The skeletal carbonate contribution to mixed terrigenous-carbonate sediments on the temperate northeastern Northland continental shelf, New Zealand

A thesis

submitted in partial fulfilment

for the degree of

Master of Science in Earth and Ocean Sciences

at the

University of Waikato

by

Danielle Claire Rogers

THE UNIVERSITY OF
WAIKATO
Te Whare Wānanga o Waikato

2012

ABSTRACT

The northeastern Northland continental shelf (NNCS) includes the coastal, shelf and uppermost slope seafloor out to depths of 210 m and over a distance of 150 km between North Cape and Ngurauru Bay slightly north of Whangarei. The nature of the surficial sediments covering NNCS is poorly known and this study uses archived and recently collected samples to begin to address this situation, with special attention to the nature and distribution of the skeletal carbonate fraction. The sediments are mainly neither carbonate-dominated as occurs in the Three Kings area immediately to the north, nor overwhelmingly terrigenous in nature as typifies more southern shelf sectors. Instead, mixed terrigenous-carbonate deposits prevail in an often patchwork mosaic distribution of facies. Carbonate content is often highest nearshore and in bays and harbours (50-80%), and generally decreases into deeper water (few-50%). The NNCS sediments are almost completely dominated by sand-sized components (60-90%) comprising gravelly sand, sand, muddy sand and gravelly muddy sand textures.

A sedimentary facies model is developed for the NNCS identifying five different facies. Facies 1 is siliciclastic quartzofeldspathic sand with minor bivalve contributions, occurring only in the northern sector. Subfacies 1a (quartz>feldspar) occurs at inner- to mid-shelf depths and is mainly derived from reworked Quaternary Karioitahi Group sand deposits and/or podzolisation and reworking of local soils. Subfacies 1b (feldspar>quartz) occurs in mid- to outer-shelf depths and is derived from the erosion of a combination of the Quaternary sand deposits (Katioitahi Group), Mesozoic basement rocks and Northland volcanic and sedimentary rocks. Facies 2 comprises mixed barnacle-siliciclastic gravel and sand at inner-shelf to uppermost slope depths in the northern sector and includes submarine basaltic and type 1 sedimentary rock fragments derived from Mesozoic basement rocks and the Tangihua Complex of the Northland Allochthon. Facies 3 consists of mixed calcareous red algae and bivalve-siliciclastic gravel and sand at inner- to mid-shelf depths in the southern sector and involves a mix of relict and modern skeletal material and sedimentary rock fragments type 2 sourced from Tertiary deposits. Facies 4 is mixed foraminiferal-siliciclastic sand and mud and occurs only in the very southern sector in two subfacies. Subfacies 4a, a mixed benthic foraminiferal-siliciclastic sand, occurs in mid-shelf depths and comprises plagioclase dominated siliciclastic material sourced from Mesozoic basement rocks. Subfacies 4b, a mixed planktic foraminiferal-siliciclastic sand and mud, occurs in mid- to outer-shelf depths and comprises rock fragments derived from Tertiary deposits which could also be a local source of the reworked planktic foraminifera at these depths. Facies 5 consists of mixed bryozoan-siliciclastic sand at mid-shelf depths and in scattered locations across the NNCS associated with rocky outcrops for bryozoan attachment. Siliciclastic material comprises plagioclase sand sourced from reworking of Mesozoic basement rocks, and sedimentary rock fragments type 2 sourced from Tertiary sediments.

The NNCS sedimentary facies model is compared with other temperate carbonate shelf models and carbonate-rich North Island shelf sectors, including Hauraki Gulf, Three Kings platform, north Kaipara continental margin and Wanganui shelf, which serves to both test and expand scenarios of cool-water carbonate sedimentation established for New Zealand. Overall, the mixed terrigenous-carbonate material on the NNCS comprises an often mosaic facies distribution with the skeletal fraction dominated by bivalve and barnacle fragments and a mixture of relict and modern material. These characteristics reflect several environmental controls, including (a) diversified substrate types (rock, shell, sand, mud); (b) variable supply and dispersal routes of terrigenous material linked to positions of hinterland estuaries/harbours and rocky versus sandy coastlines; (c) scattered and discrete areas of primary carbonate generation (the “carbonate factories”) and the subsequent selective transportation of skeletal grains; (d) local effects of nutrient-rich upwelling; and (e) the variable mix of relict and modern sediment associated with the post-glacial rise of sea level since about 20 ka.

ACKNOWLEDGEMENTS

Firstly I would like to thank my supervisors Professor Cam Nelson and Dr. Scott Nodder from the New Zealand Oceanographic Institute (NIWA). Scott is thanked for the help provided at NIWA Wellington, especially with tours and introductions to the right technical and intellectual staff who have been very valuable throughout the production of my thesis. I would especially like to thank Helen Bostock, Lisa Northcote and the rest of the team at NIWA, Wellington for the extensive help and advice. A very special thanks to Cam for his wisdom, direction and all the time spent editing my thesis.

Secondly I would like to thank Steve Hood for the assistance with petrographic analysis, valuable advice and encouragement. I would like to thank Rochelle Hansen for assistance with foraminiferal identification and Roger Briggs for assistance with volcanic rock and mineral identification and Willem for help with my textural data. A big thanks to Renat for the long hours spent training me to make thin sections, and Alan, Xu and Indar for the training and advice on X-ray diffraction. I would like to thank the science librarians, Jenny and Cheryl, for their help and advice along the way. I would like to acknowledge Jacinta and Janine from the soils lab, Annie from the chemistry lab and Chris and Annette for training, technical advice and access to essential equipment.

Finally and most importantly, I would like to thank my amazing family, friends and fellow peers especially my sister, Shelley, for the encouragement during the particularly stressful times, my partner Jarrod for his immense support and keeping me sane, my parents for the all-paid-for breaks to Australia, and last but not least my grandparents for their patience and always being there for me during the difficult times.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF PLATES

LIST OF TABLES

Chapter 1

INTRODUCTION

1.1 THE TEMPERATE CARBONATE PARADIGM

Shelf carbonate rocks or limestones are significant for geoscientists as they make up about 25% of the land based rock record, as well as being potentially excellent hydrocarbon reservoirs due to their often high porosity (Nelson, 1988). Shelf carbonates have been differentiated into warm and cool-water end-members, the former involving tropical to subtropical shelves at latitudes between 30°N and 30°S, the latter temperate or non-tropical shelves at latitudes beyond 30° N and 30°S (Nelson, 1988). Traditional carbonate shelf models have been firmly rooted in the warm-water tropical scenario. However, advances in marine research have led to an increasing awareness of the cool-water temperate carbonate story, so that carbonate sedimentation is no longer regarded as being limited to warm shallow waters at latitudes within 30°N and 30°S where upwelling and terrigenous clastic influx are typically low (James, 1984a; Ziegler *et al.*, 1984). Chave (1967) and subsequent workers supported the view that carbonate deposition can occur in any climate on shelves at any latitude as long as the dilution rate by terrigenous sediment is small (Nelson, 1988). The location of carbonate sedimentation is therefore influenced more by the tectonic framework of a region rather than its climate, as this controls the influx rate of terrigenous material (Nelson, 1988).

Non-tropical carbonates are usually constructed entirely of skeletal grains made up of taxa such as bryozoans, bivalves, barnacles, calcareous red algae and benthic foraminifera (Nelson, 1988). The depositional settings for temperate carbonates tend to be deep, unrimmed open shelves, ramps and platforms, and these carbonates may form in stable or unstable tectonic settings where water circulation is open and typically strongly storm and/or tidal current dominated (Nelson, 1988). Overall, temperate carbonates tend to have rather slow accumulation rates (<5 cm/kyr) compared to tropical carbonates (10-100 cm/kyr) (Nelson, 1988).

Temperate carbonates often have different mineralogical and geochemical properties than tropical carbonates which, in association with low carbonate sedimentation rates, produce a very different response to diagenetic processes (Table 1.1) (Smith and Nelson, 2003). Early diagenetic sea floor alteration in temperate environments is often destructive resulting in the alteration or dissolution of carbonate grains, particularly aragonitic ones. Alteration or dissolution leads to loss of grain structure, reduction in grain size and removal of grains (Smith and Nelson, 2003). Such destructive diagenesis reinforces the typically low carbonate accumulation rates for temperate shelf carbonates. Most tropical carbonates have high sedimentation rates resulting in the rapid burial of skeletal material and avoidance of prolonged exposure to potentially destructive sea floor processes (Smith and Nelson, 2003). Slow temperate carbonate precipitation, cementation and sedimentation results in slow burial of skeletal material and exposure to the destructive physical, chemical and biological processes of the seafloor zone for possibly hundreds to thousands of years (Smith and Nelson, 2003).

Table 1.1: Comparison between temperate and tropical carbonates (from Nelson et al., 1988).

TEMPERATE SHELF CARBONATES	TROPICAL SHELF CARBONATES
Unrimmed shelves	Rimmed shelves
High energy	High to low energy
Absence of hermatypic reefs (polewards of 30°N and 30°S)	Common hermatypic coral reefs (from 30°N to 30°S)
Cool water (10-18°C)	Warm water (>22°C)
Saturated to undersaturated	Saturated to supersaturated
Absence of non-skeletal grains	Common non-skeletal grains (ooids, aggregates)
Heterozoan skeletal types	Photozoan skeletal types
Bryozoans, echinoderms, bivalve molluscs, benthic and planktic foraminifera	Corals, calcareous green algae, molluscs, benthic foraminifera
Gravel and sand textures dominate	Sand and mud textures dominate
Minor carbonate mud	Abundant carbonate mud
Destructive sea-floor diagenesis	Constructive sea-floor diagenesis
Low- and intermediate-Mg calcite mineralogy	Aragonite and high-Mg calcite mineralogy
Typically low accumulation rates (<10cm/ky)	Typically high accumulation rates (>10cm/ky)

Modern shelf sediments about New Zealand consist mostly of terrigenous sands and muds with minimal carbonate material. This is a consequence of the active tectonic setting of the country athwart the Pacific-Australian convergent plate boundary and the associated volcanism, earthquakes, rapid uplift and rapid erosion producing high influx rates of terrigenous detrital sediments (Carter, 1975; Griffiths and Glasby, 1985). There are, however, portions of the New Zealand shelf which include significant areas of skeletal carbonate sedimentation, such as the Three Kings platform (Hancock, 1980; Nelson *et al.*, 1982), North Kaipara shelf (Payne *et al.*, 2010; Payne, 2010), Hauraki Gulf (Smith, 1992), Wanganui shelf (Gillespie and Nelson, 1996; Gillespie, 1992) and the Snares platform in the South Island (Head, 1985) (Figure 1.1A and B). Skeletal carbonate sedimentation is attributed to factors such as a low influx rate of terrigenous material, the presence of gravelly or rocky substrates for sessile organism attachment, and nutrient rich upwelling currents (Carter, 1975). Recent studies conducted by the National Institute of Water and Atmosphere Research (NIWA) have identified in their Bay of Islands OS 20/20 Survey Reports that the surficial sediments on the northeastern Northland continental shelf include also an often substantial carbonate component ranging widely from a few to almost 100%, with moderate values (30-60% $CaCO_3$) being typical. This deems the northeastern Northland continental shelf as appropriate to include as another area in New Zealand waters that exemplifies temperate carbonate sedimentation attributes. In this case, however, we are dealing with a range of mixed terrigenous-carbonate to purer carbonate sediments forming in a warm temperate shallow marine setting.

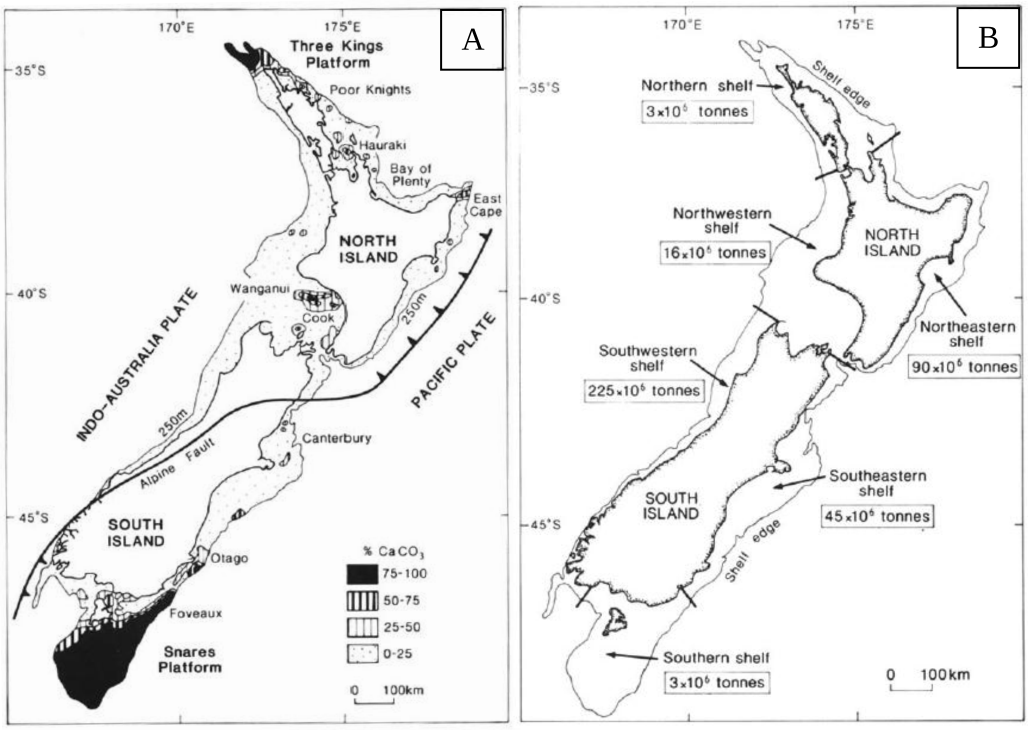


Figure 1.1: Percentage calcium carbonate distribution in surficial bottom sediments on the New Zealand shelf and uppermost slope (<250 m depth) (A), and estimates of total river borne sediment load delivered each year to six major regions of the New Zealand continental shelf (B) (from Nelson *et al*., 1988).

1.2 AIMS OF STUDY

This study utilises archived and recently collected sediment samples and seabed geophysical data to determine the nature, distribution and origin of the skeletal material contributing to the mixed terrigenous-carbonate deposits mantling the sea floor off northeastern Northland. The study area covers a distance of 150 km on the northeastern shelf of Northland between Ngurauru Bay in the south and Tom Bowling Bay at North Cape out to depths of about 210 m (Figure 1.2). For convenience, the area is referred to as the northeastern Northland continental shelf, abbreviated throughout this study as NNCS. The NNCS is divided into northern and southern sectors, but occasionally the central sector is referred to which overlaps both northern and southern sectors (Figure 1.2).

