Genus	Species	Order	Suborder	Location	Cond	Growth Form	Wt % Calc.	Wt % $MgCO_3$	Source
Cryptosula	*pallasiana*	Cheilo	Ascoph	Falmouth Mass				8.3	S&M 67
Cryptosula	*pallasiana*	Cheilo	Ascoph	Adriatic Sea		ENul	81.0	4.0	P&S 74
Diporula	*verrucosa*	Cheilo	Ascoph	Tyrrhenian Sea		ERde	100.0	7.0	P&S 74
Eschara	*cervicornis*	Cheilo	Ascoph	Brehat France				8.8	S&M 67
Eschara	*foliacea*	Cheilo	Ascoph	S. di Penta Italy				2.7	S&M 67
Escharella	*aff. reussiana*	Cheilo	Ascoph	Ionian Sea		ENul	100.0	7.0	P&S 74
Escharella	*variolosa*	Cheilo	Ascoph	Strait of Sicily		ENul	77.0	8.0	P&S 74
Escharina	*vulgaris*	Cheilo	Ascoph	Adriatic Sea		ENul	64.0	8.0	P&S 74
Escharoides	*praestans*	Cheilo	Ascoph				100.0	0-4	R&C 69
Escharoides	*coccineus*	Cheilo	Ascoph	Strait of Sicily		ENul	48.0	6.0	P&S 74
Fenestrulina	*malusii*	Cheilo	Ascoph	Strait of Sicily		ENul	100.0	8.0	P&S 74
Foveolaria	*cyclops*	Cheilo	Ascoph	Three Kings		ENul	<100	7.5	SJK 86
Galeopsis	*polyporus*	Cheilo	Ascoph	Three Kings	F	ERde	100.0	7.0	SJK 86
Galeopsis	*polyporus*	Cheilo	Ascoph	Three Kings	S	ERde	100.0	7.5	SJK 86
Galeopsis	*porcellanicus*	Cheilo	Ascoph	Three Kings	F	ERde	100.0	8.3	SJK 86
Gemelliporella	*prevailae*	Cheilo	Ascoph						R&C 69
Gemelliporina	*glabra*	Cheilo	Ascoph				20.0	4-8	R&C 69
Haplopoma	*impressum*	Cheilo	Ascoph	Strait of Sicily		ENul	100.0		P&S 74
Harmerella	*dichotoma*	Cheilo	Ascoph				100.0	4-8	R&C 69
Haswellina	*multiaviculata*	Cheilo	Ascoph	Three Kings	F		<100	7.5	SJK 86
Hippaliosina	*depressa*	Cheilo	Ascoph	Strait of Otranto		ENul			P&S 74
Hippellozoon	*novaezelandiae*	Cheilo	Ascoph	Three Kings	F	ERfe	100.0	7.0	SJK 86
Hippellozoon	*novaezelandiae*	Cheilo	Ascoph	Three Kings	S		100.0	6.3	SJK 86
Hippopodina	*feegeensis*	Cheilo	Ascoph				100.0	4-8	R&C 69
Hippopodinella	*kirchenpaueri*	Cheilo	Ascoph	Strait of Sicily		ENul	100.0	7.0	P&S 74
Hippoporina	*pertusa*	Cheilo	Ascoph				100.0	4-8	R&C 69
Hippoporina	*pertusa*	Cheilo	Ascoph	Ionian Sea		ENul	29.0	7.0	P&S 74
Hippoptraliella	*marginata*	Cheilo	Ascoph				90.0	4-8	R&C 69
Hippothoa	*hyalina*	Cheilo	Ascoph				100.0	0-4	R&C 69
Hippothoa	*hyalina*	Cheilo	Ascoph				100.0	0-4	R&C 69

Genus	Species	Order	Suborder	Location	Cond	Growth Form	Wt % Calc.	Wt % $MgCO_3$	Source
Holoporella	*albirostris*	Cheilo	Ascoph	Cedar Rapids Florida				2.6	S&M 67
Iodictyum	*sp.*	Cheilo	Ascoph	Three Kings		ERfe	100.0	7.5	SJK 86
Iodictyum	*yaldwini*	Cheilo	Ascoph	Three Kings	F	ERfe	100.0	7.5	SJK 86
Iodictyum	*yaldwini*	Cheilo	Ascoph	Three Kings	S	ERfe	100.0	8.5	SJK 86
Lekythopora	*lucida*	Cheilo	Ascoph	Ligurian Sea		ENml	100.0	7.0	P&S 74
Lepralia	*rostigera*	Cheilo	Ascoph	Cedar Rapids Florida				2.8	S&M 67
Lepralia	*sp.*	Cheilo	Ascoph	S. della Gajola Italy				5.2	S&M 67
Mamillopora	*cupula*	Cheilo	Ascoph						R&C 69
Margaretta	*cereoides*	Cheilo	Ascoph	Strait of Sicily		EF	12.0	9.0	P&S 74
Margaretta	*cereoides*	Cheilo	Ascoph	Adriatic Sea		EF	22.0	8.0	P&S 74
Metrarabdotos	*tenue*	Cheilo	Ascoph				100.0	4-8	R&C 69
Metrarabdotos	*tenue*	Cheilo	Ascoph				100.0	4-8	R&C 69
Metrarabdotos	*tenue*	Cheilo	Ascoph				100.0	4-8	R&C 69
Metrarabdotos	*unguiculatum*	Cheilo	Ascoph				48.0	4-8	R&C 69
Metrarabdotos	*unguiculatum*	Cheilo	Ascoph				54.0	4-8	R&C 69
Metrarabdotos	*unguiculatum*	Cheilo	Ascoph				75.0	4-8	R&C 69
Microporella	*grisea*	Cheilo	Ascoph	Australia				1.1	S&M 67
Microporella	*umbonata*	Cheilo	Ascoph	Florida			100.0	4-8	R&C 69
Microporella	*ciliata*	Cheilo	Ascoph	Adriatic Sea		ENul	53.0	6.0	P&S 74
Myriapora	*truncata*	Cheilo	Ascoph	Strait of Sicily		ERde	100.0	9.0	P&S 74
Palmicellaria	*aff. skenei*	Cheilo	Ascoph	Adriatic Sea		ERde	100.0	7.0	P&S 74
Parasmittina	*nitida*	Cheilo	Ascoph	Vineyard Sound				0.6	S&M 67
Parasmittina	*nitida*	Cheilo	Ascoph	Vineyard Sound				0.7	S&M 67
Parasmittina	*nitida*	Cheilo	Ascoph	Vineyard Sound				0.3	S&M 67
Parasmittina	*nitida*	Cheilo	Ascoph	Vineyard Sound				<1	S&M 67
Parasmittina	*spathulata*	Cheilo	Ascoph				t r		R&C 69
Parasmittina	*spathulata*	Cheilo	Ascoph				17.0	4-8	R&C 69
Parasmittina	*raigii*	Cheilo	Ascoph	Strait of Sicily		ENul			P&S 74
Petralia	*undata*	Cheilo	Ascoph	Australia			100.0	8.0	B&W 90
Philodopora	*pacifica*						100.0	5.0	S70

Genus	Species	Order	Suborder	Location	Cond	Growth Form	Wt % Calc.	Wt % $MgCO_3$	Source
Porella	*smitti*	Cheilo	Ascoph	Yarmouth Nova Scotia			100.0	8.0	S&M 67
Porella	*smitti*	Cheilo	Ascoph	Yarmouth Nova Scotia			100.0	7.9	S&M 67
Porella	*cervicornis*	Cheilo	Ascoph	Strait of Sicily		ERro	100.0	7.0	P&S 74
Porella	*colleti*	Cheilo	Ascoph	Ionian Sea		ERro	100.0	7.0	P&S 74
Ramphostomella	*argentea*	Cheilo	Ascoph	Strait of Sicily		ENul	100.0	6.0	P&S 74
Reptadeonella	*violacea*	Cheilo	Ascoph	Strait of Sicily		ENul			P&S 74
Reteporellina	*marsupiata*	Cheilo	Ascoph				100.0	4-8	R&C 69
Rhamphostomella	*bilaminata*	Cheilo	Ascoph	Cape Cod Bay Mass				5.2	S&M 67
Rhynchozoon	*armatum*	Cheilo	Ascoph	Strait of Sicily		ENml			P&S 74
Rhynchozoon	*digitatum*	Cheilo	Ascoph	Strait of Sicily		ENml	1.0	11.0	P&S 74
Schizobrachiella	*sanguinea*	Cheilo	Ascoph	Ligurian Sea		ENul	45.0	7.0	P&S 74
Schizomavella	*mucronifera*	Cheilo	Ascoph	Three Kings	F	ERro	100.0	9.5	SJK 86
Schizomavella	*arrogata*	Cheilo	Ascoph	Strait of Sicily		ENul	2.0	9.0	P&S 74
Schizomavella	*arrogata*	Cheilo	Ascoph	Strait of Sicily		ENul	3.0	8.0	P&S 74
Schizomavella	*auriculata*	Cheilo	Ascoph	Strait of Sicily		ENul	60.0	7.0	P&S 74
Schizomavella	*auriculata*	Cheilo	Ascoph	Ligurian Sea		ENul	1.0		P&S 74
Schizomavella	*auriculata*	Cheilo	Ascoph	Ligurian Sea		ENul	10.0	8.0	P&S 74
Schizomavella	*linearis*	Cheilo	Ascoph	Strait of Sicily		ENul	57.0	8.0	P&S 74
Schizoporella	*unicornis*	Cheilo	Ascoph				59.0	4-8	R&C 69
Schizoporella	*unicornis*	Cheilo	Ascoph				45.0	4-8	R&C 69
Schizoporella	*unicornis*	Cheilo	Ascoph				46.0	4-8	R&C 69
Schizoporella	*unicornis*	Cheilo	Ascoph				44.0	4-8	R&C 69
Schizoporella	*unicornis*	Cheilo	Ascoph				74.0	4-8	R&C 69
Schizoporella	*unicornis*	Cheilo	Ascoph				44.0	4-8	R&C 69
Schizoporella	*unicornis*	Cheilo	Ascoph				37.0	4-8	R&C 69
Schizoporella	*unicornis*	Cheilo	Ascoph				34.0	4-8	R&C 69
Schizoporella	*unicornis*	Cheilo	Ascoph				41.0	4-8	R&C 69
Schizoporella	*unicornis*	Cheilo	Ascoph				66.0	4-8	R&C 69
Schizoporella	*unicornis*	Cheilo	Ascoph				67.0	4-8	R&C 69
Schizoporella	*unicornis*	Cheilo	Ascoph				61.0	4-8	R&C 69

Genus	Species	Order	Suborder	Location	Cond	Growth Form	Wt % Calc.	Wt % $MgCO_3$	Source
Schizoporella	*unicornis*	Cheilo	Ascoph				75.0	4-8	R&C 69
Schizoporella	*unicornis*	Cheilo	Ascoph				28.0	4-8	R&C 69
Schizoporella	*unicornis*	Cheilo	Ascoph				47.0	4-8	R&C 69
Schizoporella	*unicornis*	Cheilo	Ascoph	Vineyard Sound				0.6	S&M 67
Schizoporella	*unicornis*	Cheilo	Ascoph	Florida				4.7	S&M 67
Schizoporella	*unicornis*	Cheilo	Ascoph	Vineyard Sound			<100	4.0	S&M 67
Schizoporella	*unicornis*	Cheilo	Ascoph	Vineyard Sound				5.1	S&M 67
Schizoporella	*unicornis*	Cheilo	Ascoph	Vineyard Sound				3.4	S&M 67
Schizoporella	*unicornis*	Cheilo	Ascoph	Vineyard Sound				3.6	S&M 67
Schizoporella	*unicornis*	Cheilo	Ascoph	Cape May New Jersey			100.0	4.0	S&M 67
Schizoporella	*"ansata"*	Cheilo	Ascoph	Strait of Sicily		ENul	13.0	8.0	P&S 74
Schizoporella	*longirostris*	Cheilo	Ascoph	Ligurian Sea		ENul	14.0	7.0	P&S 74
Schizoporella	*magnifica*	Cheilo	Ascoph	Strait of Otranto		ENul	19.0	6.0	P&S 74
Schizoporella	*unicornis*	Cheilo	Ascoph	Strait of Sicily		ENul	23.0	8.0	P&S 74
Schizotheca	*fissa*	Cheilo	Ascoph	Strait of Sicily		ENul	69.0	8.0	P&S 74
Schizotheca	*serratimargo*	Cheilo	Ascoph	Strait of Sicily		ERfo	70.0	6.0	P&S 74
Schizotheca	*serratimargo*	Cheilo	Ascoph	Strait of Otranto		ENul	53.0	7.0	P&S 74
Sertella	*couchii*	Cheilo	Ascoph	Strait of Sicily		ERfe	100.0	7.0	P&S 74
Sertella	*mediterranea*	Cheilo	Ascoph	Strait of Sicily		ERfe	100.0	7.0	P&S 74
Sertella	*septentrionalis*	Cheilo	Ascoph	Strait of Sicily		ERfe	100.0	7.0	P&S 74
Smittina	*cheilostoma*	Cheilo	Ascoph	Strait of Sicily		ENul			P&S 74
Smittoidea	*prolifica*	Cheilo	Ascoph				26.0	4-8	R&C 69
Smittoidea	*ophidiana*	Cheilo	Ascoph	Ionian Sea		ENul			P&S 74
Steginoporella	*magnifica*	Cheilo	Ascoph	Three Kings	F		100.0	5.0	SJK 86
Steginoporella	*perplexa*	Cheilo	Ascoph	Three Kings	F		100.0	4.8	SJK 86
Stephanosella	*biaperta*	Cheilo	Ascoph	Strait of Sicily		ENul	13.0	9.0	P&S 74
Stylopoma	*sp.*	Cheilo	Ascoph	Strait of Sicily		ENml	11.0	6.0	P&S 74
Styloporma	*spongites*	Cheilo	Ascoph						R&C 69
Tessarodoma	*boreale*	Cheilo	Ascoph	Tyrrhenian Sea		ERde	100.0	6.0	P&S 74
Tremogasterina	*granulata*	Cheilo	Ascoph				68.0	4-8	R&C 69

Genus	Species	Order	Suborder	Location	Cond	Growth Form	Wt % Calc.	Wt % $MgCO_3$	Source
Tremogasterina	*lanceolata*	Cheilo	Ascoph				58.0	4-8	R&C 69
Trypostega	*cf. papillata*	Cheilo	Ascoph	Strait of Sicily		ENul	100.0	9.0	P&S 74
Turbicellepora	*coronopus*	Cheilo	Ascoph	Strait of Sicily		ENml	100.0	7.0	P&S 74
Turbicellepora	*coronopus*	Cheilo	Ascoph	Strait of Sicily		ENml	100.0	6.0	P&S 74
Watersipora	*subovoidea*	Cheilo	Ascoph				100.0	0-4	R&C 69

NOTES: Systematics and location details as reported in source.

Taxa abbreviated from those given in Appendix Table AI.1.

Condition: F-collected live, S-taken from sediment, R-subfossil or fossil.

Colonial growth forms following system in Nelson et al. (1988).

No calcite/aragonite ratio available from earlier works (not using XRD techniques).

Mg content corrected to wt% MgCO in calcite, not calculated in all-aragonite specimens.

Sources: Carter and Wheeler, 1917, 1922; Schopf and Manheim, 1967; Rucker and Carver, 1969; Smith, 1970; Poluzzi and Sartori, 1973,1974; Keane, 1986; Bone and Wass, 1990.

Table A2.2: Locations of sediments from which bryozoan samples were obtained.

SAMPLE	Latitude (°S)	Longitude (°E)	Depth (m)	Source
A441	41.13	174.65	210	NZOI
B488	46.48	166.24	164	NZOI
B567	46.00	170.92	126	NZOI
B568	46.00	170.72	73	NZOI
B574	47.33	168.22	113	NZOI
B581	48.00	168.10	138	UW
B582	48.00	167.63	143	NZOI
C**	36.45	175.30	50	AMS
C176	39.67	173.95	40	NZOI
D038	51.97	165.47	252	NZOI
D044	47.50	168.01	120	UW
D104	50.82	166.26	95	NZOI
D114	44.20	173.30	84	NZOI
DPG1	25.17	167.17	20	DPG
DPG2	41.17	174.67	20	DPG
DPG3	41.13	174.50	30	DPG
DPG4	40.80	174.17	40	DPG
DPG5	49.75	179.00	—	DPG
E026	47.68	167.40	144	UW
E027	47.67	167.65	131	UW
E028	47.66	167.92	143	UW
E559	35.45	174.75	102	NZOI
E644	37.01	176.08	73	NZOI
E817	46.23	166.48	218	NZOI
E820	46.58	165.97	220	NZOI
E833	46.95	168.15	53	NZOI
E842	33.90	172.28	187	NZOI
E849	33.92	171.53	216	NZOI
E862	32.47	167.52	130	NZOI
G007	48.02	167.62	148	UW
G009	48.00	166.59	170	UW
K**	36.45	174.92	40	AMS
L**	36.28	174.67	50	AMS
LF, LS	36.27	174.80	20	AMS
OF	36.72	175.83	20	AMS
P448	34.39	172.47	101	CSN
P454	34.25	172.16	292	CSN
P458	34.23	171.94	200	CSN
P489	34.30	172.68	88	CSN
P492	34.36	172.61	85	CSN
P507	34.15	172.75	100	CSN
P558	33.98	171.72	178	CSN
P609	40.01	174.08	75	JG
P614	40.17	174.58	90	JG
RW	34.98	173.94	90	AMS
T**	36.60	174.90	30	AMS

NOTES: Samples with ** may be any of several samples taken in the same area.
Latitude and longitude have been converted to decimals.
Sources are AMS - collected by the author; CSN - Dr. C.S. Nelson, University of Waikato; DPG - Dr. D.P. Gordon, NZOI; JG - J. Gillespie, University of Waikato; NZOI - New Zealand Oceanographic Institute, Wellington; UW - University of Waikato archives.

Table A2.3: Spatial coverage of mineralogical bryozoan samples.

species	total number of samples	Subtropical DPG1	Pacific and Three Kings Plateau TK	P448	P454	P458	P492	P489	P507	P551	P558	E849	E842	Northland FW	E559	C**	K**	L**	Hauraki Gulf LF/S	CF	Bay of Plenty E644	Wanganui C176	P609	P614	Cook Strait A441	DPG2	DPG3	DPG4	Canterbury and Otago shelves D114	B567	B568	South Fiordland B488	E817	E820	Stewart Island/Snares Islands B574	B581	D044	E026	E027	E028	E833	G007	G009	SNm	Sub-Antarctic Islands D038	D104	DPG5
Adeonellopsis sp.	40		1	3	1	1	1	1															1	1	1				1	1		1	1	1	4	2	1	11	1		3	1		1		
Annectocyma sp.	4		1	1						1														1																							
Arachnopusia unicornis	11			2	1		1		1							2		2						2																							
Bugula dentata	1													1																																	
Caberea zelandica	2							1				1																																			
Cellaria immersa	25		1	2	1	1	1	1		1	1		1			3		1				1	1	1	1				1			1		1				1	1			1			1	
Cellaria tenuirostris	2													1					1																											
Celleporaria agglutinans	7			1									1	1					3				1																							
Celleporella cancer	1													1																																	
Celleporina costazii	18		1	1	1		1			1	2					2	2	1				1	1								1				1			1	1							
Celleporina grandis	1																						1																							
Chaperia acanthina	5			2			1		1									1																												
Chaperiopsis tintinnabula	3								1		2																																			
Chlastosella splendida	6			1			1		1	1	2																																			
Cinctipora elegans	20																					1	1					7		1	1		1			1	1	1	1		1	1	1	1		
Conescharellina angulopora	1								1																																					
Cornuticella taurina	1																			1																											
Disporella gordoni	1													1																																	
Escharina waiparensis	3																																				1	1		1								
Escharoides excavata	1				1																																									
Euthyroides episcopalis	1																								1																						
Euthyroides jellyae	1																										1																			
Foveolaria cyclops	22			2	1	1	1	1		1	1							2	1	1													1		1	1	1	1	1		1	2		1		
Galeopsis polyporus	12			1	1						1			1		1	1	2			1		1	1	1																					
Galeopsis porcellanicus	27		1	1		1	1			1	2			1		2	1	2	2	1		1	1	1					1							1	1	1	1		1	1				1
Gemellipora eburnea	1	1																																												
Gigantopora pupa	1																1																													
Hemipustulopora harmeri	1													1																																	
Hippellozoon novaezelandiae	7				1				1							1	1	1					1	1																							
Hippomenella vellicata	5			1	1						1													1																		1					
Hornera foliacea	3															1								1															1								
Hornera sp.	20			1	1	1	1		1	1		1									1	1	1	1	1				1								1	1			1	3		1			
Idmidroneiforms	2		1						1																																					
Iodictyum yaldwynii	8		1	1	1		1	1	1	1		1																																		
Lichenopora sp.	6		1	1		1					1								1																							1				
Macropora grandis	1																1																													
Margaretta barbata	3			1							1																										1										
Mecynoecia purpurascens	20		1	1	1		1									3	1	2	2				1	1							1					2		1	1						1	
Melicerita chathamensis	2		1		1																																								
Menipea zelandica	3							1	1		1																																			
Metroperiella mucronifera	10		1	1	2	2			1	1	1																												1							
Odontoporella adpressa	2						1												1																											
Otionella squamosa	15		1	1	1				1							4	2	1												1				1		2										
Patsyella flemingi	4															1	1	2																											
Steginoporella magnifica	15			3	1	1	1	1	1	1	1					3	2																												
Steginoporella neozelanica	47		1	2		1	1	1	1	1						1		2	34	1	1																									
Steginoporella perplexa	6			2				1				1				1	1																												
Telopora buski	26		1	3	1	1	1	1		1	1				1	3		1					1	1							1					1	1	2			1	1		1	1	
TOTAL	424	1	14	35	18	11	15	10	14	12	18	4	2	8	1	28	14	20	45	3	3	3	11	16	4	1	1	1	9	3	2	6	1	4	1	6	12	7	22	7	1	7	12	1	5	4	1

Table A2.4: Mineralogies of 48 species of New Zealand bryozoans.

Results of x-ray diffraction analyses. XRD traces available from Earth Sciences Department, University of Waikato. Listed alphabetically by species, with date of XRD analysis, calcite peak position and interpretation of Mg content following Chave (1952). Peak height ratio is calculated as the sum of the heights of the aragonite peaks divided by the sum of the heights of the aragonite peaks and the calcite peak. Percent calcite calculated using calibration curve determined using standard mixtures of aragonite and calcite (Figure 2B.4).

Locations as follows:

STP Subtropical Pacific
TKP Three Kings Plateau
NLD Northland
HKG Hauraki Gulf
BOP Bay of Plenty/Coromandel
WNG Wanganui/Taranaki
CKS Cook Strait
CNT Canterbury shelf
OTG Otago shelf
SFL South Fiordland
STS Steward Island/Snares
SAI Subantarctic Islands

* means a single individual was the whole sample.

Adeonellopsis sp.

Sample Data				Mg Content	Calcite-Aragonite			
Spl no.	Species	Location	Date	Carbonate Mineral	Ca Peak Position	wt% $MgCO_3$	Peak Ht. Ratio	% Calcite
P448a	Adeo sp	TKP	30-5-90	Bimineral	29.58	5.0	0.72	11.3
P448b	Adeo sp	TKP	30-5-90	Bimineral	29.57	4.7	0.72	11.3
P448c	Adeo sp	TKP	30-5-90	Bimineral	29.56	4.3	0.78	8.0
P454	Adeo sp	TKP	30-5-90	Aragonite				
P458	Adeo sp	TKP	30-5-90	Bimineral	29.62	6.3	0.85	5.0
P489	Adeo sp	TKP	30-5-90	Aragonite				
P492	Adeo sp	TKP	30-5-90	Aragonite				
TK	Adeo sp	TKP	29-7-89	Bimineral	29.66	7.7	0.78	8.0
B581a	Adeo sp	STS	30-5-90	Aragonite				
B581b	Adeo sp	STS	30-5-90	Aragonite				
B581c	Adeo sp	STS	30-5-90	Aragonite				
B581d	Adeo sp	STS	30-5-90	Aragonite				
D44a	Adeo sp	STS	13-6-90	Bimineral	29.55	4.0	0.85	5.0
D44b	Adeo sp	STS	13-6-90	Aragonite				
E26	Adeo sp	STS	27-6-90	Bimineral	29.67	8.0	0.89	3.6
E27	Adeo sp	STS	30-5-90	Bimineral	29.56	4.3	0.84	5.4
E28	Adeo sp	STS	3-7-90	Aragonite				
G7a	Adeo sp	STS	30-5-90	Bimineral	29.58	5.0	0.82	6.2
G7b	Adeo sp	STS	30-5-90	Bimineral	29.62	6.3	0.83	5.8
G7c	Adeo sp	STS	30-5-90	Aragonite				
G9	Adeo sp	STS	5-6-90	Bimineral	29.70	9.0	0.84	5.4
B488	Adeo sp	SFL	8-1-90	Aragonite				
D38	Adeo sp	SAI	8-1-91	Bimineral	29.62	6.3	0.90	3.2
D114	Adeo sp	CNT	8-1-91	Aragonite				
E817	Adeo sp	SFL	8-1-91	Aragonite				
E820	Adeo sp	FLD	8-1-91	Bimineral	29.62	6.3	0.77	8.6
P609	Adeo sp	WNG	11-1-91	Bimineral	29.62	6.3	0.85	5.0
B567	Adeo sp	OTG	22-1-91	Aragonite				
P614	Adeo sp	WNG	24-1-91	Aragonite				
A441	Adeo sp	CKS	22-1-91	Aragonite				

Annectocyma sp.

Sample Data				Mg Content	Calcite-Aragonite			
Spl no.	Species	Location	Date	Carbonate Mineral	Ca Peak Position	wt% $MgCO_3$	Peak Ht. Ratio	% Calcite
TK	Ann sp	TKP	29-7-89	Calcite	29.51	2.7		
P614	Ann sp	WNG	22-1-91	Calcite	29.56	4.3		
P448	Ann sp	TKP	22-1-91	Calcite	29.6	5.7		
P551	Ann sp	TKP	22-1-91	Calcite	29.52	3.0		

Arachnopusia unicornis

Sample Data				Mg Content	Calcite-Aragonite			
Spl no.	Species	Location	Date	Carbonate Mineral	Ca Peak Position	wt% $MgCO_3$	Peak Ht. Ratio	% Calcite
P448	Arac uni	TKP	29-9-89	Calcite	29.64	7.0		
P614	Arac uni	WNG	11-1-91	Calcite	29.56	4.3		
C11	Arac uni	HKG	10-1-91	Calcite	29.57	4.7		
C60	Arac uni	HKG	10-1-91	Calcite	29.6	5.7		
L17	Arac uni	HKG	10-1-91	Calcite	29.58	5.0		
L33	Arac uni	HKG	10-1-91	Calcite	29.6	5.7		
P448	Arac uni	TKP	10-1-91	Calcite	29.59	5.3		
P454	Arac uni	TKP	10-1-91	Calcite	29.55	4.0		
P492	Arac uni	TKP	10-1-91	Bimineral	29.62	6.3	0.27	54.4
P614	Arac uni	WNG	22-1-91	Calcite	29.58	5.0		
P507	Arac uni	TKP	24-1-91	Bimineral	29.6	5.7	0.41	37.0

Bugula flabellata

Sample Data				Mg Content	Calcite-Aragonite			
Spl no.	Species	Location	Date	Carbonate Mineral	Ca Peak Position	wt% MgCO	Peak Ht. Ratio	% Calcite
RW-E	Bug flab	NLD	11-1-91	Calcite	29.62	6.3		

Caberea zelandica

Sample Data				Mg Content	Calcite-Aragonite			
Spl no.	Species	Location	Date	Carbonate Mineral	Ca Peak Position	wt% MgCO	Peak Ht. Ratio	% Calcite
E849	Cab zel	TKP	10-1-91	Calcite	29.51	2.7		
P489	Cab zel	TKP	29-9-90	Calcite	29.51	2.7		

Cellaria immersa

Sample Data				Mg Content	Calcite-Aragonite			
Spl no.	Species	Location	Date	Carbonate Mineral	Ca Peak Position	wt% MgCO	Peak Ht. Ratio	% Calcite
P448a	Cell imm	TKP	20-6-90	Calcite	29.56	4.3		
P448b	Cell imm	TKP	25-6-90	Calcite	29.56	4.3		
P454	Cell imm	TKP	20-6-90	Calcite	29.53	3.3		
P458	Cell imm	TKP	20-6-90	Calcite	29.51	2.7		
P489	Cell imm	TKP	20-6-90	Calcite	29.54	3.7		
P492	Cell imm	TKP	20-6-90	Calcite	29.56	4.3		
P551	Cell imm	TKP	20-6-90	Calcite	29.52	3.0		
P558	Cell imm	TKP	20-6-90	Calcite	29.56	4.3		
TK	Cell imm	TKP	29-7-89	Calcite	29.53	3.3		
L17	Cell imm	HKG	20-6-90	Calcite	29.52	3.0		
C11	Cell imm	HKG	25-6-90	Calcite	29.55	4.0		
C60	Cell imm	HKG	20-6-90	Calcite	29.49	2.0		
C60a	Cell imm	HKG	20-6-90	Calcite	29.54	3.7		
E26	Cell imm	STS	20-6-90	Calcite	29.50	2.3		
E27	Cell imm	STS	20-6-90	Calcite	29.50	2.3		

G9	Cell imm	STS	20-6-90	Calcite	29.52	3.0
B488	Cell imm	SFL	10-1-91	Calcite	29.56	4.3
D104	Cell imm	SAI	10-1-91	Calcite	29.59	5.3
D114	Cell imm	CNT	11-1-91	Calcite	29.5	2.3
E820	Cell imm	SFL	11-1-91	Calcite	29.54	3.7
E842	Cell imm	TKP	11-1-91	Calcite	29.54	3.7
P609	Cell imm	WNG	11-1-91	Calcite	29.5	2.3
P614	Cell imm	WNG	22-1-91	Calcite	29.54	3.7
A441	Cell imm	CKS	22-1-91	Calcite	29.48	1.7
C176	Cell imm	WNG	22-1-91	Calcite	29.54	3.7