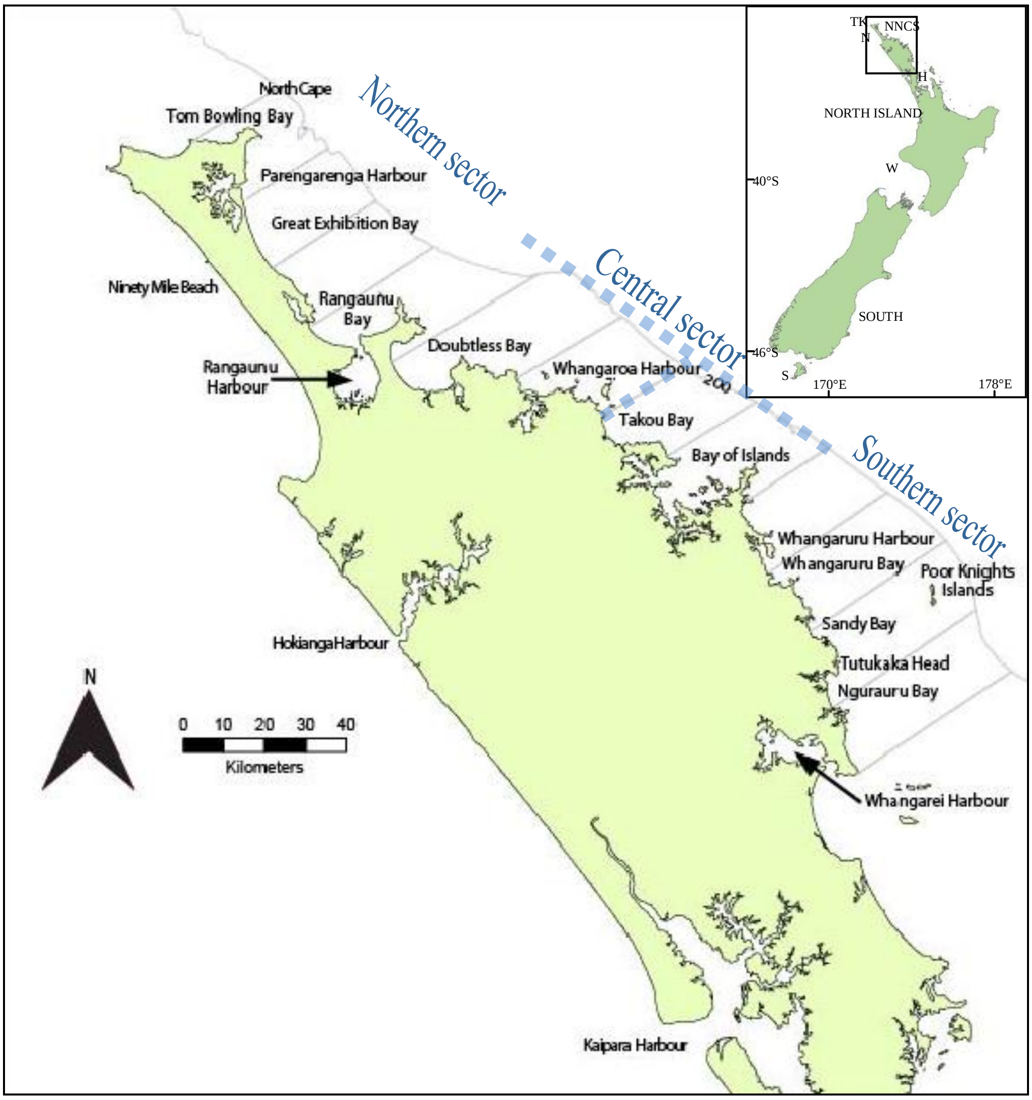


Figure 1.2: Northeastern Northland continental shelf (NNCS) region (hatched area) showing locality names of bordering bays and harbours. For ease of regional reference in this study the NNCS is divided into northern and southern sectors, and sometimes a central sector is also distinguished which effectively is the overlap zone of the northern and southern sectors. Inset abbreviations are TK – Three Kings; NK – North Kaipara; HG – Hauraki Gulf; W – Wanganui; S – Snares.

The main aims of this study are as follows:

1. Summarise existing knowledge of the sedimentary-biological-oceanographic system or environment for the NNCS.

2. Map the distribution of the textural and carbonate compositional content of the surficial sediments over the NNCS and determine the proportions of the main skeletal taxonomic groups (whole or fragmented) and, where possible, the species responsible for this carbonate fraction. Produce relevant lithofacies and/or biofacies maps for the NNCS, or for parts of it.

3. Determine the bulk mineralogy of sediment samples, with special attention to the nature of the carbonate mineral types (i.e. low-, intermediate- and high-Mg calcite, and aragonite).

4. Describe any early diagenetic sea floor alteration features affecting the skeletal material, such as abrasion, bioerosion (macro- and microscale) and dissolution.

5. Use shell preservation condition/colour and bathymetrically misplaced species to distinguish between modern and relict carbonate sediment.

6. In light of the above, interpret the origin(s) and significance of the skeletal carbonate fraction on the NNCS (e.g. *in situ*, transported/reworked, carbonate factories/sources, dispersal routes, age(s), fate), and develop a schematic sedimentary facies model (or models) to account for the carbonates.

7. Compare outcomes with available information for the carbonate shelf deposits from other North Island shelves, including Hauraki Gulf, Three Kings platform, north Kaipara continental margin and Wanganui shelf. Conclude by highlighting those aspects that have particular relevance to advancing our understanding of modern and ancient (mixed terrigenous) cool-water carbonate sedimentation in general.

1.3 THESIS FORMAT

Chapter 2 of this thesis describes the northeastern Northland study area including the onland geology, geomorphology, oceanography, ecology and seabed substrates. Chapter 3 describes the sample locations and the methods of sample collection and laboratory analysis. Chapters 4, 5 and 6 discuss the sediment texture, the bulk sediment composition and mineralogy, and the skeletal types (including preservation and carbonate mineralogy) on the NNCS respectively. Chapter 7 discusses and interprets these descriptions and is divided into the controls on sedimentation on the NNCS, the interpretation of skeletal carbonates (including preservation and sediment ages and a comparison of the skeletal types to the modern ecology), a sedimentary facies model for the NNCS, and wraps up with a summary of temperate carbonate sedimentation (which includes a comparison of the NNCS to a temperate carbonate textural sedimentation model and other North Island occurrences and the place of the NNCS in the temperate carbonate model). Chapter 8 ends the thesis with the main conclusions and suggestions for further research.

Chapter 2

STUDY AREA

2.1 ONLAND GEOLOGY

2.1.1 Generalised geology of Northland

The Northland region is a largely tectonically stable part of New Zealand so there are relatively low levels of terrigenous sediment input to the coastline. At ~1.2 Mt yr^{-1}, the eastern Northland region has one of the lowest suspended riverine sediment inputs in New Zealand due to its low relief and small catchment sizes (Hicks and Shankar, 2003). This potentially sets up prime conditions for carbonate sedimentation in the offshore northeastern Northland region.

The Northland peninsula is part of the NW-SE trending Reinga Ridge (Figure 2.1) which was part of the Gondwana margin that spilt away from the supercontinent in the Late Cretaceous (Herzer *et al*., 1995). A very generalised onland geology map of northern Northland is shown in Figure 2.2.

Basement rocks (Figure 2.2.) are potentially of Late Triassic and Jurassic age, although locally include some Permian strata. Often simply referred to as Mesozoic basement rocks, within the NNCS they include the Mount Camel Terrane and Waipapa Terrane of indurated sandstone and siltstone, typically greywacke and argillite, and local submarine basalt and basaltic andesite lavas (Hayward, 1993; Issac *et al*., 1994; Issac, 1996; Herzer *et al*., 1997).

In the Late Cretaceous and Paleogene, a passive margin flanked both sides of the landmass now incorporating the Northland peninsula (Isaac *et al.*, 1994). The Oligocene was characterised by the opening of South Fiji Basin followed, in the Late Oligocene and Early Miocene, by mass subsidence of almost the whole Northland region to bathyal depths (Hayward et al, 1989; Herzer, 1993).

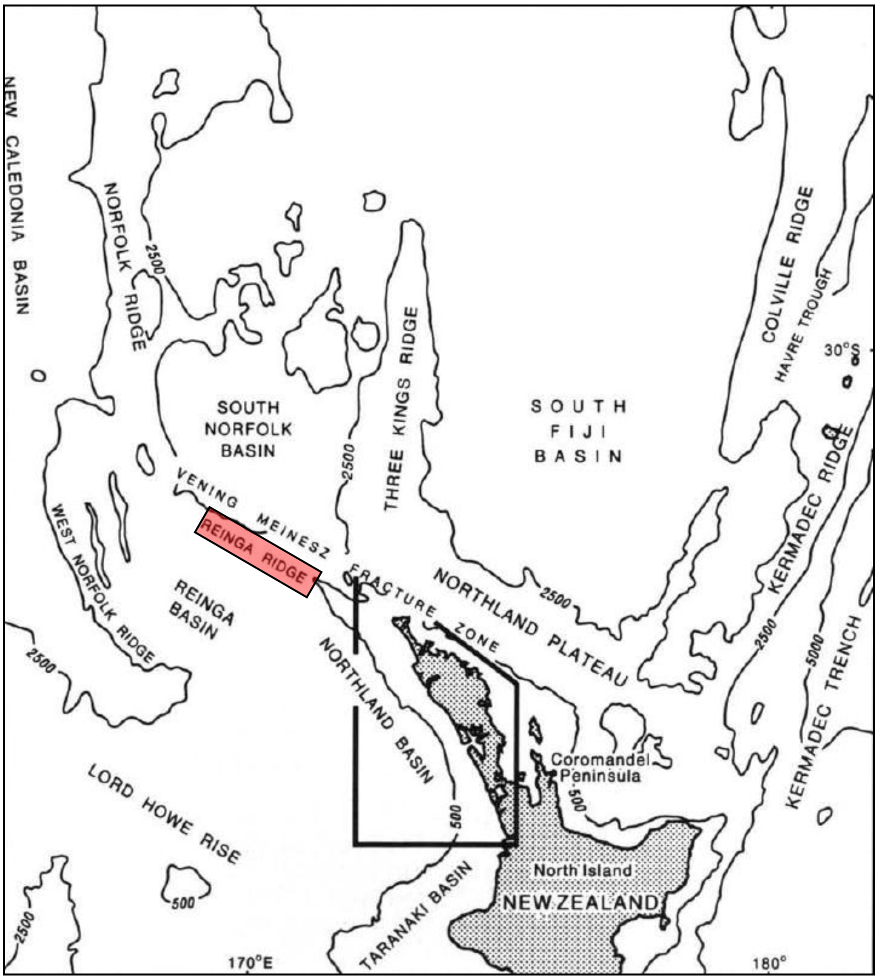


Figure 2.1: Main physiological features of northern New Zealand (from Herzer et al., 1995)

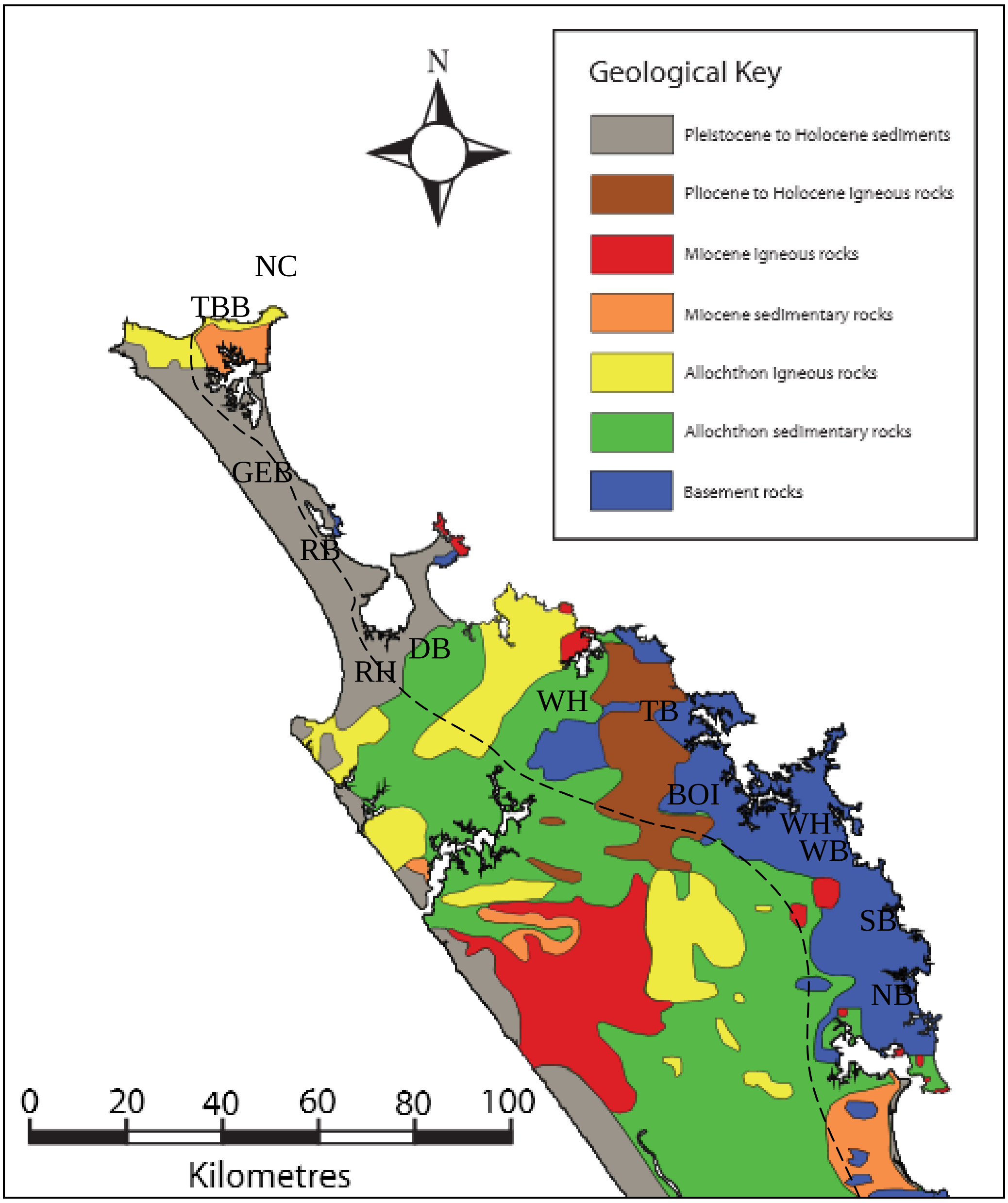


Figure 2.2: Generalised onland geology of the northern Northland region (modified from Issac et al., 1994; Isaac, 1996; Rait, 2000; Edbrook, 2001; Spörli and Harrison, 2004). Boundaries are approximate only. Details of the lithologies involved are included in text. The dashed line approximately delineates the catchment divide between west and east flowing rivers (or streams), the latter providing the main source rock geology for the offshore NNCS sediments.

The Northland Allochthon (Figure 2.2) was formed in the earliest Miocene by the obduction onto Northland of the offshore northeastern sedimentary continental margin and adjoining oceanic crust (Ballance and Spörli, 1979; Brothers and Delaloye, 1982; Hayward *et al.*, 1989; Herzer and Isaac, 1992). Its present surface and subsurface distribution is outlined in Figure 2.3. The Northland Allochthon formations (Allochthon igneous and sedimentary rocks in Figure 2.2) consist of very deformed and faulted units ranging in age from Early Cretaceous to earliest

Miocene. They are grouped into four complexes - the sedimentary Tupoa, Mangakahia and Motatau Complexes and the igneous Tangihua Complex (Issac *et al*., 1994). The Early Cretaceous Tupoa Complex comprises conglomerate, pebbly sandstone, sandstone, interbedded sandstone and mudstone found only in exposures along the northeastern Northland coastline (Hayward, 1993; Issac *et al*., 1994; Issac, 1996). The Late Cretaceous to Eocene Mangakahia Complex consists of terrigenous sediments with minor amounts of limestone and chert (Hayward, 1993; Issac *et al*., 1994). The Early Eocene to earliest Miocene Motatau Complex comprises carbonate-rich rocks, while the Early Cretaceous to Paleocene Tangihua Complex consists of submarine basaltic lava and basalt, dolerite and gabbro intrusives (Issac *et al*., 1994; Issac, 1996; Edbrooke, 2001).

The Miocene sedimentary rocks (Figure 2.2) belong in three groups, the Waitemata Group, the Otaua Group and the Parengarenga Group. The Early Miocene Waitemata Group and the Early Miocene Otaua Group occur only in southern and western Northland and consist of conglomerate, sandstone, siltstone and mudstone sourced from the Northland Allochthon and Waitakere Volcanic Arc sediments (Figure 2.2). The Parengarenga Group consists of bathyal calcareous mudstone, muddy sandstone, conglomerate and pebbly sandstone sourced from the Mount Camel Terrane and the Waitakere Volcanic Arc deposits (Hayward, 1993; Issac *et al*., 1994).

The earliest Miocene obduction across Northland was partly overlapped and followed by the introduction of calcalkaline volcanism which increased in the Early Miocene along the length of the Northland peninsula, forming the Miocene igneous rocks (Figure 2.2 and 2.3) (Hayward, 1993). Based on geological and geophysical observations two parallel NW-SE trending belts of Miocene calcalkaline volcanoes occur on each side of the Northland peninsula (Figure 2.3). Evidence for these volcanoes lies buried on land mostly in the western belt, while the eastern belt has largely been eroded away (Herzer *et al*., 1995). At least fifty volcanic centres have been identified on seismic profiles and one of particular significance to the present study is the major Whangaroa Volcanic Centre in the northeast of the peninsula (Figure 2.3).

The Pliocene and Holocene igneous rocks (Figure 2.2) are sourced from the basaltic Kerikeri Volcanics and consist of monogenetic scoria cones and lava flows within the Kaikohe-Bay of Islands and Puhipuhi-Whangarei fields (Issac *et al*., 1994; Edbrooke, 2001). The Pleistocene and Holocene sediments (Figure 2.2) in the study area belong in the Pliocene to Early Pleistocene aged Awhitu Group and the Pleistocene to Holocene aged Karioitahi Group. The Awhitu Group mainly comprises moderately to poorly consolidated quartzofeldspathic sandstone (Issac *et al*., 1994; Issac, 1996; Edbrooke, 2001). The Karioitahi Group comprises moderately consolidated to unconsolidated coastal dune, swamp, fluvial and lacustrine deposits (Issac *et al*., 1994; Issac, 1996; Edbrooke, 2001).

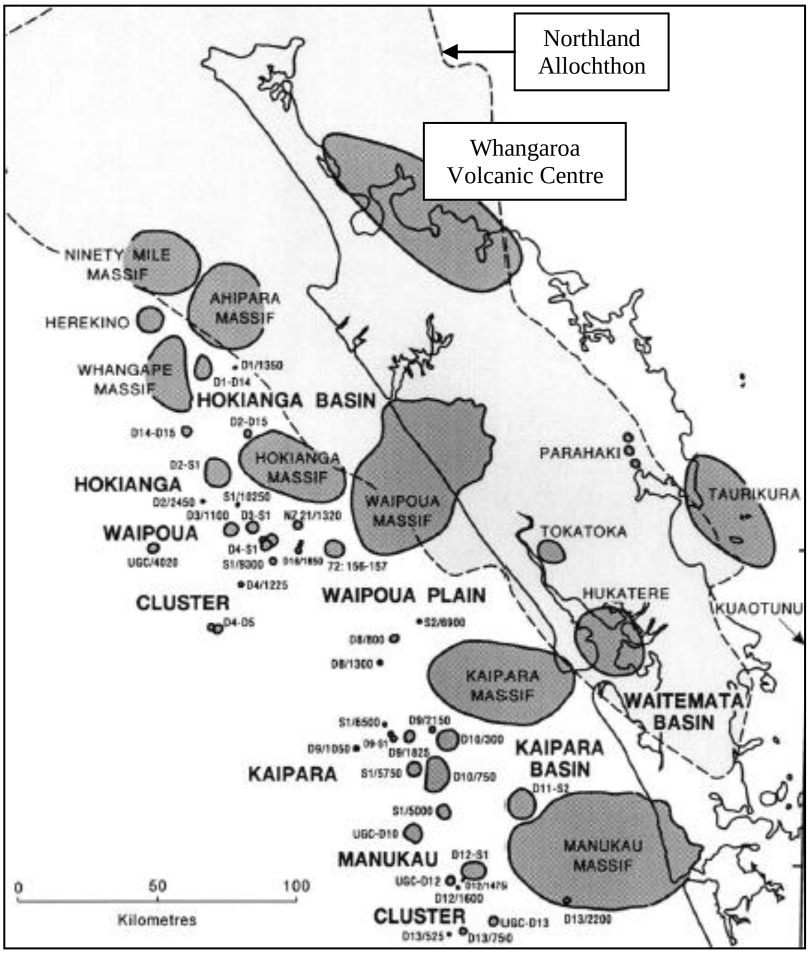


Figure 2.3: Map showing the distribution of basaltic (to andesitic) volcanic centres in and offshore Northland peninsula (from Herzer et al., 1995). Note the extensive distribution of volcanics in the northeast, forming the Whangaroa Volcanic Centre. The dashed line outlines the present extent of the earliest Miocene Northland Allochthon.

2.1.2 Geology on the northeastern side of Northland peninsula

The geology of significance on the northeastern side of Northland is shown by a catchment divide line in Figure 2.2. The geology will be described from north to south along the study area, while the lithology of the rock types are mentioned in the previous section. The northernmost sector in and around Tom Bowling Bay at North Cape comprises Miocene sedimentary rocks and Northland Allochthon igneous rocks. The Miocene sedimentary rocks belong in the Parengarenga Group and include the Tom Bowling Formation at North Cape (Hayward, 1993; Issac *et al*., 1994).

Pleistocene and Holocene sediment dominates the onland stretch from Parengarenga Harbour to Doubtless Bay. Great Exhibition Bay, with postulated uplift rates as high as 0.3 mm yr^{-1} (Pillans, 1990), is bounded by uplifted Pleistocene marine terraces. Ricketts (1979) was of the opinion that the quartz-rich sand in Great Exhibition Bay originated from reworked Pleistocene deposits.

Pliocene to Holocene igneous rocks, Miocene igneous rocks and Allochthon igneous rocks are all found within the Whangaroa Volcanic Centre from Rangaunu Bay to Whangaroa Harbour. Pleistocene to Holocene igneous rocks occur in the catchment area between Whangaroa Harbour and Bay of Islands. Miocene igneous rocks are present between Rangaunu and Doubtless Bay, and in Whangaroa Harbour. Allochthon igneous rocks occur in the southern Doubtless Bay area and also Tom Bowling Bay area at North Cape.

The earliest Miocene Northland Allochthon deposits of importance comprise the Early Cretaceous Tupoa Complex with outcrops occurring only in Doubtless Bay and Whangaroa Harbour.

Mesozoic basement rocks are prominent in the catchment area between Whangaroa Harbour in the north, through to Whangarei Harbour in the south.

Overall, northeastern Northland geology consists mainly of Pleistocene to Holocene sediments in the northern sector, a mixture of earliest Miocene Northland Allochthon and Miocene sedimentary and volcanic rocks in the central sector, and Mesozoic basement rocks in the southern sector. Pleistocene to Holocene sediments in the northern sector consist of unconsolidated coastal dune sands belonging to the Karioitahi Group (Issac *et al*., 1994; Issac, 1996; Edbrooke, 2001). In the central sector, the earliest Miocene Northland Allochthon rocks consist mostly of the Early Cretaceous Tupoa Complex comprising conglomerate, pebbly sandstone, sandstone, and interbedded sandstone and mudstone (Hayward, 1993; Issac *et al*., 1994; Issac, 1996). The Miocene rocks in the central sector contain only the Parengarenga Group comprising bathyal calcareous mudstone, muddy sandstone, conglomerate and pebbly sandstone sourced from the Mount Camel Terrane and the Waitakere Volcanic Arc deposits (Hayward, 1993; Issac *et al*., 1994). In the southern sector the Mesozoic basement rocks comprise indurated sandstone and siltstone, typically greywacke and argillite, and local submarine basalt and basaltic andesite lavas (Hayward, 1993; Issac *et al*., 1994; Issac, 1996; Herzer *et al*., 1997).

2.2 GEOMORPHOLOGY

2.2.1 Coastline morphology

The northeastern Northland study area covers a north to south distance of 150 km and has an irregular shape due to the many bays and harbours along the coastline (Figure 2.4).

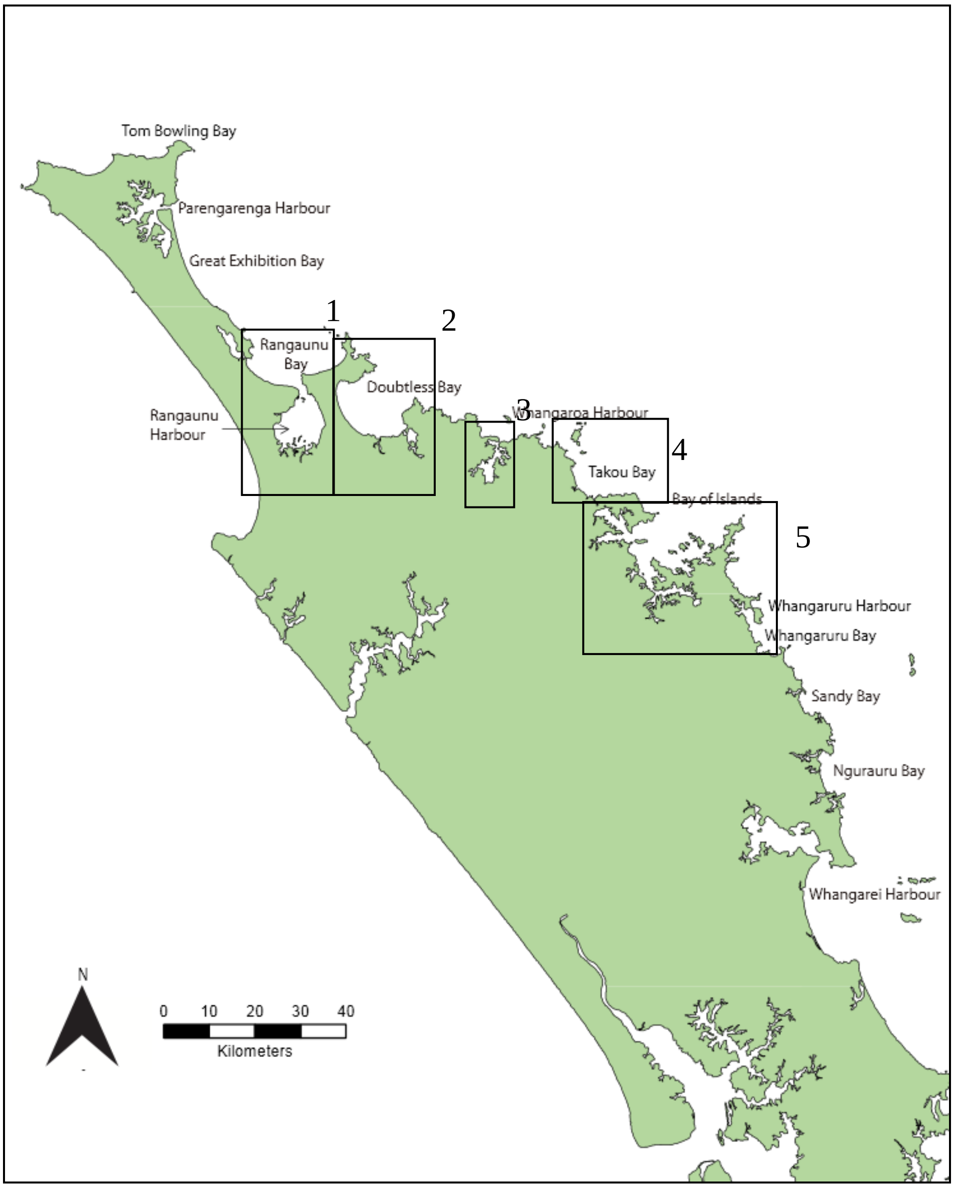


Figure 2.4: The NNCS showing locality names of bordering bays and harbours and locations (blocks 1-5) of the main bays and harbours with fresh water inputs (see Table 2.1).

In the northern sector of northeastern Northland the main harbours are Parengarenga Harbour, Rangaunu Harbour and Whangaroa Harbour (Figure 2.4). Parengarenga Harbour has an area of about 63 km^2 and receives an annual fresh water runoff of 7 m^3 s^{-1} (Table 2.1) (Heath, 1976d). The beach and dune sands around Parengarenga Harbour and most of Great Exhibition Bay consist of fine grained white sands referred to by Schofield (1970) as the 'Parengarenga Sand Facies'. These sands are well sorted and silica rich (95%) and are thought to be derived from either the podzolisation of soils in the catchment (Schofield, 1970) or from reworked older Pleistocene deposits (Ricketts, 1979). Rangaunu Harbour (Figure 2.5) is a shallow estuary which has a surface area of 97 km^2 and an average annual fresh water input of 8 m^3 s^{-1}, mainly from the Awanui River (Table

2.1) (Heath, 1976d; Pickrill, 1986). Whangaroa Harbour (Figure 2.6) is adjacent to Stephenson Island and houses many smaller bays and inlets as well as two smaller islands called Ohauroro Island and Milford Island. The Kaeo and Pupuke Rivers drain into Whangaroa Harbour with an average annual inflow 7 m^3 s^{-1} (Table 2.1) (Heath, 1976d).

Figure 2.5: Rangaunu Harbour (locality shown in block 1 in Figure 2.4) (Modified from http://maps/google.com).

Figure 2.6: Whangaroa Harbour (locality shown in block 3 in Figure 2.4). (Modified from http://maps/google.com).

The main bays in the northern sector are Tom Bowling Bay, Great Exhibition Bay, Rangaunu Bay, Doubtless Bay and Whangaroa Bay (Figure 2.4). Great Exhibition Bay is a long, straight coastal section with no freshwater river input. Rangaunu Bay and Doubtless Bay both have relatively enclosed morphologies. Rangaunu Bay has essentially no freshwater input while Doubtless Bay (Figure 2.7) has freshwater discharge from two rivers, the Oruru River which flows into Taipa Bay, and the Oruaiti River which flows into Mangonui Harbour within Doubtless Bay. The average annual freshwater inflow into Doubtless Bay is estimated at 2 $m^3 s^{-1}$ (Table 2.1) (Heath, 1976d).

Figure 2.7: Doubtless Bay (locality shown in block 2 in Figure 2.4). (Modified from http://maps/google.com).

Figure 2.8: Takou Bay (locality shown in block 4 in Figure 2.4). (Modified from http://maps/google.com).