Cellaria tenuirostrius

Sample Data				Mg Content	Calcite-Aragonite			
Spl no.	Species	Location	Date	Carbonate Mineral	Ca Peak Position	wt% MgCO	Peak Ht. Ratio	% Calcite
LS	Cell ten	HKG	29-9-89	Calcite	29.55	4.0		
RWD	Cell ten	NLD	11-1-91	Calcite	29.54	3.7		

Celleporaria agglutinans

Sample Data				Mg Content	Calcite-Aragonite			
Spl no.	Species	Location	Date	Carbonate Mineral	Ca Peak Position	wt% MgCO	Peak Ht. Ratio	% Calcite
LFa	Clr agg	HKG	13-6-90	Calcite	29.62	6.3		
LFb	Clr agg	HKG	13-6-90	Calcite	29.62	6.3		
E842	Clr agg	TKP	11-1-91	Calcite	29.57	4.7		
P448	Clr agg	TKP	11-1-91	Calcite	29.59	5.3		
MB	Clr agg	HKG	11-1-91	Calcite	29.58	5.0		
P609	Clr agg	WNG	11-1-91	Calcite	29.56	4.3		
RW	Clr agg	NLD	11-2-91	Calcite	29.57	4.7		

Celleporella cancer

Sample Data				Mg Content	Calcite-Aragonite			
Spl no.	Species	Location	Date	Carbonate Mineral	Ca Peak Position	wt% MgCO	Peak Ht. Ratio	% Calcite
RW	Clla can	NLD	13-2-91	Calcite	29.4	0		

Celleporina costazii

Sample Data				Mg Content	Calcite-Aragonite			
Spl no.	Species	Location	Date	Carbonate Mineral	Ca Peak Position	wt% MgCO	Peak Ht. Ratio	% Calcite
TK	Cln cost	TKP	29-7-89	Calcite	29.58	5.0		
P448	Cln cost	TKP	3-7-90	Calcite	29.62	6.3		
P454	Cln cost	TKP	3-7-90	Calcite	29.60	5.7		
P492	Cln cost	TKP	4-7-90	Calcite	29.62	6.3		
P551	Cln cost	TKP	3-7-90	Calcite	29.58	5.0		
P558n	Cln cost	TKP	4-7-90	Calcite	29.62	6.3		
P558o	Cln cost	TKP	8-7-90	Calcite	29.62	6.3		
C12	Cln cost	HKG	13-7-90	Calcite	29.65	7.3		
C60	Cln cost	HKG	13-7-90	Calcite	29.61	6.0		
K6	Cln cost	HKG	3-7-90	Calcite	29.58	5.0		
K21	Cln cost	HKG	13-7-90	Calcite	29.56	4.3		
L17	Cln cost	HKG	13-7-90	Calcite	29.60	5.7		
D44	Cln cost	HKG	13-7-90	Calcite	29.57	4.7		
E27	Cln cost	HKG	8-7-90	Calcite	29.59	5.3		
E28	Cln cost	STS	3-7-90	Calcite	29.56	4.3		
B488	Cln cost	SFL	10-1-91	Calcite	29.61	6.0		
P690	Cln cost	WNG	22-1-91	Calcite	29.6	5.7		
P614	Cln cost	WNG	22-1-91	Bimineral	29.6	5.7	0.12	75.8

Celleporina grandis

Sample Data				Mg Content	Calcite-Aragonite			
Spl no.	Species	Location	Date	Carbonate Mineral	Ca Peak Position	wt% $MgCO_3$	Peak Ht. Ratio	% Calcite
P614	Cln gr	WNG	22-1-91	Calcite	29.55	4.0		

Chaperia acanthina

Sample Data				Mg Content	Calcite-Aragonite			
Spl no.	Species	Location	Date	Carbonate Mineral	Ca Peak Position	wt% MgCO	Peak Ht. Ratio	% Calcite
P448	Chap ac	TKP	10-1-91	Bimineral	29.55	4.0	0.47	31.3
P492	Chap ac	TKP	10-1-91	Bimineral	29.59	5.3	0.73	10.8
L13	Chap ac	HKG	10-1-91	Calcite	29.55	4.0		
P448	Chap ac	TKP	29-9-89	Calcite	29.54	3.7		
P507	Chap ac	TKP	24-1-91	Bimineral	29.54	3.7	0.59	20.2

Chaperiopsis tintinnabula

Sample Data				Mg Content	Calcite-Aragonite			
Spl no.	Species	Location	Date	Carbonate Mineral	Ca Peak Position	wt% MgCO	Peak Ht. Ratio	% Calcite
P558	Chpr tin	TKP	29-9-89	Calcite	29.60	5.7		
P558	Chpr tin	HKG	11-1-91	Calcite	29.63	6.7		
P507	Chpr tin	TKP	24-1-91	Calcite	29.6	5.7		

Chiastosella splendida

Sample Data				Mg Content	Calcite-Aragonite			
Spl no.	Species	Location	Date	Carbonate Mineral	Ca Peak Position	wt% MgCO	Peak Ht. Ratio	% Calcite
P448	Chia spl	TKP	4-7-90	Calcite	29.61	6.0		
P492	Chia spl	TKP	10-7-90	Calcite	29.56	4.3		
P551	Chia spl	TKP	10-7-90	Calcite	29.60	5.7		
P558	Chia spl	TKP	29-9-89	Calcite	29.61	6.0		
P558b	Chia spl	TKP	4-7-90	Calcite	29.60	5.7		
P507	Chia spl	TKP	24-1-91	Bimineral	29.62	6.3	0.62	18.0

Cinctipora elegans

Sample Data				Mg Content	Calcite-Aragonite			
Spl no.	Species	Location	Date	Carbonate Mineral	Ca Peak Position	wt% MgCO	Peak Ht. Ratio	% Calcite
B488	Cin eleg	SFL	7-1-91	Calcite	29.45	0.7		
D38	Cin eleg	SAI	7-1-91	Calcite	29.45	0.7		
D104	Cin eleg	SAI	7-1-91	Calcite	29.45	0.7		
D114a	Cin eleg	CNT	7-1-91	Calcite	29.40	0		
D114b	Cin eleg	CNT	7-1-91	Calcite	29.42	0		
D114c	Cin eleg	CNT	7-1-91	Calcite	29.39	0		
D114d	Cin eleg	CNT	7-1-91	Calcite	29.43	0		
D114e	Cin eleg	CNT	7-1-91	Calcite	29.44	0.3		
D114f	Cin eleg	CNT	7-1-91	Calcite	29.42	0		
D114g	Cin eleg	CNT	7-1-91	Calcite	29.41	0		
E26	Cin eleg	STS	8-1-90	Calcite	29.44	0.3		
E27	Cin eleg	STS	8-1-90	Calcite	29.46	1.0		
E28	Cin eleg	STS	8-1-91	Calcite	29.42	0		
E820	Cin eleg	SFL	8-1-91	Calcite	29.46	1.0		
E833	Cin eleg	STS	8-1-91	Calcite	29.42	0		
G9	Cin eleg	STS	8-1-91	Calcite	29.45	0.7		
STSm	Cin eleg	STS	29-5-89	Calcite	29.54	3.7		
P609	Cin eleg	WNG	22-1-91	Bimineral	29.45	0.7	0.11	78.4
B568	Cin eleg	OTG	22-1-91	Bimineral	29.45	0.7	0.21	62.4

P614	Cin eleg	WNG	22-1-91	Calcite	29.48	1.7		

Conescharellina angulopora

Sample Data				Mg Content	Calcite-Aragonite			
				Carbonate	Ca Peak	wt%	Peak Ht.	
Spl no.	Species	Location	Date	Mineral	Position	MgCO	Ratio	% Calcite
P507	Con ang	TKP	24-1-91	Bimineral	29.56	4.3	0.30	50.0

Cornuticella taurina

Sample Data				Mg Content	Calcite-Aragonite			
				Carbonate	Ca Peak	wt%	Peak Ht.	
Spl no.	Species	Location	Date	Mineral	Position	MgCO	Ratio	% Calcite
DPG	Corn tau	CKS	10-1-91	Calcite	29.58	5.0		

Disporella gordoni

Sample Data				Mg Content	Calcite-Aragonite			
				Carbonate	Ca Peak	wt%	Peak Ht.	
Spl no.	Species	Location	Date	Mineral	Position	MgCO	Ratio	% Calcite
RW	Disp gor	NLD	13-2-91	Calcite	29.53	3.3		

Escharina waiparensis

Sample Data				Mg Content	Calcite-Aragonite			
				Carbonate	Ca Peak	wt%	Peak Ht.	
Spl no.	Species	Location	Date	Mineral	Position	MgCO	Ratio	% Calcite
B581	Esc waip	STS	22-1-91	Calcite	29.6	5.7		
D44	Esc waip	STS	22-1-91	Calcite	29.63	6.7		
E28	Esc waip	STS	22-1-91	Calcite	29.62	6.3		

Escharoides excavata

Sample Data				Mg Content	Calcite-Aragonite			
				Carbonate	Ca Peak	wt%	Peak Ht.	
Spl no.	Species	Location	Date	Mineral	Position	MgCO	Ratio	% Calcite
P454	Esch exc	TKP	22-1-91	Calcite	29.58	5.0		

Euthyroides episcopalis

Sample Data				Mg Content	Calcite-Aragonite			
				Carbonate	Ca Peak	wt%	Peak Ht.	
Spl no.	Species	Location	Date	Mineral	Position	MgCO	Ratio	% Calcite
DPG2	Euth epis	CKS	22-1-91	Calcite	29.69	8.0		

Euthyroides jellyae

Sample Data				Mg Content	Calcite-Aragonite			
				Carbonate	Ca Peak	wt%	Peak Ht.	
Spl no.	Species	Location	Date	Mineral	Position	MgCO	Ratio	% Calcite
DPG4	Euth jell	CKS	22-1-91	Bimineral	29.68	8.3	0.31	49.5

Foveolaria cyclops

Sample Data				Mg Content	Calcite-Aragonite			
				Carbonate	Ca Peak	wt%	Peak Ht.	
Spl no.	Species	Location	Date	Mineral	Position	MgCO	Ratio	% Calcite
P448	Fov cy	TKP	29-9-89	Bimineral	29.58	5.0	0.38	40.8
P448b	Fov cy	TKP	27-6-90	Bimineral	29.61	6.0	0.21	62.7
P454	Fov cy	TKP	27-6-90	Bimineral	29.62	6.3	0.41	37.4
P458	Fov cy	TKP	27-6-90	Bimineral	29.64	7.0	0.22	61.3
P489	Fov cy	TKP	27-6-90	Calcite	29.63	6.7		

P492	Fov cy	TKP	27-6-90	Calcite	29.58	5.0		
P551	Fov cy	TKP	27-6-90	Calcite	29.59	5.3		
P558	Fov cy	TKP	27-6-90	Bimineral	29.64	7.0	0.22	61.3
LS	Fov cy	HKG	10-7-90	Calcite	29.63	6.7		
L13	Fov cy	HKG	27-6-90	Calcite	29.62	6.3		
L17	Fov cy	HKG	10-7-90	Calcite	29.62	6.3		
OF	Fov cy	BOP	27-6-90	Bimineral	29.63	6.7	0.26	55.8
B581	Fov cy	STS	27-6-90	Bimineral	29.61	6.0	0.31	49.2
D44	Fov cy	STS	3-7-90	Bimineral	29.62	6.3	0.44	34.2
E26	Fov cy	STS	27-6-90	Bimineral	29.60	5.7	0.30	50.5
E27	Fov cy	STS	27-6-90	Bimineral	29.59	5.3	0.25	57.1
E28	Fov cy	STS	27-6-90	Bimineral	29.60	5.7	0.35	44.3
G7	Fov cy	STS	27-6-90	Bimineral	29.60	5.7	0.44	34.2
G9a	Fov cy	STS encr	27-6-90	Bimineral	29.60	5.7	0.32	48.0
G9b	Fov cy	STS bran	27-6-90	Bimineral	29.56	4.3	0.33	46.7
D38	Fov cy	SAI	24-1-91	Bimineral	29.61	6.0	0.26	55.3
E820	Fov cy	SFL	24-1-91	Bimineral	29.62	6.3	0.28	52.9

Galeopsis polyporus

Sample Data				Mg Content	Calcite-Aragonite			
Spl no.	Species	Location	Date	Carbonate Mineral	Ca Peak Position	wt% MgCO	Peak Ht. Ratio	% Calcite
P558	Gal poly	TKP	29-9-89	Calcite	29.59	5.3		
A441	Gal poly	CKS	24-1-91	Calcite	29.64	7.0		
C60	Gal poly	HKG	24-1-91	Calcite	29.64	7.0		
E644	Gal poly	BOP	24-1-91	Calcite	29.64	7.0		
K21	Gal poly	HKG	24-1-91	Calcite	29.66	7.7		
L13	Gal poly	HKG	24-1-91	Calcite	29.64	7.0		
L17	Gal poly	HKG	24-1-91	Calcite	29.66	7.7		
P454	Gal poly	TKP	24-1-91	Calcite	29.65	7.3		
P448	Gal poly	TKP	24-1-91	Calcite	29.66	7.7		
P609	Gal poly	WNG	24-1-91	Calcite	29.63	6.7		
P614	Gal poly	WNG	24-1-91	Calcite	29.64	7.0		
RW	Gal poly	NLD	13-2-91	Calcite	29.66	7.7		

Galeopsis porcellanicus

Sample Data				Mg Content	Calcite-Aragonite			
Spl no.	Species	Location	Date	Carbonate Mineral	Ca Peak Position	wt% MgCO	Peak Ht. Ratio	% Calcite
TK	Gal sp	TKP	29-7-89	Calcite	29.61	6.0		
P448	Gal porc	TKP	3-7-90	Calcite	29.61	6.0		
P458	Gal porc	TKP	3-7-90	Calcite	29.64	7.0		
P492	Gal porc	TKP	3-7-90	Calcite	29.62	6.3		
P551	Gal porc	TKP	3-7-90	Calcite	29.58	5.0		
P558	Gal porc	TKP	29-9-89	Calcite	29.64	7.0		
P558	Gal porc	TKP	3-7-90	Calcite	29.64	7.0		
LF	Gal porc	HKG	4-7-90	Calcite	29.64	7.0		
LS	Gal porc	HKG	4-7-90	Calcite	29.63	6.7		
OF	Gal porc	HKG	4-7-90	Calcite	29.64	7.0		
C11	Gal porc	HKG	4-7-90	Calcite	29.64	7.0		
K21	Gal porc	HKG	10-7-90	Calcite	29.63	6.7		
L13	Gal porc	HKG	4-7-90	Calcite	29.66	7.7		
L17	Gal porc	HKG	4-7-90	Calcite	29.62	6.3		
D44	Gal porc	STS	4-7-90	Calcite	29.62	6.3		
E26	Gal porc	STS	4-7-90	Calcite	29.60	5.7		
E27	Gal porc	STS	4-7-90	Calcite	29.60	5.7		
E28	Gal porc	STS	4-7-90	Calcite	29.59	5.3		
G7	Gal porc	STS	4-7-90	Calcite	29.57	4.7		
G9	Gal porc	STS	4-7-90	Calcite	29.63	6.7		
DPG5	Gal porc	SAI	24-1-91	Calcite	29.6	5.7		
B567	Gal porc	OTG	24-1-91	Calcite	29.64	7.0		

C60	Gal porc	HKG	24-1-91	Calcite	29.61	6.0
C176	Gal porc	WNG	24-1-91	Calcite	29.63	6.7
P609	Gal porc	WNG	24-1-91	Calcite	29.62	6.3
P614	Gal porc	WNG	24-1-91	Calcite	29.62	6.3
RW	Gal porc	NLD	13-2-91	Calcite	29.62	6.3

Gemellipora eburnea

Sample Data				Mg Content	Calcite-Aragonite			
Spl no.	Species	Location	Date	Carbonate Mineral	Ca Peak Position	wt% MgCO	Peak Ht. Ratio	% Calcite
DPG	Gem eb	STP	24-1-91	Calcite	29.64	7.0		

Gigantopora pupa

Sample Data				Mg Content	Calcite-Aragonite			
Spl no.	Species	Location	Date	Carbonate Mineral	Ca Peak Position	wt% MgCO	Peak Ht. Ratio	% Calcite
K6	Gig pupa	HKG	24-1-91	Calcite	29.62	6.3		

Hippellozoon novaezelandiae

Sample Data				Mg Content	Calcite-Aragonite			
Spl no.	Species	Location	Date	Carbonate Mineral	Ca Peak Position	wt% MgCO	Peak Ht. Ratio	% Calcite
C60	Hipp nov	HKG	24-1-91	Calcite	29.65	7.3		
K21	Hipp nov	HKG	24-1-91	Calcite	29.63	6.7		
L17	Hipp nov	HKG	24-1-91	Calcite	29.64	7.0		
P454	Hipp nov	TKP	24-1-91	Calcite	29.64	7.0		
P507	Hipp nov	TKP	24-1-91	Calcite	29.62	6.3		
P609	Hipp nov	WNG	31-1-91	Calcite	29.62	6.3		
P614	Hipp nov	WNG	31-1-91	Calcite	29.61	6.0		

Hemipustulopora harmeri

Sample Data				Mg Content	Calcite-Aragonite			
Spl no.	Species	Location	Date	Carbonate Mineral	Ca Peak Position	wt% MgCO	Peak Ht. Ratio	% Calcite
RW	Hem harm	NLD	13-2-91	Calcite	29.6	5.7		

Hippomenella vellicata

Sample Data				Mg Content	Calcite-Aragonite			
Spl no.	Species	Location	Date	Carbonate Mineral	Ca Peak Position	wt% MgCO	Peak Ht. Ratio	% Calcite
G9	Hipp vell	STS	29-9-89	Calcite	29.60	5.7		
P448	Hipp vell	TKP	31-1-91	Calcite	29.61	6.0		
P454	Hipp vell	TKP	31-1-91	Bimineral	29.61	6.0	0.17	68.6
P558	Hipp vell	TKP	11-2-91	Calcite	29.61	6.0		
P614	Hipp vell	WNG	11-2-91	Bimineral	29.58	5.0	0.15	71.3

Hornera foliacea

Sample Data				Mg Content	Calcite-Aragonite			
Spl no.	Species	Location	Date	Carbonate Mineral	Ca Peak Position	wt% MgCO	Peak Ht. Ratio	% Calcite
C60	Horn fol	HKG	11-2-91	Calcite	29.6	5.7		
E27	Horn fol	STS	11-2-91	Calcite	29.47	1.3		
P614	Horn fol	WNG	11-2-91	Calcite	29.46	1.0		

Hornera sp.

Sample Data				Mg Content	Calcite-Aragonite			
Spl no.	Species	Location	Date	Carbonate Mineral	Ca Peak Position	wt% MgCO	Peak Ht. Ratio	% Calcite
A441	Horn sp	CKS	11-2-91	Calcite	29.42	0		
B567	Horn sp	OTG	11-2-91	Calcite	29.56	4.3		
C176	Horn sp	TKP	11-2-91	Calcite	29.44	0.3		
D38	Horn sp	SAI	11-2-91	Calcite	29.51	2.7		
E849	Horn sp	TKP	11-2-91	Calcite	29.42	0		
E644	Horn sp	BOP	11-2-91	Calcite	29.51	2.7		
P507	Horn sp	TKP	11-2-91	Calcite	29.45	0.7		
P609	Horn sp	WNG	11-2-91	Calcite	29.45	0.7		
P64	Horn sp	WNG	11-2-91	Calcite	29.42	0		
P448	Horn sp	TKP	21-6-90	Calcite	29.47	1.3		
P454	Horn sp	TKP	21-6-90	Calcite	29.50	2.3		
P458	Horn sp	TKP	21-6-90	Calcite	29.49	2.0		
P492	Horn sp	TKP	21-6-90	Calcite	29.43	0		
P551	Horn sp	TKP	21-6-90	Calcite	29.43	0		
E26	Horn sp	STS	21-6-90	Calcite	29.53	3.3		
E27	Horn sp	STS	21-6-90	Calcite	29.50	2.3		
G7	Horn sp	STS	21-6-90	Calcite	29.49	2.0		
G9a	Horn sp	STS	21-6-90	Calcite	29.43	0		
G9b	Horn sp	STS	21-6-90	Calcite	29.46	1.0		
G9c	Horn sp	STS	29-9-89	Calcite	29.48	1.7		

Idmidroneiforms

Sample Data				Mg Content	Calcite-Aragonite			
Spl no.	Species	Location	Date	Carbonate Mineral	Ca Peak Position	wt% MgCO	Peak Ht. Ratio	% Calcite
TKP	Idmid	TKP	7-8-89	Calcite	29.57	4.7		
P507	Idmid	TKP	13-2-91	Calcite	29.5	2.3		

Iodictyum yaldwinii

Sample Data				Mg Content	Calcite-Aragonite			
Spl no.	Species	Location	Date	Carbonate Mineral	Ca Peak Position	wt% MgCO	Peak Ht. Ratio	% Calcite
TKP	Iod yald	TKP	29-7-89	Calcite	29.60	5.7		
P448	Iod yald	TKP	25-6-90	Calcite	29.64	7.0		
P454	Iod yald	TKP	3-7-90	Calcite	29.60	5.7		
P489	Iod yald	TKP	5-7-90	Calcite	29.65	7.3		
P492	Iod yald	TKP	5-7-90	Calcite	29.64	7.0		
P551	Iod yald	TKP	3-7-90	Calcite	29.62	6.3		
E849	Iod yald	TKP	13-2-91	Calcite	29.69	8.7		
P507	Iod yald	TKP	13-2-91	Calcite	29.64	7.0		

Lichenopora sp.

Sample Data				Mg Content	Calcite-Aragonite			
Spl no.	Species	Location	Date	Carbonate Mineral	Ca Peak Position	wt% MgCO	Peak Ht. Ratio	% Calcite
P448	Lich sp	TKP	10-7-90	Calcite	29.52	3.0		
P458	Lich sp	TKP	10-7-90	Calcite	29.64	7.0		
P558	Lich sp	TKP	10-7-90	Calcite	29.54	3.7		
TKP	Lich sp	TKP	29-7-89	Calcite	29.60	5.7		
PBF	Lich sp	HKG	4-7-90	Calcite	29.50	2.3		
G9	Lich sp	STS	10-7-90	Calcite	29.58	5.0		

Macropora grandis

Sample Data				Mg Content	Calcite-Aragonite			
Spl no.	Species	Location	Date	Carbonate Mineral	Ca Peak Position	wt% MgCO	Peak Ht. Ratio	% Calcite
K6	Mac gran	HKG	13-2-91	Calcite	29.60	5.7		

Margaretta barbata

Sample Data				Mg Content	Calcite-Aragonite			
Spl no.	Species	Location	Date	Carbonate Mineral	Ca Peak Position	wt% MgCO	Peak Ht. Ratio	% Calcite
D44	Mar barb	STS	13-2-91	Calcite	29.64	7.0		
P448	Mar barb	TKP	13-2-91	Calcite	29.66	7.7		
P558	Mar barb	TKP	13-2-91	Calcite	29.67	8.0		

Mecynoecia purpurascens and family

Sample Data				Mg Content	Calcite-Aragonite			
Spl no.	Species	Location	Date	Carbonate Mineral	Ca Peak Position	wt% MgCO	Peak Ht. Ratio	% Calcite
TKP	Mec pur	TKP	7-8-89	Calcite	29.45	0.7		
P448	Mec pur	TKP	3-7-90	Calcite	29.46	1.0		
P454	Mec pur	TKP	9-7-90	Calcite	29.46	1.0		
P492	Mec pur	TKP	9-7-90	Calcite	29.46	1.0		
LF	Mec pur	HKG	9-7-90	Calcite	29.47	1.3		
LS	Mec pur	HKG	10-7-90	Calcite	29.48	1.7		
K6	Mec pur	HKG	3-7-90	Calcite	29.45	0.7		
L13	Mec pur	HKG	20-6-90	Calcite	29.47	1.3		
C11	Mec pur	HKG	3-7-90	Calcite	29.45	0.7		
C12	Mec pur	HKG	10-7-90	Calcite	29.47	1.3		
C60	Mec pur	HKG	20-6-90	Calcite	29.49	2.0		
L17	Mec pur	HKG	10-7-90	Calcite	29.47	1.3		
D44	Mec pur	STS	3-7-90	Calcite	29.52	3.0		
D44b	Mec pur	STS	10-7-90	Calcite	29.52	3.0		
B488	Mec pur	SFL	13-2-91	Calcite	29.42	0		
D104	Mec pur	SAI	13-2-91	Calcite	29.55	4.0		
P609	Mec purp	WNG	13-2-91	Calcite	29.44	0.3		
P614	cf Mec	WNG	13-2-91	Calcite	29.42	0		
E28	cf Mec	STS	13-2-91	Calcite	29.58	5.0		
E27	cf M.p.	STS	20-6-90	Calcite	29.58	5.0		

Melicerita chathamensis

Sample Data				Mg Content	Calcite-Aragonite			
Spl no.	Species	Location	Date	Carbonate Mineral	Ca Peak Position	wt% MgCO	Peak Ht. Ratio	% Calcite
TKP	Mel chat	TKP	7-8-89	Calcite	29.68	8.3		
P454	Mel chat	TKP	13-2-91	Calcite	29.63	6.7		

Menipea zelandica

Sample Data				Mg Content	Calcite-Aragonite			
Spl no.	Species	Location	Date	Carbonate Mineral	Ca Peak Position	wt% MgCO	Peak Ht. Ratio	% Calcite
P489	Men zel	TKP	13-2-91	Calcite	29.58	5.0		
P507	Men zel	TKP	13-2-91	Calcite	29.56	4.3		
P558	Men zel	TKP	13-2-91	Calcite	29.60	5.7		

Metroperiella mucronifera

Sample Data				Mg Content	Calcite-Aragonite			
Spl no.	Species	Location	Date	Carbonate Mineral	Ca Peak Position	wt% MgCO	Peak Ht. Ratio	% Calcite
TKP	Met muc	TKP	7-8-89	Calcite	29.67	8.0		
P448	Met muc	TKP	27-6-90	Calcite	29.66	7.7		
P454	Met muc	TKP	27-6-90	Calcite	29.66	7.7		
P458a	Met muc	TKP old	27-6-90	Calcite	29.66	7.7		
P458b	Met muc	TKP fr	27-6-90	Calcite	29.66	7.7		
P551	Met muc	TKP	27-6-90	Calcite	29.62	6.3		
P558	Met muc	TKP	27-6-90	Calcite	29.65	7.3		
E27	Met muc	STS	27-6-90	Calcite	29.64	7.0		
P454	Met muc	TKP	13-2-91	Bimineral	29.66	7.7	0.32	47.7
P507	Met muc	TKP	13-2-91	Calcite	29.67	8.0		

Odontoporella adpressa

Sample Data				Mg Content	Calcite-Aragonite			
Spl no.	Species	Location	Date	Carbonate Mineral	Ca Peak Position	wt% MgCO	Peak Ht. Ratio	% Calcite
LS	Odo adpr	HKG	13-2-91	Bimineral	29.64	7.0	0.78	8.1
P492	Odo adpr	TKP	13-2-91	Bimineral	29.68	8.3	0.59	19.9

Otionella squamosa

Sample Data				Mg Content	Calcite-Aragonite			
Spl no.	Species	Location	Date	Carbonate Mineral	Ca Peak Position	wt% MgCO	Peak Ht. Ratio	% Calcite
TKP	Otio sq	TKP	7-8-89	Aragonite				
P448	Otio sq	TKP	25-6-90	Aragonite				
P454	Otio sq	TKP	3-7-90	Aragonite				
K6*	Otio sq	HKG	3-7-90	Aragonite				
L17n	Otio sq	HKG	13-7-90	Aragonite				
C11	Otio sq	HKG	25-6-90	Aragonite				
C12	Otio sq	HKG	10-7-90	Bimineral	29.68	8.3	0.76	9.0
C60	Otio sq	HKG	13-6-90	Bimineral	29.57	4.7	0.77	8.5
C60b	Otio sq	HKG	13-7-90	Aragonite				
K21	Otio sq	HKG	10-7-90	Aragonite				
D44	Otio sq	STS	13-6-90	Aragonite				
D44*	Otio sq	STS	3-7-90	Calcite	29.55	4.0		
B568	Otio sq	OTG	13-2-91	Aragonite				
B574	Otio sq	STS	13-2-91	Aragonite				
P507	Otio sq	TKP	13-2-91	Bimineral	29.64	7.0	0.87	4.3

Patsyella flemingi

Sample Data				Mg Content	Calcite-Aragonite			
Spl no.	Species	Location	Date	Carbonate Mineral	Ca Peak Position	wt% MgCO	Peak Ht. Ratio	% Calcite
C12	Pat flem	HKG	14-2-91	Calcite	29.56	4.3		
K6	Pat flem	HKG	14-2-91	Bimineral	29.56	4.3	0.25	57.1
L13	Pat flem	HKG	14-2-91	Calcite	29.61	6.0		
L17	Pat flem	HKG	14-2-91	Calcite	29.58	5.0		

Steginoporella magnifica

Sample Data				Mg Content	Calcite-Aragonite			
Spl no.	Species	Location	Date	Carbonate Mineral	Ca Peak Position	wt% MgCO	Peak Ht. Ratio	% Calcite
P448a	Steg mag	TKP	21-6-90	Calcite	29.57	4.7		
P448b	Steg mag	TKP	21-6-90	Calcite	29.58	5.0		
P448c	Steg mag	TKP	29-9-89	Calcite	29.56	4.3		

P454*	Steg mag	TKP	21-6-90	Calcite	29.56	4.3		
P458	Steg mag	TKP	21-6-90	Calcite	29.60	5.7		
P489	Steg mag	TKP	21-6-90	Calcite	29.54	3.7		
P492	Steg mag	TKP	21-6-90	Calcite	29.56	4.3		
P507	Steg mag	TKP	14-2-91	Bimineral	29.55	4.0	0.24	58.5
P551	Steg mag	TKP	21-6-90	Calcite	29.51	2.7		
P558	Steg mag	TKP	21-6-90	Calcite	29.60	5.7		
C11	Steg mag	HKG	3-7-90	Calcite	29.56	4.3		
C12	Steg mag	HKG	10-7-90	Calcite	29.58	5.0		
C60	Steg mag	HKG	10-7-90	Calcite	29.56	4.3		
K6	Steg mag	HKG	3-7-90	Calcite	29.50	2.3		
K21	Steg mag	HKG	10-7-90	Calcite	29.58	5.0		

Steginoporella neozelanica

Sample Data				Mg Content	Calcite-Aragonite			
Spl no.	Species	Location	Date	Carbonate Mineral	Ca Peak Position	wt% MgCO	Peak Ht. Ratio	% Calcite
different branches from same organism								
B1	Steg neo	HKG	5-6-90	Calcite	29.56	4.3		
B2	Steg neo	HKG	5-6-90	Calcite	29.55	4.0		
B3	Steg neo	HKG	5-6-90	Calcite	29.57	4.7		
B4	Steg neo	HKG	5-6-90	Calcite	29.54	3.7		
B5	Steg neo	HKG	5-6-90	Calcite	29.54	3.7		
B6	Steg neo	HKG	5-6-90	Calcite	29.54	3.7		
B7	Steg neo	HKG	5-6-90	Calcite	29.58	5.0		
B8	Steg neo	HKG	5-6-90	Calcite	29.55	4.0		
B9	Steg neo	HKG	5-6-90	Calcite	29.58	5.0		
B10	Steg neo	HKG	7-6-90	Calcite	29.51	2.7		
B12	Steg neo	HKG	7-6-90	Calcite	29.54	3.7		
different branches from same organism								
D1	Steg neo	HKG	5-6-90	Calcite	29.53	3.3		
D2	Steg neo	HKG	5-6-90	Calcite	29.57	4.7		
D3	Steg neo	HKG	5-6-90	Calcite	29.52	3.0		
D4	Steg neo	HKG	5-6-90	Calcite	29.53	3.3		
D5	Steg neo	HKG	7-6-90	Calcite	29.52	3.0		
D6	Steg neo	HKG	7-6-90	Calcite	29.53	3.3		
D7	Steg neo	HKG	7-6-90	Calcite	29.52	3.0		
D8	Steg neo	HKG	7-6-90	Calcite	29.53	3.3		
D10	Steg neo	HKG	7-6-90	Calcite	29.56	4.3		
D11	Steg neo	HKG	7-6-90	Calcite	29.54	3.7		
D12	Steg neo	HKG	7-6-90	Calcite	29.51	2.7		
D13	Steg neo	HKG	7-6-90	Calcite	29.52	3.0		--
D14	Steg neo	HKG	7-6-90	Calcite	29.56	4.3		
D15	Steg neo	HKG	13-6-90	Calcite	29.58	5.0		
D16	Steg neo	HKG	13-6-90	Calcite	29.54	3.7		
D17&18	Steg neo	HKG	13-6-90	Calcite	29.55	4.0		
D19	Steg neo	HKG	13-6-90	Calcite	29.50	2.3		
D20	Steg neo	HKG	13-6-90	Calcite	29.52	3.0		
D21	Steg neo	HKG	13-6-90	Calcite	29.55	4.0		
D21b	Steg neo	HKG	13-6-90	Calcite	29.56	4.3		
D21c	Steg neo	HKG	13-6-90	Calcite	29.55	4.0		
P448	Steg neo	TKP	13-6-90	Calcite	29.54	3.7		
P448b	Steg neo	TKP	29-9-89	Calcite	29.59	5.3		
P458	Steg neo	TKP	13-6-90	Calcite	29.59	5.3		
P489	Steg neo	TKP	13-6-90	Calcite	29.56	4.3		
P492	Steg neo	TKP	13-6-90	Calcite	29.54	3.7		
E644	Steg neo	BOP	14-2-91	Calcite	29.54	3.7		
P507	Steg neo	TKP	14-2-91	Bimineral	29.52	3.0	0.31	49.5
P551	Steg neo	TKP	13-6-90	Calcite	29.57	4.7		
TKP	Steg neo	TKP mix	7-8-89	Calcite	29.55	4.0		

LF	Steg neo	HKG	13-6-90	Calcite	29.54	3.7
LS	Steg neo	HKG	7-8-90	Calcite	29.54	3.7
OF	Steg neo	BOP	10-7-90	Calcite	29.53	3.3
L17	Steg neo	HKG	13-6-90	Calcite	29.55	4.0
L17a	Steg neo	HKG	10-7-90	Calcite	29.53	3.3
C12	Steg neo	HKG	10-7-90	Calcite	29.54	3.7

Steginoporella perplexa

Sample Data				Mg Content	Calcite-Aragonite			
Spl no.	Species	Location	Date	Carbonate Mineral	Ca Peak Position	wt% MgCO	Peak Ht. Ratio	% Calcite
P448	Steg per	TKP	29-9-89	Calcite	29.55	4.0		
C11	Steg per	HKG	14-2-91	Calcite	29.53	3.3		
E849	Steg per	TKP	14-2-91	Calcite	29.56	4.3		
K21	Steg per	HKG	14-2-91	Bimineral	29.57	4.7	0.36	42.7
P448	Steg per	TKP	14-2-91	Bimineral	29.53	3.3	0.32	47.5
P489	Steg per	TKP	14-2-91	Bimineral	29.51	2.7	0.18	66.5

Telopora buski

Sample Data				Mg Content	Calcite-Aragonite			
Spl no.	Species	Location	Date	Carbonate Mineral	Ca Peak Position	wt% MgCO	Peak Ht. Ratio	% Calcite
P448a	Tel busk	TKP	15-6-90	Calcite	29.52	3.0		
P448b	Tel busk	TKP	15-6-90	Calcite	29.50	2.3		
P448c	Tel busk	TKP	27-6-90	Calcite	29.48	1.7		
P454	Tel busk	TKP	15-6-90	Calcite	29.56	4.3		
P458	Tel busk	TKP	15-6-90	Calcite	29.52	3.0		
P489	Tel busk	TKP	15-6-90	Calcite	29.54	3.7		
P492	Tel busk	TKP	15-6-90	Calcite	29.50	2.3		
P551	Tel busk	TKP	15-6-90	Calcite	29.50	2.3		
P558	Tel busk	TKP	15-6-90	Calcite	29.56	4.3		
TKP	Tel busk	TKP	7-8-89	Calcite	29.54	3.7		
C11	Tel busk	HKG	27-6-90	Calcite	29.49	2.0		
C60	Tel busk	HKG	10-7-90	Calcite	29.54	3.7		
L17	Tel busk	HKG	15-6-90	Calcite	29.49	2.0		
D44	Tel busk	STS	15-6-90	Calcite	29.50	2.3		
E26	Tel busk	STS	27-6-90	Calcite	29.50	2.3		
E27	Tel busk	STS	15-6-90	Calcite	29.48	1.7		
E27b	Tel busk	STS	27-6-90	Calcite	29.45	0.7		
G7	Tel busk	STS	15-6-90	Calcite	29.50	2.3		
G9	Tel busk	STS	15-6-90	Calcite	29.48	1.7		
D38	Tel busk	SAI	14-2-91	Calcite	29.56	4.3		
D104	Tel busk	SAI	14-2-91	Calcite	29.49	2.0		
B488	Tel busk	SFL	14-2-91	Calcite	29.56	4.3		
E559	Tel busk	NLD	14-2-91	Calcite	29.54	3.7		
C12	Tel busk	HKG	14-2-91	Calcite	29.56	4.3		
P609	Tel busk	WNG	14-2-91	Calcite	29.5	2.3		
P614	Tel busk	WNG	14-2-91	Calcite	29.51	2.7		

Table A2.5 Mineralogical statistics of 48 New Zealand species studied.

		Wt% calcite					Wt % $MgCO_3$				
Species	n	min	max	range	mean	std dev	min	max	range	mean	std dev
Adeonellopsis sp.	30	0.0	11.3	11.3	3.1	3.7	4.0	9.0	5.0	5.7	1.5
Annectocyma sp.	4	0.0	100.0	100.0	100.0	0.0	2.7	5.7	3.0	3.9	1.4
Arachnopusia unicornis	11	37.0	100.0	63.0	90.1	22.3	4.0	7.0	3.0	5.3	0.9
Bugula dentata	1	0.0	100.0	100.0	100.0	0.0	6.3	6.3	0.0	6.3	0.0
Caberea zelandica	2	0.0	100.0	100.0	100.0	0.0	2.7	2.7	0.0	2.7	0.0
Cellaria immersa	25	0.0	100.0	100.0	100.0	0.0	1.7	4.3	2.6	3.4	0.9
Cellaria tenuirostris	2	0.0	100.0	100.0	100.0	0.0	3.7	4.0	0.3	3.9	0.2
Celleporaria agglutinans	7	0.0	100.0	100.0	100.0	0.0	4.3	6.3	2.0	5.2	0.8
Celleporella cancer	1	0.0	100.0	100.0	100.0	0.0	0.0	0.0	0.0	0.0	0.0
Celleporina costazii	18	75.8	100.0	24.2	98.7	5.7	4.3	7.3	3.0	5.6	0.8
Celleporina grandis	1	0.0	100.0	100.0	100.0	0.0	4.0	4.0	0.0	4.0	0.0
Chaperia acanthina	5	10.8	100.0	89.2	52.5	44.0	3.7	5.3	1.6	4.1	0.7
Chaperiopsis tintinnabula	3	0.0	100.0	100.0	100.0	0.0	5.7	6.7	1.0	6.0	0.6
Chiastosella splendida	6	18.0	100.0	82.0	86.3	33.5	4.3	6.3	2.0	5.7	0.7
Cinctipora elegans	20	62.4	100.0	37.6	97.0	9.5	0.0	3.7	3.7	0.6	0.9
Conescharellina angulopora	1	0.0	100.0	100.0	50.0	0.0	4.3	4.3	0.0	4.3	0.0
Cornuticella taurina	1	0.0	100.0	100.0	100.0	0.0	5.0	5.0	0.0	5.0	0.0
Diaperoecia sp.	4	0.0	100.0	100.0	100.0	0.0	2.7	5.7	3.0	3.9	1.4
Disporella gordoni	1	0.0	100.0	100.0	100.0	0.0	3.3	3.3	0.0	3.3	0.0
Escharina waiparensis	3	0.0	100.0	100.0	100.0	0.0	5.7	6.7	1.0	6.2	0.5
Escharoides excavata	1	0.0	100.0	100.0	100.0	0.0	5.0	5.0	0.0	5.0	0.0
Euthyroides episcopalis	1	0.0	100.0	100.0	100.0	0.0	8.0	8.0	0.0	8.0	0.0
Euthyroides jellyae	1	0.0	100.0	100.0	49.5	0.0	8.3	8.3	0.0	8.3	0.0
Foveolaria cyclops	22	34.2	100.0	65.8	63.3	24.4	4.3	7.0	2.7	6.0	0.7
Galeopsis polyporus	12	0.0	100.0	100.0	100.0	0.0	5.3	7.7	2.4	7.1	0.7
Galeopsis porcellanicus	27	0.0	100.0	100.0	100.0	0.0	4.7	7.7	3.0	6.4	0.7
Gemellipora eburnea	1	0.0	100.0	100.0	100.0	0.0	7.0	7.0	0.0	7.0	0.0
Gigantopora pupa	1	0.0	100.0	100.0	100.0	0.0	6.3	6.3	0.0	6.3	0.0
Hemipustulopora harmeri	1	0.0	100.0	100.0	100.0	0.0	5.7	5.7	0.0	5.7	0.0

Species	n	Wt% calcite					Wt % $MgCO_3$				
		min	max	range	mean	std dev	min	max	range	mean	std dev
Hippellozoon novaezelandiae	7	0.0	100.0	100.0	100.0	0.0	6.0	7.3	1.3	6.7	0.5
Hippomenella vellicata	5	68.6	100.0	31.4	88.0	16.5	5.0	6.0	1.0	5.7	0.4
Hornera foliacea	3	0.0	100.0	100.0	100.0	0.0	1.0	5.7	4.7	2.7	2.6
Hornera sp.	20	0.0	100.0	100.0	100.0	0.0	0.0	4.3	4.3	1.4	1.3
Idmidroneiforms	2	0.0	100.0	100.0	100.0	0.0	2.3	4.7	2.4	3.5	1.7
Iodictyum yaldwynii	8	0.0	100.0	100.0	100.0	0.0	5.7	8.7	3.0	6.8	1.0
Lichenopora sp.	6	0.0	100.0	100.0	100.0	0.0	2.3	7.0	4.7	4.5	1.8
Macropora grandis	1	0.0	100.0	100.0	100.0	0.0	5.7	5.7	0.0	5.7	0.0
Margaretta barbata	3	0.0	100.0	100.0	100.0	0.0	7.0	8.0	1.0	7.6	0.5
Mecynoecia purpurascens	20	0.0	100.0	100.0	100.0	0.0	0.0	5.0	5.0	1.7	1.5
Melicerita chathamensis	2	0.0	100.0	100.0	100.0	0.0	6.7	8.3	1.6	7.5	1.1
Menipea zelandica	3	0.0	100.0	100.0	100.0	0.0	4.3	5.7	1.4	5.0	0.7
Metroperiella mucronifera	10	47.7	100.0	52.3	94.8	16.5	6.3	8.0	1.7	7.5	0.5
Odontoporella adpressa	2	8.1	19.9	11.8	14.0	8.3	7.0	8.3	1.3	7.7	0.9
Otionella squamosa	14	0.0	9.0	9.0	1.6	3.3	4.0	8.3	4.3	6.0	2.0
Patsyella flemingi	4	57.1	100.0	42.9	89.3	21.5	4.3	6.0	1.7	4.9	0.8
Steginoporella magnifica	15	58.5	100.0	41.5	97.2	10.7	2.3	5.7	3.4	4.4	1.0
Steginoporella neozelanica	15	0.0	100.0	100.0	100.0	0.0	3.0	5.3	2.3	3.7	0.7
Steginoporella perplexa	6	42.7	100.0	57.3	76.1	27.3	2.7	4.7	2.0	3.7	0.7
Telopora buski	26	0.0	100.0	100.0	100.0	0.0	0.7	4.3	3.6	2.8	1.0

Table A2.6: Weight % $MgCO_3$ in calcite in different aged segments of (A) *Steginoporella neozelanica* and (B) various bryozoans from published studies (Poluzzi and Sartori, 1974).

A. sample	base	middle	tip
B3	4.7	4	3.7
B4	4.3	4	2.7
D1	4.3	3.7	2.3
F1	4.3	3.7	3.7

B. species (min, taxon)	older	middle	younger
Schizomavella arrogata (bimin, cheilo)	8.0		7.0
Hornera striata (calc, cyclo)	4.0	1.0	1.0
Turbicellepora coronupus (calc, cheilo)	7.0		6.0
Frondipora verrucosa (calc, cyclo)	7.0		5.0
Steginoporella neozelanica (calc, cheilo)	4.4	3.9	3.1

Table A2.7: Mineralogy of *Steginoporella neozelanica* at Leigh.

Location	Colony	Sample	Branches	Wt % calcite	Wt % $MgCO_3$
B	1	a	1-	100	4.0
B	1	b	1	100	3.3
B	1	c	1	100	3.0
B	1	d	1	100	3.3
B	1	e	2	100	3.7
B	1	f	2	100	3.0
B	1	g	4	100	3.7
B	2	a	1	100	3.3
B	2	b	1	100	4.3
B	2	c	1	100	3.3
B	2	d	1	100	4.0
B	2	e	1	100	3.0
B	2	f	1	100	4.0
B	2	g	1	100	4.0
B	2	h	3	100	3.3
B	2	i	5	100	4.0
B	3		all	100	4.7
B	4		all	100	3.7
B	5		all	100	3.7
B	6		all	100	3.7
B	7		all	100	5.0
B	8		all	100	4.0
B	9		all	100	5.0
B	10		all	100	2.7
B	12		all	100	3.7
D	1		all	100	3.3
D	2		all	100	4.7
D	3		all	100	3.0
D	4		all	100	3.3
D	5		all	100	3.0
D	6		all	100	3.3
D	7		all	100	3.0
D	8		all	100	3.3
D	10		all	100	4.3
D	11		all	100	3.7
D	12		all	100	2.7
D	13		all	100	3.0
D	14		all	100	4.3
D	15		all	100	5.0
D	16		all	100	3.7
D	17		all	100	4.0
D	19		all	100	2.3
D	20		all	100	3.0
D	21	a	3	100	4.0
D	21	b	4	100	4.3
D	21	c	3	100	4.0

Table A2.8: Mineralogies of colonies removed from the same sediment sample.

Species	Sample	Wt% calcite	Wt% $MgCO_3$
Adeonellopsis sp.	B581	0.0	0.0
		0.0	0.0
		0.0	0.0
		0.0	0.0
Adeonellopsis sp.	G007	6.2	5.0
		5.8	6.3
		0.0	0.0
Cinctipora elegans	D114	100.0	0.0
		100.0	0.0
		100.0	0.0
		100.0	0.0
		100.0	0.3
		100.0	0.0
		100.0	0.0
Hornera sp.	G009	100.0	0.0
		100.0	1.0
		100.0	1.7
Steginoporella magnifica	P448	100.0	4.7
		100.0	5.0
		100.0	4.3
Telopora buski	P448	100.0	3.0
		100.0	2.3
		100.0	1.7

Table A2.9: Mineralogy of ten bryozoan species at many sample locations.

Species and sample information	Sample location	Wt% $MgCO_3$	Wt% Calcite	Latitude (°S)	Longitude (°E)	Depth (m)
Adeonellopsis sp.	A441	0.0	0.0	41.13	174.65	210
cheilostomata:ascophora	B488	0.0	0.0	46.48	166.24	164
bimineral & aragonite	B567	0.0	0.0	46.00	170.92	126
29 samples	B581	0.0	0.0	48.00	168.10	138
	B581	0.0	0.0	48.00	168.10	138
	B581	0.0	0.0	48.00	168.10	138
	B581	0.0	0.0	48.00	168.10	138
	D038	6.3	3.2	51.97	165.47	252
	D044	4.0	5.0	47.50	168.01	120
	D044	0.0	0.0	47.50	168.01	120
	D114	0.0	0.0	44.20	173.30	84
	E026	8.0	3.6	47.68	167.40	144
	E027	4.3	5.4	47.67	167.65	131
	E028	0.0	0.0	47.66	167.92	143
	E817	0.0	0.0	46.23	166.48	218
	E820	6.3	8.6	46.58	165.97	220
	G007	5.0	6.2	48.02	167.62	148
	G007	6.3	5.8	48.02	167.62	148
	G007	0.0	0.0	48.02	167.62	148
	G009	9.0	5.4	48.00	166.59	170
	P448	5.0	8.0	34.39	172.47	101
	P448	4.7	11.3	34.39	172.47	101
	P448	4.3	11.3	34.39	172.47	101
	P454	0.0	0.0	34.25	172.16	292
	P458	6.3	5.0	34.23	171.94	200
	P489	0.0	0.0	34.30	172.68	88
	P492	0.0	0.0	34.36	172.61	85
	P609	6.3	5.0	40.01	174.08	75
	P614	0.0	0.0	40.17	174.58	90
Cellaria immersa	A441	1.7	100.0	41.13	174.65	210
cheilostomata:anasca	B488	4.3	100.0	46.48	166.24	164
calcite	C11	4.0	100.0	36.45	175.30	50
22 samples	C60	2.0	100.0	36.45	175.30	50
	C60	3.7	100.0	36.45	175.30	50
	C176	3.7	100.0	39.67	173.95	40
	D104	5.3	100.0	50.82	166.26	95
	D114	2.3	100.0	44.20	173.30	84
	E026	2.3	100.0	47.68	167.40	144
	E027	2.3	100.0	47.67	167.65	131
	E820	3.7	100.0	46.58	165.97	220
	E842	3.7	100.0	33.90	172.28	187
	G009	3.0	100.0	48.00	166.59	170
	L17	3.0	100.0	36.28	174.67	50
	P448	4.3	100.0	34.39	172.47	101
	P454	3.3	100.0	34.25	172.16	292
	P458	2.7	100.0	34.23	171.94	200
	P489	3.7	100.0	34.30	172.68	88
	P492	4.3	100.0	34.36	172.61	85
	P558	4.3	100.0	33.98	171.72	178

Species and sample information	Sample location	Wt% $MgCO_3$	Wt% Calcite	Latitude (°S)	Longitude (°E)	Depth (m)
Mecynoecia purpurascens	C11	0.7	100.0	36.45	175.30	50
cyclostomata	C12	1.3	100.0	36.45	175.30	50
calcite	C60	2.0	100.0	36.45	175.30	50
14 samples	D044	3.0	100.0	47.50	168.01	120
	D104	4.0	100.0	50.82	166.26	95
	K6	0.7	100.0	36.45	174.92	40
	L13	1.3	100.0	36.28	174.67	50
	L17	1.3	100.0	36.28	174.67	50
	LF	1.3	100.0	36.27	174.80	20
	LS	1.7	100.0	36.27	174.80	20
	P448	1.0	100.0	34.39	172.47	101
	P454	1.0	100.0	34.25	172.16	292
	P492	1.0	100.0	34.36	172.61	85
	P609	0.3	100.0	40.01	174.08	75
Otionella squamosa	B568	0.0	0.0	46.00	170.72	73
cheilostomata:anasca	B574	0.0	0.0	47.33	168.22	113
aragonite & bimineral	C11	0.0	0.0	36.45	175.30	50
13 samples	C12	8.3	9.0	36.45	175.30	50
	C60	4.7	8.5	36.45	175.30	50
	C60	0.0	0.0	36.45	175.30	50
	D044	0.0	0.0	47.50	168.01	120
	K6	0.0	0.0	36.45	174.92	40
	K21	0.0	0.0	36.45	174.92	40
	L17	0.0	0.0	36.28	174.67	50
	P448	0.0	0.0	34.39	172.47	101
	P454	0.0	0.0	34.25	172.16	292
	P507	7.0	4.3	34.15	172.75	100
Telopora buski	B488	4.3	100.0	46.48	166.24	164
cyclostomata	C11	2.0	100.0	36.45	175.30	50
calcite	C60	3.7	100.0	36.45	175.30	50
24 samples	C12	4.3	100.0	36.45	175.30	50
	D038	4.3	100.0	51.97	165.47	252
	D044	2.3	100.0	47.50	168.01	120
	D104	2.0	100.0	50.82	166.26	95
	E026	2.3	100.0	47.68	167.40	144
	E027	1.7	100.0	47.67	167.65	131
	E027	0.7	100.0	47.67	167.65	131
	E559	3.7	100.0	35.45	174.75	102
	G007	2.3	100.0	48.02	167.62	148
	G009	1.7	100.0	48.00	166.59	170
	L17	2.0	100.0	36.28	174.67	50
	P448	3.0	100.0	34.39	172.47	101
	P448	2.3	100.0	34.39	172.47	101
	P448	1.7	100.0	34.39	172.47	101
	P454	4.3	100.0	34.25	172.16	292
	P458	3.0	100.0	34.23	171.94	200
	P489	3.7	100.0	34.30	172.68	88
	P492	2.3	100.0	34.36	172.61	85
	P558	4.3	100.0	33.98	171.72	178
	P609	2.3	100.0	40.01	174.08	75
	P614	2.7	100.0	40.17	174.58	90

Species and sample information	Sample location	Wt% $MgCO_3$	Wt% Calcite	Latitude (°S)	Longitude (°E)	Depth (m)
	P448	6.0	62.7	34.39	172.47	101
	P454	6.3	37.4	34.25	172.16	292
	P458	7.0	61.3	34.23	171.94	200
	P489	6.7	100.0	34.30	172.68	88
	P492	5.0	100.0	34.36	172.61	85
	P558	7.0	61.3	33.98	171.72	178
Galeopsis porcellanicus	B567	7.0	100.0	46.00	170.92	126
cheilostomata:ascophora	C11	7.0	100.0	36.45	175.30	50
Mg calcite	C60	6.0	100.0	36.45	175.30	50
24 samples	C176	6.7	100.0	39.67	173.95	40
	D044	6.3	100.0	47.50	168.01	120
	DPG5	5.7	100.0	49.75	179.00	
	E026	5.7	100.0	47.68	167.40	144
	E027	5.7	100.0	47.67	167.65	131
	E028	5.3	100.0	47.66	167.92	143
	G007	4.7	100.0	48.02	167.62	148
	G009	6.7	100.0	48.00	166.59	170
	K21	6.7	100.0	36.45	174.92	40
	L13	7.7	100.0	36.28	174.67	50
	L17	6.3	100.0	36.28	174.67	50
	LF	7.0	100.0	36.27	174.80	20
	LS	6.7	100.0	36.27	174.80	20
	OF	7.0	100.0	36.72	175.83	20
	P448	6.0	100.0	34.39	172.47	101
	P458	7.0	100.0	34.23	171.94	200
	P492	6.3	100.0	34.36	172.61	85
	P558	7.0	100.0	33.98	171.72	178
	P609	6.3	100.0	40.01	174.08	75
	P614	6.3	100.0	40.17	174.58	90
	RW	6.3	100.0	34.98	173.94	90
Hornera sp.	A441	0.0	100.0	41.13	174.65	210
cyclostomata	B567	4.3	100.0	46.00	170.92	126
calcite	C176	0.3	100.0	39.67	173.95	40
19 samples	D038	2.7	100.0	51.97	165.47	252
	E026	3.3	100.0	47.68	167.40	144
	E027	2.3	100.0	47.67	167.65	131
	E644	2.7	100.0	37.01	176.08	73
	E849	0.0	100.0	33.92	171.53	216
	G007	2.0	100.0	48.02	167.62	148
	G009	0.0	100.0	48.00	166.59	170
	G009	1.0	100.0	48.00	166.59	170
	G009	1.7	100.0	48.00	166.59	170
	P448	1.3	100.0	34.39	172.47	101
	P454	2.3	100.0	34.25	172.16	292
	P458	2.0	100.0	34.23	171.94	200
	P492	0.0	100.0	34.36	172.61	85
	P507	0.7	100.0	34.15	172.75	100
	P609	0.7	100.0	40.01	174.08	75
	P614	0.0	100.0	40.17	174.58	90

Species and sample information	Sample location	Wt% $MgCO_3$	Wt% Calcite	Latitude (°S)	Longitude (°E)	Depth (m)
	P609	2.3	100.0	40.01	174.08	75
	P614	3.7	100.0	40.17	174.58	90
Celleporina costazii	B488	6.0	100.0	46.48	166.24	164
cheilostomata:ascophora	C12	7.3	100.0	36.45	175.30	50
calcite	C60	6.0	100.0	36.45	175.30	50
14 samples	D044	4.7	100.0	47.50	168.01	120
	E027	5.3	100.0	47.67	167.65	131
	E028	4.3	100.0	47.66	167.92	143
	K6	5.0	100.0	36.45	174.92	40
	K21	4.3	100.0	36.45	174.92	40
	L17	5.7	100.0	36.28	174.67	50
	P448	6.3	100.0	34.39	172.47	101
	P454	5.7	100.0	34.25	172.16	292
	P492	6.3	100.0	34.36	172.61	85
	P558	6.3	100.0	33.98	171.72	178
	P609	5.7	100.0	40.01	174.08	75
Cinctipora elegans	B488	0.7	100.0	46.48	166.24	164
cyclostomata	B568	0.7	62.4	46.00	170.72	73
calcite	D038	0.7	100.0	51.97	165.47	252
19 samples	D104	0.7	100.0	50.82	166.26	95
	D114	0.0	100.0	44.20	173.30	84
	D114	0.0	100.0	44.20	173.30	84
	D114	0.0	100.0	44.20	173.30	84
	D114	0.0	100.0	44.20	173.30	84
	D114	0.3	100.0	44.20	173.30	84
	D114	0.0	100.0	44.20	173.30	84
	D114	0.0	100.0	44.20	173.30	84
	E026	0.3	100.0	47.68	167.40	144
	E027	1.0	100.0	47.67	167.65	131
	E028	0.0	100.0	47.66	167.92	143
	E820	1.0	100.0	46.58	165.97	220
	E833	0.0	100.0	46.95	168.15	53
	G009	0.7	100.0	48.00	166.59	170
	P609	0.7	78.4	40.01	174.08	75
	P614	1.7	100.0	40.17	174.58	90
Foveolaria cyclops	B581	6.0	49.2	48.00	168.10	138
cheilostomata:anasca	D038	6.0	55.3	51.97	165.47	252
bimineral	D044	6.3	34.2	47.50	168.01	120
21 samples	E026	5.7	50.5	47.68	167.40	144
	E027	5.3	57.1	47.67	167.65	131
	E028	5.7	44.3	47.66	167.92	143
	E820	6.3	52.9	46.58	165.97	220
	G007	5.7	34.2	48.02	167.62	148
	G009	5.7	48.0	48.00	166.59	170
	G009	4.3	46.7	48.00	166.59	170
	L13	6.3	100.0	36.28	174.67	50
	L17	6.3	100.0	36.28	174.67	50
	LS	6.7	100.0	36.27	174.80	20
	OF	6.7	55.8	36.72	175.83	20
	P448	5.0	40.8	34.39	172.47	101

Table A2.10: Mineralogy of bryozoan taxa.