The southern sector of the northeastern Northland coast is bordered by rugged hills due to the presence of highly deformed greywacke bedrock resulting in a coastline that is rocky, steep and very convoluted with an abundance of sea cliffs, headlands, estuaries, inlets and small bays (Gillie 1979a, b). The major bays in the southern sector are Takou Bay and the Bay of Islands. Takou Bay (Figure 2.8) is an exposed and semi-rounded bay which receives fresh water from two rivers, the Takou River and the Tahoranui River. Matauri Bay, a smaller and less significant bay with the Cavalli Islands adjacent to it, exists north of Takou Bay. The Bay of Islands (Figure 2.9) is a complex and sheltered bay which houses many islands, bays and inlets. It receives the highest average annual fresh water runoff, estimated at 46 m^3s^{-1} (Table 2.1), mainly from the Kawakawa River in the south, the Waitangi River in the west, and the Kerikeri River in the north which discharges fresh water into the Kerikeri Inlet. South of the Bay of Islands there are many smaller and less significant bays and one harbour, the Whangaruru Harbour (Figure 2.9), which receives 0.2 m^3s^{-1} average annual freshwater runoff (Table 2.1) (Heath, 1976d). Figure 2.10 summarises the annual average freshwater runoff in the main bays and harbours in the NNCS region. Clearly the Bay of Islands has much higher freshwater input annually than any of the other bays and harbours in northeastern Northland peninsula. However, even the annual freshwater input of the Bay of Islands is low when compared with the inlets of Firth of Thames at 115 m^3s^{-1}, Hawkes Bay at 438 m^3s^{-1}, Tasman Bay at 256 m^3s^{-1}, and the Waikato River which has a mean flow alone of 400 m^3s^{-1} (Heath, 1976d; Environment Waikato, 2008).

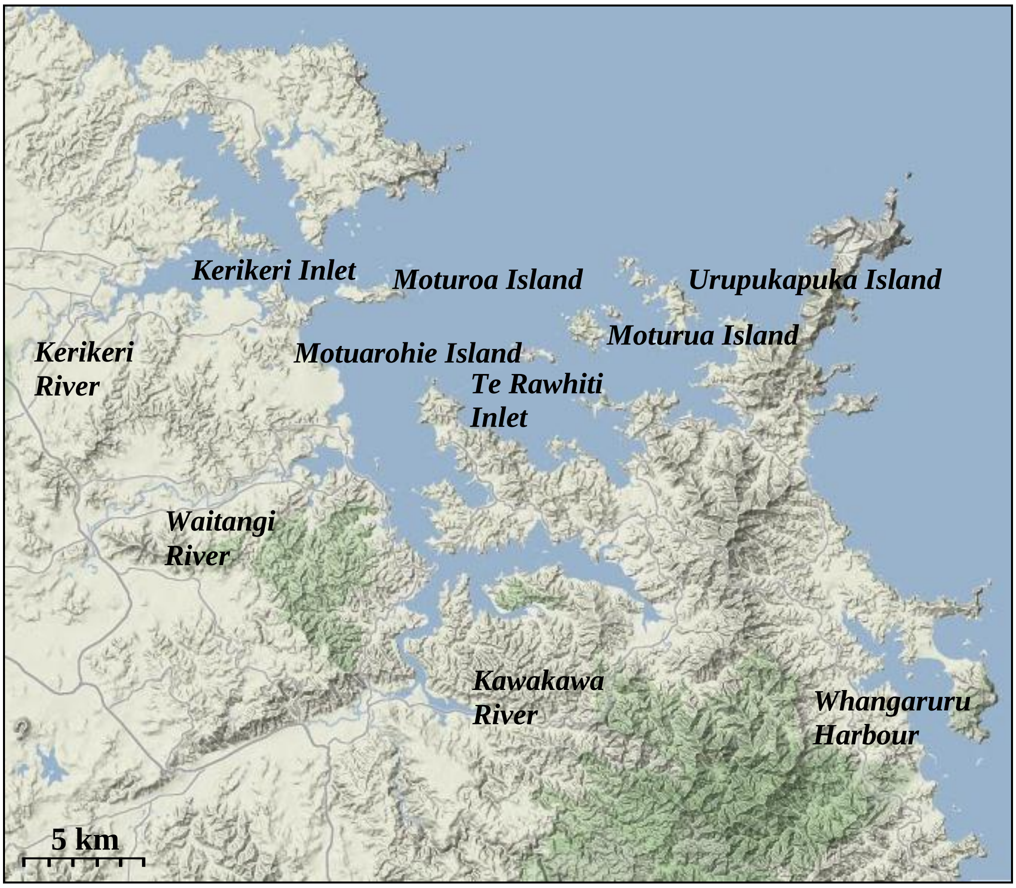


Figure 2.9: Bay of Islands and Whangaruru Harbour (locality shown in block 5 in Figure 2.4). (Modified from http://maps/google.com).

Table 2.1: Average annual freshwater runoff into the main inlets on the northeastern Northland coast (from Heath, 1976d)

Inlets	Average annual runoff (m^3s^{-1})
Parengarenga	7
Rangaunu	8
Doubtless	2
Whangaroa	7
Bay of Islands	46
Whangaruru	0.2

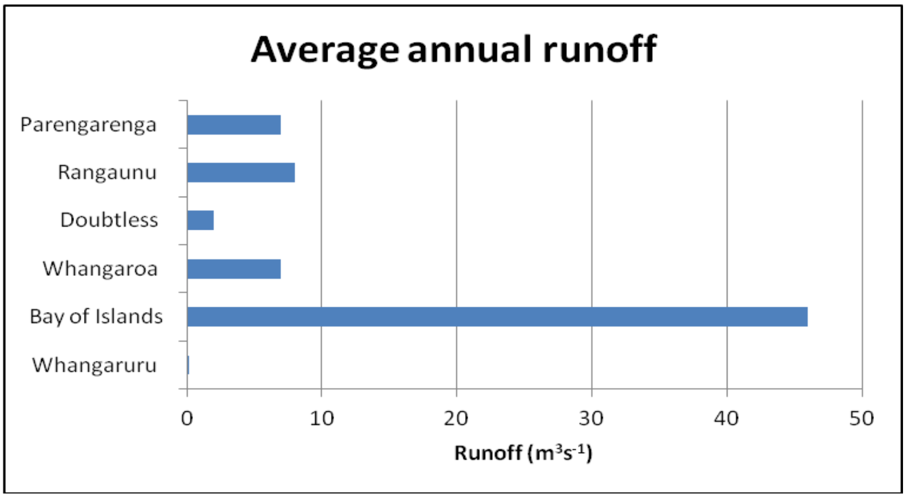


Figure 2.10: Average annual freshwater runoff into the main inlets on the northeastern Northland coast (Heath, 1976d)

2.2.2 Bathymetry and bottom profiles

The contour bathymetry off northeastern Northland was mapped by NIWA (Wellington) during the OS 20/20 Bay of Islands Coastal Survey Project from 2008 to 2010 (Figure 2.11). The bathymetric contours off northeastern Northland are relatively irregular. Beyond shelf depths in the northernmost sector the topography is rough and steep leading down to the deep slope floor. Off Parengarenga Harbour and Great Exhibition Bay are several narrow submarine canyons and small terraces at about 400 m water depth, with especially rough slope and seafloor topography. At about 400 m water depth, the largest terrace (T1 in Figure 2.11) positioned in line with Rangaunu and Doubtless Bay, appears to be a near mirror image of the bays.

The southern sector of the northeastern Northland continental margin has smoother topography and a more gradual decline down slope. Offshore from the Bay of Islands is a large terrace at 800-900 m water depth (T2 in Figure 2.11) followed by a rapid topographic drop. Another less pronounced terrace occurs adjacent to Whangaruru Bay and Harbour at about 500 m water depth (T3 in Figure 2.11). These two terraces (T2 and T3) are the main offshore morphological features in the southern sector of the northeastern Northland continental margin. A series of small banks also occur at 300-400 m water depth offshore from the Bay of Islands (B1 in Figure 2.11).

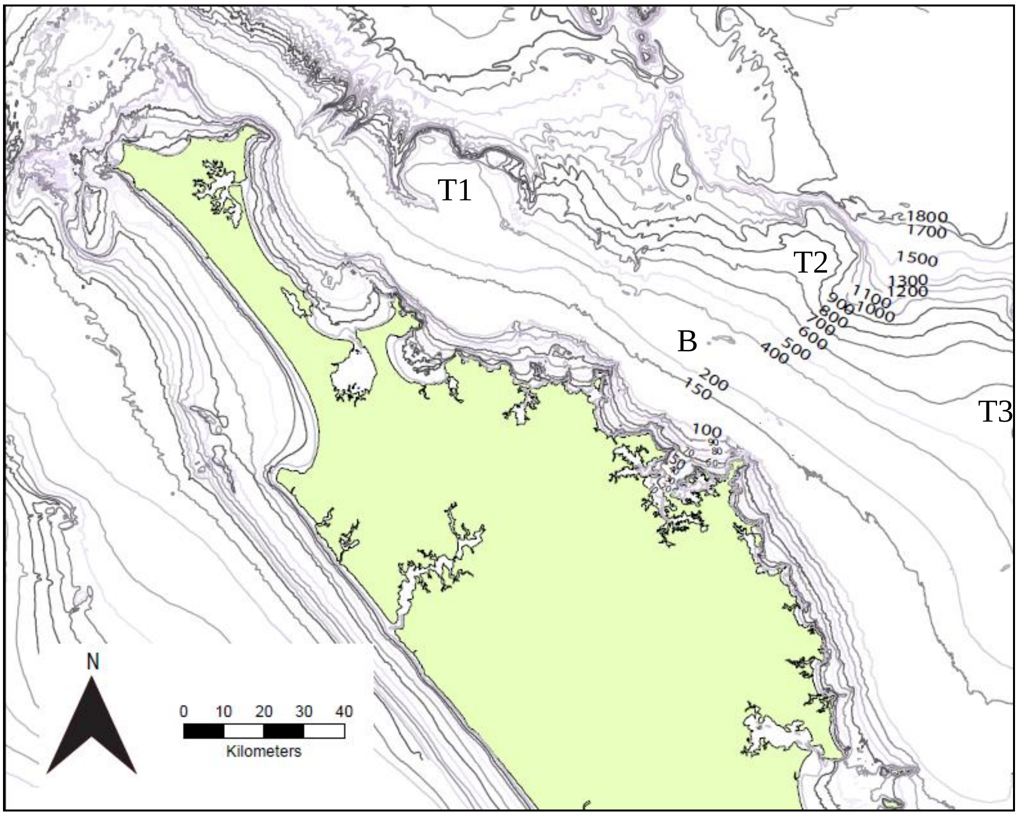


Figure 2.11: Contour bathymetry map off northeastern Northland (modified from NIWA contour data). T1, T2 and T3 are terraces and B1 is a series of banks. Note that contour lines at 300 m, 1400 m and 1600 m were not created and are not included.

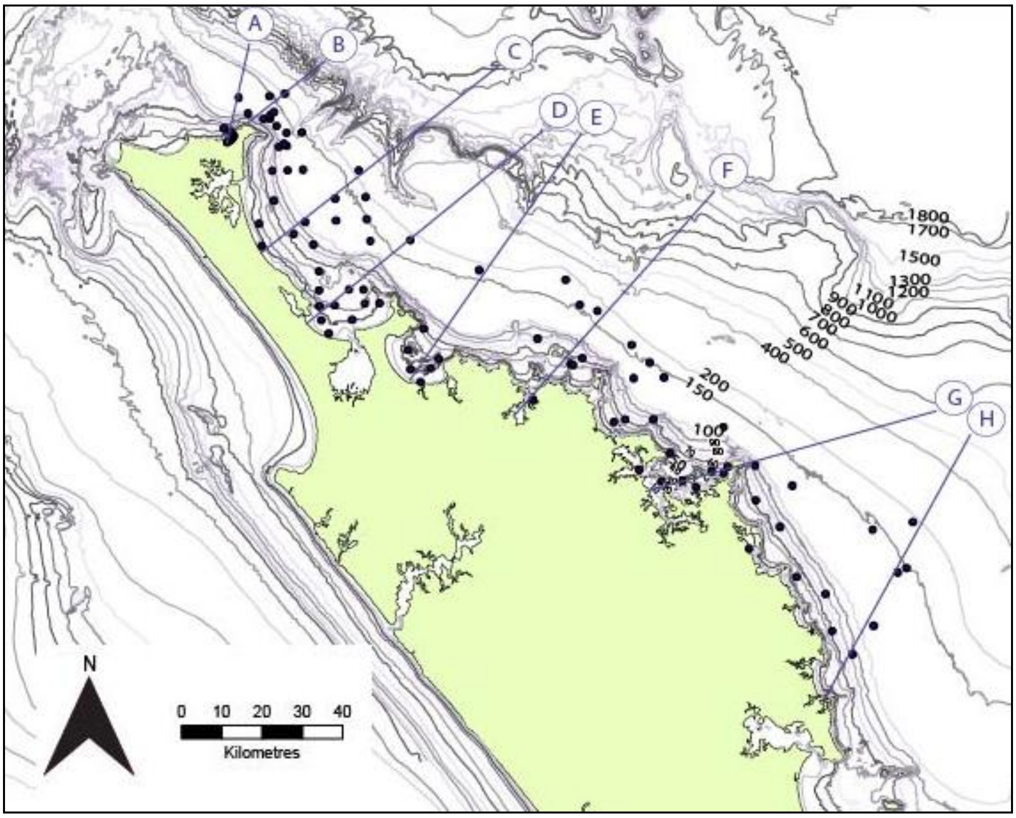


Figure 2.12: Location of 8 bathymetric transects (A-H) off northeastern Northland (see Figure 2.13 and 2.14).

Eight bathymetric profiles (A-H) have been constructed along transects off northeastern Northland (Figure 2.12) which reveal a shelf break ranging in water depth from 150 to 200 m. Bathymetric profiles A and B are located off Tom Bowling Bay and North Cape and run 25 km from the coastline out to slope depths. Bathymetric profiles C to H are located off Great Exhibition Bay, Rangaunu Bay, Doubtless Bay, Whangaroa Harbour, Bay of Islands and Nguraura Bay and all run 75 km from the coastline out to slope seafloor depths. The shelf statistics for profiles A to H, showing shelf width, shelf break, shelf gradient, and slope angle are summarised in Table 2.2.

Profile A (Figure 2.13A) has a wider shelf (18 km from the coastline) than profile B (13.5 km from the coastline) (Figure 2.13B) and also seemingly has a shallower shelf break at 150 m depth compared to profile B at 200 m depth, contributing to the much greater gradient for profile B of 14.8 m/km (Table 2.2). Both profiles show a relatively smooth shelf surface which becomes slightly depressed a few km offshore. Both have a relatively sharp shelf break and a steep slope, but in profile B the slope levels out near 800 m depth followed by another steep descent.

Profile C (Figure 2.13C) has a shelf break at about 150 m depth some 27 km offshore. The slope bathymetry is similar to that in profile B, steeply declining but interrupted by a small mound partway down slope.

Profile D (Figure 2.13D) has a wider shelf (34 km) than profile C and a shelf break at 200 m depth some 34 km from the coastline. The shelf bathymetry appears to be slightly elevated nearer shore. The slope is relatively gentle, making the shelf break difficult to determine, and only begins to rapidly steepen after 400 m depth, beyond which it is interrupted by a minor terrace level at about 700 m depth.

Profile E (Figure 2.14E) has a slightly narrower shelf by 4 km than profile D with a shallower shelf break at 150 m depth. There is a slight dip midway through the shelf with a gentle shelf break and slope which also has a slight dip in bathymetry near 600 m water depth.