Taxon	Species	n	Min	Mean wt % Calcite	Mean wt % $MgCO_3$
CYCLOSTOMATA	*Cinctipora elegans*	20	B/C	97.0	0.6
	Annectocyma sp.	4	lo C	100.0	3.9
	Disporella gordoni	1	lo C	100.0	3.3
	Hemipustulopora harmeri	1	mid C	100.0	5.7
	Hornera foliacea	3	lo C	100.0	2.7
	Hornera sp.	20	lo C	100.0	1.4
	Idmidroneiforms	2	lo C	100.0	3.5
	Lichenopora sp.	6	mid C	100.0	4.5
	Mecynoecia purpurascens	20	lo C	100.0	1.7
	Telopora buski	26	lo C	100.0	2.8
CHEILOSTOMATA	*Chaperia acanthina*	5	B/C	52.5	4.1
ANASCA	*Chaperiopsis tintinnabula*	3	mid C	100.0	6.0
Calloporoidea	*Foveolaria cyclops*	22	B/C	63.3	6.0
	Patsyella flemingi	4	B/C	89.3	4.9
Buguloidea	*Bugula dentata*	1	hi C	100.0	6.3
	Caberea zelandica	2	lo C	100.0	2.7
	Menipea zelandica	3	mid C	100.0	5.0
Microporoidea	*Macropora grandis*	1	mid C	100.0	5.7
	Otionella squamosa	14	B/A	1.6	6.0
	Steginoporella magnifica	15	mid C	97.2	4.4
	Steginoporella neozelanica	15	mid C	100.0	3.7
	Steginoporella perplexa	6	mid C	76.1	3.7
Cellarioidea	*Cellaria immersa*	25	lo C	100.0	3.4
	Cellaria tenuirostris	2	lo C	100.0	3.9
	Melicerita chathamensis	2	hi C	100.0	7.5
ASCOPHORA	*Euthyroides episcopalis*	1	hi C	100.0	8.0
Cribriomorpha	*Euthyroides jellyae*	1	hi C	49.5	8.3
Hippothoomorpha	*Celleporella cancer*	1	lo C	100.0	0.0
	Gemellipora eburnea	1	hi C	100.0	7.0
Umbonulomorpha	*Adeonellopsis sp.*	30	B/A	3.1	5.7
	Arachnopusia unicornis	11	B/C	90.1	5.3
	Celleporaria agglutinans	7	mid C	100.0	5.2
	Cornuticella taurina	1	mid C	100.0	5.0
	Escharoides excavata	1	mid C	100.0	5.0
Lepraliomorpha	*Celleporina costazii*	18	mid C	98.7	5.6
	Celleporina grandis	1	lo C	100.0	4.0
	Chiastosella splendida	6	mid C	86.3	5.7
	Conescharellina angulopora	1	B/C	50.0	4.3
	Escharina waiparensis	3	mid C	100.0	6.2
	Galeopsis polyporus	12	hi C	100.0	7.1
	Galeopsis porcellanicus	27	hi C	100.0	6.4
	Gigantopora pupa	1	hi C	100.0	6.3
	Hippellozoon novaezelandiae	7	hi C	100.0	6.7
	Hippomenella vellicata	5	mid C	88.0	5.7
	Iodictyum yaldwynii	8	hi C	100.0	6.8
	Margaretta barbata	3	hi C	100.0	7.6
	Metroperiella mucronifera	10	hi C	94.8	7.5
	Odontoporella adpressa	2	B/A	14.0	7.7

Table A2.11: Mineralogy of colonial growth forms.

Growth form	Number species	Number specimens	Calcite mean	Calcite std. dev	$MgCO_3$ mean	$MgCO_3$ std. dev.
ENul	12	64	78.4	30.0	5.1	1.4
ENml	2	25	99.0	4.8	5.8	0.9
ERde	4	60	100.0	0.0	5.0	2.5
ERfe	3	18	100.0	0.0	6.1	1.9
ERfo	3	17	87.1	21.8	5.6	1.0
ERma	1	1	100.0	0.0	4.0	0.0
ERra	3	32	100.0	0.0	3.2	1.3
ERro	10	94	50.7	36.1	3.0	3.0
EF	9	85	99.4	5.5	3.9	1.2
FL	2	15	11.5	27.7	1.9	2.9

Table A2.12: Mineralogy of different growth forms of *Foveolaria cyclops*.

Growth form	Number samples	Mean wt% Calcite	Mean wt% $MgCO_3$
ERro	3	51.6	5.5
ENul	19	65.1	6.0

Table A2.13: Mg content of five common species according to preservation state of samples (in wt% $MgCO_3$).

		Mecynoecia purpurascens lo C	*Steginoporella neozelanica* mid C	*Galeopsis porcellanicus* hi C	*Foveolaria cyclops* B/C
LIVING	RW			6.3	
	LF	1.3	3.7	7.0	
	MB				
	OF		3.3	7.0	6.7
FRESH SEDIMENT	P448	1.0	5.3	6.0	5.0
			3.7		6.0
	P458		5.3	7.0	7.0
	P492	1.0	3.7	6.3	5.0
	P558			7.0	7.0
	P609	0.3		6.3	
	LS	1.7	3.7	6.7	6.7
	D44	3.0	3.0	6.3	6.3
DEGRADED SEDIMENT	L17	1.3	4.0	6.3	6.3
			3.3		
	P454	1.0			6.3
	E28	5.0		5.3	5.7
	G9			6.7	5.7
					4.3

Table A2.14: Calcite/aragonite ratio in bimineral specimens of *Foveolaria cyclops* according to preservation state of samples.

		Calcite/aragonite ratio (wt% calcite)
LIVING	E820	52.9
	D38	55.3
	OF	55.8
FRESH SEDIMENT	P448	40.8
	P448	62.7
	P458	61.3
	P558	61.3
	D44	34.2
DEGRADED SEDIMENT	P454	37.4
	E26	50.5
	E27	57.1
	E28	44.3
	G7	34.2
	G9	48.0
	G9	46.7

Table A3.1: Sample coverage of geochemistry study. Abbreviations as in Table AI.2.

Species	# spls	Mineralogy	TKP	HKG	BOP	WNG	CKS	CNT	SFL	STS	SAI
Adeonellopsis sp.	6	B/A				1		1	1	2	1
Annectocyma sp.	2	lo C	1			1					
Arachnopusia unicornis	4	B/C		2		1				1	
Cellaria immersa	7	lo C	2	1		1			1	2	
Celleporaria agglutinans	4	mid C		2		1				1	
Celleporina costazii	3	mid C	2			1					
Cinctipora elegans	4	lo C				1		1		1	1
Cornuticella taurina	1	mid C					1				
Escharina waiparensis	1	mid C								1	
Euthyroides episcopalis	1	hi C					1				
Euthyroides jellyae	1	hi C					1				
Foveolaria cyclops	2	B/C				1			1		
Galeopsis polyporus	5	hi C	2	1		1					1
Galeopsis porcellanicus	5	hi C	1	2						1	1
Hippellozoon novaezelandiae	4	hi C	2	1		1					
Hornera sp.	6	lo C	2			1				2	1
Iodictyum yaldwini	1	hi C	1								
Macropora grandis	1	mid C		1							
Mecynoecia purpurascens	7	lo C	1	4		2					
Menipea zelanica	2	mid C	2								
Metroperiella mucronifera	1	hi C	1								
Otionella squamosa	5	B/A	2	3							
Patsyella flemingi	2	B/C		2							
Steginoporella magnifica	3	mid C	1	1						1	
Steginoporella neozelanica	3	mid C	1	1	1						
Steginoporella perplexa !	2	mid C	2								
Telopora buski	5	lo C	1	3		1					
TOTALS (No. species : 30)	88		24	24	1	14	3	2	3	12	5

Table A3.2: Co-precipitates in carbonate in some New Zealand bryozoans.

EH code	AMS code	Species	Sample number	Sample location	Content of element in µg/g				
					% sol	Ca	Mg	Sr	Mn	Fe
I7	A.1.B	*Adeonellopsis sp.*	D114	CNT	96.4	406144	1328	6548	12	195
I8	A.1.X	*Adeonellopsis sp.*	E26	STS	95.7	383861	3250	6472	46	737
I9	A.1.C	*Adeonellopsis sp.*	E820	SFL	99.2	426293	2714	6527	12	56
J7	A.1.A	*Adeonellopsis sp.*	D38	STS	98.0	405968	1282	7183	17	86
L1	A.1.R	*Adeonellopsis sp.*	D44	STS	96.8	353765	2550	6900	35	459
I1	A.11.D	*Annectocyma sp.*	P448	TKP	89.8	261194	16246	2256	23	884
J3	A.2.I	*Arachnopusia unicornis*	C12	HKG	90.8	358397	21927	2035	77	910
J8	A.2.Z	*Arachnopusia unicornis*	L21	HKG	92.2	343668	19387	1965	26	646
J11	A.2.Y	*Arachnopusia unicornis*	L33	HKG	92.5	363189	20622	2136	27	960
J4	A.3.I	*Cellaria immersa*	C12	HKG	91.7	383197	15430	2459	81	924
J10	A.3.D	*Cellaria immersa*	P448	TKP	95.2	379590	18008	2331	18	489
K3	A.3.X	*Cellaria immersa*	E26	STS	93.7	350297	15796	2132	43	572
K10	A.3.C	*Cellaria immersa*	E820	SFL	96.7	350318	14579	2247	30	182
L3	A.3.W	*Cellaria immersa*	P454	TKP	99.3	359345	15118	1990	18	247
J2	A.3.S	*Cellaria immersa*	E27	STS	96.8	373754	14507	2262	55	490
I11	A.6.P	*Celleporaria agglutinans*	LF	HKG	96.8	377051	22827	2222	13	90
K9	A.6.I	*Celleporaria agglutinans*	C12	HKG	88.3	360753	23527	1952	76	985
L5	A.6.AA	*Celleporaria agglutinans*	B482	STS	97.2	351535	19803	2027	38	90
K1	A.5.W	*Celleporina costazii*	P454	TKP	97.9	375392	21856	2095	12	274
I10	A.5.G	*Celleporina costazii*	P558	TKP	100.0	362647	21555	1843	17	306
J6	A.9.B	*Cinctipora elegans*	D114	CNT	92.3	385324	9292	2747	13	188
L8	A.9.T	*Cinctipora elegans*	G9	STS	99.2	358904	12396	2369	55	257
K7	A.9.A	*Cinctipora elegans*	D38	SAI	98.7	346743	11054	2414	28	144
I12	A.10.ZZ	*Cornuticella taurina*	DPG3	CKS	79.7	340380	22071	1885	71	649
K11	A.12.R	*Escharina waiparensis*	D44	STS	100.0	335508	18919	1892	60	1109
K4	A.13.ZZ	*Euthyroides episcopalis*	DPG2	CKS	61.5	301741	27466	1779	172	1973
H12	A.14.ZZ	*Euthyroides jellyae*	DPG4	CKS	65.1	224178	28756	1749	141	1174
J1	A.15.A	*Foveolaria cyclops*	D38	SAI	95.6	380208	14375	3958	28	128

EH code	AMS code	Species	Sample number	Sample location	% sol	Content of element in µg/g Ca	Mg	Sr	Mn	Fe
L2	A.16.A	*Galeopsis polyporus*	D38	SAI	99.6	349794	21216	1882	23	140
L4	A.16.W	*Galeopsis polyporus*	P454	TKP	99.1	338068	23047	1839	19	246
L7	A.16.D	*Galeopsis polyporus*	P448	TKP	94.5	339630	25844	1817	18	760
L9	A.16.N	*Galeopsis polyporus*	L17	HKG	96.6	342765	26685	1787	19	421
E2	A.17.D	*Galeopsis porcellanicus*	P448	TKP	93.9	364964	23635	2054	17	750
H8	A.17.ZZ	*Galeopsis porcellanicus*	DPG5	SAI	96.2	237805	20528	1862	14	97
I6	A.17.BB	*Galeopsis porcellanicus*	C10	HKG	95.1	379495	23247	1629	15	546
J9	A.17.P	*Galeopsis porcellanicus*	LF	HKG	98.8	356763	23616	1778	18	100
E7	A.18.BB	*Hippellozoon novaezelandiae*	C10	HKG	93.8	377358	26288	1969	18	1607
G11	A.18.W	*Hippellozoon novaezelandiae*	P454	TKP	99.0	303074	22225	1876	14	264
H4	A.20.D	*Hornera sp.*	P448	TKP	95.9	296846	12369	2742	17	653
E11	A.20.S	*Hornera sp.*	E27	STS	97.9	397163	13872	2613	51	403
I4	A.20.T	*Hornera sp.*	G9	STS	97.5	382442	13733	2260	32	335
K8	A.20.W	*Hornera sp.*	P454	TKP	100.0	368623	12397	2309	30	647
K12	A.20.A	*Hornera sp.*	D38	SAI	100.0	371984	14008	2225	46	292
J5	A.22.W	*Iodictyum yaldwini*	P454	TKP	98.6	373431	25742	1754	20	266
I2	A.24.I	*Macropora grandis*	C12	HKG	93.0	253253	23974	2452	77	811
F12	A.25.CC	*Mecynoecia purpurascens*	LS	HKG	94.1	330807	11671	2543	32	436
G12	A.25.BB	*Mecynoecia purpurascens*	C10	HKG	98.9	271680	11009	2202	34	1226
I3	A.25.I	*Mecynoecia purpurascens*	C12	HKG	89.0	382605	12012	2547	142	1134
L10	A.25.H	*Mecynoecia purpurascens*	C11	HKG	89.6	353502	12889	2474	141	1455
K6	A.27.G	*Menipea zelandica*	P558	TKP	100.0	358072	20193	1783	40	324
I5	A.28.W	*Metroperiella mucronifera*	P454	TKP	96.9	380975	27212	1633	21	291
G7	A.29.Y	*Otionella squamosa*	L33	HKG	91.3	321565	4745	5757	19	8500
H3	A.29.N	*Otionella squamosa*	L17	HKG	93.7	308627	1507	6731	12	885
H5	A.29.BB	*Otionella squamosa*	C10	HKG	91.7	305585	3045	6544	13	1992
H7	A.29.F	*Otionella squamosa*	P492	TKP	95.7	262925	1179	6459	11	298
L6	A.29.W	*Otionella squamosa*	P454	TKP	96.7	378994	3612	5784	12	362
K5	A.30.I	*Patsyella flemingi*	C12	HKG	89.6	350256	21282	2226	75	928
G2	A.31.W	*Steginoporella magnifica*	P454	TKP	94.4	340094	17473	1962	21	460
E12	A.31.D	*Steginoporella magnifica*	P448	TKP	91.2	399518	16966	1565	14	359

EH code	AMS code	Species	Sample number	Sample location	% sol	Content of element in µg/g Ca	Mg	Sr	Mn	Fe
K2	A.31.BB	*Steginoporella magnifica*	C10	HKG	77.0	358274	18304	2064	20	1284
J12	A.32.Q	*Steginoporella neozelanica*	OF	BOP	100.0	367671	15104	2007	23	275
G5	A.32.D	*Steginoporella neozelanica*	P448	TKP	83.3	328181	16552	2038	22	866
H10	A.33.E	*Steginoporella perplexa*	P489	TKP	80.7	255840	15944	2064	12	302
G1	A.34.I	*Telopora buski*	C12	HKG	89.2	345588	16544	2243	117	1345
H2	A 34.Z	*Telopora buski*	L21	HKG	88.6	301047	14660	2241	52	1199
H6	A.34.BB	*Telopora buski*	L10	HKG	87.4	303315	16133	2337	46	2155
		Mean			93.42	346029	16168	2794	39	752
		Maximum value			100	426293	28756	7183	172	8500
		Minimum value			61.47	224178	1179	1565	11	56
		Range			38.53	202114	27576	5617	162	8444

NOTES: EH code is the technician's work code. AMS code is a combination of species (number) and location (letter). Sample numbers are listed in Table 2B.1, except for the Hauraki Gulf samples, which are listed in Chapter 5.
% sol means percent of original weight accounted for in analysis.

Table A3.3: Stable isotopes in some New Zealand bryozoans.

AMS code	Species	Sample number	Sample location	isotope (mg/g PDB) $\delta^{18}O$	$\delta^{13}C$
A.1.B	*Adeonellopsis sp.*	D114	CNT	1.82	2.19
A.1.X	*Adeonellopsis sp.*	E26	STS	2.35	2.68
A.1.C	*Adeonellopsis sp.*	E820	SFL	1.97	2.18
A.1.A	*Adeonellopsis sp.*	D38	STS	2.72	2.49
A.1.R	*Adeonellopsis sp.*	D44	STS	2.26	2.73
A.1.EE	*Adeonellopsis sp.*	P609	WNG	0.89	2.45
A.11.D	*Annectocyma sp.*	P448	TKP	0.89	0.96
A.11.FF	*Annectocyma sp.*	P614	WNG	0.06	0.89
A.2.I	*Arachnopusia unicornis*	C12	HKG	0.48	0.34
A.2.Z	*Arachnopusia unicornis*	L21	HKG	1.19	0.83
A.2.Y	*Arachnopusia unicornis*	L33	HKG	0.92	0.58
A.2.EE	*Arachnopusia unicornis*	P609	WNG	-0.47	0.77
A.3.I	*Cellaria immersa*	C12	HKG	0.66	1.04
A.3.D	*Cellaria immersa*	P448	TKP	1.24	1.35
A.3.X	*Cellaria immersa*	E26	STS	1.58	1.58
A.3.C	*Cellaria immersa*	E820	SFL	1.84	1.56
A.3.W	*Cellaria immersa*	P454	TKP	2.37	1.57
A.3.S	*Cellaria immersa*	E27	STS	1.84	1.66
A.3.FF	*Cellaria immersa*	P614	WNG	0.40	1.23
A.6.P	*Celleporaria agglutinans*	LF	HKG	0.25	0.00
A.6.I	*Celleporaria agglutinans*	C12	HKG	0.74	0.67
A.6.AA	*Celleporaria agglutinans*	B482	STS	1.30	0.83
A.6.EE	*Celleporaria agglutinans*	P609	WNG	0.04	1.00
A.5.W	*Celleporina costazii*	P454	TKP	2.26	1.68
A.5.G	*Celleporina costazii*	P558	TKP	1.68	1.74
A.5.EE	*Celleporina costazii*	P609	WNG	0.29	1.55
A.7.FF	*Celleporina grandis*	P614	WNG	-0.06	1.29
A.9.B	*Cinctipora elegans*	D114	CNT	1.93	1.22
A.9.T	*Cinctipora elegans*	G9	STS	1.50	1.26
A.9.A	*Cinctipora elegans*	D38	SAI	1.79	1.40
A.9.EE	*Cinctipora elegans*	P609	WNG	0.16	1.10
A.10.ZZ	*Cornuticella taurina*	DPG3	CKS	0.57	-0.55
A.12.R	*Escharina waiparensis*	D44	STS	1.26	1.58
A.13.ZZ	*Euthyroides episcopalis*	DPG2	CKS	0.65	-0.91
A.14.ZZ	*Euthyroides jellyae*	DPG4	CKS	1.48	0.95
A.15.A	*Foveolaria cyclops*	D38	SAI	2.16	1.52
A.15.HH	*Foveolaria cyclops*	B488	STS	0.55	1.68
A.15.II	*Foveolaria cyclops*	P507	TKP	0.37	1.59
A.16.A	*Galeopsis polyporus*	D38	SAI	1.94	0.94
A.16.W	*Galeopsis polyporus*	P454	TKP	1.56	1.03
A.16.D	*Galeopsis polyporus*	P448	TKP	0.96	0.89
A.16.N	*Galeopsis polyporus*	L17	HKG	0.84	0.10
A.16.EE	*Galeopsis polyporus*	P609	WNG	-0.33	0.38
A.17.D	*Galeopsis porcellanicus*	P448	TKP	1.27	1.58
A.17.ZZ	*Galeopsis porcellanicus*	DPG5	SAI	1.87	1.69
A.17.BB	*Galeopsis porcellanicus*	C10	HKG	0.99	1.52
A.17.P	*Galeopsis porcellanicus*	LF	HKG	0.88	0.97
A.17.M	*Galeopsis porcellanicus*	L13	HKG	-0.67	1.56

AMS code	Species	Sample number	Sample location	Sample isotope (mg/g PDB) $\delta^{18}O$	$\delta^{13}C$
A.18.BB	*Hippellozoon novaezelandia*	C10	HKG	0.88	2.15
A.18.W	*Hippellozoon novaezelandia*	P454	TKP	1.76	1.83
A.18.II	*Hippellozoon novaezelandia*	P507	TKP	-0.28	1.80
A.18.EE	*Hippellozoon novaezelandia*	P609	WNG	0.44	2.13
A.19.GG	*Hippomenella vellicata*	E842	TKP	0.24	1.65
A.19.FF	*Hippomenella vellicata*	P614	WNG	0.43	0.94
A.20.D	*Hornera sp.*	P448	TKP	0.94	1.38
A.20.S	*Hornera sp.*	E27	STS	1.47	1.60
A.20.T	*Hornera sp.*	G9	STS	1.80	1.61
A.20.W	*Hornera sp.*	P454	TKP	1.58	1.62
A.20.A	*Hornera sp.*	D38	SAI	1.97	1.56
A.20.FF	*Hornera sp.*	P614	WNG	0.60	1.57
A.21.M	Idmidroneiforms	L13	HKG	-0.73	0.40
A.22.W	*Iodictyum yaldwini*	P454	TKP	1.97	1.72
A.24.I	*Macropora grandis*	C12	HKG	1.00	-0.08
A.25.CC	*Mecynoecia purpurascens*	LS	HKG	0.36	-0.64
A.25.BB	*Mecynoecia purpurascens*	C10	HKG	0.56	0.28
A.25.I	*Mecynoecia purpurascens*	C12	HKG	1.02	0.00
A.25.H	*Mecynoecia purpurascens*	C11	HKG	-0.80	-4.50
A.25.II	*Mecynoecia purpurascens*	P507	TKP	0.12	0.62
A.25.EE	*Mecynoecia purpurascens*	P609	WNG	0.53	-0.51
A.25FF	*Mecynoecia purpurascens*	P614	WNG	0.15	-0.02
A.27.G	*Menipea zelandica*	P558	TKP	1.56	1.37
A.27.II	*Menipea zelandica*	P507	TKP	0.07	1.00
A.28.W	*Metroperiella mucronifera*	P454	TKP	1.59	2.01
A.29.Y	*Otionella squamosa*	L33	HKG	1.67	2.49
A.29.N	*Otionella squamosa*	L17	HKG	1.41	2.70
A.29.BB	*Otionella squamosa*	C10	HKG	1.37	2.58
A.29.F	*Otionella squamosa*	P492	TKP	1.57	2.81
A.29.W	*Otionella squamosa*	P454	TKP	2.75	2.65
A.30.I	*Patsyella flemingi*	C12	HKG	1.44	0.91
A.30.M	*Patsyella flemingi*	L13	HKG	-0.46	0.66
A.31.W	*Steginoporella magnifica*	P454	TKP	1.64	-0.03
A.31.D	*Steginoporella magnifica*	P448	TKP	0.73	-0.09
A.31.BB	*Steginoporella magnifica*	C10	HKG	0.58	0.63
A.32.Q	*Steginoporella neozelanica*	OF	BOP	0.30	-1.81
A.32.D	*Steginoporella neozelanica*	P448	TKP	0.39	-1.48
A.33.E	*Steginoporella perplexa*	P489	TKP	0.72	-1.06
A.33.II	*Steginoporella perplexa*	P507	TKP	-0.13	-1.08
A.32.M	*Steginporella neozelanica*	L13	HKG	-1.35	-3.08
A.34.I	*Telopora buski*	C12	HKG	0.55	0.78
A 34.Z	*Telopora buski*	L21	HKG	0.92	0.89
A.34.BB	*Telopora buski*	L10	HKG	0.94	1.02
A.34.EE	*Telopora buski*	P609	WNT	-0.57	1.06
A.34.II	*Telopora buski*	P507	TKP	0.49	1.39
	MEAN			0.94	1.00

NOTES: AMS code is a combination of species (number) and location (letter). Sample numbers are listed in Table 2B.1, except for the Hauraki Gulf samples, which are listed in Chapter 5.

Table A3.4: Comparison of Mg content in some New Zealand bryozoans as measured by atomic absorption (AA) and X-ray diffraction (XRD).

Method	AA	AA	AA	AA	XRD	XRD
Species	Mg in µg/g	wt% Mg	wt% $MgCO_3$	mean for species	wt% $MgCO_3$	mean for species
Adeonellopsis sp.	1328	0.13	0.5	0.8		
Adeonellopsis sp.	3250	0.33	1.1			
Adeonellopsis sp.	2714	0.27	0.9			
Adeonellopsis sp.	1282	0.13	0.4			
Adeonellopsis sp.	2550	0.25	0.9			
Annectocyma sp.	16246	1.62	5.6	5.6	5.7	3.9
Arachnopusia unicornis	21927	2.19	7.6	7.2	4.7	5.3
Arachnopusia unicornis	19387	1.94	6.7		5.0	
Arachnopusia unicornis	20622	2.06	7.2		5.7	
Cellaria immersa	15430	1.54	5.4	5.4	4.0	3.4
Cellaria immersa	18008	1.80	6.2		4.3	
Cellaria immersa	15796	1.58	5.5		2.3	
Cellaria immersa	14579	1.46	5.1		3.7	
Cellaria immersa	15118	1.51	5.2		3.3	
Cellaria immersa	14507	1.45	5.0		2.3	
Celleporaria agglutinans	22827	2.28	7.9	7.7	6.3	5.2
Celleporaria agglutinans	23527	2.35	8.2			
Celleporaria agglutinans	19803	1.98	6.9			
Celleporina costazii	21856	2.19	7.6	7.5	5.7	5.6
Celleporina costazii	21555	2.16	7.5		6.3	
Cinctipora elegans	9292	0.93	3.2	3.8	0.0	0.6
Cinctipora elegans	12396	1.24	4.3		0.7	
Cinctipora elegans	11054	1.11	3.8		0.7	
Cornuticella taurina	22071	2.21	7.7	7.7	5.0	5.0
Escharina waiparensis	18919	1.89	6.6	6.6	6.7	6.2
Euthyroides episcopalis	27466	2.75	9.5	9.5	8.0	8.0
Euthyroides jellyae	28756	2.88	10.0	10.0	8.3	8.3
Foveolaria cyclops	14375	1.44	5.0	5.0	6.0	6.0
Galeopsis polyporus	21216	2.12	7.4	8.4		7.1
Galeopsis polyporus	23047	2.30	8.0		7.3	
Galeopsis polyporus	25844	2.58	9.0		7.7	
Galeopsis polyporus	26685	2.67	9.3		7.7	
Galeopsis porcellanicus	23635	2.36	8.2	7.9	6.0	6.4
Galeopsis porcellanicus	20528	2.05	7.1		5.7	
Galeopsis porcellanicus	23247	2.32	8.1		7.0	
Galeopsis porcellanicus	23616	2.36	8.2		7.0	
Hippellozoon novaezelandi	26288	2.63	9.1	8.4	7.3	6.7
Hippellozoon novaezelandi	22225	2.22	7.7		7.0	
Hornera sp.	12369	1.24	4.3	4.6	1.3	1.4
Hornera sp.	13872	1.39	4.8		2.3	
Hornera sp.	13733	1.37	4.8		1.0	
Hornera sp.	12397	1.24	4.3		2.3	
Hornera sp.	14008	1.40	4.9		2.7	
Iodictyum yaldwini	25742	2.57	8.9	8.9	5.7	6.8
Macropora grandis	23974	2.40	8.3	8.3		5.7

Method	AA	AA	AA	AA	XRD	XRD
Species	Mg in µg/g	wt% Mg	wt% $MgCO_3$	mean for species	wt% $MgCO_3$	mean for species
Mecynoecia purpurascens	11671	1.17	4.0	4.1	1.7	1.7
Mecynoecia purpurascens	11009	1.10	3.8			
Mecynoecia purpurascens	12012	1.20	4.2		1.3	
Mecynoecia purpurascens	12889	1.29	4.5		0.7	
Menipea zelandica	20193	2.02	7.0	7.0	5.7	5.0
Metroperiella mucronifera	27212	2.72	9.4	9.4	7.7	7.5
Otionella squamosa	4745	0.47	1.6	1.0		
Otionella squamosa	1507	0.15	0.5			
Otionella squamosa	3045	0.30	1.1			
Otionella squamosa	1179	0.12	0.4			
Otionella squamosa	3612	0.36	1.3			
Patsyella flemingi	21282	2.13	7.4	7.4	4.3	4.9
Steginoporella magnifica	17473	1.75	6.1	6.1	4.3	4.4
Steginoporella magnifica	16966	1.70	5.9		4.7	
Steginoporella magnifica	18304	1.83	6.3		4.3	
Steginoporella neozelanica	15104	1.51	5.2	5.5	3.3	3.7
Steginoporella neozelanica	16552	1.66	5.7		3.7	
Steginoporella perplexa	15944	1.59	5.5	5.5	2.7	3.7
Telopora buski	16544	1.65	5.7	5.5	4.3	2.8
Telopora buski	14660	1.47	5.1		2.0	
Telopora buski	16133	1.61	5.6		2.0	
Mean	16168	1.62	5.6		4.42	

Table A3.5: Statistics describing the degree of correlation between depth and various geochemical measures in four species of New Zealand bryozoans (see Figures 3D.21 - 3D.24).

	New Zealand bryozoans							
Geochemical	*Adeonellopsis*		*Otionella*		*Hornera*		*Cellaria*	
measures	R^2	slope	R^2	slope	R^2	slope	R^2	slope
Mg	0.041	-	0.057	+	0.001	-	0.755	-
Sr	0.445	+	0.339	-	0.643	-	0.029	-
Mn	0.023	-	0.081	-	0.041	+	0.435	-
Fe	0.131	-	0.131	-	0.002	-	0.760	-
	0.605	+	0.965	+	0.557	+	0.781	+
	0.010	+	0.017	+	0.213	+	0.514	+

NOTES: Ca, Mg, Sr, Mn, and Fe are all measured in µg/g.
$\delta^{18}O$ and $\delta^{13}C$ are measured in mg/g PBD.
R^2 refers to the R-squared statistic which describes how well the data fit the linear regression. A value of 1.0 is the largest possible.
The slope of the line indicates the kind of relationship: a positive or inverse correlation.

Table A4.1: Results of tumbling experiment.