Profile F (Figure 2.14F) has a wider shelf (36 km) than profile E and a gentle deeper shelf break at 200 m below sea level. The shelf has slightly raised bathymetry nearer the coastline while the slope is particularly smooth and uninterrupted.

Profile G (Figure 2.14G) off the Bay of Islands, has a very wide shelf of 44 km compared to the other profiles in the northern sector of the study area. The shelf break occurs at 200 m depth below sea level, as in profile F. The transect also interacts with land and the shelf topography is therefore uneven, although the slope topography is very smooth and gently inclined.

Profile H (Figure 2.14H) has the widest shelf of 49 km and a noticeable shelf break at 200 m depth. The shelf is slightly raised close to the shoreline and the shelf and slope have very smooth and gently inclined topography.

Table 2.2: Shelf statistics for bathymetric profiles A-H in Figure 2.12.

Shelf statistics	A	B	C	D	E	F	G	H
Shelf width (km)	18	13.5	27	34	30	36	44	49
Shelf break (m)	150	200	150	200	150	200	200	200
Shelf gradient	8.3 m/km	14.8 m/km	5.6 m/km	5.9 m/km	5 m/km	5.6 m/km	4.5 m/km	4.1 m/km
Slope angle (°)	0.48	0.85	0.32	0.34	0.29	0.32	0.26	0.23

Overall, in the northern sector of the NNCS, the topography is rougher and steeper leading down to the deep slope floor compared to that in the southern sector which is much smoother with a more gradual decline down slope (Figure 2.11). Bathymetric profiles in the northern sector of the NNCS generally have narrower shelf widths and slightly shallower shelf breaks than in the southernmost sector (Figure 2.13 and 2.14 and Table 2.2). The shelf gradients and the slope angles are highest in profiles A and B indicating a steeper shelf in the northernmost sector (Table 2.2). The shelf flattens out towards the southernmost sector as indicated by lower shelf gradients and slope angles (Table 2.2).

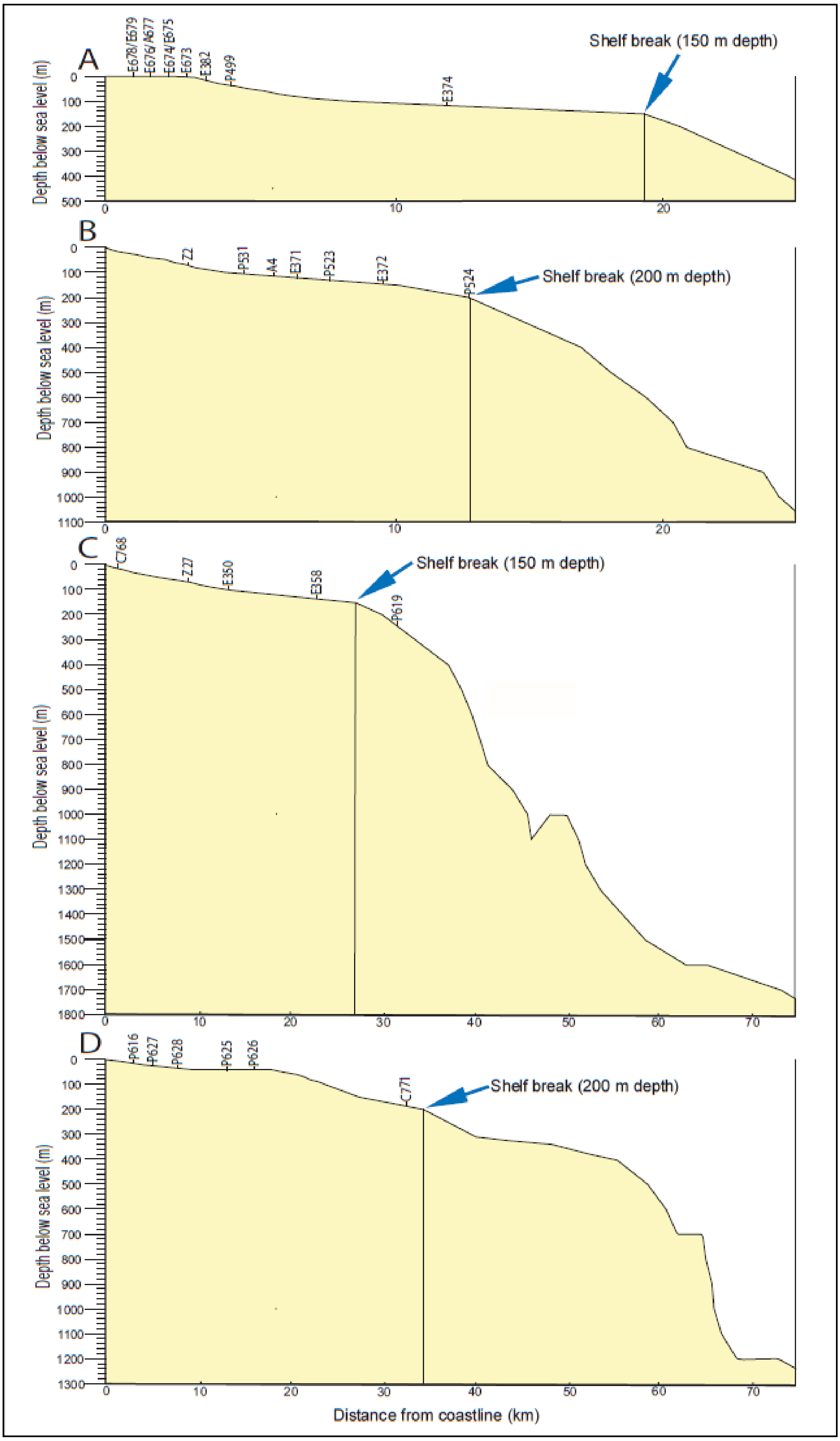


Figure 2.13: Bathymetric profiles (A-D) along transects shown in Figure 2.12. Shelf breaks estimated only.

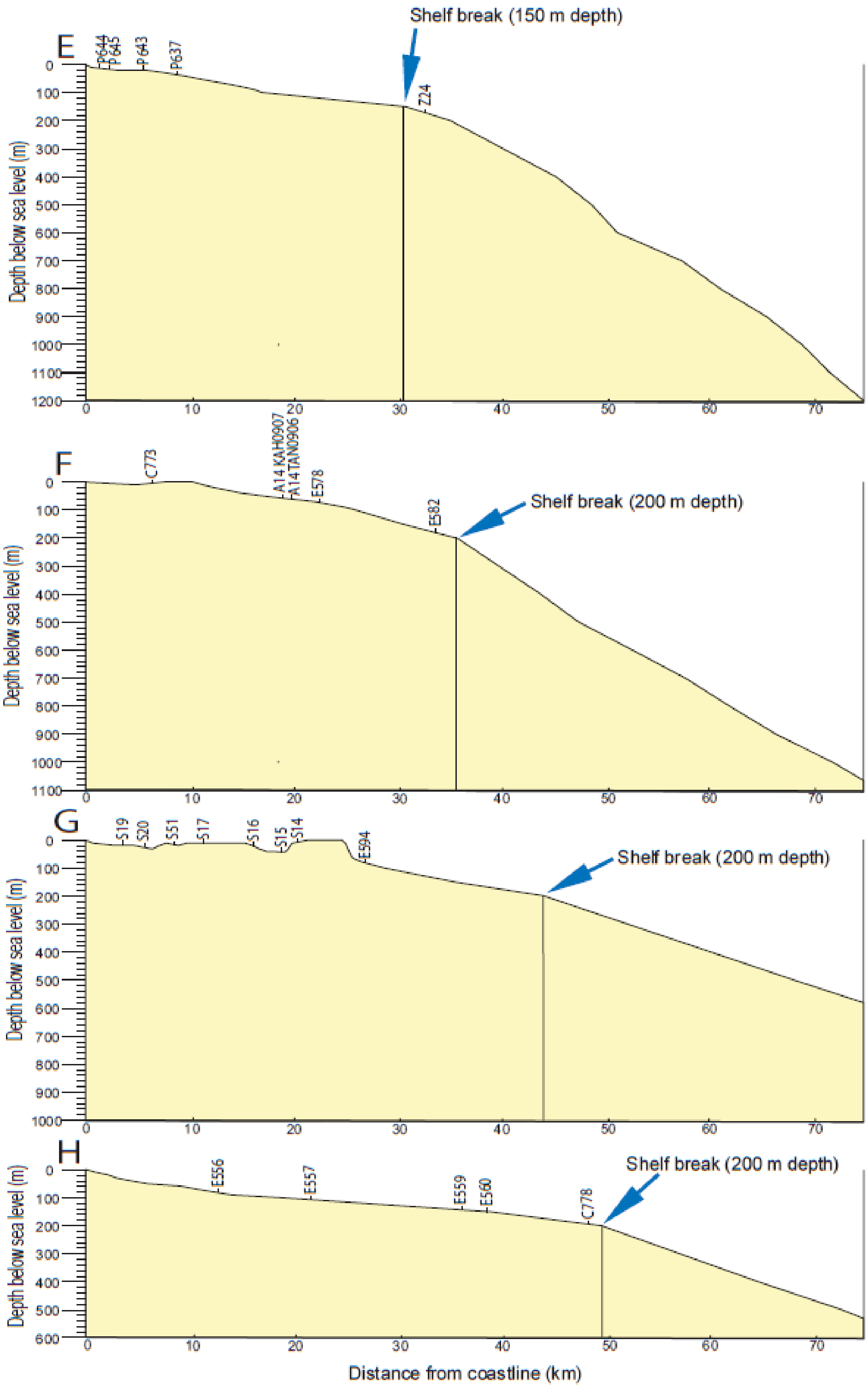


Figure 2.14: Bathymetry profiles (E-H) along transects shown in Figure 2.12. Shelf breaks estimated only.

2.3 OCEANOGRAPHY

2.3.1 Wind and wave climate

Weather systems pass across New Zealand from west to east and are associated with the northwesterly and southerly winds which blow offshore on the northern coast (Pickrill and Mitchell, 1979). However, tropical cyclones passing north of New Zealand, blocking anticyclones, and depressions moving down from the northwest all produce strong northeast winds which in turn produce northeasterly waves (Christopherson, 1977; Gillie, 1979).

These wind directions are verified in wind data from northeastern Northland (Figure 2.15) from between 2005 and 2009, as shown in wind roses in Figures 2.16 to 2.19. Purerua winds are most commonly northerlies and easterlies with the most common speeds at 2-4 ms^{-1} (Figure 2.16). Kerikeri winds come from an easterly direction with the most common speeds at 1-2 ms^{-1}. Kaikohe, being an inland observation station, often receives southwesterly winds as well as northeasterly winds with the most common speeds at 0-5 ms^{-1}. Whangarei receives northeasterly and southeasterly winds with the most common speeds at 0-2 ms^{-1}.

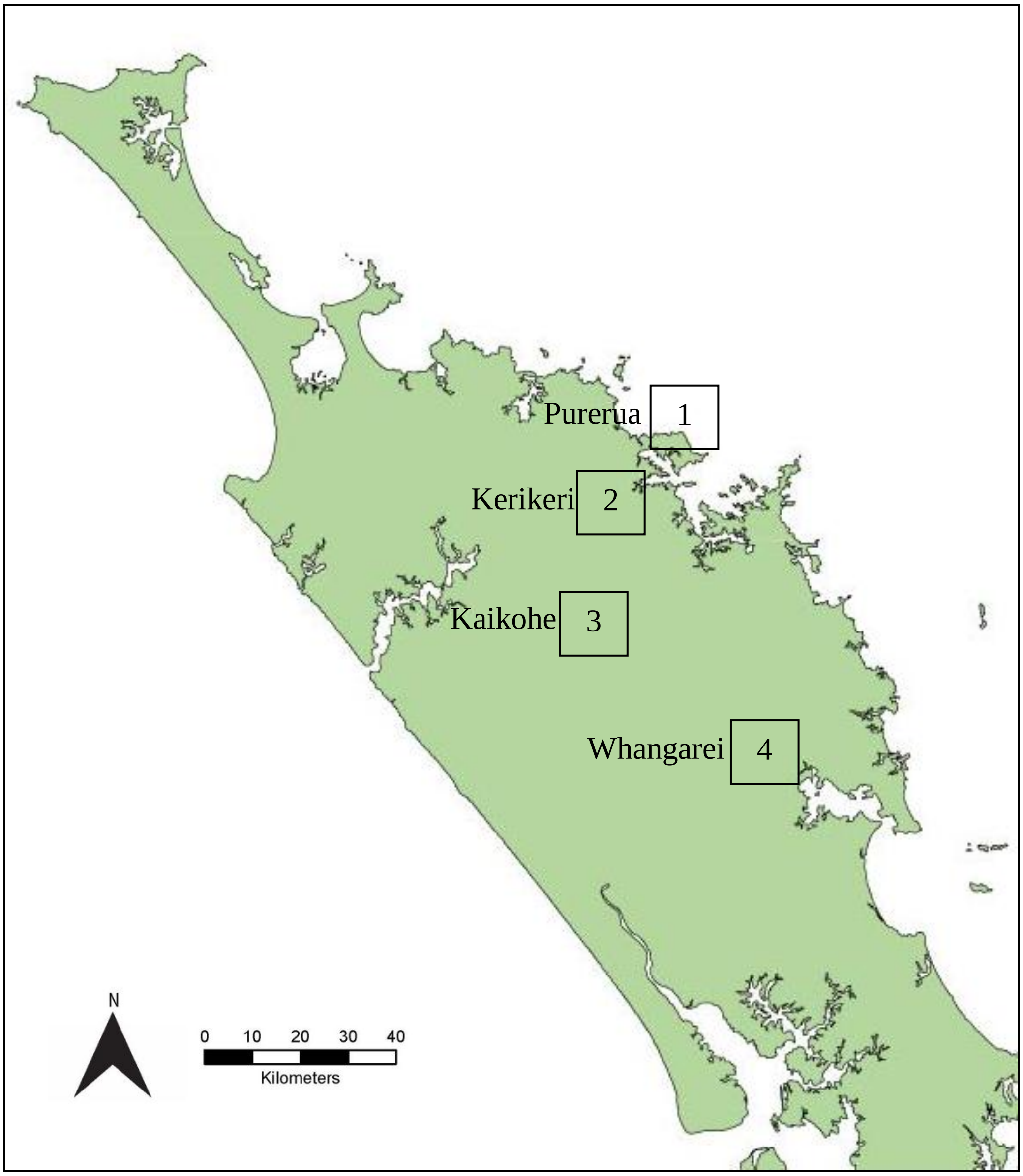


Figure 2.15: Locations of four wind observation stations in Northland. Raw data from these stations were used to construct the wind roses in Figures 2.16 to 2.19.