	Time	Raw data: weight of size fraction in grams							Percent of total inital sample							
Sample	(h)	cg	fg	vcs	cs	ms	fs	vfs	% cg	% fg	% vcs	% cs	% ms	% fs	% vfs	% m
DE-N	0	2.46	9.23	1.89	0.00	0.00	0.00	0.00	18.1	68.0	13.9	0.0	0.0	0.0	0.0	0.0
DE-N	1	2.85	8.87	1.62	0.25	0.00	0.02	0.03	21.0	65.3	11.9	1.8	0.0	0.1	0.2	0.0
DE-N	3	1.84	9.03	2.40	0.38	0.03	0.04	0.06	13.5	66.5	17.7	2.8	0.2	0.3	0.4	0.0
DE-N	7	2.29	7.96	2.79	0.39	0.04	0.04	0.06	16.9	58.6	20.5	2.9	0.3	0.3	0.4	0.1
DE-N	15	0.71	8.73	3.39	0.50	0.05	0.07	0.08	5.2	64.3	25.0	3.7	0.4	0.5	0.6	0.4
DE-N	31	0.80	8.16	3.59	0.53	0.05	0.07	0.09	5.9	60.1	26.4	3.9	0.4	0.5	0.7	2.1
DE-N	63	0.43	7.48	4.29	0.54	0.08	0.07	0.09	3.2	55.1	31.6	4.0	0.6	0.5	0.7	4.4
DE-O	0	5.73	21.16	2.78	0.00	0.00	0.00	0.00	19.3	71.3	9.4	0.0	0.0	0.0	0.0	0.0
DE-O	1	7.43	19.71	1.99	0.05	0.01	0.06	0.05	25.1	66.5	6.7	0.2	0.0	0.2	0.2	0.1
DE-O	3	6.16	19.43	3.11	0.08	0.04	0.07	0.09	20.8	65.5	10.5	0.3	0.1	0.2	0.3	2.3
DE-O	7	4.62	20.64	3.10	0.15	0.05	0.11	0.10	15.6	69.6	10.5	0.5	0.2	0.4	0.3	3.0
DE-O	15	3.90	20.17	3.87	0.19	0.08	0.15	0.13	13.1	68.0	13.0	0.6	0.3	0.5	0.4	3.9
DE-O	31	3.21	19.66	4.28	0.22	0.07	0.15	0.14	10.8	66.3	14.4	0.7	0.2	0.5	0.5	6.5
DE-O	63	3.78	17.88	4.61	0.30	0.08	0.12	0.20	12.7	60.3	15.5	1.0	0.3	0.4	0.7	9.1
DE-O	127	2.59	16.48	6.18	0.31	0.07	0.15	0.16	8.7	55.6	20.8	1.0	0.2	0.5	0.5	12.5
EF-N	0	2.52	3.61	1.13	0.00	0.00	0.00	0.00	34.7	49.7	15.6	0.0	0.0	0.0	0.0	0.0
EF-N	1	1.71	4.56	0.80	0.09	0.01	0.03	0.01	23.6	62.8	11.0	1.2	0.1	0.4	0.1	0.7
EF-N	3	2.64	3.43	0.91	0.11	0.00	0.05	0.03	36.4	47.2	12.5	1.5	0.0	0.7	0.4	1.2
EF-N	7	2.33	3.58	1.00	0.11	0.02	0.06	0.04	32.1	49.3	13.8	1.5	0.3	0.8	0.6	1.7
EF-N	31	1.57	3.73	1.30	0.13	0.02	0.08	0.06	21.6	51.4	17.9	1.8	0.3	1.1	0.8	5.1
EF-N	63	1.89	3.29	1.22	0.21	0.02	0.09	0.07	26.0	45.3	16.8	2.9	0.3	1.2	1.0	6.5
EF-N	127	1.41	2.99	1.62	0.24	0.04	0.12	0.08	19.4	41.2	22.3	3.3	0.6	1.7	1.1	10.5
EF-O	0	8.12	22.08	2.18	0.00	0.00	0.00	0.00	25.1	68.2	6.7	0.0	0.0	0.0	0.0	0.0
EF-O	1	10.12	20.38	1.36	0.05	0.05	0.11	0.07	31.3	62.9	4.2	0.2	0.2	0.3	0.2	1.0
EF-O	3	8.91	21.09	1.37	0.02	0.10	0.22	0.13	27.5	65.1	4.2	0.1	0.3	0.7	0.4	2.1
EF-O	7	10.13	19.34	1.38	0.05	0.15	0.37	0.21	31.3	59.7	4.3	0.2	0.5	1.1	0.6	3.0
EF-O	15	10.05	18.13	1.77	0.04	0.18	0.47	0.27	31.0	56.0	5.5	0.1	0.6	1.5	0.8	5.4
EF-O	31	7.99	18.82	1.95	0.05	0.23	0.58	0.35	24.7	58.1	6.0	0.2	0.7	1.8	1.1	8.5
EF-O	63	9.20	16.01	1.75	0.11	0.31	0.73	0.42	28.4	49.4	5.4	0.3	1.0	2.3	1.3	13.2
EF-O	127	7.37	15.35	1.82	0.15	0.29	0.78	0.40	22.8	47.4	5.6	0.5	0.9	2.4	1.2	20.4

Sample	Time (h)	Raw data: weight of size fraction in grams							Percent of total inital sample							
		cg	fg	vcs	cs	ms	fs	vfs	% cg	% fg	% vcs	% cs	% ms	% fs	% vfs	% m
FE-N	0	8.51	5.61	0.23	0.00	0.00	0.00	0.00	59.3	39.1	1.6	0.0	0.0	0.0	0.0	0.0
FE-N	1	8.07	5.84	0.34	0.02	0.00	0.00	0.01	56.2	40.7	2.4	0.1	0.0	0.0	0.1	0.5
FE-N	3	6.87	6.82	0.44	0.09	0.04	0.06	0.04	47.9	47.5	3.1	0.6	0.3	0.4	0.3	0.0
FE-N	7	6.90	6.62	0.46	0.08	0.05	0.07	0.05	48.1	46.1	3.2	0.6	0.3	0.5	0.3	0.8
FE-N	15	6.47	6.83	0.54	0.10	0.05	0.08	0.08	45.1	47.6	3.8	0.7	0.3	0.6	0.6	1.4
FE-N	31	5.97	7.05	0.55	0.13	0.05	0.10	0.08	41.6	49.1	3.8	0.9	0.3	0.7	0.6	2.9
FE-N	36	5.07	7.61	0.49	0.18	0.07	0.10	0.08	35.3	53.0	3.4	1.3	0.5	0.7	0.6	5.2
FE-N	127	5.21	7.11	0.59	0.19	0.09	0.11	0.08	36.3	49.5	4.1	1.3	0.6	0.8	0.6	6.8
FE-O	0	22.10	10.03	0.46	0.00	0.00	0.00	0.00	67.8	30.8	1.4	0.0	0.0	0.0	0.0	0.0
FE-O	1	22.33	9.32	0.35	0.03	0.01	0.05	0.03	68.5	28.6	1.1	0.1	0.0	0.2	0.1	1.4
FE-O	3	21.57	9.55	0.44	0.07	0.05	0.07	0.06	66.2	29.3	1.4	0.2	0.2	0.2	0.2	2.4
FE-O	7	20.89	9.72	0.49	0.10	0.07	0.13	0.09	64.1	29.8	1.5	0.3	0.2	0.4	0.3	3.4
FE-O	15	19.22	10.56	0.51	0.13	0.07	0.14	0.13	59.0	32.4	1.6	0.4	0.2	0.4	0.4	5.6
FE-O	31	18.67	10.24	0.64	0.18	0.09	0.20	0.17	57.3	31.4	2.0	0.6	0.3	0.6	0.5	7.4
FE-O	63	18.04	9.72	0.68	0.18	0.10	0.20	0.20	55.4	29.8	2.1	0.6	0.3	0.6	0.6	10.6
FE-O	127	15.59	10.60	0.82	0.21	0.11	0.19	0.19	47.8	32.5	2.5	0.6	0.3	0.6	0.6	15.0
FL-N	0	7.54	19.49	0.51	0.00	0.00	0.00	0.00	27.4	70.8	1.9	0.0	0.0	0.0	0.0	0.0
FL-N	1	7.20	19.67	0.51	0.02	0.00	0.01	0.03	26.1	71.4	1.9	0.1	0.0	0.0	0.1	0.4
FL-N	3	6.92	19.59	0.55	0.02	0.00	0.04	0.16	25.1	71.1	2.0	0.1	0.0	0.1	0.6	0.9
FL-N	7	6.89	19.35	0.63	0.06	0.00	0.15	0.13	25.0	70.3	2.3	0.2	0.0	0.5	0.5	1.2
FL-N	31	6.36	19.27	0.72	0.08	0.02	0.20	0.20	23.1	70.0	2.6	0.3	0.1	0.7	0.7	2.5
FL-N	63	6.47	18.86	0.69	0.09	0.00	0.23	0.23	23.5	68.5	2.5	0.3	0.0	0.8	0.8	3.5
FL-N	127	5.94	18.86	0.81	0.08	0.02	0.21	0.27	21.6	68.5	2.9	0.3	0.1	0.8	1.0	4.9
FL-O	0	27.74	32.43	0.31	0.00	0.00	0.00	0.00	45.9	53.6	0.5	0.0	0.0	0.0	0.0	0.0
FL-O	1	27.63	31.75	0.33	0.00	0.00	0.19	0.12	45.7	52.5	0.5	0.0	0.0	0.3	0.2	0.8
FL-O	3	26.92	31.60	0.29	0.00	0.01	0.33	0.23	44.5	52.2	0.5	0.0	0.0	0.5	0.4	1.8
FL-O	7	26.05	31.73	0.34	0.01	0.03	0.43	0.32	43.1	52.5	0.6	0.0	0.0	0.7	0.5	2.6
FL-O	15	24.58	31.96	0.41	0.01	0.02	0.50	0.46	40.6	52.8	0.7	0.0	0.0	0.8	0.8	4.2
FL-O	31	24.34	30.57	0.42	0.03	0.02	0.53	0.57	40.2	50.5	0.7	0.0	0.0	0.9	0.9	6.6
FL-O	63	21.83	32.00	0.45	0.02	0.03	0.47	0.61	36.1	52.9	0.7	0.0	0.0	0.8	1.0	8.4
FL-O	127	20.23	31.85	0.67	0.02	0.02	0.38	0.58	33.4	52.7	1.1	0.0	0.0	0.6	1.0	11.1
ML-N	0	20.68	3.81	0.07	0.00	0.00	0.00	0.00	84.2	15.5	0.3	0.0	0.0	0.0	0.0	0.0

	Time	Raw data: weight of size fraction in grams							Percent of total inital sample							
Sample	(h)	cg	fg	vcs	cs	ms	fs	vfs	% cg	% fg	% vcs	% cs	% ms	% fs	% vfs	% m
ML-N	1	19.87	3.75	0.07	0.00	0.00	0.10	0.21	80.9	15.3	0.3	0.0	0.0	0.4	0.9	2.3
ML-N	3	19.09	3.67	0.09	0.02	0.02	0.22	0.51	77.7	14.9	0.4	0.1	0.1	0.9	2.1	3.7
ML-N	7	17.82	3.72	0.09	0.03	0.04	0.34	0.60	72.6	15.1	0.4	0.1	0.2	1.4	2.4	7.8
ML-N	15	16.13	4.00	0.16	0.08	0.04	0.45	0.69	65.7	16.3	0.7	0.3	0.2	1.8	2.8	12.3
ML-N	31	14.58	3.84	0.12	0.11	0.05	0.59	0.74	59.4	15.6	0.5	0.4	0.2	2.4	3.0	18.4
ML-N	63	11.95	4.24	0.14	0.12	0.04	0.68	0.68	48.7	17.3	0.6	0.5	0.2	2.8	2.8	27.3
ML-N	127	8.96	4.31	0.19	0.12	0.04	0.11	0.55	36.5	17.5	0.8	0.5	0.2	0.4	2.2	41.9
ML-O	0	32.14	3.24	0.03	0.00	0.00	0.00	0.00	90.8	9.1	0.1	0.0	0.0	0.0	0.0	0.0
ML-O	1	30.32	3.75	0.06	0.01	0.03	0.08	0.21	85.6	10.6	0.2	0.0	0.1	0.2	0.6	2.7
ML-O	3	29.93	3.19	0.06	0.03	0.04	0.18	0.38	84.5	9.0	0.2	0.1	0.1	0.5	1.1	4.5
ML-O	7	27.69	3.77	0.06	0.03	0.05	0.21	0.54	78.2	10.6	0.2	0.1	0.1	0.6	1.5	8.6
ML-O	15	24.76	4.36	0.08	0.05	0.05	0.23	0.68	69.9	12.3	0.2	0.1	0.1	0.6	1.9	14.7
ML-O	31	22.15	4.42	0.12	0.05	0.07	0.24	0.69	62.6	12.5	0.3	0.1	0.2	0.7	1.9	21.7
ML-O	63	18.12	4.98	0.12	0.05	0.06	0.24	0.63	51.2	14.1	0.3	0.1	0.2	0.7	1.8	31.7
ML-O	127	12.63	6.06	0.19	0.07	0.07	0.24	0.60	35.7	17.1	0.5	0.2	0.2	0.7	1.7	43.9
RA-N	0	0.56	2.54	0.32	0.00	0.00	0.00	0.00	16.4	74.3	9.4	0.0	0.0	0.0	0.0	0.0
RA-N	1	0.51	2.48	0.31	0.00	0.00	0.00	0.00	14.9	72.5	9.1	0.0	0.0	0.0	0.0	0.0
RA-N	3	0.47	2.49	0.35	0.04	0.02	0.02	0.00	13.7	72.8	10.2	1.2	0.6	0.6	0.0	0.9
RA-N	7	0.49	2.32	0.44	0.08	0.01	0.01	0.00	14.3	67.8	12.9	2.3	0.3	0.3	0.0	2.0
RA-N	15	0.37	2.31	0.52	0.11	0.04	0.03	0.02	10.8	67.5	15.2	3.2	1.2	0.9	0.6	0.6
RA-N	31	0.39	2.18	0.55	0.11	0.03	0.04	0.03	11.4	63.7	16.1	3.2	0.9	1.2	0.9	2.6
RA-N	63	0.27	2.07	0.57	0.13	0.03	0.05	0.03	7.9	60.5	16.7	3.8	0.9	1.5	0.9	7.9
RA-O	0	2.48	5.92	0.50	0.00	0.00	0.00	0.00	27.9	66.5	5.6	0.0	0.0	0.0	0.0	0.0
RA-O	1	2.33	5.99	0.47	0.02	0.01	0.01	0.02	26.2	67.3	5.3	0.2	0.1	0.1	0.2	0.6
RA-O	3	2.05	6.05	0.62	0.03	0.07	0.02	0.03	23.0	68.0	7.0	0.3	0.8	0.2	0.3	0.3
RA-O	7	1.88	5.99	0.65	0.04	0.03	0.02	0.03	21.1	67.3	7.3	0.4	0.3	0.2	0.3	2.9
RA-O	15	1.82	5.66	0.61	0.05	0.04	0.07	0.06	20.4	63.6	6.9	0.6	0.4	0.8	0.7	6.6
RA-O	31	1.16	5.51	0.97	0.05	0.04	0.06	0.06	13.0	61.9	10.9	0.6	0.4	0.7	0.7	11.8
RA-O	63	1.13	4.70	1.09	0.08	0.05	0.08	0.07	12.7	52.8	12.2	0.9	0.6	0.9	0.8	19.1
RA-O	127	0.77	3.93	1.26	0.07	0.05	0.08	0.08	8.7	44.2	14.2	0.8	0.6	0.9	0.9	29.9
RO-N	0	10.25	5.46	0.49	0.00	0.00	0.00	0.00	63.3	33.7	3.0	0.0	0.0	0.0	0.0	0.0
RO-N	1	9.34	6.16	0.47	0.02	0.00	0.04	0.03	57.7	38.0	2.9	0.1	0.0	0.2	0.2	0.9

	Time	Raw data: weight of size fraction in grams							Percent of total inital sample							
Sample	(h)	cg	fg	vcs	cs	ms	fs	vfs	% cg	% fg	% vcs	% cs	% ms	% fs	% vfs	% m
RO-N	3	6.76	8.20	0.69	0.04	0.03	0.09	0.04	41.7	50.6	4.3	0.2	0.2	0.6	0.2	2.2
RO-N	7	8.59	5.95	0.86	0.07	0.05	0.12	0.07	53.0	36.7	5.3	0.4	0.3	0.7	0.4	3.0
RO-N	15	5.98	8.06	0.97	0.08	0.06	0.15	0.09	36.9	49.8	6.0	0.5	0.4	0.9	0.6	5.0
RO-N	31	5.49	7.97	1.09	0.09	0.06	0.18	0.11	33.9	49.2	6.7	0.6	0.4	1.1	0.7	7.5
RO-N	63	4.49	8.11	1.17	0.13	0.10	0.18	0.11	27.7	50.1	7.2	0.8	0.6	1.1	0.7	11.8
RO-N	127	3.90	7.47	1.39	0.13	0.10	0.19	0.11	24.1	46.1	8.6	0.8	0.6	1.2	0.7	18.0
RO-O	0	17.11	13.25	0.60	0.00	0.00	0.00	0.00	55.3	42.8	1.9	0.0	0.0	0.0	0.0	0.0
RO-O	1	17.20	12.77	0.48	0.02	0.03	0.06	0.07	55.6	41.2	1.6	0.1	0.1	0.2	0.2	1.1
RO-O	3	15.56	14.05	0.45	0.01	0.06	0.10	0.11	50.3	45.4	1.5	0.0	0.2	0.3	0.4	2.0
RO-O	7	19.11	9.31	0.74	0.05	0.09	0.17	0.17	61.7	30.1	2.4	0.2	0.3	0.5	0.5	4.3
RO-O	15	16.72	10.82	0.61	0.05	0.09	0.20	0.19	54.0	34.9	2.0	0.2	0.3	0.6	0.6	7.4
RO-O	31	12.94	13.14	0.99	0.07	0.11	0.25	0.22	41.8	42.4	3.2	0.2	0.4	0.8	0.7	10.5
RO-O	63	11.15	12.76	1.32	0.09	0.12	0.25	0.26	36.0	41.2	4.3	0.3	0.4	0.8	0.8	16.2
RO-O	127	8.63	12.74	1.81	0.08	0.12	0.26	0.25	27.9	41.1	5.8	0.3	0.4	0.8	0.8	22.8
UL-N	0	9.98	5.50	0.23	0.00	0.00	0.00	0.00	63.5	35.0	1.5	0.0	0.0	0.0	0.0	0.0
UL-N	1	9.18	5.90	0.27	0.02	0.02	0.11	0.03	58.4	37.6	1.7	0.1	0.1	0.7	0.2	1.1
UL-N	3	9.49	5.22	0.29	0.05	0.05	0.23	0.09	60.4	33.2	1.8	0.3	0.3	1.5	0.6	1.8
UL-N	7	8.02	6.26	0.35	0.10	0.08	0.35	0.14	51.1	39.8	2.2	0.6	0.5	2.2	0.9	2.5
UL-N	15	7.76	5.98	0.39	0.13	0.11	0.46	0.21	49.4	38.1	2.5	0.8	0.7	2.9	1.3	4.3
UL-N	31	7.44	5.76	0.39	0.14	0.13	0.60	0.25	47.4	36.7	2.5	0.9	0.8	3.8	1.6	6.4
UL-N	63	6.60	4.82	0.44	0.15	0.15	0.69	0.30	42.0	30.7	2.8	1.0	1.0	4.4	1.9	16.3
UL-N	127	5.95	5.41	0.41	0.16	0.16	0.74	0.36	37.9	34.4	2.6	1.0	1.0	4.7	2.3	16.0
UL-O	0	14.59	10.24	0.22	0.00	0.00	0.00	0.00	58.2	40.9	0.9	0.0	0.0	0.0	0.0	0.0
UL-O	1	13.70	10.39	0.23	0.01	0.07	0.22	0.09	54.7	41.5	0.9	0.0	0.3	0.9	0.4	1.4
UL-O	3	14.53	8.99	0.25	0.04	0.17	0.42	0.17	58.0	35.9	1.0	0.2	0.7	1.7	0.7	1.9
UL-O	7	13.33	9.35	0.29	0.04	0.23	0.59	0.24	53.2	37.3	1.2	0.2	0.9	2.4	1.0	3.9
UL-O	15	12.59	9.01	0.23	0.06	0.30	0.75	0.38	50.3	36.0	0.9	0.2	1.2	3.0	1.5	6.9
UL-O	31	10.42	9.66	0.38	0.06	0.38	1.08	0.47	41.6	38.6	1.5	0.2	1.5	4.3	1.9	10.4
UL-O	63	9.88	8.46	0.35	0.08	0.45	1.28	0.58	39.4	33.8	1.4	0.3	1.8	5.1	2.3	15.9
UL-O	127	6.57	9.08	0.56 !	0.09	0.47	1.50	0.66	26.2	36.2	2.2	0.4	1.9	6.0	2.6	24.4

NOTES: Samples: first 2 letters give growth form; third letter indicates freshness (N = fresh looking, O = degraded looking).
Time given in hours from beginning of experiment (cumulative).
Size fractions are: cg - coarse gravel (>4 mm); fg - fine gravel (2-4 mm); vcs - very coarse sand (1-2 mm); cs - coarse sand (0.5-1 mm); ms - medium sand (0.25-0.5 mm); fs - fine sand (0.125-0.25 mm); vfs - very fine sand (0.063-0.125 mm); m - mud (< 0.063 mm).

Table A4.2: Weights and wt% and % carbonate of muds collected after 63 and 127 h tumbling.

Sample	Wt mud (g) after 63 h	Wt% mud after 63 h	Wt mud (g) after 127 h	Wt% mud after 127 h	% $CaCO_3$ after 127 h
DE-N			0.26	1.92	59
DE-O			0.68	2.29	64
EF-N	0.06	0.83	0.17	2.34	59
EF-O	1.19	3.68	1.91	5.90	62
FE-N	0.02	0.14	0.15	1.05	
FE-O	0.65	2.00	1.10	3.38	62
FL-N	0.14	0.51	0.19	0.69	61
FL-O	0.98	1.62	1.30	2.15	56
ML-N			2.70	10.99	62
ML-O	1.00	2.82	3.81	10.76	69
RA-N			0.15	4.39	74
RA-O			0.68	8.76	66
RO-N	0.57	3.46	0.82	4.97	61
RO-O	1.25	4.21	1.68	5.43	71
UL-N			0.82	5.22	62
UL-O	3.10	12.38	1.73	6.91	61

Table A4.3: Mineralogies of muds generated by abrasion of bryozoans.

		Mineralogy of species		Mineralogy of mud	
Sample	Major species present	Wt% calcite	Wt% $MgCO_3$	Wt% calcite	Wt% $MgCO_3$
DE-O-64	*Mecynoecia purpurascens*	100	1.7	100	3.7
	Galeopsis sp.	100	7.0		
EF-O-64	*Steginoporella neozelanica*	100	3.7	100	3.3
	Cellaria immersa	100	3.4		
FE-O-64	*Hippellozoon novaezelandi*	100	6.7	100	4.3
	Iodictyum yaldwyni	100	6.8		
FL-O-64	*Otionella sp.*	2	6.0	6	n/a
ML-O-64	*Celleporaria sp.*	100	5.2	100	4.0
	Celleporina sp.	100	5.0		
RA-O-64	*Telopora buski*	100	2.8	100	3.0
	Lichenopora sp.	100	4.5		
RO-O-64	*Annectocyma sp.*	100	3.9	100	1.3
	Cinctipora elegans	97	0.6		
	Adeonellopsis sp.	3	5.7		
UL-O-64	*Steginoporella perplexa*	76	3.7	100	4.3
	Arachnopusia unicornis	90	5.3		

NOTES: Mineralogy determined by X-ray diffractometry (see Chapter 2).

Table A4.4: Calculating transport distance of tumbling experiment (after Argast et al., 1987).

Given:	Time = 127 h Speed = 25 rpm Diameter = 19.5 cm
Assume:	Because bryozoans are small and not heavy, they stay fairly close to the walls of the barrel. Let diameter of most bryozoan travel be located at 75% to 90% of diameter of barrel.
Calculate:	Diameter of travel = 14.6 to 17.6 cm Circumference of these diameters = 45.9 to 55.3 cm Number of revolutions in 127 h = 190,500 revs. Distance travelled in these revs = 8,743,950 to 10,534,650 cm Distance travelled = 87.4 to 105.4 km

Table A4.5: Results from immersion of *Otionella sqamosa* in sea water over different periods of time.

Sample	Date deployed	Wt (g) at start	Date collected	Wt (g) at end	Change in wt (g)	% Wt change	Days in sea	Rate (g/y)	% Rate (%/y)
MB2	18-Sep-90	0.04	6-Nov-90	0.04	0.00	0.00	49	0.00	0.00
MB28	16-May-91	0.02	13-Aug-91	0.01	-0.01	-0.50	89	-0.04	-2.05
MB17	1-Aug-90	0.02	6-Nov-90	0.02	0.00	0.00	97	0.00	0.00
MB22	1-Aug-90	0.04	6-Nov-90	0.03	-0.01	-0.25	97	-0.04	-0.94
MB26	1-Aug-90	0.02	6-Nov-90	0.03	0.01	0.50	97	0.04	1.88
MB8	1-Aug-90	0.04	6-Nov-90	0.04	0.00	0.00	97	0.00	0.00
MB13	1-Aug-90	0.03	16-May-91	0.01	-0.02	-0.67	288	-0.03	-0.84
MB15	1-Aug-90	0.04	16-May-91	0.04	0.00	0.00	288	0.00	0.00
MB4	1-Aug-90	0.03	16-May-91	0.03	0.00	0.00	288	0.00	0.00
MB9	1-Aug-90	0.03	16-May-91	0.01	-0.02	-0.67	288	-0.03	-0.84
MB21	1-Aug-90	0.04	13-Aug-91	0.04	0.00	0.00	377	0.00	0.00
MB23	1-Aug-90	0.02	13-Aug-91	0.02	0.00	0.00	377	0.00	0.00
MB25	1-Aug-90	0.02	13-Aug-91	0.02	0.00	0.00	377	0.00	0.00
Mean		0.03		0.03	0.00	-0.12	216	-0.01	-0.22

Table A4.6: Raw data for all specimens in dissolution experiment.

		Weight (g) at time (min)													
Vat	Species	0	30	60	90	120	150	180	210	240	270	300	330	360	390
1	1	49	32	14	5	0									
2	1	47	31	18	7	1	0								
3	1	44	25	12	5	0									
4	1	85	61	44	33										
5	1	44	30	20	8	4	2	1	0						
6	1	19	11	8	5	0									
7	1	65	50	36	28	17	9	3	0						
8	1	31	22	15	6	4	3	0							
9	1	37	27	18		7	2	0							
10	1	28	19	9	2	1	0								
1	2	3	2	0											
2	2	3	3	0											
3	2	7	0												
4	2	2	1	0											
5	2	6	2	1	0										
6	2	5	2	1	0										
7	2	2	1	0											
8	2	4	0												
9	2	4	3	1	0										
10	2	5	2	0											
1	3	3	0												
2	3	7	1	0											
3	3	5	4	2	0										
4	3	8	4	0											
5	3	6	0												
6	3	7	4	0											
7	3	4	1	0											
8	3	6	3	0											
9	3	5	4	2	1	0									
10	3	9	3	0											
1	4	25	10	3	0										
2	4	20	9	2	0										
3	4	18	9	3	0										

Vat	Species	Weight (g) at time (min) 0	30	60	90	120	150	180	210	240	270	300	330	360	390
4	4	16	6	1	0										
5	4	16	8	3	0										
6	4	18	10	5	2	0									
7	4	24	10	1	0										
8	4	20	11	7	4	0									
9	4	5	2	0											
10	4	8	3	1	0										
1	5	22	14	8	4	1	0								
2	5	42	24	6	2	0									
3	5	8	1	0											
4	5	23	11	4	2	0									
5	5	10	0												
6	5	23	7	3	0										
7	5	7	2	0											
8	5	6	2	0											
9	5	9	2		1	0									
10	5	7	0												
1	6	98	90	85	80	75	69	66		59		50		47	44
2	6	81	72	67	61	58	52	46	44	40		35		28	
3	6	76	74	67	63	59	54	50	48		39		32	29	
4	6	75	67	62	58	52	46	42	38		34		28	26	
5	6	97	90	85	77	70	67	62	57	53		53	45	40	
6	6	118	113	106	100	93	88	83	75		74		64	62	58
7	6	91	86	80	71	65	59	57	51		45		38	35	
8	6	92	88	80	70	62	59	54	46	44		33		26	
9	6	120	109	102	95	93	89	80	77		70		63	56	55
10	6	89	83	77	69	65	61	57		49		41		35	
1	7	38	26	13	4	0									
2	7	23	14	7	0										
3	7	26	15	11	5	1	0								
4	7	22	15	9	4	0									
5	7	26	14	5	2	0									
6	7	27	15	5	0										
7	7	14	6	3	1	0									

Vat	Species	Weight (g) at time (min) 0	30	60	90	120	150	180	210	240	270	300	330	360	390
8	7	16	8	1	0										
9	7	17	10	5	3	0									
10	7	16	9	4	2	0									
1	8	24	16	8	2	0									
2	8	38	24	11	6	1	0								
3	8	20	7	1	0										
4	8	38	24	10	0										
5	8	19	13	0											
6	8	33	19	9	2	0									
7	8	35	23	6	2	0									
8	8	26	16	5	0										
9	8	42	26	14	8	3	1	0							
10	8	32	21	8	1	0									
1	9	30	20	12	6	1	1	0							
2	9	17	15	9	2	1	0								
3	9	13	8	5	1	0									
4	9	27	20	14	7	0									
5	9	16	10	6	3	1	0								
6	9	21	14	10	9	6	1	0							
7	9	14	8	5	0										
8	9	39	28	20	13	8	3	1	0						
9	9	16	9	6	6	3	2	1	0						
10	9	18	11	6	2	0									
1	10	29	24	17	12	6	2	0							
2	10	22	17	8	4	1	0								
3	10	40	31	23	14	10	5	2	1	0					
4	10	22	14	9	5	0									
5	10	23	17	12	8	3	1	0							
6	10	37	26	20	15	10	5	4	0						
7	10	25	18	13	9	4	2	0							
8	10	32	25	21	16	12	10	8	5	0					
9	10	34	23	18	11	6	2	2	1	0					
10	10	26	19	11	4	0									
1	11	13	8	3	0										

Vat	Species	Weight (g) at time (min) 0	30	60	90	120	150	180	210	240	270	300	330	360	390
2	11	14	7	2	0										
3	11	12	6	2	0										
4	11	15	9	4	0										
5	11	15	7	3											
6	11	13	7	2	0										
7	11	10	5	3	0										
8	11	9	2	2	0										
9	11	11	5	2	1	0									
10	11	8	2	1	0										
1	12	15	11	6	0										
2	12	13	8	2	0										
3	12	15	9	5	0	9	3	2	0						
4	12	4	2	0											
5	12	4	2	0											
6	12	9	7	1	0										
7	12	9	5	2	0										
8	12	6	3	0											
9	12	13	10	6	5	1	0								
10	12	13	8	5	0										
1	13	16	11	7	3	0									
2	13	46	35	25	16	11	8	5	1	0					
3	13	45	36	27	18	22	15	9	0						
4	13	21	16	11	7	3	0								
5	13	80	64	45	35	29	23	14	10	7	4		2	0	
6	13	38	26	14	4	1	0								
7	13	20	14	8	3	1	0								
8	13	58	38	21	9	3	0								
9	13	34	25	17	9	6	1	0							
10	13	15	8	4	0										

NOTES: Vat number refers to the 10 replicate experiments.
Species: 1 - Hornera sp., 2 - Lichenopora sp., 3- Mecynoecia purpurascens, 4 - Telopora buski, 5 - Foveolaria cyclops, 6 - Otionella sp., 7 - Steginoporella magnifica, 8 - Steginoporella neozelanica, 9 - Adeonellopsis sp., 10 - Celleporina costazii, 11 - Chiastosella splendida, 12 - Galeopsis porcellanicus, 13 - Iodictyum yaldwynii.

Table A4.7: Percent weight loss over time for all specimens in dissolution experiment.

		Percent initial weight lost at time (min)												
Vat	Species	30	60	90	120	150	180	210	240	270	300	330	360	390
1	1	34.7	71.4	89.8	100.0									
2	1	34.0	61.7	85.1	97.9	100.0								
3	1	43.2	72.7	88.6	100.0									
4	1	28.2	48.2	61.2										
5	1	31.8	54.5	81.8	90.9	95.5	97.7	100.0						
6	1	42.1	57.9	73.7	100.0									
7	1	23.1	44.6	56.9	73.8	86.2	95.4	100.0						
8	1	29.0	51.6	80.6	87.1	90.3	100.0							
9	1	27.0	51.4		81.1	94.6	100.0							
10	1	32.1	67.9	92.9	96.4	100.0								
1	2	33.3	100.0											
2	2	0.0	100.0											
3	2	100.0												
4	2	50.0	100.0											
5	2	66.7	83.3	100.0										
6	2	60.0	80.0	100.0										
7	2	50.0	100.0											
8	2	100.0												
9	2	25.0	75.0	100.0										
10	2	60.0	100.0											
1	3	100.0												
2	3	85.7	100.0											
3	3	20.0	60.0	100.0										
4	3	50.0	100.0											
5	3	100.0												
6	3	42.9	100.0											
7	3	75.0	100.0											
8	3	50.0	100.0											
9	3	20.0	60.0	80.0	100.0									
10	3	66.7	100.0											
1	4	60.0	88.0	100.0										
2	4	55.0	90.0	100.0										
3	4	50.0	83.3	100.0										

Vat	Species	Percent initial weight lost at time (min) 30	60	90	120	150	180	210	240	270	300	330	360	390
4	4	62.5	93.8	100.0										
5	4	50.0	81.3	100.0										
6	4	44.4	72.2	88.9	100.0									
7	4	58.3	95.8	100.0										
8	4	45.0	65.0	80.0	100.0									
9	4	60.0	100.0											
10	4	62.5	87.5	100.0										
1	5	36.4	63.6	81.8	95.5	100.0								
2	5	42.9	85.7	95.2	100.0									
3	5	87.5	100.0											
4	5	52.2	82.6	91.3	100.0									
5	5	100.0												
6	5	69.6	87.0	100.0										
7	5	71.4	100.0											
8	5	66.7	100.0											
9	5	77.8		88.9	100.0									
10	5	100.0												
1	6	8.2	13.3	18.4	23.5	29.6	32.7		39.8		49.0		52.0	55.1
2	6	11.1	17.3	24.7	28.4	35.8	43.2	45.7	50.6		56.8		65.4	
3	6	2.6	11.8	17.1	22.4	28.9	34.2	36.8		48.7		57.9	61.8	
4	6	10.7	17.3	22.7	30.7	38.7	44.0	49.3		54.7		62.7	65.3	
5	6	7.2	12.4	20.6	27.8	30.9	36.1	41.2	45.4		45.4	53.6	58.8	
6	6	4.2	10.2	15.3	21.2	25.4	29.7	36.4		37.3		45.8	47.5	50.8
7	6	5.5	12.1	22.0	28.6	35.2	37.4	44.0		50.5		58.2	61.5	
8	6	4.3	13.0	23.9	32.6	35.9	41.3	50.0	52.2		64.1		71.7	
9	6	9.2	15.0	20.8	22.5	25.8	33.3	35.8		41.7		47.5	53.3	54.2
10	6	6.7	13.5	22.5	27.0	31.5	36.0		44.9		53.9		60.7	
1	7	31.6	65.8	89.5	100.0									
2	7	39.1	69.6	100.0										
3	7	42.3	57.7	80.8	96.2	100.0								
4	7	31.8	59.1	81.8	100.0									
5	7	46.2	80.8	92.3	100.0									
6	7	44.4	81.5	100.0										
7	7	57.1	78.6	92.9	100.0									

Vat	Species	Percent initial weight lost at time (min) 30	60	90	120	150	180	210	240	270	300	330	360	390
8	7	50.0	93.8	100.0										
9	7	41.2	70.6	82.4	100.0									
10	7	43.8	75.0	87.5	100.0									
1	8	33.3	66.7	91.7	100.0									
2	8	36.8	71.1	84.2	97.4	100.0								
3	8	65.0	95.0	100.0										
4	8	36.8	73.7	100.0										
5	8	31.6	100.0											
6	8	42.4	72.7	93.9	100.0									
7	8	34.3	82.9	94.3	100.0									
8	8	38.5	80.8	100.0										
9	8	38.1	66.7	81.0	92.9	97.6	100.0							
10	8	34.4	75.0	96.9	100.0									
1	9	33.3	60.0	80.0	96.7	96.7	100.0							
2	9	11.8	47.1	88.2	94.1	100.0								
3	9	38.5	61.5	92.3	100.0									
4	9	25.9	48.1	74.1	100.0									
5	9	37.5	62.5	81.3	93.8	100.0								
6	9	33.3	52.4	57.1	71.4	95.2	100.0							
7	9	42.9	64.3	100.0										
8	9	28.2	48.7	66.7	79.5	92.3	97.4	100.0						
9	9	43.8	62.5	62.5	81.3	87.5	93.8	100.0						
10	9	38.9	66.7	88.9	100.0									
1	10	17.2	41.4	58.6	79.3	93.1	100.0							
2	10	22.7	63.6	81.8	95.5	100.0								
3	10	22.5	42.5	65.0	75.0	87.5	95.0	97.5	100.0					
4	10	36.4	59.1	77.3	100.0									
5	10	26.1	47.8	65.2	87.0	95.7	100.0							
6	10	29.7	45.9	59.5	73.0	86.5	89.2	100.0						
7	10	28.0	48.0	64.0	84.0	92.0	100.0							
8	10	21.9	34.4	50.0	62.5	68.8	75.0	84.4	100.0					
9	10	32.4	47.1	67.6	82.4	94.1	94.1	97.1	100.0					
10	10	26.9	57.7	84.6	100.0									
1	11	38.5	76.9	100.0										

Vat	Species	Percent initial weight lost at time (min) 30	60	90	120	150	180	210	240	270	300	330	360	390
2	11	50.0	85.7	100.0										
3	11	50.0	83.3	100.0										
4	11	40.0	73.3	100.0										
5	11	53.3	80.0											
6	11	46.2	84.6	100.0										
7	11	50.0	70.0	100.0										
8	11	77.8	77.8	100.0										
9	11	54.5	81.8	90.9	100.0									
10	11	75.0	87.5	100.0										
1	12	26.7	60.0	100.0										
2	12	38.5	84.6	100.0										
3	12	40.0	66.7	100.0	40.0	80.0	86.7	100.0						
4	12	50.0	100.0											
5	12	50.0	100.0											
6	12	22.2	88.9	100.0										
7	12	44.4	77.8	100.0										
8	12	50.0	100.0											
9	12	23.1	53.8	61.5	92.3	100.0								
10	12	38.5	61.5	100.0										
1	13	31.3	56.3	81.3	100.0									
2	13	23.9	45.7	65.2	76.1	82.6	89.1	97.8	100.0					
3	13	20.0	40.0	60.0	51.1	66.7	80.0	100.0						
4	13	23.8	47.6	66.7	85.7	100.0								
5	13	20.0	43.8	56.3	63.8	71.3	82.5	87.5	91.3	95.0		97.5	100.0	
6	13	31.6	63.2	89.5	97.4	100.0								
7	13	30.0	60.0	85.0	95.0	100.0								
8	13	34.5	63.8	84.5	94.8	100.0								
9	13	26.5	50.0	73.5	82.4	97.1	100.0							
10	13	46.7	73.3	100.0			273.3							

NOTES: Vat number refers to the 10 replicate experiments.

Species: 1 - Hornera sp., 2 - Lichenopora sp., 3- Mecynoecia purpurascens, 4 - Telopora buski, 5 - Foveolaria cyclops, 6 - Otionella sp., 7 - Steginoporella magnifica, 8 - Steginoporella neozelanica, 9 - Adeonellopsis sp., 10 - Celleporina costazii, 11 - Chiastosella splendida, 12 - Galeopsis porcellanicus, 13 - Iodictyum yaldwyni.

Table A4.8: Dissolution parameters for all specimens in dissolution experiment.

Vat	Species	W30	DHL	TTD
1	1	34.7	42	120
1	2	33.3	36	60
1	3	100.0	15	30
1	4	60.0	27	90
1	5	36.4	44	150
1	6	8.2	318	390
1	7	31.6	46	120
1	8	33.3	45	120
1	9	33.3	48	180
1	10	17.2	93	180
1	11	38.5	40	90
1	12	26.7	51	90
1	13	31.3	54	120
2	1	34.0	45	150
2	2	0.0	45	60
2	3	85.7	18	60
2	4	55.0	27	90
2	5	42.9	34	120
2	6	11.1	234	390
2	7	39.1	39	90
2	8	36.8	40	150
2	9	11.8	63	150
2	10	22.7	48	150
2	11	50.0	30	90
2	12	38.5	39	90
2	13	23.9	63	240
3	1	43.2	38	120
3	2	100.0	14	30
3	3	20.0	51	90
3	4	50.0	30	90
3	5	87.5	18	60
3	6	2.6	282	390
3	7	42.3	44	150
3	8	65.0	24	90
3	9	38.5	42	120
3	10	22.5	70	270
3	11	50.0	30	90
3	12	40.0	42	90
3	13	20.0	75	210
4	1	28.2	63	210
4	2	50.0	30	60
4	3	50.0	30	60
4	4	62.5	24	90
4	5	52.2	28	120
4	6	10.7	216	390
4	7	31.8	50	120
4	8	36.8	40	90

Vat	Species	W30	DHL	TTD
4	9	25.9	63	120
4	10	36.4	48	120
4	11	40.0	40	90
4	12	50.0	30	60
4	13	23.8	63	150
5	1	31.8	54	210
5	2	66.7	21	90
5	3	100.0	30	30
5	4	50.0	30	90
5	5	100.0	15	30
5	6	7.2	303	390
5	7	46.2	33	120
5	8	31.6	38	60
5	9	37.5	42	150
5	10	26.1	63	180
5	11	53.3	27	90
5	12	50.0	30	60
5	13	20.0	75	360
6	1	42.1	42	120
6	2	60.0	24	90
6	3	42.9	35	60
6	4	44.4	36	120
6	5	69.6	21	90
6	6	4.2	381	390
6	7	44.4	33	90
6	8	42.4	38	120
6	9	33.3	57	180
6	10	29.7	68	210
6	11	46.2	33	90
6	12	22.2	42	90
6	13	31.6	48	150
7	1	23.1	72	210
7	2	50.0	30	60
7	3	75.0	18	60
7	4	58.3	24	90
7	5	71.4	21	60
7	6	5.5	267	390
7	7	57.1	26	120
7	8	34.3	40	120
7	9	42.9	36	90
7	10	28.0	63	180
7	11	50.0	30	90
7	12	44.4	36	90
7	13	30.0	51	150
8	1	29.0	57	180
8	2	100.0	15	30
8	3	50.0	30	60
8	4	45.0	36	120
8	5	66.7	21	90

Vat	Species	W30	DHL	TTD
8	6	4.3	210	390
8	7	50.0	30	90
8	8	38.5	38	90
8	9	28.2	63	210
8	10	21.9	90	240
8	11	77.8	21	90
8	12	50.0	30	60
8	13	34.5	46	150
9	1	27.0	54	180
9	2	25.0	42	90
9	3	20.0	48	120
9	4	60.0	21	60
9	5	77.8	18	120
9	6	9.2	342	390
9	7	41.2	39	120
9	8	38.1	42	180
9	9	43.8	39	210
9	10	32.4	63	270
9	11	54.5	27	120
9	12	23.1	57	150
9	13	26.5	60	180
10	1	32.1	45	150
10	2	60.0	24	60
10	3	66.7	22	60
10	4	62.5	24	90
10	5	100.0	15	30
10	6	6.7	273	390
10	7	43.8	36	120
10	8	34.4	42	120
10	9	38.9	42	120
10	10	26.9	52	120
10	11	75.0	18	90
10	12	38.5	45	90
10	13	46.7	33	90

Vat number refers to the 10 replicate experiments.

Species: 1 - Hornera sp., 2 - Lichenopora sp., 3- Mecynoecia purpurascens, 4 - Telopora buski, 5- Foveolaria cyclops, 6 - Otionella sp., 7 - Steginoporella magnifica, 8 - Steginoporella neozelanica, 9 - Adeonellopsis sp., 10 - Celleporina costazii, 11 - Chiastosella splendida, 12 - Galeopsis porcellanicus, 13 - Iodictyum yaldwyni.

Dissolution parameters: W30 - % initial wt lost after 30 min, DHL - time for specimen to reach half of initial wt (min), TTL - time for total dissolution (min).

Table A6.1: Sediment sample locations.

Samples indicated with a * were used mainly for verification of trends, not analyzed thoroughly.
Sources: AMS - this study; NZOI - New Zealand Oceanographic Institute; HMNZS - Auckland University archives (Greig, 1982).
Methods used for collection of sample, where recorded: G - grab; D - dredge; T - trawl; C - core.

Sample	Latitude (°S)	Longitude (°E)	Depth (m)	Source of sample	Date	Coll. meth.	U.W. archive
AMS-C01	36° 27.5'	175° 27.5'	54	AMS	24-1-90	G	29288
AMS-C02	36° 27.5'	175° 25.0'	56	AMS	24-1-90	G	29289
AMS-C03	36° 25.0'	175° 25.0'	45	AMS	24-1-90	G	29290
AMS-C04	36° 25.0'	175° 27.5'	45	AMS	24-1-90	G	29291
AMS-C05	36° 22.5'	175° 27.5'	47	AMS	24-1-90	G	29292
AMS-C06	36° 22.5'	175° 25.0'	45	AMS	24-1-90	G	29293
AMS-C07	36° 20.0'	175° 27.5'	34	AMS	24-1-90	G	29294
AMS-C08	36° 20.0'	175° 25.0'	40	AMS	24-1-90	G	29295
AMS-C09	36° 20.0'	175° 22.5'	43	AMS	24-1-90	G	29296
AMS-C10	36° 22.5'	175° 22.5'	50	AMS	24-1-90	G	29297
AMS-C11	36° 25.0'	175° 22.5'	47	AMS	24-1-90	G	29298
AMS-C12	36° 27.5'	175° 22.5'	53	AMS	24-1-90	G	29299
AMS-C13	36° 27.5'	175° 20.0'	41	AMS	26-1-90	G	29300
AMS-C14	36° 26.3'	175° 20.0'	47	AMS	26-1-90	G	29301
AMS-C15	36° 25.0'	175° 20.0'	61	AMS	25-1-90	G	29302
AMS-C16	36° 22.5'	175° 20.0'	49	AMS	24-1-90	G	29303
AMS-C17	36° 20.0'	175° 20.0'	45	AMS	24-1-90	G	29304
AMS-C18	36° 20.0'	175° 17.5'	45	AMS	24-1-90	G	29305
AMS-C19	36° 22.5'	175° 17.5'	49	AMS	24-1-90	G	29306
AMS-C20	36° 25.0'	175° 17.5'	45	AMS	25-1-90	G	29307
AMS-C21	36° 27.5'	175° 17.5'	52	AMS	25-1-90	G	29308
AMS-C22	36° 30.0'	175° 17.5'	49	AMS	25-1-90	G	29309
AMS-C23	36° 32.5'	175° 17.5'	41	AMS	26-1-90	G	29310
AMS-C24	36° 32.5'	175° 15.0'	41	AMS	26-1-90	G	29311
AMS-C25	36° 30.0'	175° 15.0'	47	AMS	25-1-90	G	29312
AMS-C26	36° 30.0'	175° 15.0'	47	AMS	25-1-90	G	29313
AMS-C27	36° 25.0'	175° 15.0'	47	AMS	25-1-90	G	29314
AMS-C29	36° 22.5'	175° 12.5'	49	AMS	25-1-90	G	29315
AMS-C30	36° 25.0'	175° 12.5'	47	AMS	25-1-90	G	29316
AMS-C31	36° 27.5'	175° 12.5'	47	AMS	25-1-90	G	29317
AMS-C32	36° 28.8'	175° 12.5'	47	AMS	25-1-90	G	29318
AMS-C33	36° 30.0'	175° 12.5'	47	AMS	25-1-90	G	29319
AMS-C34	36° 30.0'	175° 10.0'	47	AMS	25-1-90	G	29320
AMS-C35	36° 27.5'	175° 10.0'	49	AMS	25-1-90	G	29321
AMS-C36	36° 25.0'	175° 10.0'	50	AMS	25-1-90	G	29322
AMS-C37	36° 22.5'	175° 10.0'	49	AMS	25-1-90	G	29323
AMS-C40	36° 22.5'	175° 7.5'	49	AMS	25-1-90	G	29324
AMS-C43	36° 27.5'	175° 7.5'	49	AMS	25-1-90	G	29325
AMS-C44	36° 30.0'	175° 7.5'	43	AMS	25-1-90	G	29326
AMS-C45	36° 32.5'	175° 7.5'	47	AMS	25-1-90	G	29327
AMS-C47	36° 30.0'	175° 5.0'	45	AMS	25-1-90	G	29328
AMS-C48	36° 27.5'	175° 5.0'	47	AMS	25-1-90	G	29329

Sample	Latitude (°S)	Longitude (°E)	Depth (m)	Source of sample	Date	Coll. meth.	U.W. archive
AMS-C49	36° 25.0'	175° 5.0'	50	AMS	25-1-90	G	29330
AMS-C50	36° 22.5'	175° 5.0'	49	AMS	25-1-90	G	29331
AMS-C53	36° 22.5'	175° 2.5'	47	AMS	25-1-90	G	29332
AMS-C54	36° 25.0'	175° 2.5'	49	AMS	25-1-90	G	29333
AMS-C55	36° 27.5'	175° 2.5'	45	AMS	25-1-90	G	29334
AMS-C58	36° 26.5'	175° 7.5'	47	AMS	25-1-90	G	29335
AMS-C59	36° 29.0'	175° 27.5'	52	AMS	26-1-90	G	29336
AMS-C60	36° 26.3'	175° 22.5'	50	AMS	26-1-90	G	29337
AMS-C61	36° 26.3'	175° 25.0'	54	AMS	26-1-90	G	29338
AMS-C62	36° 26.3'	175° 27.5'	50	AMS	26-1-90	G	29339
AMS-K01	36° 23.5'	174° 51.7'	10	AMS	9-10-89	G	29340
AMS-K02	36° 23.5'	174° 53.3'	33	AMS	9-10-89	G	29341
AMS-K03	36° 24.6'	174° 53.8'	36	AMS	9-10-89	G	29342
AMS-K04	36° 24.8'	174° 54.9'	46	AMS	9-10-89	G	29343
AMS-K05	36° 26.1'	174° 54.6'	44	AMS	9-10-89	G	29344
AMS-K06	36° 27.2'	174° 55.0'	36	AMS	9-10-89	G	29345
AMS-K07	36° 27.4'	174° 56.3'	49	AMS	9-10-89	G	29346
AMS-K08	36° 28.3'	174° 56.0'	63	AMS	9-10-89	G	29347
AMS-K09	36° 28.2'	174° 55.0'	38	AMS	9-10-89	G	29348
AMS-K10	36° 28.0'	174° 53.9'	37	AMS	9-10-89	G	29349
AMS-K11	36° 28.0'	174° 52.8'	35	AMS	9-10-89	G	29350
AMS-K12	36° 27.9	174° 51.5'	28	AMS	9-10-89	G	29351
AMS-K13	36° 28.0'	174° 50.3'	27	AMS	9-10-89	G	29352
AMS-K14	36° 28.9'	174° 50.3'	30	AMS	9-10-89	G	29353
AMS-K15	36° 28.9'	174° 51.4'	33	AMS	9-10-89	G	29354
AMS-K17	36° 27.1'	174° 53.9'	38	AMS	9-10-89	G	29355
AMS-K18	36° 30.3'	174° 55.1'	42	AMS	10-10-89	G	29356
AMS-K19	36° 29.3'	174° 55.1'	41	AMS	10-10-89	G	29357
AMS-K20	36° 29.3'	174° 56.4'	49	AMS	10-10-89	G	29358
AMS-K21	36° 27.1'	174° 54.5'	42	AMS	10-10-89	G	29359
AMS-K22	36° 26.4'	174° 55.1'	44	AMS	10-10-89	G	29360
AMS-L01	36° 15.3'	174° 55.3'	52	AMS	11-10-89	G	29361
AMS-L02	36° 15.3'	174° 57.8'	55	AMS	11-10-89	G	29362
AMS-L03	36° 15.3'	175° 0.9'	50	AMS	11-10-89	G	29363
AMS-L04	36° 15.3'	175° 2.5'	50	AMS	11-10-89	G	29364
AMS-L05	36° 13.1'	175° 2.5'	42	AMS	11-10-89	G	29365
AMS-L06	36° 13.1'	175° 0.6'	50	AMS	11-10-89	G	29366
AMS-L07	36° 13.1'	174° 57.8'	54	AMS	11-10-89	G	29367
AMS-L08	36° 13.1'	174° 55.3'	54	AMS	11-10-89	G	29368
AMS-L09	36° 11.8'	174° 52.5'	58	AMS	30-4-90	G	29369
AMS-L10	36° 11.8'	174° 55.0'	53	AMS	30-4-90	G	29370
AMS-L11	36° 11.8'	174° 57.5'	53	AMS	30-4-90	G	29371
AMS-L12	36° 11.8'	175° 0.0'	53	AMS	30-4-90	G	29372
AMS-L13	36° 11.8'	175° 2.5'	30	AMS	30-4-90	G	29373
AMS-L14	36° 10.0'	175° 2.5'	58	AMS	30-4-90	G	29374
AMS-L15	36° 10.0'	175° 0.0'	59	AMS	30-4-90	G	29375
AMS-L16	36° 10.0'	174° 57.5'	53	AMS	30-4-90	G	29376
AMS-L17	36° 10.0'	174° 55.0'	52	AMS	30-4-90	G	29377
AMS-L18	36° 10.0'	174° 52.5'	60	AMS	30-4-90	G	29378

Sample	Latitude (°S)	Longitude (°E)	Depth (m)	Source of sample	Date	Coll. meth.	U.W. archive
AMS-L19	36° 7.9'	175° 2.5'	64	AMS	17-9-90	G	29379
AMS-L20	36° 6.1'	175° 2.5'	69	AMS	17-9-90	G	29380
AMS-L21	36° 5.0'	175° 2.5'	71	AMS	17-9-90	G	29381
AMS-L22	36° 1.8'	175° 2.5'	77	AMS	17-9-90	G	29382
AMS-L23	36° 0.0'	175° 2.5'		AMS	17-9-90	G	29383
AMS-L24	36° 0.0'	175° 0.0'	91	AMS	17-9-90	G	29384
AMS-L25	36° 1.8'	175° 0.0'	82	AMS	17-9-90	G	29385
AMS-L26	36° 5.0'	175° 0.0'	71	AMS	17-9-90	G	29386
AMS-L27	36° 6.1'	175° 0.0'	66	AMS	17-9-90	G	29387
AMS-L28	36° 7.9'	175° 0.0'	64	AMS	17-9-90	G	29388
AMS-L29	36° 7.9'	174° 57.5'	64	AMS	17-9-90	G	29389
AMS-L30	36° 7.9'	174° 55.0'	62	AMS	17-9-90	G	29390
AMS-L31	36° 7.9'	174° 52.5'	64	AMS	17-9-90	G	29391
AMS-L32	36° 7.9'	174° 50.0'	54	AMS	17-9-90	G	29392
AMS-L33	36° 10.0'	174° 50.0'	58	AMS	17-9-90	G	29393
AMS-L34	36° 10.0'	174° 47.5'	53	AMS	17-9-90	G	29394
AMS-L35	36° 12.0'	174° 50.0'	56	AMS	18-9-90	G	29395
AMS-L36	36° 12.0'	174° 47.5'	48	AMS	18-9-90	G	29396
AMS-L37	36° 12.0'	174° 45.0'	45	AMS	18-9-90	G	29397
AMS-L38	36° 12.0'	174° 42.5'	34	AMS	18-9-90	G	29398
AMS-L39	36° 10.0'	174° 42.5'	45	AMS	18-9-90	G	29399
AMS-L40	36° 10.0'	174° 45.0'	47	AMS	18-9-90	G	29400
AMS-L41	36° 7.9'	174° 47.5'	53	AMS	18-9-90	G	29401
AMS-L42	36° 6.1'	174° 57.5'	67	AMS	19-9-90	G	29402
AMS-L43	36° 5.0'	174° 57.5'	72	AMS	19-9-90	G	29403
AMS-L44	36° 1.8'	174° 57.5'	86	AMS	19-9-90	G	29404
AMS-L45	36° 1.8'	174° 55.0'	79	AMS	19-9-90	G	29405
AMS-L46	36° 5.0'	174° 55.0'	72	AMS	19-9-90	G	29406
AMS-L47	36° 6.1'	174° 55.0'	63	AMS	19-9-90	G	29407
AMS-L48	36° 6.1'	174° 52.5'	60	AMS	19-9-90	G	29408
AMS-L49	36° 5.0'	174° 52.5'	66	AMS	19-9-90	G	29409
AMS-L50	36° 1.8'	174° 52.5'	77	AMS	19-9-90	G	-29410
AMS-L51	36° 1.8'	174° 50.0'	71	AMS	19-9-90	G	29411
AMS-L52	36° 5.0'	174° 50.0'	61	AMS	19-9-90	G	29412
AMS-L53	36° 6.1'	174° 50.0'	58	AMS	19-9-90	G	29413
AMS-L54	36° 9.1'	174° 48.9'	56	AMS	19-9-90	G	29414
AMS-L55	36° 9.1'	174° 51.1'	59	AMS	19-9-90	G	29415
AMS-L56	36° 11.2'	174° 51.1'	56	AMS	19-9-90	G	29416
AMS-L57	36° 11.2'	174° 48.9'	52	AMS	19-9-90	G	29417
AMS-T01	36° 36.7'	174° 52.8'	24	AMS	10-10-89	G	29418
AMS-T02	36° 36.5'	174° 51.6'	27	AMS	10-10-89	G	29419
AMS-T03	36° 37.5'	174° 51.6'	26	AMS	10-10-89	G	29420
AMS-T04	36° 37.5'	174° 52.9'	26	AMS	10-10-89	G	29421
AMS-T05	36° 37.5'	174° 54.1'	34	AMS	10-10-89	G	29422
AMS-T06	36° 37.5'	174° 55.3'	36	AMS	10-10-89	G	29423
AMS-T07	36° 37.5'	174° 56.6'	38	AMS	10-10-89	G	29424
AMS-T08	36° 36.5'	174° 56.6'	40	AMS	10-10-89	G	29425
AMS-T09	36° 36.5'	174° 55.3'	29	AMS	10-10-89	G	29426
AMS-T10	36° 37.0'	174° 55.3'	34	AMS	10-10-89	G	29427

Sample	Latitude (°S)	Longitude (°E)	Depth (m)	Source of sample	Date	Coll. meth.	U.W. archive
AMS-T11	36° 36.5'	174° 54.7'	32	AMS	10-10-89	G	29428
AMS-T12	36° 36.0'	174° 55.3'	38	AMS	10-10-89	G	29429
E0602*	36° 2.1'	174° 47.9'	59	NZOI 553	2-9-66	G	29430
F0037*	36° 1.5'	174° 58.0'	84	NZOI 533	9-11-64	G	
G0427*	36° 26.0'	175° 25.0'	55	NZOI 586	24-2-69	G	
G0438*	36° 6.0'	174° 52.5'	62	NZOI 586	25-2-69	G	
G0439*	36° 10.0'	174° 54.0'	54	NZOI 586	25-2-69	G	
G0440*	36° 14.0'	174° 56.0'	54	NZOI 586	25-2-69	G	
G75/12*	36° 25.1'	175° 23.7'	46	HMNZS Tui	1975	G	
G75/13*	36° 25.0'	175° 17.6'	43	HMNZS Tui	1975	G	
G75/14*	36° 25.1'	175° 11.5'	46	HMNZS Tui	1975	G	
G75/15*	36° 25.0'	175° 5.1'	44	HMNZS Tui	1975	GC	
G75/17*	36° 24.9'	174° 53.4'	30	HMNZS Tui	1975	G	
G75/19*	36° 29.9'	174° 55.1'	36	HMNZS Tui	1975	GC	
G75/21*	36° 30.0'	175° 6.7'	43	HMNZS Tui	1975	GC	
G75/23*	36° 30.1'	175° 18.5'	37	HMNZS Tui	1975	G	
G75/29*	36° 36.8'	174° 52.4'	30	HMNZS Tui	1975	G	
G75/7*	36° 19.9'	175° 20.5'	46	HMNZS Tui	1975	G	
G75/8*	36° 20.1'	175° 14.3'	43	HMNZS Tui	1975	G	
G75/9*	36° 19.4'	175° 8.1'	45	HMNZS Tui	1975	G	
G80/15*	36° 52.9'	175° 18.7'	34	HMNZS Tui	1975	G	
G80/43*	36° 24.4'	175° 24.0'	61	HMNZS Tui	1975	G	
G80/44*	36° 22.9'	175° 25.3'	49	HMNZS Tui	1975	G	
GO441*	36° 12.0'	175° 0.0'	52	NZOI 586	25-2-69	G	
H0482*	36° 27.1'	175° 2.2'	42	NZOI 1007	14-7-73	GC	
H0491*	36° 20.5'	175° 17.1'	40	NZOI 1007	17-7-73	C	
I0049*	36° 0.5'	174° 59.5'	92	NZOI 1035	9-5-75	DT	
I0053*	36° 12.1'	174° 55.0'	56	NZOI 1035	11-5-75	D	
I0056*	36° 23.0'	175° 13.1'	50	NZOI 1035	11-5-75	DT	
Z2177*	36° 29.4'	174° 53.5'	35	NZOI 9075	1-12-56		
Z2178*	36° 28.4'	174° 54.0'	35	NZOI 9075	1-12-56		
Z2179*	36° 27.3'	174° 54.0'	40	NZOI 9075	1-12-56		
Z2180*	36° 25.4'	174° 54.2'	42	NZOI 9075	1-12-56		
Z2181*	36° 24.1'	174° 54.0'	42	NZOI 9075	1-12-56		
Z2203*	36° 22.0'	175° 6.1'	49	NZOI 9075	1-12-56		
Z2204*	36° 23.4'	175° 6.2'	49	NZOI 9075	1-12-56		
Z2205*	36° 24.3'	175° 6.1'	49	NZOI 9075	1-12-56		
Z2206*	36° 25.4'	175° 6.1'	49	NZOI 9075	1-12-56		
Z2207*	36° 27.0'	175° 6.1'	48	NZOI 9075	1-12-56		
Z2208*	36° 28.0'	175° 6.1'	46	NZOI 9075	1-12-56		
Z2223*	36° 30.2'	175° 12.2'	46	NZOI 9075	1-12-56		
Z2224*	36° 29.2'	175° 12.2'	48	NZOI 9075	1-12-56		
Z2225*	36° 28.0'	175° 12.2'	46	NZOI 9075	1-12-56		
Z2226*	36° 27.1'	175° 12.1'	48	NZOI 9075	1-12-56		
Z2229*	36° 23.4'	175° 12.0'	48	NZOI 9075	1-12-56		
Z2230*	36° 22.2'	175° 12.0'	49	NZOI 9075	1-12-56		
Z2231*	36° 20.0'	175° 12.0'	49	NZOI 9075	1-12-56		
Z2239*	36° 29.1'	175° 18.3'	68	NZOI 9075	1-12-56		
Z2240*	36° 28.3'	175° 18.3'	53	NZOI 9075	1-12-56		

Sample	Latitude (°S)	Longitude (°E)	Depth (m)	Source of sample	Date	Coll. meth.	U.W. archive
Z2241*	36° 27.2'	175° 18.3'	53	NZOI 9075	1-12-56		
Z2242*	36° 26.2'	175° 18.3'	57	NZOI 9075	1-12-56		
Z2243*	36° 25.0'	175° 18.3'	53	NZOI 9075	1-12-56		
Z2244*	36° 23.5'	175° 18.3'	48	NZOI 9075	1-12-56		
Z2254*	36° 28.5'	174° 54.5'	37	NZOI 9075	12-5-67	D	

Table A6.2: Texture and carbonate content of Hauraki Gulf sediments.