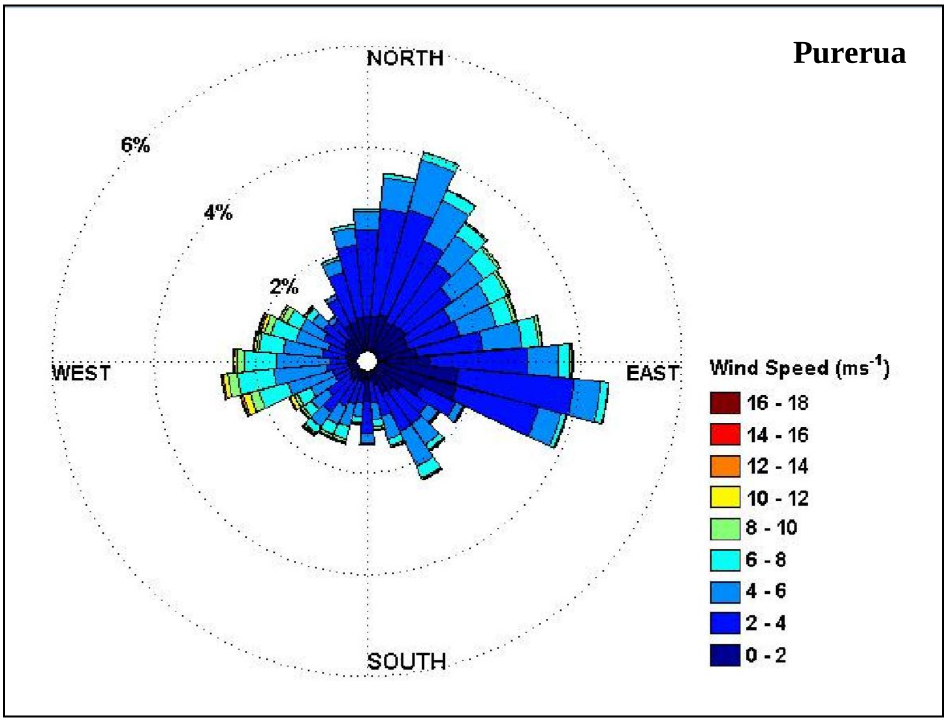


Figure 2.16: Purerua (station 1 in Figure 2.15) wind rose constructed from four years of data from 2005-2009. The wind rose shows the percent frequency of the directions surface wind came from, and the average speeds (ms-1) for each wind direction. Made using raw data from the National Climate Database, NIWA Website.

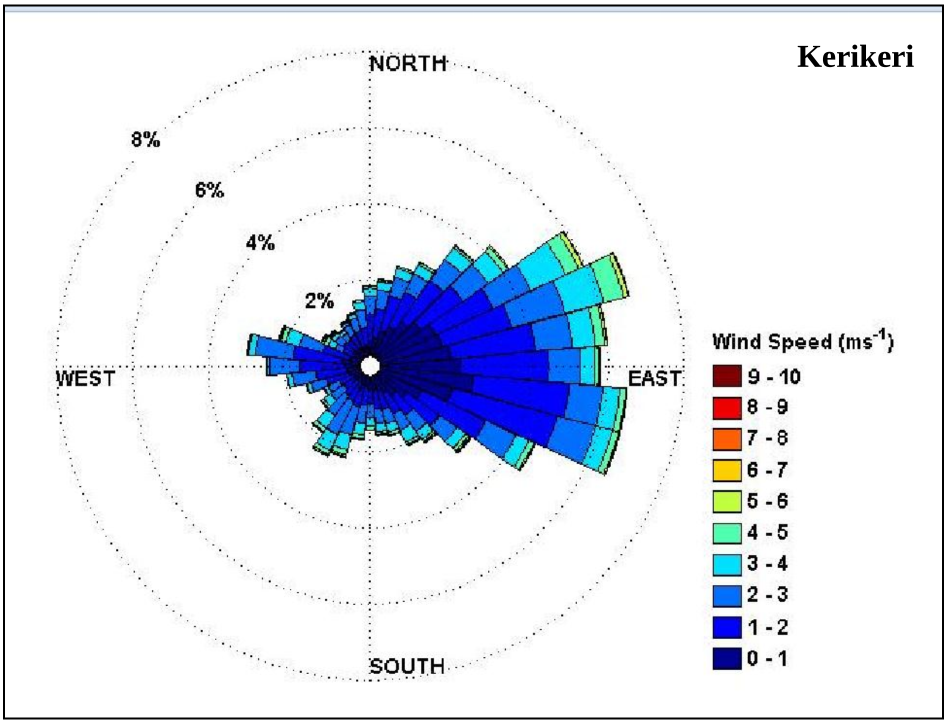


Figure 2.17: Kerikeri (station 2 in Figure 2.15) wind rose constructed from four years of data from 2005-2009. The wind rose shows the percent frequency of the directions surface wind came from, and the average speeds (ms-1) for each wind direction. Made using raw data from the National Climate Database, NIWA Website.

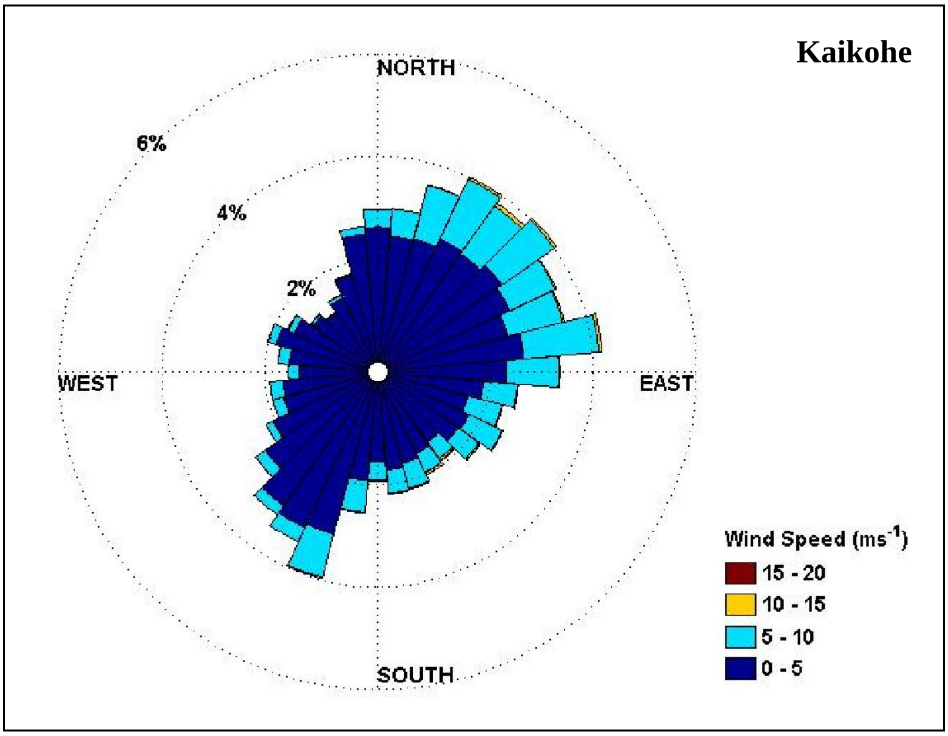


Figure 2.18: Kaikohe (station 3 in Figure 2.15) wind rose constructed from four years of data from 2005-2009. The wind rose shows the percent frequency of the directions surface wind came from, and the average speeds (ms-1) for each wind direction. Made using raw data from the National Climate Database, NIWA Website.

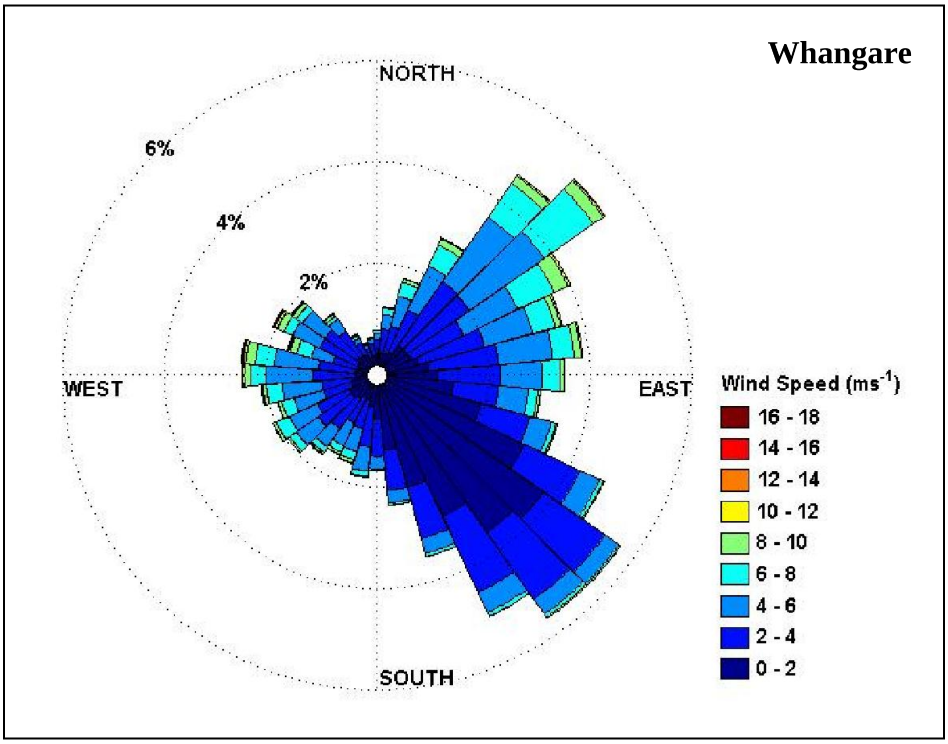


Figure 2.19: Whangarei (station 4 in Figure 2.15) wind rose constructed from four years of data from 2005-2009. The wind rose shows the percent frequency of the directions surface wind came from, and the average speeds (ms-1) for each wind direction. Made using raw data from the National Climate Database, NIWA Website.

The northeastern coast is lee shore sheltered from any prevailing westerly and southerly waves generated from weather systems passing across New Zealand, resulting in smaller wave heights than at other coastal areas of New Zealand (Pickrill and Mitchell, 1979). Wind roses (Figures 16 to 19) would suggest that waves mostly approach from a northeasterly direction. Deep water wave records from East Cape agree with this, showing the predominant approach direction to be from the north through to east with heights of 0.5-1.5 m and periods of 5-7 seconds. Wave heights observed from the beach have been estimated at 0.4-0.8 m with periods of 9-12 seconds.

2.3.2 Currents and circulation

Currents are ultimately affected by river runoff, tides and winds (Carter, 1975). On the northeastern New Zealand coast the river runoff is minor with the highest by far in the Bay of Islands with an average annual freshwater runoff of 46 m^3s^{-1} (Table 2.1 and Figure 2.10). It is therefore assumed that the currents on the NNCS will not be affected to a large extent by river run-off.

The tides are controlled by the gravitational attraction of the waters around New Zealand to the sun and the moon causing a rhythmic rise and fall of sea level noticed particularly in coastal embayments (Heath, 1982). Around the New Zealand coast the tidal currents are directed anticlockwise and are at a maximum speed at high tide (Heath, 1982). At low tide the tidal currents are directed clockwise and are at lower speeds (Heath, 1982). The phase of the main lunar and solar tides has a complete range from 0-360° in New Zealand (Heath, 1982). As a consequence, the waters around the Northland peninsula have very rapid phase changes which often result in abnormally strong tidal flows in this region with the capability of transporting sediment (Heath, 1982). The tidal flows dominate the time-averaged mean flow (Heath, 1982). This can influence the direction of the peak flow and direction of sediment transport (Heath, 1982).

In northern New Zealand the main surface current system occurs where subtropical Southwest Pacific water moves southwestwards as the Trade Wind Drift (Carter, 1975) (Figure 2.20). The major offshore oceanic current affecting the eastern side of Northland is the southeast flowing East Auckland Current which forms from the interaction of the Trade Wind Drift with northernmost New Zealand (Carter, 1975). Currents between North Cape and 35°S are relatively strong with some maximum values of about at 30 cm s^{-1} (Stanton *et al*., 1997). The outer shelf and upper slope off northeastern Northland are affected by highly variable and often moderately strong currents with speeds of 10->20 cm s^{-1} measured in the East Auckland Current (Stanton *et al*., 1997). The inner shelf is mainly affected by strong tidal currents around headlands along the coast (Summerhayes, 1969a)

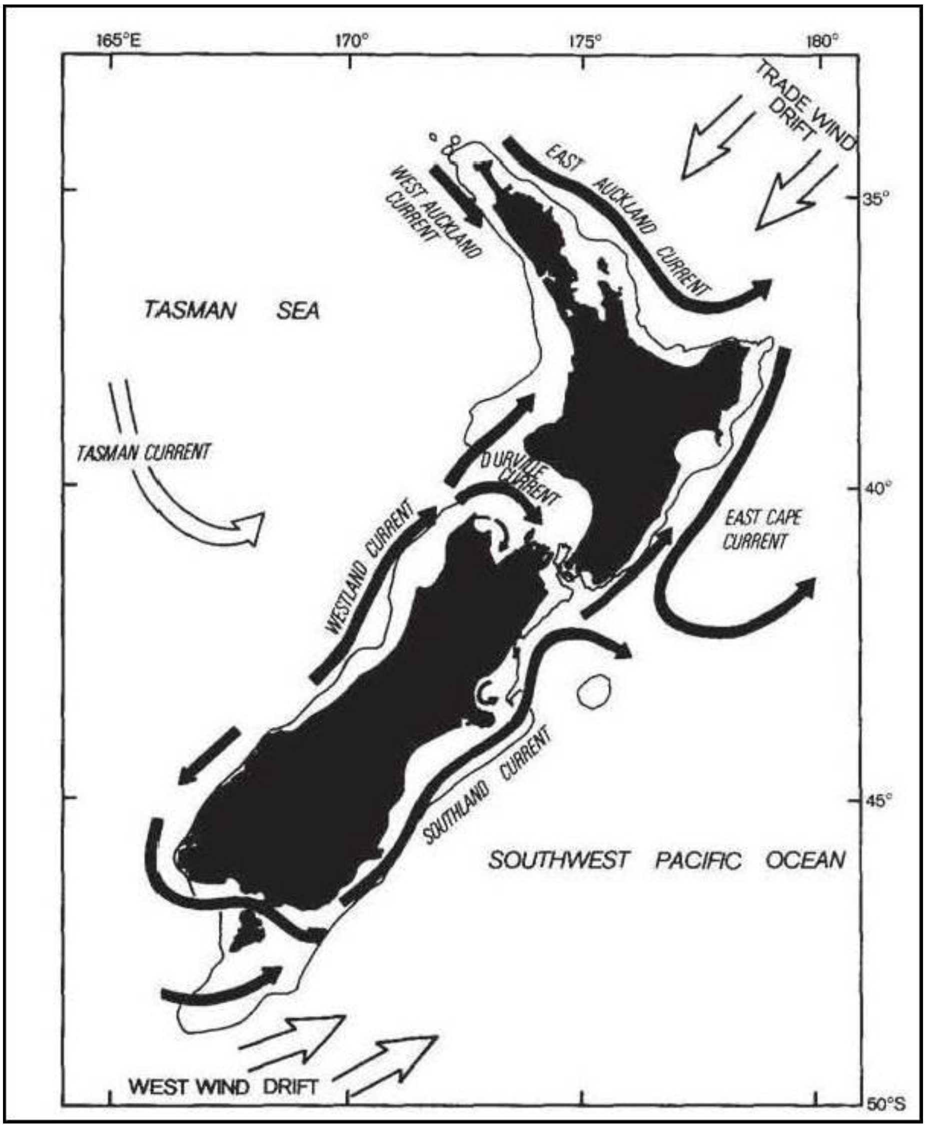


Figure 2.20: Main regional currents (West Wind Drift, Trade Wind Drift) and local New Zealand currents. (From Carter, 1975).