Notes: % Mud, sand and gravel determined by wet sieving. Folk (1968) class determined from these percents. Folk classes: G - gravel, S - sand, M - mud, g - gravelly, s - sandy, m - muddy. Modal and mean grain sizes and sorting calculated by graphical method for gravel and sand only. Modal grain sizes: cg - coarse gravel (> 4 mm), vcs - very coarse sand (1-2 mm), cs - coarse sand (0.5-1mm), ms - medium sand (0.25-0.5mm), fs - find sand (0.125-0.25mm), vfs - very fine sand (0.063-0.125mm). Wt% $CaCO_3$ determined by acid digestion and/or autotitration.

AMS Sample	wt % Mud	wt % Sand	wt % Gravel	Folk Class	Modal grain size	Mean grain size (Ø)	Sorting Coeff.	Wt% $CaCO_3$	Wt% $CaCO_3$ in mud
C01	17.2	72.7	10.1	gmS	ms	1.04	1.63	27.9	
C02	4.7	74.7	20.6	gS	cs	0.23	1.46	47.3	
C03	2.5	87.1	10.4	gS	ms	1.29	1.27	26.0	
C04	4.1	40.2	55.7	sG	cs	-0.19	1.42	53.0	
C05	1.1	83.5	15.4	gS	cs	0.41	1.20	31.5	
C06	0.8	85.6	13.6	gS	ms	1.12	1.29	36.4	
C07	2.0	83.2	14.8	gS	ms	1.14	1.48	67.0	
C08	1.5	88.1	10.4	gS	ms	1.21	1.25	35.8	
C09	2.5	89.0	8.5	gS	ms	1.32	1.43	39.0	
C10	5.7	75.1	19.2	gS	ms	0.65	1.41	38.1	
C11	1.7	80.0	18.3	gS	ms	0.17	1.41	45.2	
C12	1.5	43.5	55.0	sG	cg	-1.03	0.97	80.8	
C13	0.0	72.0	28.0	gS	vcs	-0.20	0.96	85.2	
C14	3.1	80.9	16.0	gS	ms	0.42	1.42	50.8	
C15	21.0	76.1	2.9	mS	ms	1.82	1.03	32.4	
C16	6.8	80.6	12.6	gS	ms	0.99	1.44	38.2	
C17	14.6	76.4	9.0	gmS	ms	1.28	1.38	38.8	
C18	10.3	75.8	13.9	gmS	ms	0.89	1.64	40.9	
C19	6.1	89.5	4.4	S	ms	1.67	1.06	27.2	
C20	6.1	67.8	26.1	gS	fs	0.43	1.88	48.4	
C21	12.2	74.8	13.0	gmS	ms	1.28	1.53	31.7	
C22	21.2	63.9	14.9	gmS				28.8	
C23	36.5	56.2	7.3	gmS	fs	1.91	1.69	42.2	
C24	36.2	58.9	4.9	mS	fs	1.46	1.60	27.6	
C25	26.0	57.3	16.7	gmS	fs	0.65	1.99	44.2	
C26	18.6	63.0	18.4	gmS	fs	1.39	1.69	39.6	
C27	17.8	77.7	4.5	mS	fs	1.92	1.27	39.6	
C29	27.8	67.9	4.3	mS				40.8	
C30	27.9	69.3	2.8	mS	fs	2.35	1.26	32.6	
C31	25.3	56.9	17.8	gmS	fs	1.81	1.68	42.4	
C32	17.5	63.3	19.2	gmS	fs	0.76	2.03	41.1	
C33	27.7	61.6	10.7	gmS	fs	1.86	1.64	37.9	
C34	30.3	58.2	11.5	gmS	fs	1.08	2.18	45.6	
C35	25.8	65.8	8.4	gmS	fs	1.61	1.79	34.0	
C36	27.0	63.8	9.2	gmS	vfs	2.31	1.58	33.9	
C37	29.3	67.1	3.6	mS				39.6	
C40	21.6	62.3	16.1	gmS	fs/vfs	1.56	1.94	44.2	
C43	28.9	64.5	6.6	gmS	fs	1.83	1.56	27.3	
C44	32.2	64.7	3.1	mS	fs	2.36	1.22	17.3	
C45	42.4	51.5	6.1	gmS	fs	1.83	1.81	28.0	

AMS Sample	wt % Mud	wt % Sand	wt % Gravel	Folk Class	Modal grain size	Mean grain size (Ø)	Sorting Coeff.	Wt% $CaCO_3$	Wt% $CaCO_3$ in mud
C47	27.0	65.9	7.1	gmS	fs	2.40	1.39	29.9	
C48	27.6	63.7	8.7	gmS	vfs	2.33	1.61	35.5	
C49	34.6	56.2	9.2	gmS	fs	2.28	1.51	34.3	
C50	24.3	67.1	8.6	gmS	fs	1.47	1.98	38.9	
C53	23.1	59.6	17.3	gmS	fs	2.34	1.53	42.8	
C54	30.9	61.3	7.8	gmS	fs	2.13	1.54	31.3	
C55	29.7	62.9	7.4	gmS	fs	1.78	1.56	26.6	
C58	31.0	65.0	4.0	mS	vfs	1.75	1.85	32.5	
C59	31.9	57.7	10.4	gmS	cs	0.22	1.30	46.5	
C60	1.5	71.6	26.9	gS	ms	0.08	1.57	42.7	
C61	1.4	76.4	22.2	gS	ms	0.75	1.17	38.9	
C62	0.9	84.6	14.5	gS	cs	0.14	0.99	34.7	
K01	1.3	78.9	19.8	gS				37.0	
K02	32.5	62.0	5.5	gmS	fs	1.73	1.62	36.7	
K03	18.5	77.5	4.0	mS	fs	2.09	1.02	25.2	
K04	30.2	67.9	1.9	mS	fs	2.24	0.96	24.8	
K05	23.8	63.8	12.4	gmS	fs	0.90	1.69	48.9	
K06	1.2	59.6	39.2	sG	vcs	-0.24	1.45	90.2	
K07	33.5	55.1	11.4	gmS				46.9	
K08	45.1	48.7	6.2	gmS	ms/fs	1.10	1.56	43.0	
K09	16.0	79.9	4.1	mS	fs	2.08	1.06	28.1	
K10	25.7	62.7	11.6	gmS	fs	1.49	1.50	31.4	
K11	19.4	55.9	24.7	gmS	fs	0.55	1.75	53.4	
K12	23.0	59.2	17.8	gmS	fs	0.56	1.92	52.5	
K13	42.9	44.1	13.0	gmS	fs	1.12	2.00	37.7	
K14	72.4	26.8	0.8	sM				13.3	
K15	60.1	35.4	4.5	sM				17.6	
K17	11.1	60.8	28.1	gmS	cs	-0.24	1.50	83.8	15.7
K18	61.5	38.5	0.0	sM	fs	2.14	1.22	23.2	
K19	45.0	55.0	0.0	mS	fs	2.41	0.76	13.0	
K20	43.6	50.3	6.1	gmS	fs	2.20	1.17	16.8	
K21	20.4	66.1	13.5	gmS	ms	1.27	1.34	44.1	
K22	21.0	63.4	15.6	gmS				53.3	
L01	4.3	94.3	1.4	S	fs	1.91	0.81	18.4	
L02	17.7	73.0	9.3	gmS	fs	1.97	1.29	35.7	
L03	16.3	79.8	3.9	mS	fs	2.01	1.26	38.0	
L04	23.1	73.9	3.0	mS	fs	2.22	1.28	61.7	
L05	2.2	55.2	42.6	sG	fs	0.72	1.72	80.5	
L06	9.8	83.4	6.8	gmS	ms	1.53	1.58	47.4	
L07	5.6	90.7	3.7	S	fs	2.00	1.05	29.4	
L08	3.9	94.9	1.2	S	ms	1.89	0.84	35.8	
L09	3.5	22.9	73.6	msG	cg	-1.11	1.14	55.1	
L10	2.3	95.6	2.1	S	fs	1.99	0.83	26.7	
L11	2.0	95.7	2.3	S	ms	1.14	0.83	33.6	
L12	4.1	93.1	2.8	S	fs	2.10	1.31	57.7	
L13	1.3	65.1	33.6	sG	cs	-0.07	1.38	86.7	
L14	17.3	82.0	0.7	mS	fs	2.28	1.37	38.7	
L15	4.7	93.6	1.7	S	vfs	2.67	1.24	39.7	

AMS Sample	wt % Mud	wt % Sand	wt % Gravel	Folk Class	Modal grain size	Mean grain size (Ø)	Sorting Coeff.	Wt% $CaCO_3$	Wt% $CaCO_3$ in mud
L16	3.4	94.6	2.0	S	fs	2.09	1.16	35.0	
L17	2.3	84.0	13.7	gS	cs	0.46	1.21	54.8	
L18	25.9	73.3	0.8	mS	vfs	2.68	1.17	46.1	
L19	16.8	78.3	4.9	mS	fs	1.82	1.72	43.6	
L20	31.4	61.6	7.0	gmS	ms	1.54	1.64	51.4	
L21	26.7	59.3	14.0	gmS	cs	0.55	1.75	57.8	
L22	18.4	79.6	2.0	mS	ms	1.91	1.08	38.2	
L23	51.6	46.3	2.1	mS	fs/vfs	2.42	1.12	40.2	
L24	51.3	47.1	1.6	mS	ms	1.97	1.35	42.8	
L25	31.7	66.6	1.7	mS	fs	2.18	1.15	40.9	
L26	12.5	84.4	3.1	mS	ms	1.94	0.91	30.6	
L27	20.0	74.3	5.7	gmS	fs	1.88	1.29	49.8	
L28	14.9	81.7	3.4	mS	fs	2.06	1.20	40.6	
L29	15.7	81.2	3.1	mS	fs	2.08	1.23	45.7	
L30	25.0	73.3	1.7	mS	vfs	2.62	1.18	38.5	
L31	23.8	74.9	1.3	mS	fs	2.57	1.10	40.8	
L32	0.9	88.5	10.6	gS	ms	1.14	0.98	31.5	
L33	1.3	65.7	33.0	sG	cs	-0.07	1.35	59.8	
L34	2.8	96.4	0.8	S	fs	2.16	0.74	17.4	
L35	4.0	89.8	6.2	gS	fs	1.93	1.20	27.8	
L36	1.1	96.3	2.6	S	fs	2.06	0.80	18.5	
L37	1.6	98.1	0.3	S	fs	2.40	0.66	14.7	
L38	0.0	99.3	0.7	S	cs	0.94	0.71	11.9	
L39	3.6	96.0	0.4	S	fs	2.32	0.70	12.7	
L40	3.7	95.7	0.6	S	fs	2.27	0.73	12.9	
L41	4.7	90.3	5.0	S	fs	1.73	1.23	41.2	
L42	22.0	74.6	3.4	mS	fs	2.36	1.20	45.1	
L43	27.6	67.9	4.5	mS	fs	1.78	1.43	44.4	
L44	47.3	50.7	2.0	mS	fs	2.43	1.09	36.8	
L45	31.0	67.3	1.7	mS	fs	2.35	0.97	32.0	
L46	22.7	75.1	2.2	mS	fs	2.30	1.13	34.7	
L47	3.8	93.3	2.9	S	ms	1.28	1.11	42.5	
L48	13.1	84.2	2.7	mS	fs	2.22	0.95	32.1	
L49	13.7	82.8	3.5	mS	fs	2.27	1.06	31.4	
L50	41.3	58.0	0.7	mS	fs	2.43	1.09	38.0	
L51	29.4	69.4	1.2	mS				34.0	
L52	10.5	86.0	3.5	mS	fs	1.91	1.19	27.7	
L53	13.6	86.2	0.2	mS	fs	2.18	0.95	34.9	
L54	0.3	92.6	7.1	gS	ms	0.88	1.09	47.7	
L55	0.6	50.5	48.9	sG	cg	-0.34	1.46	74.4	
L56	19.8	74.5	5.7	gmS	fs	1.71	1.60	42.6	
L57	2.5	95.7	1.8	S	fs	2.12	0.82	16.2	
T01	91.3	8.7	0.0	M				16.4	6.9
T02	27.3	43.3	29.4	gmS	cg	0.26	1.87	53.7	
T03	95.8	4.2	0.0	M				12.6	4.4
T04	96.8	3.2	0.0	M				12.0	5
T05	44.3	35.2	20.5	gsM	cg	0.21	1.85	35.5	
T06	94.9	5.1	0.0	M				15.5	5.2

AMS Sample	wt % Mud	wt % Sand	wt % Gravel	Folk Class	Modal grain size	Mean grain size (Ø)	Sorting Coeff.	Wt% $CaCO_3$	Wt% $CaCO_3$ in mud
T07	96.8	3.2	0.0	M				16.9	7
T08	92.1	7.9	0.0	M				13.4	8
T09	0.8	55.6	43.6	sG	vcs	-0.54	1.30	93.6	
T10	27.0	63.0	10.0	gmS	fs	1.64	1.43	30.0	
T11	10.3	54.2	35.5	msG	vcs	-0.18	1.55	75.3	
T12	81.4	18.6	0.0	sM				20.4	7.7

Table A6.3: Percent skeletal components in > 1mm carbonate fraction in samples with >50% carbonate.

AMS sample	Coelenterata	Bryozoa	Brachiopoda	Annelida	Bivalvia	Gastropoda	Other Mollusca	Cirripedia	Decapoda	Echinoidea	Other Biogenic
C04	0.3%	4.1%	0.3%	0.4%	82.5%	10.2%	0.2%	1.4%	0.6%	0.0%	0.0%
C07	0.0%	27.7%	0.4%	4.3%	57.6%	7.8%	0.2%	1.6%	0.2%	0.0%	0.2%
C12	0.5%	7.4%	0.3%	0.3%	82.0%	4.7%	0.3%	2.8%	0.3%	1.6%	0.0%
C13	0.7%	16.5%	0.2%	0.5%	57.2%	15.2%	0.2%	7.3%	0.2%	0.7%	1.2%
C14	1.8%	8.0%	0.3%	1.3%	69.1%	16.6%	0.0%	1.8%	0.3%	0.7%	0.0%
C26	3.8%	0.9%	4.7%	0.2%	88.3%	1.9%	0.0%	0.2%	0.0%	0.0%	0.0%
K05	0.3%	0.3%	0.0%	0.3%	75.9%	19.0%	0.2%	3.9%	0.0%	0.0%	0.0%
K06	0.2%	3.5%	0.0%	0.4%	61.3%	11.9%	0.0%	21.2%	0.0%	0.2%	1.3%
K11	0.4%	4.6%	0.2%	0.2%	68.8%	13.0%	0.2%	12.4%	0.0%	0.2%	0.0%
K12	1.6%	0.9%	0.0%	0.0%	35.5%	40.7%	0.0%	18.5%	0.0%	0.2%	2.6%
K17	0.2%	2.6%	0.0%	0.5%	85.2%	8.5%	0.0%	3.1%	0.0%	0.0%	0.0%
K21	0.2%	6.2%	4.6%	0.2%	74.6%	11.5%	0.0%	2.2%	0.0%	0.4%	0.0%
K22	18.8%	0.8%	0.2%	0.2%	58.8%	10.0%	0.0%	11.1%	0.0%	0.0%	0.0%
L01	0.0%	8.3%	0.2%	0.9%	58.6%	16.9%	0.0%	13.1%	0.4%	0.2%	1.4%
L02	0.2%	7.6%	0.5%	0.0%	79.0%	9.5%	0.2%	2.2%	0.2%	0.2%	0.4%
L03	0.7%	4.5%	1.5%	0.0%	78.6%	10.2%	0.0%	3.9%	0.0%	0.2%	0.4%
L04	0.4%	5.4%	0.0%	0.0%	68.6%	19.9%	0.6%	4.8%	0.0%	0.2%	0.0%
L05	0.4%	9.4%	1.9%	2.4%	66.9%	5.1%	0.0%	9.3%	0.7%	3.3%	0.4%
L09	0.0%	3.9%	0.0%	0.0%	85.5%	8.7%	0.0%	1.9%	0.0%	0.0%	0.0%
L12	0.2%	17.2%	0.0%	0.2%	58.2%	18.7%	0.2%	4.5%	0.5%	0.0%	0.2%
L13	0.2%	2.5%	0.0%	0.2%	69.8%	7.0%	0.0%	18.4%	0.5%	1.3%	0.0%
L17	0.0%	11.7%	0.0%	0.2%	65.9%	15.5%	0.0%	6.4%	0.2%	0.0%	0.0%
L20	0.0%	2.5%	6.4%	0.0%	62.2%	28.1%	0.0%	0.9%	0.0%	0.0%	0.0%
L21	0.9%	5.5%	0.2%	0.2%	76.6%	13.8%	0.0%	2.3%	0.2%	0.2%	0.0%
L27	0.7%	2.9%	0.0%	0.0%	78.0%	17.8%	0.0%	0.6%	0.0%	0.0%	0.0%
L33	1.4%	5.7%	0.8%	0.0%	65.2%	20.7%	0.0%	2.0%	0.0%	4.2%	0.0%
L55	0.0%	1.9%	0.0%	0.0%	77.5%	17.2%	1.1%	1.3%	0.0%	0.8%	0.2%
T02	0.0%	0.0%	0.2%	0.0%	78.1%	21.0%	0.0%	0.2%	0.0%	0.5%	0.0%
T09	0.0%	0.0%	0.0%	0.0%	93.7%	4.9%	0.0%	1.2%	0.0%	0.2%	0.0%
T11	0.3%	0.8%	0.0%	0.0%	84.4%	11.5%	0.0%	2.6%	0.2%	0.2%	0.0%

* samples have less than 50% carbonate but were done to increase sample coverage.

Table A6.4: Major species present in some Hauraki Gulf sediment samples.

Sediment sample	C04	C07	C12	C13	C14	C26	K05	K06	K11	K12	K17	K21	K22	L10	L02	L03	L04	L05	L09	L21	L13	L17	L20	L21	L27	L23	L25	T02	T09	T11
Coelenterata																														
Culicia rubeola	x		x	x	x			x		x	x	x	x				x	x						x	x	x			x	x
Flabellum rubrum						x	x	x		x			x			x	x	x			x	x			x		x			
Kinotrochus sp.															x				x			x		x		x				
Sphenotrochus sp.					x			x																	x	x				
Bryozoa																														
Arachnopusia unicornis		x			x	x	x					x	x	x	x	x	x		x	x		x	x				x		x	
Cellaria immersa	x		x		x	x		x			x	x	x			x		x		x				x					x	x
Celleporaria agglutinans															x															
Celleporina spp.		x	x				x		x	x	x		x	x		x			x	x	x	x	x						x	x
Chaperia acanthina										x		x									x									
Chaperiopsis tintinabula			x									x	x										x							
Conescharellina angulopora	x	x												x																
Escharoides angela					x							x								x	x									
Foveolaria cyclops								x			x										x									
Galeopsis polyporus		x		x	x				x	x		x								x	x	x								
Galeopsis porcellanicus	x	x	x	x	x						x	x	x	x	x		x	x	x	x	x			x		x			x	
Hippellozoon novaezelandiae		x					x				x	x	x					x		x			x	x	x	x				
Hippomenella vellicata											x										x									
Hornera sp.		x		x				x				x	x				x	x	x			x	x							
Idmidroneiforms		x	x		x						x		x				x				x	x							x	
Lichenopora sp.				x															x		x									
Macropora grandis										x	x	x					x	x	x		x	x				x				
Mecynoecia purpurascens !	x	x	x	x	x	x		x				x	x	x			x	x	x		x	x	x	x	x		x				
Otionella sp.	x		x	x	x	x			x					x	x				x	x	x	x	x	x	x	x	x				
Patsyella flemingi		x	x	x	x	x									x		x	x				x								
Smittoidea maunganuiensis																					x									x
Steginoporella magnifica	x	x		x	x	x	x	x			x	x		x		x		x			x	x	x			x	x		x	x
Steginoporella neozelanica			x		x			x													x	x					x			

Sediment sample	C04	C07	C12	C13	C14	C26	K05	K06	K11	K12	K17	K21	K22	L01	L02	L03	L04	L05	L09	L12	L13	L17	L20	L21	L27	L33	L35	T02	T09	T11
Steginoporella perplexa										x		x						x												
Telopora buski	x	x	x	x	x			x				x	x				x	x	x	x	x		x				x			
Annelida																														
Pomatoceros sp.			x										x					x												
Salmacina sp.	x	x					x	x		x	x	x		x			x	x	x			x				x	x		x	
Spirorbis sp.	x		x	x			x	x		x	x	x	x	x				x			x	x					x		x	
Bivalvia																														
Anomia trigonopsis						x				x		x	x													x		x	x	x
Atrina zelandica						x	x	x		x		x	x	x	x	x	x					x	x	x		x				
Chlamys gemmulata			x							x		x	x											x		x	x			
Chlamys zelandiae	x	x	x	x	x	x	x	x	x	x		x	x	x	x	x	x	x		x		x	x		x		x	x	x	x
Corbula zelandica	x		x		x	x		x		x		x	x		x	x	x	x	x	x		x				x	x	x	x	x
Divaricella huttoniana										x		x	x				x					x		x						
Gari stengari	x		x		x			x										x										x	x	
Glycimeris laticostata			x					x					x					x												
Glycimeris modesta	x	x	x					x										x	x			x	x	x		x	x			
Limaria sp.						x		x		x		x	x							x	x	x					x			x
Limatula sp.								x																						x
Mesopeplum			x		x	x											x					x	x	x	x	x	x			
Myadora sp.														x	x		x		x			x		x						
Nemocardium pulchellum		x			x	x						x	x			x	x					x	x	x	x	x	x			
Notocalista multistriata		x	x			x																x		x		x				
Nucula nitidula		x	x	x		x		x		x		x	x	x	x			x	x	x				x				x	x	x
Pecten novaezelandiae				x		x	x			x		x	x	x			x					x	x		x		x			x
Pleuromeris zelandica		x		x		x	x		x			x	x	x	x		x	x	x	x		x	x		x	x	x	x	x	x
Saccella bellula												x			x		x		x				x		x	x	x			
Scalpomactra scalpellum			x									x		x				x				x		x						
Tawera spissa		x	x	x		x	x	x	x		x	x	x	x	x	x	x	x	x	x	x	x					x	x	x	x
Venericardia purpurata			x			x	x		x			x	x	x	x		x		x			x		x		x	x		x	x
Zenatia acinaces												x	x										x							

Sediment sample	C04	C07	C12	C13	C14	C26	K05	K06	K11	K12	K17	K21	K22	L01	L02	L03	L04	L05	L09	L12	L13	L17	L20	L21	L22	L23	L35	T02	T09	T11
Gastropoda																														
Amalda					x					x							x				x	x	x		x	x				x
Buccinum spp.			x					x																						
Crepidula spp.					x		x	x		x			x						x		x									
Emarginula striatula	x				x									x		x		x									x			x
Micrelenchus rufozonus	x		x	x				x										x	x		x	x		x		x				
Muricopsis octagonus														x													x			
Sigapatella										x			x					x												
Struthiolaria			x		x					x																x				
Tigali spp.																														
Trochus spp.	x		x	x			x	x		x					x			x				x					x	x		
Xenophora neozelanica																						x	x							
Xymene spp.														x	x	x				x										x
Zeacolpus sp.		x					x	x		x		x	x	x		x	x	x		x				x		x		x	x	x
Zegalerus tenuis	x	x	x		x	x		x		x	x	x	x	x			x		x		x	x	x			x		x	x	x
Cirripedia																														
Balanus trigonus	x		x	x			x	x		x	x	x	x	x	x	x	x	x	x			x		x	x	x	x	x	x	x
Notobalanus vestitus		x		x				x			x	x					x	x		x	x	x		x					x	x
Balanus decorus			x														x	x			x	x								
Echinoidea																														
Evechinus chloroticus			x	x				x			x										x					x			x	
Echinocardium cordatum										x		x	x	x	x		x							x				x	x	
Other																														
Waltonia inconspicua	x	x	x	x	x	x				x		x	x	x	x	x		x	x			x	x	x		x	x	x		x
Decapods	x	x	x	x				x				x		x			x				x	x	x						x	x
Chitons		x	x	x			x			x		x	x		x	x	x				x			x	x			x		
Scaphopods															x		x								x					
Homotrema rubrum	x	x	x													x		x									x			
Benthic foraminifera				x										x						x					x					

Table A7.1: Textural groups and characteristics.