2.3.3 Salinity and temperature

In summer the surface salinity on the mid-shelf of Northland (from water not diluted by fresh water runoff from land) ranges from 34.8 to 35.5 ‰ (Figure 2.21). Surface water temperatures in summer range from 19-21°C while bottom water temperatures range from 13.5-15°C (Figure 2.21). Northern waters have a nearly isothermal upper mixed layer about 20 m thick. Below the thermocline temperatures fall rapidly along a vertical gradient which decreases as depth increases to reach bottom temperatures of 13.5-15.0°C (Garner, 1969).

In winter there is little seasonal variability in salinity with estimates of about 35.5 ‰ in the north of New Zealand (Garner, 1969). The warmest winter water appears just off the Northland peninsula with sea surface temperatures about 16°C or slightly higher (Figure 2.21) (Garner, 1969). A vertical isotherm structure dominates the water column as a result of convective overturning destroying the summer thermocline (Garner, 1969).

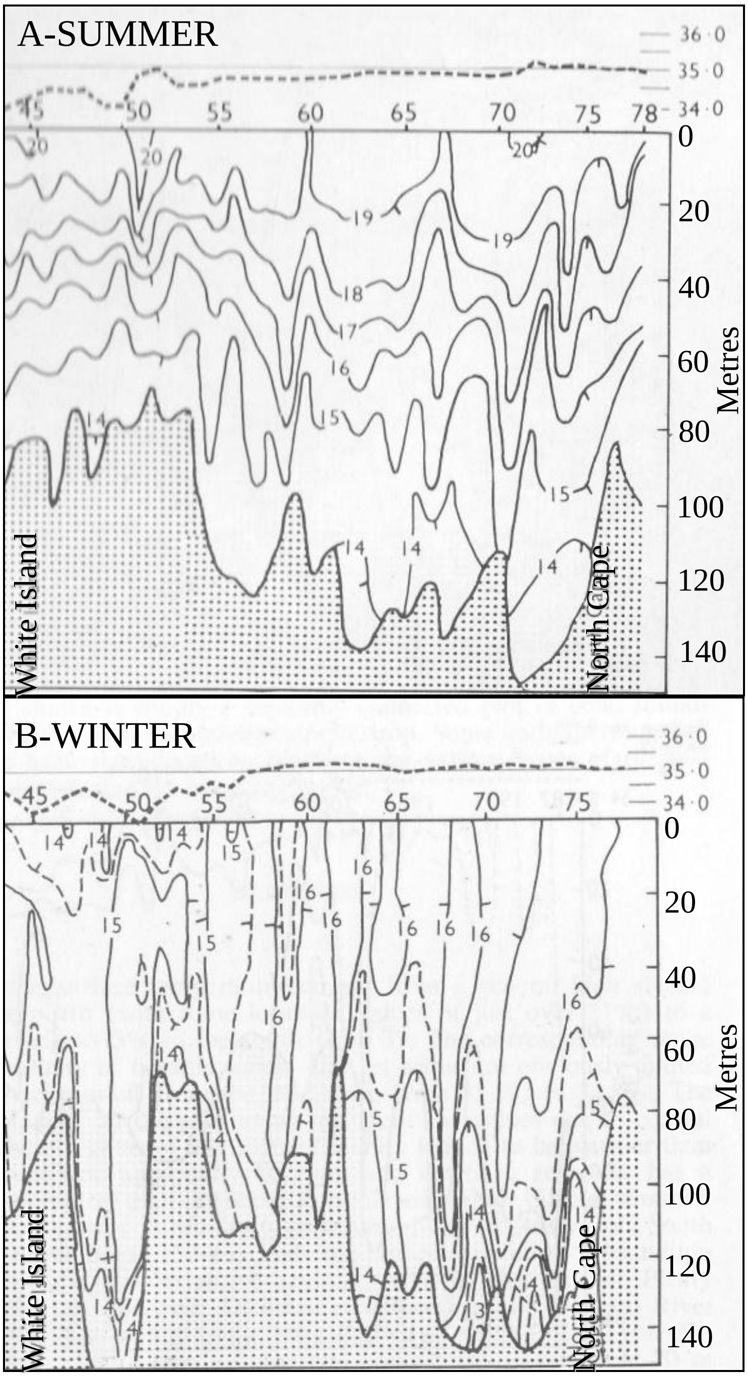


Figure 2.21: Vertical cross-sections of temperature (°C) and salinity (‰) on the mid-shelf in summer (A) and winter (B) from North Cape to White Island (Tauranga). Dotted area is sea floor bottom and dashed lines in the temperature profiles represent 0.5 °C increments. (Modified from Garner, 1969).

2.3.4 Nutrients

Phytoplankton and zooplankton contribute to the primary productivity of the marine food chain and exert a significant control on the marine environment. The spring phytoplankton bloom in New Zealand occurs from late August to mid-October and chlorophyll a concentrations (used to measure phytoplankton biomass) and primary productivity values are much higher off the east coast of New Zealand than the west coast. This may be a seasonal consequence, although high chlorophyll a values persist till December (Bradford and Roberts, 1978). The chlorophyll a concentrations off the northern sector of northeastern Northland are relatively high in the range 0.50-0.99 $mg.m^{-3}$ (Figure 2.22A) (Bradford and Roberts, 1978). In the southern sector and in deeper water off the northern sector, the chlorophyll a concentrations are lower at 0.25-0.49 $mg.m^{-3}$ (Figure 2.22A). The zooplankton biomass is more complex and shows a general trend from lower to higher concentration from north to south off northeastern Northland (Figure 2.22B) (Bradford and Roberts, 1978). At North Cape the zooplankton biomass is estimated at 50-99 $mg.m^{-3}$. Zooplankton estimates decrease to 25-49 $mg.m^{-3}$ at Parengarenga Harbour and in deeper waters in the northern sector. Progressively higher estimates occur southwards from Parengarenga Harbour to Doubtless Bay, ranging from 50-99 $mg.m^{-3}$, and from Doubtless Bay to Takou Bay, ranging from 100-299 $mg.m^{-3}$, with the highest estimates in the Bay of Islands to Ngurauru Bay area at >300 $mg.m^{-3}$ (Figure 2.22B) (Bradford and Roberts, 1978).

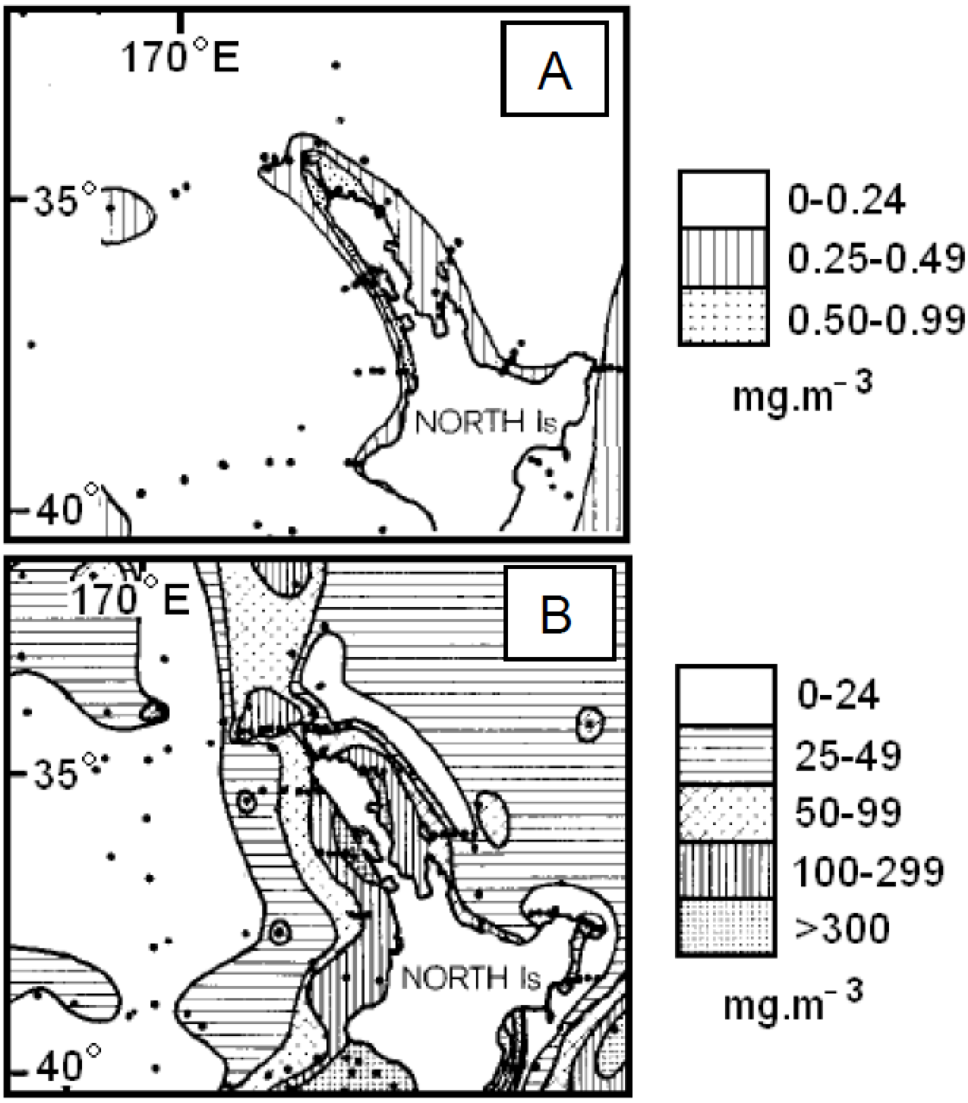


Figure 2. 22: Distribution of (A) chlorophyll a and (B) zooplankton biomass (mg.m-3) off North Island, New Zealand (from Bradford and Roberts, 1978).

2.4 ECOLOGY AND SEABED SUBSTRATES

The modern ecology was largely documented with Deep Towed Imaging System (DTIS) video imagery by NIWA during the BOI OS 20/20 Ocean Survey. High definition video transects of the seabed were collected and high resolution still photographs were taken at 15 second intervals along these transects. These images are helpful in determining, with minimal disturbance, the identity, abundance and spatial relationships of the seabed invertebrates and benthic algae as well as descriptions of the physical seabed nature over large areas (Bowden *et al*., 2010).

2.4.1 Seabed substrates

Multibeam data were collected by NIWA during the BIO OS 20/20 Coastal Survey and an acoustic backscatter map was produced (Figure 2.23). The backscatter map can be particularly valuable as it shows the distribution of soft and hard substrate types. The substrate is dominated by rocky outcrops in the nearshore zone along the northeastern Northland coastline with the exception of Great Exhibition Bay, outside Doubtless Bay and the Bay of Islands where soft substrate dominates inside and outside the Bay. The pattern becomes more complex with rock outcrops in the vicinity of North Cape and in deeper waters in the northern sector. The DTIS (Deep Towed Imaging System) images provide a generalised sediment substrate pattern as recorded in the BIO OS 20/20 Coastal Survey Reports (Chapter 9 Seafloor assemblage and habitat assessment using DTIS; Bowden *et al*., 2010). Their map is reproduced here (Figure 2.24). The North Cape region substrates have a mosaic pattern involving bedrock, boulders, sand, muddy sediment and biogenic substrate containing shell hash. From North Cape south to Doubtless Bay the sediment substrate appears mostly flat and muddy. South of Doubtless Bay to Bay of Islands the sediments are muddy with areas of sand, gravel including cobbles and boulders, bedrock, and shell hash. From Bay of Islands to Poor Knights Island, muddy sediments are present with patches of cobbles, boulders and bedrock. The central basin of the Bay of Islands consists mostly of muddy sediments while the outer Bay of Islands in deeper water consists mostly of rocky substrates. Biogenic substrates in the Bay of Islands are widely distributed but most common in Te Rawhiti Inlet (9-20 m depths) where they consist mostly of shell hash, rhodoliths, and horse mussels.

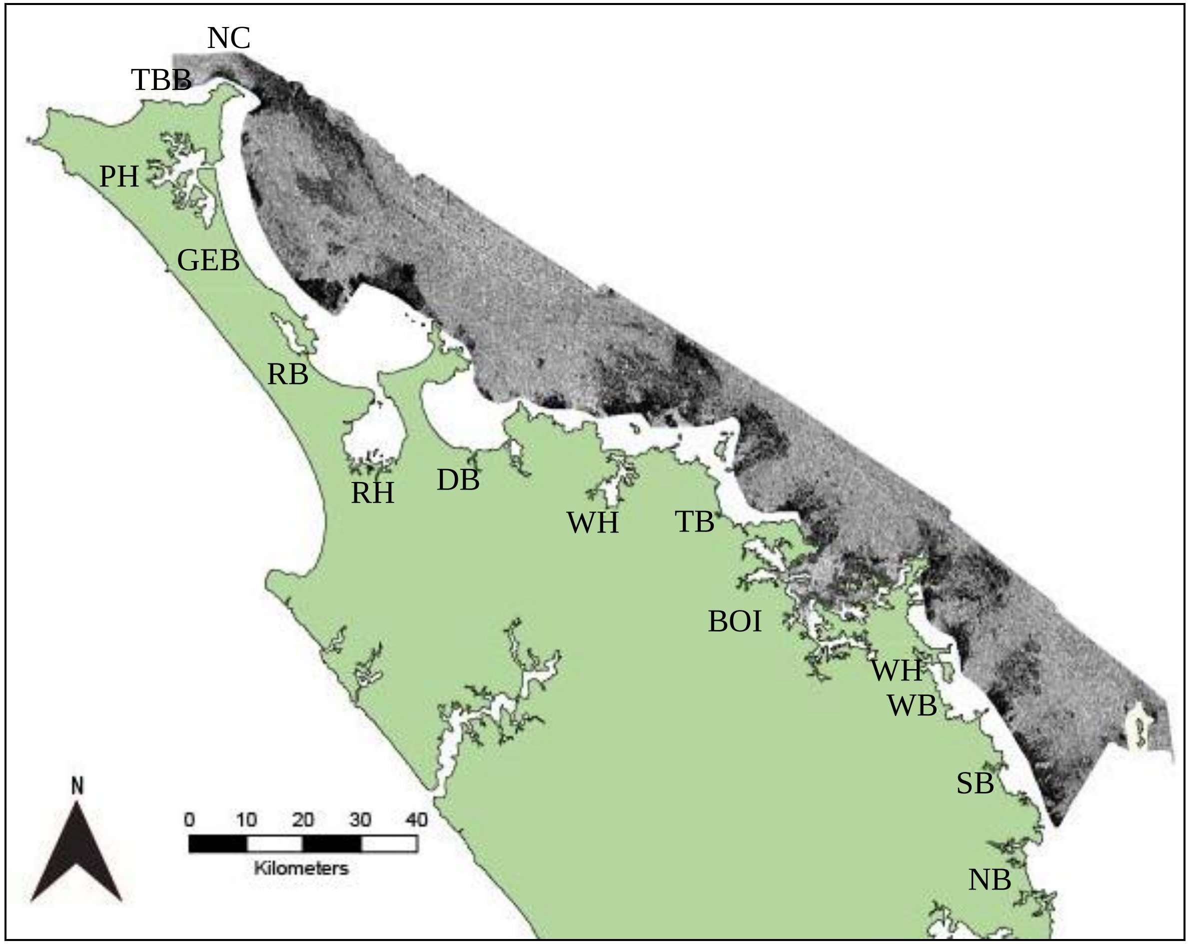


Figure 2.23: Acoustic backscatter image over portions of the NNCS (modified from www.OS20/20.org.nz/project_map). Locality name codes are defined in Figure 1.2. Dark areas on acoustic backscatter image represent hard substrates and light areas represent soft substrates.