Sample	%M	%S	%G	Mean grain size (Ø)	Sorting coefficient (Ø)
GROUP ONE					
L09	3.5	22.9	73.6	-1.11	1.14
C04	4.1	40.2	55.7	-0.19	1.42
C12	1.5	43.5	55.0	-1.03	0.97
C60	1.5	71.6	26.9	0.08	1.57
C20	6.1	67.8	26.1	0.43	1.88
L33	1.3	65.7	33.0	-0.07	1.35
C11	1.7	80.0	18.3	0.17	1.41
C02	4.7	74.7	20.6	0.23	1.46
C14	3.1	80.9	16.0	0.42	1.42
C16	6.8	80.6	12.6	0.99	1.44
C10	5.7	75.1	19.2	0.65	1.41
C18	10.3	75.8	13.9	0.89	1.64
C07	2.0	83.2	14.8	1.14	1.48
L55	0.6	50.5	48.9	-0.34	1.46
L05	2.2	55.2	42.6	0.72	1.72
T11	10.3	54.2	35.5	-0.18	1.55
K17	11.1	60.8	28.1	-0.24	1.50
L13	1.3	65.1	33.6	-0.07	1.38
K06	1.2	59.6	39.2	-0.24	1.45
T09	0.8	55.6	43.6	-0.54	1.30
C13	0.0	72.0	28.0	-0.20	0.96
mean	3.8	63.6	32.6	0.07	1.42
GROUP TWO					
L45	31.0	67.3	1.7	2.35	0.97
K04	30.2	67.9	1.9	2.24	0.96
C47	27.0	65.9	7.1	2.40	1.39
C30	27.9	69.3	2.8	2.35	1.26
C44	32.2	64.7	3.1	2.36	1.22
L03	16.3	79.8	3.9	2.01	1.26
C27	17.8	77.7	4.5	1.92	1.27
L29	15.7	81.2	3.1	2.08	1.23
L28	14.9	81.7	3.4	2.06	1.20
L14	17.3	82.0	0.7	2.28	1.37
L53	13.6	86.2	0.2	2.18	0.95
L48	13.1	84.2	2.7	2.22	0.95
L26	12.5	84.4	3.1	1.94	0.91
L49	13.7	82.8	3.5	2.27	1.06
K09	16.0	79.9	4.1	2.08	1.06
K03	18.5	77.5	4.0	2.09	1.02
L22	18.4	79.6	2.0	1.91	1.08
C15	21.0	76.1	2.9	1.82	1.03
L46	22.7	75.1	2.2	2.30	1.13
L31	23.8	74.9	1.3	2.57	1.10
L30	25.0	73.3	1.7	2.62	1.18
L18	25.9	73.3	0.8	2.68	1.17

Sample	%M	%S	%G	Mean grain size (Ø)	Sorting coefficient (Ø)
L42	22.0	74.6	3.4	2.36	1.20
L25	31.7	66.6	1.7	2.18	1.15
L04	23.1	73.9	3.0	2.22	1.28
C21	12.2	74.8	13.0	1.28	1.53
C01	17.2	72.7	10.1	1.04	1.63
C26	18.6	63.0	18.4	1.39	1.69
L56	19.8	74.5	5.7	1.71	1.60
L19	16.8	78.3	4.9	1.82	1.72
L06	9.8	83.4	6.8	1.53	1.58
L43	27.6	67.9	4.5	1.78	1.43
L27	20.0	74.3	5.7	1.88	1.29
L02	17.7	73.0	9.3	1.97	1.29
C17	14.6	76.4	9.0	1.28	1.38
K21	20.4	66.1	13.5	1.27	1.34
C22	21.2	63.9	14.9		
C29	27.8	67.9	4.3		
C37	29.3	67.1	3.6		
K22	21.0	63.4	15.6		
L51	29.4	69.4	1.2		
mean	20.8	74.0	5.1	2.01	1.25
GROUP THREE					
L40	3.7	95.7	0.6	2.27	0.73
L39	3.6	96.0	0.4	2.32	0.70
L37	1.6	98.1	0.3	2.40	0.66
L57	2.5	95.7	1.8	2.12	0.82
L36	1.1	96.3	2.6	2.06	0.80
L34	2.8	96.4	0.8	2.16	0.74
L01	4.3	94.3	1.4	1.91	0.81
L38	0.0	99.3	0.7	0.94	0.71
L54	0.3	92.6	7.1	0.88	1.09
L17	2.3	84.0	13.7	0.46	1.21
C62	0.9	84.6	14.5	0.14	0.99
C05	1.1	83.5	15.4	0.41	1.20
C61	1.4	76.4	22.2	0.75	1.17
L16	3.4	94.6	2.0	2.09	1.16
L15	4.7	93.6	1.7	2.67	1.24
L12	4.1	93.1	2.8	2.10	1.31
L10	2.3	95.6	2.1	1.99	0.83
L08	3.9	94.9	1.2	1.89	0.84
L32	0.9	88.5	10.6	1.14	0.98
L11	2.0	95.7	2.3	1.14	0.83
L07	5.6	90.7	3.7	2.00	1.05
C19	6.1	89.5	4.4	1.67	1.06
L35	4.0	89.8	6.2	1.93	1.20
L52	10.5	86.0	3.5	1.91	1.19
L47	3.8	93.3	2.9	1.28	1.11
L41	4.7	90.3	5.0	1.73	1.23
C08	1.5	88.1	10.4	1.21	1.25

Sample	%M	%S	%G	Mean grain size (Ø)	Sorting coefficient (Ø)
C06	0.8	85.6	13.6	1.12	1.29
C09	2.5	89.0	8.5	1.32	1.43
C03	2.5	87.1	10.4	1.29	1.27
K01	1.3	78.9	19.8		
mean	2.9	90.9	6.2	1.58	1.03
GROUP FOUR					
L44	47.3	50.7	2.0	2.43	1.09
L23	51.6	46.3	2.1	2.42	1.12
L50	41.3	58.0	0.7	2.43	1.09
K20	43.6	50.3	6.1	2.20	1.17
K19	45.0	55.0	0.0	2.41	0.76
K18	61.5	38.5	0.0	2.14	1.22
C58	31.0	65.0	4.0	1.75	1.85
C35	25.8	65.8	8.4	1.61	1.79
K02	32.5	62.0	5.5	1.73	1.62
C33	27.7	61.6	10.7	1.86	1.64
C23	36.5	56.2	7.3	1.91	1.69
L20	31.4	61.6	7.0	1.54	1.64
C53	23.1	59.6	17.3	2.34	1.53
C31	25.3	56.9	17.8	1.81	1.68
C55	29.7	62.9	7.4	1.78	1.56
C43	28.9	64.5	6.6	1.83	1.56
T10	27.0	63.0	10.0	1.64	1.43
K10	25.7	62.7	11.6	1.49	1.50
C48	27.6	63.7	8.7	2.33	1.61
C36	27.0	63.8	9.2	2.31	1.58
C54	30.9	61.3	7.8	2.13	1.54
C49	34.6	56.2	9.2	2.28	1.51
C45	42.4	51.5	6.1	1.83	1.81
C24	36.2	58.9	4.9	1.46	1.60
L24	51.3	47.1	1.6	1.97	1.35
K08	45.1	48.7	6.2	1.10	1.56
C50	24.3	67.1	8.6	1.47	1.98
C40	21.6	62.3	16.1	1.56	1.94
C34	30.3	58.2	11.5	1.08	2.18
L21	26.7	59.3	14.0	0.55	1.75
K05	23.8	63.8	12.4	0.90	1.69
K12	23.0	59.2	17.8	0.56	1.92
C25	26.0	57.3	16.7	0.65	1.99
C32	17.5	63.3	19.2	0.76	2.03
T05	44.3	35.2	20.5	0.21	1.85
K13	42.9	44.1	13.0	1.12	2.00
T02	27.3	43.3	29.4	0.26	1.87
K11	19.4	55.9	24.7	0.55	1.75
C59	31.9	57.7	10.4	0.22	1.30
K07	33.5	55.1	11.4		
mean	33.1	56.8	10.1	1.55	1.61

Sample	%M	%S	%G	Mean grain size (Ø)	Sorting coefficient (Ø)
GROUP FIVE					
K14	72.4	26.8	0.8		
K15	60.1	35.4	4.5		
T01	91.3	8.7	0.0		
T03	95.8	4.2	0.0		
T04	96.8	3.2	0.0		
T06	94.9	5.1	0.0		
T07	96.8	3.2	0.0		
T08	92.1	7.9	0.0		
T12	81.4	18.6	0.0		
mean	86.8	12.6	0.6		

Note: Samples in order of cluster analysis.

Table A7.2: Skeletal groups and characteristics.

	Sample	Coel	Bry	Brach	Ann	Biv	Gast	Moll	Cirr	Dec	Ech	Other
GROUP A	L1	0.00%	8.25%	0.21%	0.94%	58.62%	16.93%	0.00%	13.06%	0.42%	0.21%	1.36%
	C13	0.73%	16.46%	0.21%	0.52%	57.23%	15.20%	0.21%	7.34%	0.21%	0.73%	1.15%
	L17	0.00%	11.69%	0.00%	0.22%	65.90%	15.52%	0.00%	6.45%	0.22%	0.00%	0.00%
	C14	1.85%	7.97%	0.28%	1.28%	69.13%	16.64%	0.00%	1.85%	0.28%	0.71%	0.00%
	L12	0.25%	17.16%	0.00%	0.25%	58.21%	18.66%	0.25%	4.48%	0.50%	0.00%	0.25%
	L13	0.21%	2.54%	0.00%	0.21%	69.81%	6.99%	0.00%	18.43%	0.53%	1.27%	0.00%
	K6	0.20%	3.48%	0.00%	0.41%	61.27%	11.89%	0.00%	21.21%	0.00%	0.20%	1.33%
	L33	1.37%	5.70%	0.84%	0.00%	65.19%	20.68%	0.00%	2.00%	0.00%	4.22%	0.00%
	L5	0.40%	9.45%	1.91%	2.41%	66.93%	5.13%	0.00%	9.35%	0.70%	3.32%	0.40%
mean		0.56%	9.19%	0.38%	0.69%	63.59%	14.18%	0.05%	9.35%	0.32%	1.19%	0.50%
GROUP B	K21	0.20%	6.22%	4.62%	0.20%	74.60%	11.55%	0.00%	2.21%	0.00%	0.40%	0.00%
	C26	3.80%	0.90%	4.70%	0.20%	88.30%	1.90%	0.00%	0.20%	0.00%	0.00%	0.00%
	L20	0.00%	2.45%	6.40%	0.00%	62.22%	28.07%	0.00%	0.85%	0.00%	0.00%	0.00%
	L4	0.40%	5.41%	0.00%	0.00%	68.64%	19.94%	0.60%	4.81%	0.00%	0.20%	0.00%
	K11	0.40%	4.62%	0.20%	0.20%	68.78%	12.95%	0.20%	12.45%	0.00%	0.20%	0.00%
	C12	0.50%	7.43%	0.25%	0.25%	81.99%	4.66%	0.25%	2.77%	0.25%	1.64%	0.00%
	C4	0.31%	4.08%	0.31%	0.41%	82.47%	10.19%	0.20%	1.43%	0.61%	0.00%	0.00%
	T2	0.00%	0.00%	0.20%	0.00%	78.06%	21.04%	0.00%	0.20%	0.00%	0.50%	0.00%
	L27	0.72%	2.89%	0.00%	0.00%	78.02%	17.75%	0.00%	0.62%	0.00%	0.00%	0.00%
	K5	0.32%	0.32%	0.00%	0.32%	75.95%	18.99%	0.21%	3.90%	0.00%	0.00%	0.00%
	L9	0.00%	3.85%	0.00%	0.00%	85.55%	8.67%	0.00%	1.93%	0.00%	0.00%	0.00%
	K17	0.20%	2.55%	0.00%	0.51%	85.20%	8.47%	0.00%	3.06%	0.00%	0.00%	0.00%
	T9	0.00%	0.00%	0.00%	0.00%	93.70%	4.90%	0.00%	1.20%	0.00%	0.20%	0.00%
	T11	0.32%	0.75%	0.00%	0.00%	84.39%	11.52%	0.00%	2.58%	0.22%	0.22%	0.00%
	L21	0.92%	5.52%	0.23%	0.23%	76.55%	13.79%	0.00%	2.30%	0.23%	0.23%	0.00%
	L3	0.70%	4.51%	1.50%	0.00%	78.56%	10.22%	0.00%	3.91%	0.00%	0.20%	0.40%
	L2	0.20%	7.65%	0.50%	0.00%	78.97%	9.46%	0.20%	2.21%	0.20%	0.20%	0.40%
	L55	0.00%	1.88%	0.00%	0.00%	77.48%	17.22%	1.10%	1.32%	0.00%	0.77%	0.22%
mean		0.50%	3.39%	1.05%	0.13%	78.86%	12.85%	0.15%	2.66%	0.08%	0.26%	0.06%
GROUP C	K22	18.85%	0.82%	0.21%	0.21%	58.81%	9.99%	0.00%	11.12%	0.00%	0.00%	0.00%
	C7	0.00%	27.67%	0.40%	4.30%	57.64%	7.79%	0.20%	1.60%	0.20%	0.00%	0.20%
	K12	1.61%	0.90%	0.00%	0.00%	35.54%	40.66%	0.00%	18.47%	0.00%	0.20%	2.61%

Abbreviations: Coel - Coelenterata, Bry - Bryozoa, Brach - Brachipoda, Ann - Annelida, Biv - Bivalvia, Gast - Gastropoda, Moll - Other Mollusca, Cirr - Cirripedia, Dec - Decapoda, Ech - Echinoidea, Other - Other biogenic.

Appendix Table A8.1: Weight change in molluscs in the Hauraki Gulf over time.

Sample	Date deployed	Wt (g) at start	Date collected	Wt (g) at end	Change in wt (g)	% wt change	Days in sea	Rate (g/y)	% rate (%/y)
Austrovenus stutchberyi									
MB2	18-Sep-90	0.61	6-Nov-90	0.61	0.00	0.0%	49	0.000	0.000
MB28	16-May-91	0.58	13-Aug-91	0.59	0.01	1.7%	89	0.041	0.071
MB17	1-Aug-90	0.70	6-Nov-90	0.70	0.00	0.0%	97	0.000	0.000
MB22	1-Aug-90	1.26	6-Nov-90	1.26	0.00	0.0%	97	0.000	0.000
MB26	1-Aug-90	1.12	6-Nov-90	1.16	0.04	3.6%	97	0.151	0.134
MB8	1-Aug-90	3.09	6-Nov-90	3.15	0.06	1.9%	97	0.226	0.073
MB27	16-May-91	1.00	21-Nov-91	1.02	0.02	2.0%	189	0.039	0.039
MB12	1-Aug-90	0.88	16-May-91	0.85	-0.03	-3.4%	288	-0.038	-0.043
MB13	1-Aug-90	1.06	16-May-91	1.05	-0.01	-0.9%	288	-0.013	-0.012
MB15	1-Aug-90	0.78	16-May-91	0.77	-0.01	-1.3%	288	-0.013	-0.016
MB4	1-Aug-90	1.17	16-May-91	1.18	0.01	0.9%	288	0.013	0.011
MB9	1-Aug-90	1.40	16-May-91	1.29	-0.11	-7.9%	288	-0.139	-0.100
MB11	1-Aug-90	1.59	13-Aug-91	1.75	0.16	10.1%	377	0.155	0.097
MB21	1-Aug-90	3.09	13-Aug-91	3.10	0.01	0.3%	377	0.010	0.003
MB23	1-Aug-90	1.70	13-Aug-91	1.72	0.02	1.2%	377	0.019	0.011
MB25	1-Aug-90	1.16	13-Aug-91	1.20	0.04	3.4%	377	0.039	0.033
MB3	1-Aug-90	0.65	13-Aug-91	0.73	0.08	12.3%	377	0.077	0.119
MB14	1-Aug-90	1.11	21-Nov-91	1.14	0.03	2.7%	477	0.023	0.021
MB16	1-Aug-90	0.96	21-Nov-91	0.75	-0.21	-21.9%	477	-0.161	-0.167
MB18	1-Aug-90	0.45	21-Nov-91	0.44	-0.01	-2.2%	477	-0.008	-0.017
MB19	1-Aug-90	1.59	21-Nov-91	1.69	0.10	6.3%	477	0.077	0.048
Chlamys delicatula									
MB2	18-Sep-90	0.79	6-Nov-90	0.78	-0.01	-1.3%	49	-0.074	-0.094
MB28	16-May-91	0.57	13-Aug-91	0.58	0.01	1.8%	89	0.041	0.072
MB17	1-Aug-90	0.49	6-Nov-90	0.50	0.01	2.0%	97	0.038	0.077
MB22	1-Aug-90	0.41	6-Nov-90	0.37	-0.04	-9.8%	97	-0.151	-0.367
MB26	1-Aug-90	1.00	6-Nov-90	0.96	-0.04	-4.0%	97	-0.151	-0.151
MB8	1-Aug-90	1.70	6-Nov-90	1.70	0.00	0.0%	97	0.000	0.000

Sample	Date deployed	Wt (g) at start	Date collected	Wt (g) at end	Change in wt (g)	% wt change	Days in sea	Rate (g/y)	% rate (%/y)
MB27	16-May-91	0.95	21-Nov-91	0.93	-0.02	-2.1%	189	-0.039	-0.041
MB12	1-Aug-90	0.42	16-May-91	0.41	-0.01	-2.4%	288	-0.013	-0.030
MB13	1-Aug-90	0.82	16-May-91	0.82	0.00	0.0%	288	0.000	0.000
MB15	1-Aug-90	0.77	16-May-91	0.78	0.01	1.3%	288	0.013	0.016
MB4	1-Aug-90	0.73	16-May-91	0.73	0.00	0.0%	288	0.000	0.000
MB9	1-Aug-90	0.73	16-May-91	0.70	-0.03	-4.1%	288	-0.038	-0.052
MB11	1-Aug-90	0.45	13-Aug-91	0.46	0.01	2.2%	377	0.010	0.022
MB21	1-Aug-90	0.56	13-Aug-91	0.59	0.03	5.4%	377	0.029	0.052
MB23	1-Aug-90	0.43	13-Aug-91	0.42	-0.01	-2.3%	377	-0.010	-0.023
MB25	1-Aug-90	1.09	13-Aug-91	1.13	0.04	3.7%	377	0.039	0.036
MB3	1-Aug-90	0.69	13-Aug-91	0.74	0.05	7.2%	377	0.048	0.070
MB14	1-Aug-90	0.49	21-Nov-91	0.48	-0.01	-2.0%	477	-0.008	-0.016
MB16	1-Aug-90	0.47	21-Nov-91	0.45	-0.02	-4.3%	477	-0.015	-0.033
MB18	1-Aug-90	0.29	21-Nov-91	0.29	0.00	0.0%	477	0.000	0.000
MB19	1-Aug-90	0.91	21-Nov-91	0.98	0.07	7.7%	477	0.054	0.059
Paphies australis									
MB2	18-Sep-90	6.01	6-Nov-90	5.99	-0.02	-0.3%	49	-0.149	-0.025
MB28	16-May-91	4.75	13-Aug-91	4.76	0.01	0.2%	89	0.041	0.009
MB17	1-Aug-90	1.11	6-Nov-90	1.11	0.00	0.0%	97	0.000	0.000
MB22	1-Aug-90	8.75	6-Nov-90	8.75	0.00	0.0%	97	0.000	0.000
MB26	1-Aug-90	4.65	6-Nov-90	4.76	0.11	2.4%	97	0.414	0.089
MB8	1-Aug-90	7.63	6-Nov-90	7.70	0.07	0.9%	97	0.263	0.035
MB27	16-May-91	1.42	21-Nov-91	1.45	0.03	2.1%	189	0.058	0.041
MB12	1-Aug-90	5.55	16-May-91	5.69	0.14	2.5%	288	0.177	0.032
MB13	1-Aug-90	5.06	16-May-91	5.03	-0.03	-0.6%	288	-0.038	-0.008
MB15	1-Aug-90	4.09	16-May-91	4.31	0.22	5.4%	288	0.279	0.068
MB4	1-Aug-90	7.45	16-May-91	7.50	0.05	0.7%	288	0.063	0.009
MB9	1-Aug-90	6.17	16-May-91	6.17	0.00	0.0%	288	0.000	0.000
MB11	1-Aug-90	4.27	13-Aug-91	4.29	0.02	0.5%	377	0.019	0.005
MB21	1-Aug-90	8.00	13-Aug-91	8.05	0.05	0.6%	377	0.048	0.006
MB23	1-Aug-90	9.52	13-Aug-91	9.60	0.08	0.8%	377	0.077	0.008

Sample	Date deployed	Wt (g) at start	Date collected	Wt (g) at end	Change in wt (g)	% wt change	Days in sea	Rate (g/y)	% rate (%/y)
MB25	1-Aug-90	4.86	13-Aug-91	4.86	0.00	0.0%	377	0.000	0.000
MB3	1-Aug-90	2.43	13-Aug-91	2.45	0.02	0.8%	377	0.019	0.008
MB14	1-Aug-90	2.81	21-Nov-91	2.86	0.05	1.8%	477	0.038	0.014
MB16	1-Aug-90	1.65	21-Nov-91	1.67	0.02	1.2%	477	0.015	0.009
MB18	1-Aug-90	3.20	21-Nov-91	3.31	0.11	3.4%	477	0.084	0.026
MB19	1-Aug-90	3.31	21-Nov-91	3.26	-0.05	-1.5%	477	-0.038	-0.012
Pecten novaezelandiae									
MB2	18-Sep-90	0.70	6-Nov-90	0.69	-0.01	-1.4%	49	-0.074	-0.106
MB28	16-May-91	3.12	13-Aug-91	3.12	0.00	0.0%	89	0.000	0.000
MB17	1-Aug-90	0.57	6-Nov-90	0.56	-0.01	-1.8%	97	-0.038	-0.066
MB22	1-Aug-90	2.67	6-Nov-90	2.65	-0.02	-0.7%	97	-0.075	-0.028
MB26	1-Aug-90	0.79	6-Nov-90	0.79	0.00	0.0%	97	0.000	0.000
MB8	1-Aug-90	1.38	6-Nov-90	1.38	0.00	0.0%	97	0.000	0.000
MB27	16-May-91	1.19	21-Nov-91	1.21	0.02	1.7%	189	0.039	0.032
MB12	1-Aug-90	0.57	16-May-91	0.52	-0.05	-8.8%	288	-0.063	-0.111
MB13	1-Aug-90	3.50	16-May-91	3.53	0.03	0.9%	288	0.038	0.011
MB15	1-Aug-90	0.48	16-May-91	0.05	-0.43	-89.4%	288	-0.544	-1.133
MB4	1-Aug-90	0.85	16-May-91	0.82	-0.03	-3.5%	288	-0.038	-0.045
MB9	1-Aug-90	1.63	16-May-91	1.61	-0.02	-1.2%	288	-0.025	-0.016
MB11	1-Aug-90	0.81	13-Aug-91	0.79	-0.02	-2.5%	377	-0.019	-0.024
MB21	1-Aug-90	3.26	13-Aug-91	3.27	0.01	0.3%	377	0.010	0.003
MB23	1-Aug-90	4.03	13-Aug-91	4.06	0.03	0.7%	377	0.029	0.007
MB25	1-Aug-90	0.85	13-Aug-91	0.89	0.04	4.7%	377	0.039	0.046
MB3	1-Aug-90	1.55	13-Aug-91	1.59	0.04	2.6%	377	0.039	0.025
MB14	1-Aug-90	2.28	21-Nov-91	2.37	0.09	3.9%	477	0.069	0.030
MB16	1-Aug-90	1.03	21-Nov-91	1.02	-0.01	-1.0%	477	-0.008	-0.007
MB18	1-Aug-90	1.18	21-Nov-91	1.18	0.00	0.0%	477	0.000	0.000
MB19	1-Aug-90	0.54	21-Nov-91	0.44	-0.10	-18.5%	477	-0.077	-0.142
Perna caniculus									
MB2	18-Sep-90	1.07	6-Nov-90	1.05	-0.02	-1.9%	49	-0.149	-0.139
MB28	16-May-91	1.51	13-Aug-91	1.45	-0.06	-4.0%	89	-0.246	-0.163

Sample	Date deployed	Wt (g) at start	Date collected	Wt (g) at end	Change in wt (g)	% wt change	Days in sea	Rate (g/y)	% rate (%/y)
MB17	1-Aug-90	1.10	6-Nov-90	1.12	0.02	1.8%	97	0.075	0.068
MB22	1-Aug-90	1.67	6-Nov-90	1.62	-0.05	-3.0%	97	-0.188	-0.113
MB26	1-Aug-90	1.62	6-Nov-90	1.58	-0.04	-2.5%	97	-0.151	-0.093
MB8	1-Aug-90	1.52	6-Nov-90	1.50	-0.02	-1.3%	97	-0.075	-0.050
MB27	16-May-91	1.23	21-Nov-91	1.20	-0.03	-2.4%	189	-0.058	-0.047
MB12	1-Aug-90	1.33	16-May-91	1.33	0.00	0.0%	288	0.000	0.000
MB13	1-Aug-90	0.89	16-May-91	0.89	0.00	0.0%	288	0.000	0.000
MB15	1-Aug-90	1.22	16-May-91	1.25	0.03	2.5%	288	0.038	0.031
MB4	1-Aug-90	2.07	16-May-91	1.99	-0.08	-3.9%	288	-0.101	-0.049
MB9	1-Aug-90	1.63	16-May-91	1.50	-0.13	-8.0%	288	-0.165	-0.101
MB11	1-Aug-90	1.42	13-Aug-91	1.38	-0.04	-2.8%	377	-0.039	-0.027
MB21	1-Aug-90	1.02	13-Aug-91	1.10	0.08	7.8%	377	0.077	0.076
MB23	1-Aug-90	0.53	13-Aug-91	0.56	0.03	5.7%	377	0.029	0.055
MB25	1-Aug-90	1.04	13-Aug-91	1.02	-0.02	-1.9%	377	-0.019	-0.019
MB3	1-Aug-90	0.38	13-Aug-91	0.38	0.00	0.0%	377	0.000	0.000
MB14	1-Aug-90	0.73	21-Nov-91	0.70	-0.03	-4.1%	477	-0.023	-0.031
MB16	1-Aug-90	0.51	21-Nov-91	0.47	-0.04	-7.8%	477	-0.031	-0.060
MB18	1-Aug-90	1.00	21-Nov-91	0.99	-0.01	-1.0%	477	-0.008	-0.008
MB19	1-Aug-90	2.02	21-Nov-91	1.86	-0.16	-7.9%	477	-0.122	-0.061

Table A8.2: Radiocarbon ages for mollusc shells with different degrees of bioerosion, taken from Hauraki Gulf sediments.

Species	Sample location	Degree of bioerosion	Age (y)	Error	University of Waikato Number
Pecten novaezelandiae	AMS-L57	none (live)	> Modern	±0.8%	Wk2246
Pecten novaezelandiae	AMS-L55	light	> Modern	±1.4%	Wk2247
Pecten novaezelandiae	AMS-L55	moderate	> Modern	±2.3%	Wk2248
Pecten novaezelandiae	AMS-L55	heavy	350	±190 y	Wk2249
Tawera spissa	AMS-L13	nearly fresh	720	±220 y	Wk2250
Tawera spissa	AMS-L13	light	1160	±200 y	Wk2251
Tawera spissa	AMS-L13	moderate	1320	±210 y	Wk2252
Tawera spissa	AMS-L13	heavy	1170	±240 y	Wk2253
Struthiolaria papulosa	AMS-T11	light	> Modern	±2.5%	Wk2261
Struthiolaria papulosa	AMS-T11	moderate	> Modern	±2.4%	Wk2262
Struthiolaria papulosa	AMS-T11	heavy	840	±210 y	Wk2263

NOTES: For sample locations, see Figure 6A.1.

"> Modern" means the shell has been alive since 1950 (defined as "present").

Table A10.1: Data from some published literature on modern temperate shelf carbonate sediments.

Paper	Location	Climate	Latitude	Maximum % $CaCO_3$	Common taxa	Diagenetic processes	Mineralogy	Other
Raymond and Hutchins 1932	N. Scotland	T	58°N	97	mo	abr sort		
Raymond and Stetson 1932	Gulf of Maine,USA	T	44°N	67	mo ba ec			
Boillot 1965	English Ch.	T	50°N		mo ba op br sp			
Conolly and von der Borch 1967	S Australia	sT	S		br mo sp fo			
Hulsemann 1967	NE USA	T	38-42°N	35	mo de ec wm br co al			
Smith 1970	S California USA		32-34°N		al br mo ec	diss	c a d m	
Wass et al. 1970	S Australia	sT	35-40°S		br			
Dobson et al. 1971	S Irish Sea	T	53°N	100	wm ba br mo ec op			
Sisser 1971	South Africa	sT	32-37°S	85		diss	a c m	
Molnia and Pilkey 1972	Carolina Shelf USA	sT	33-35°N	25	fo mo ba ec	bio abr	c a m	carb mud
Muller and Milliman 1973	SW Grand Bank Newfoundland	T	45°N	80	ba mo ec fo	abr		relict
Askelsson 1974	NW Iceland	P	65°N	55	mo	bio		
Birch 1977	W. South Africa	sT	30-35°S	95	fo wm			
Gunatilaka 1977	Connemara W. Ireland	T	53 °N	55	al mo ba ec	bio disag	c a m	
Slatt 1977	Grand bank Newfoundland	T	43-48°N	86	ba mo br ec fo	abr		
Alexandersson 1978	Skagerrak	T			mo ba ec al fo	diss	a c m	

Paper	Location	Climate	Latitude	Maximum $\%CaCO_3$	Common taxa	Diagenetic processes	Mineralogy	Other
Marshall and Davies 1978	E. Australia	Tr - T	30-40°S	100	br mo fo			
Farrow et al. 1978	W Scotland	T	56°N	89	ba mo al ec br fo			
Bosence 1979	E Ireland	T	54°N		al mo	bio abr		
Bouysse et al. 1979	W English Channel	T	50°N		br			
Wilson 1979	Scotland Rockall Bank	T	56-61°N		mo ba wm brach br			
Scoffin et al. 1980	Rockall Bank NE Atlantic	T	57°N		br wm mo ec fo	bio	c a	
Rao 1981	Tasmania	T	43°S		br mo fo ec sp al	cem	c	pellets, micrite
Farrow et al. 1982 MS	NE Orkneys Scotland	T	59°N	99	bi ba br wm	bio		
Nelson et al. 1982	N New Zealand	T	34°S	100	br mo co ba al		c m a	
Farrow 1983	Hebrides Scotland	T	57°N	75	mo ba wm ec fo op	bio cem		
Nelson and Bornhold 1983	Vancouver Canada	T	51°N	100	mo ba br fo	diss bio	c m a	
Nelson and Bornhold 1984	Vancouver	T	51°N	100	br mo ba fo		m c a	
	N New Zealand	T	34°S	100	br mo ba fo		m c a	
Nelson and Hancock 1984	N New Zealand	T	34°S	100	br mo co al fo			
Nelson and Lawrence 1984	Brit Columbia Canada	T	49°N			cem	m	nodules
Smith 1984	Gulf of Maine USA	T	44°N	86	ba mo ec fo			
Farrow and Durant 1985	Cobb Seamount NE Pacific	T	47°N	100	mo br ec fo			
Leonard et al. 1981	Gulf of Maine USA	T	44°N	69	ba mo ec		c	

Paper	Location	Climate	Latitude	Maximum $\%CaCO_3$	Common taxa	Diagenetic processes	Mineralogy	Other
Nelson and Jordan 1986	N New Zealand	T	34°S	90	br mo al wm co fo		m c a	
Milliman and Petricca 1987	Tromsø Norway	P	70°N	95	al mo ba ec br fo	bio diss cem		
Perissoratis et al 1987	N Greece	T	41°N	60	fo	bioclasts		
Collins 1988	SW Australia	sT	32°S		br al mo fo ec	bio cem gla		
Darmoian and Lindqvist 1988	Arabian Gulf	sT	30°N	85	fo mo os ba de br co as ec		c d	mixed terr
Domack 1988	E Antarctica	P	67°S		ba br os mo fo al			
Gostin et al. 1988	S Australia	sT	34°S		br al fo ec mo			
Nelson et al. 1988	N New Zealand S New Zealand	sT T	34°S 47°S	100	br mo fo br mo fo	bio	c m a	
Scoffin 1988	W Scotland	T	56°N		mo ba ec wm br fo al			
Scoffin and Bowes 1988	Porcupine Bank W Ireland	T	51-54°N	92	mo ba br			
Wilson 1988	Britain	T	56-60°N		mo ba co br bio ec wm			
Bone and Wass 1990	S Australia	T	36°S		br wm	buildups	m	
Smith 1992	N New Zealand	T	36°S	92	mo br ba	bio	c m a	see Ch 6.

Abbreviations:

Climate sT subtropical; T temperate; P polar.

Taxa al algae; as asteroids; ba barnacles; br bryozoans; brach brachiopods; co corals; ec echinoids; fo foraminifera; mo molluscs; op ophiuroids; sp sponges; wm worms.

Processes abr abrasion; bio bioerosion; cem cementation; diss dissolution; disagg disaggregation; sort sorting.

Mineralogy a aragonite; c low-Mg calcite; m high-Mg calcite.

Table A11.1: Bryozoan colonial growth forms in Hauraki Gulf carbonate sediments. Facies as defined in Chapter 9, Section A. Colonial growth form abbreviations given in Figure IB.1.

	Water depth	
Facies	<50 m	>50 m
High-carbonate muddy sand	**ENul** **ERde** ENml FLmo ERra EFar	**ERde** ENml ENul FLmo EFar ERro
Muddy sand	generally few ERde ENml FLmo ERfe	**ENul** FLmo ERfe ENml ERde
Sand	**FLmo** ERde ENul EFar	**ENul** **FLmo** ERro ERfo ERde ENml
Mud	generally few ENml	no samples