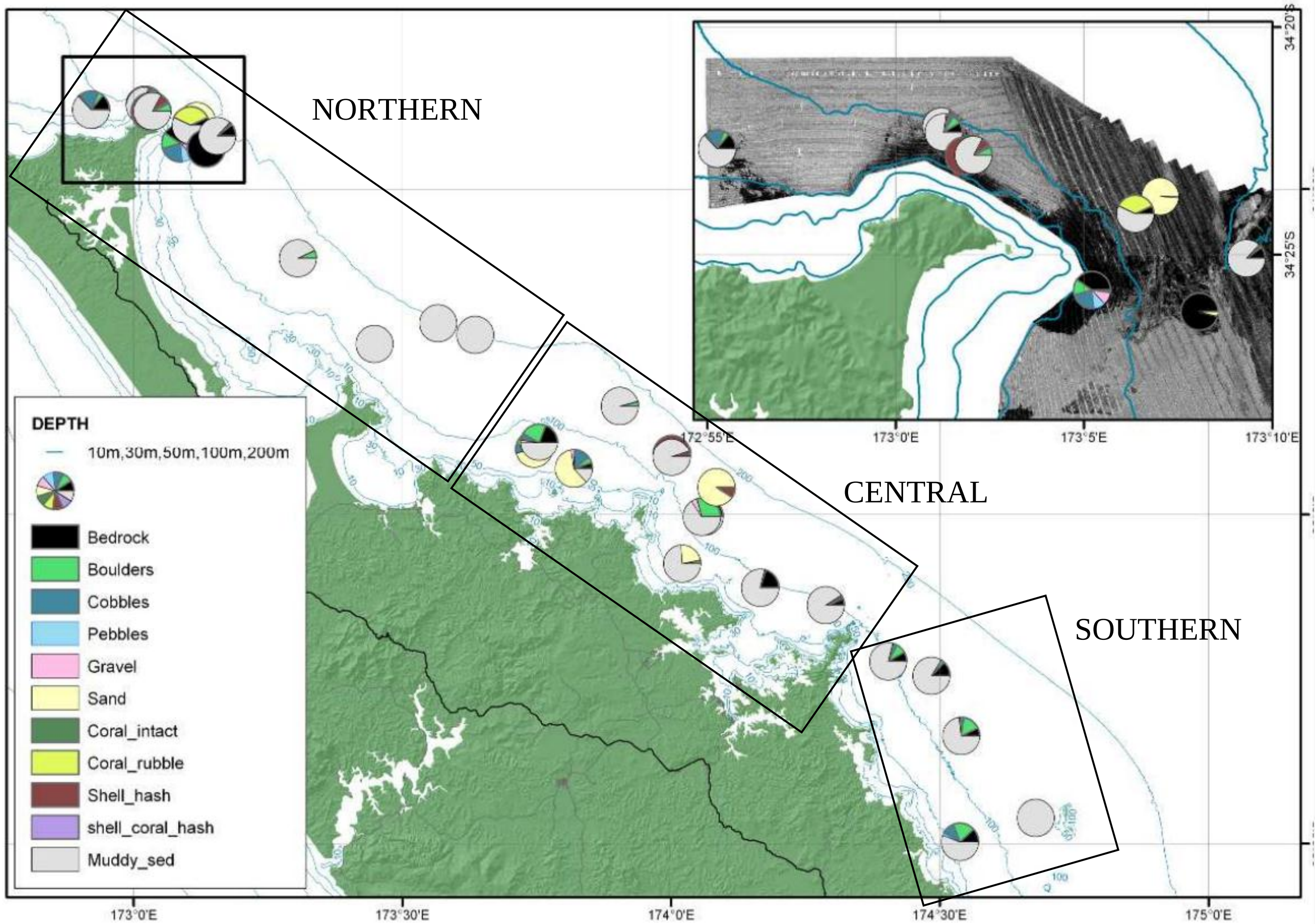


Figure 2.24: Seabed substrate character from North Cape to Nguraura Bay summarised in pie diagrams (Bowden et al., 2010). The study area is divided onto the northern, central and southern sectors for this section. The Enlarged section shows the acoustic backscatter map off North Cape.

2.4.2 Benthic invertebrates

DTIS (Deep Towed Imaging System) images were very useful for documenting the modern ecology of the benthic invertebrates, including the sessile fauna, the mobile invertebrates and the echinoderm classes that occur on the NNCS (Figure 2.5, 2.26 and 2.27). The generalised distribution of benthic invertebrates is detailed in the BIO OS 20/20 Coastal Survey Reports (Chapter 9 Seafloor assemblage and habitat assessment using DTIS; Bowden *et al.*, 2010), and is summarised below. At North Cape the stations had the highest number of taxa per transect (max. richness of 70 taxa in one transect) and consisted of assemblages which were rich in sponges and other sessile invertebrates. The species abundances were highest in this area which coincided with the high species richness. At North Cape and south of Whangaroa Harbour, the diversity was highest with a combination of high taxon richness and high species abundances. Muddy sediment generally had lower numbers of taxa (less than 15 per transect) and the NNCS from North Cape to Doubtless Bay had the lowest diversity.

In the Bay of Islands the highest densities occurred in the Te Rawhiti Inlet associated with sediments consisting of accumulations of mixed shell hash and rhodoliths. Towards the mouth of the bay the invertebrate faunal taxa were highest per transect as the area was dominated by rock, although the number of individual organisms was only moderate. The highest number of individual organisms was recorded at two sites in the Te Rawhiti Inlet where there is a very large population of *Atrina zealandica* (horse mussel). The most abundant fauna detected by video in the Bay of Islands were horse mussels, sponges and anthozoans. Common mobile invertebrates included asteroids, echinoids, gastropod molluscs, and decapod crustaceans.

Figure 2.28 shows the total number of benthic invertebrate taxa recorded in DTIS video transects for the northern, central and southern sections of the study area. Data are assembled according to phylum and class levels. The diagram shows that the most common phylum is Porifera (sponges), which are found throughout the study area but most especially in the northern sector (Figure 2.5). The second most common phylum involves the Cnidaria (Anthozoa and Hydrozoa) in Figure 2.5, which are also most common in the northern sector but also in the central and southern sectors of the study area. Echinodermata (echinoderms) are almost solely present in the northern sector (Figure 2.27) while Malacostraca (crustaceans) are present throughout the NNCS but are dominant in the very northern and southern parts of the study area (Figure 2.6). Bryozoa (bryozoans) occur only in the central and southern sectors of the study area (Figure 2.25). The benthic invertebrate taxa that were the least common in the study area are Mollusca (molluscs, including bivalves, gastropods, cephalopods and scaphopods), Ascidiacea (seasquirts) and Polychaeta (worms) (Figure 2.5 and 2.6).

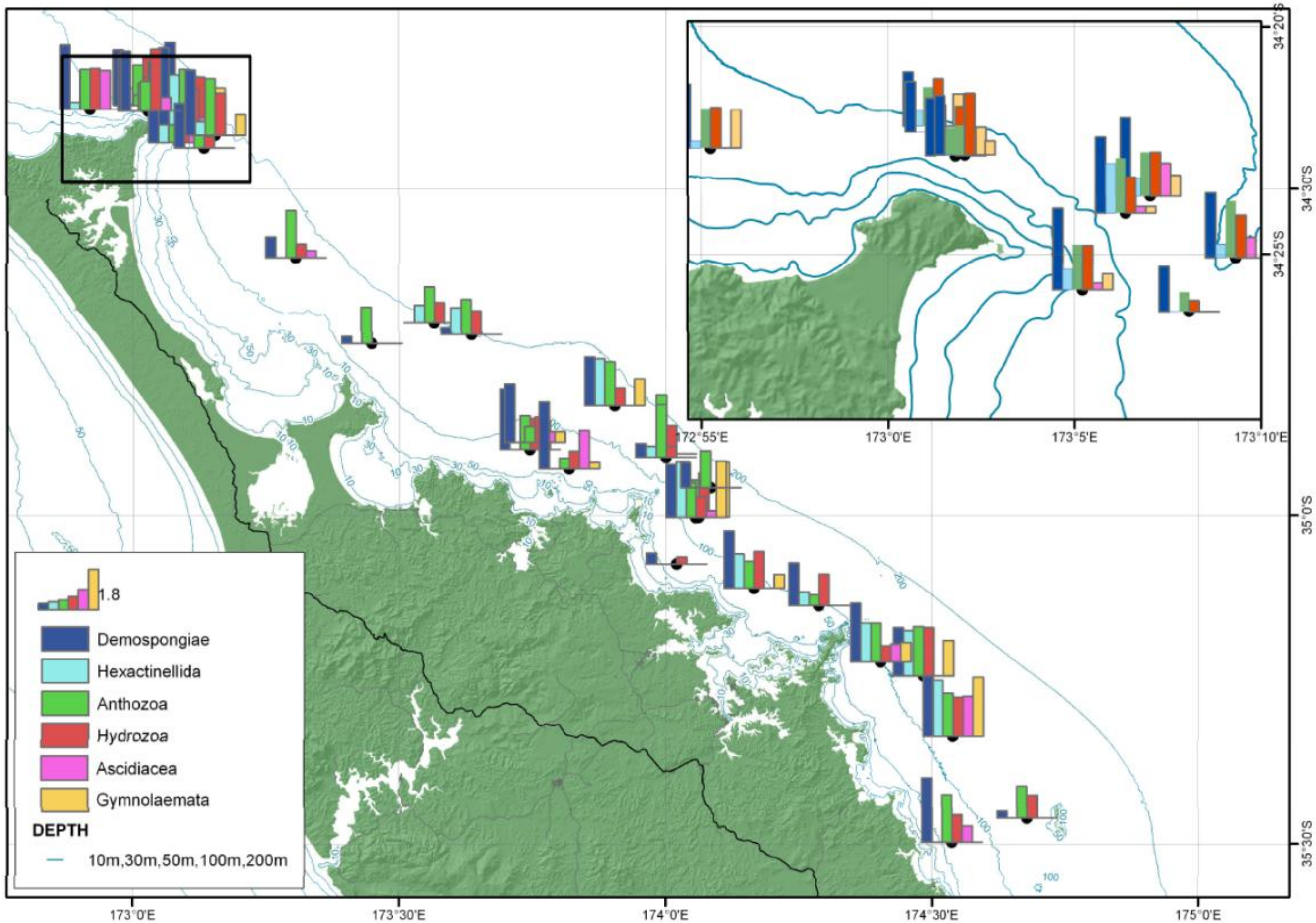


Figure 2.25: Sessile fauna recorded by DTIS video on the NNCS, with enlarged inset off North Cape. Bars show the log10 transformed abundances of each class, so that double the length of a bar means the abundance is ten times greater (Bowden et al., 2010). Demospongae and Hexactinelida are sponges; Anthozoa include solitary corals, anemones and seapens; Hydrozoa are hydroids; Ascidiacea are sea squirts; and Gymnolaemata are bryozoans.

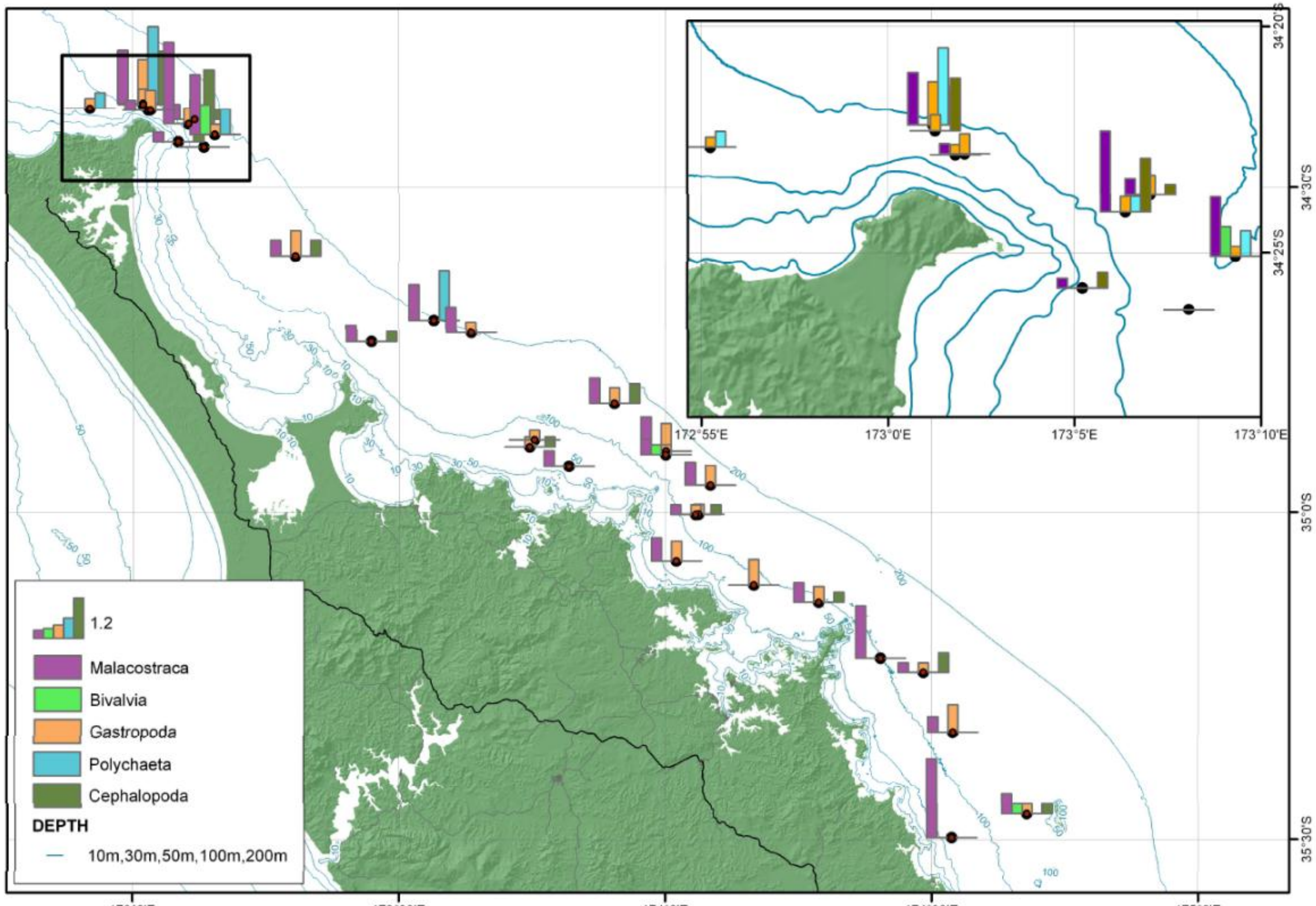


Figure 2.26: Mobile invertebrate fauna recorded by DTIS video on the NNCS, with enlarged inset off North Cape. Bars show the log10 transformed abundances of each class, so that double the length of a bar means the abundance is ten times greater (Bowden et al., 2010).). Malocostraca are crustaceans; Bivalvia are bivalve molluscs; Gastropoda are snails and seaslugs; Polychaeta are worms; and Cephalopoda are octopus and squid.

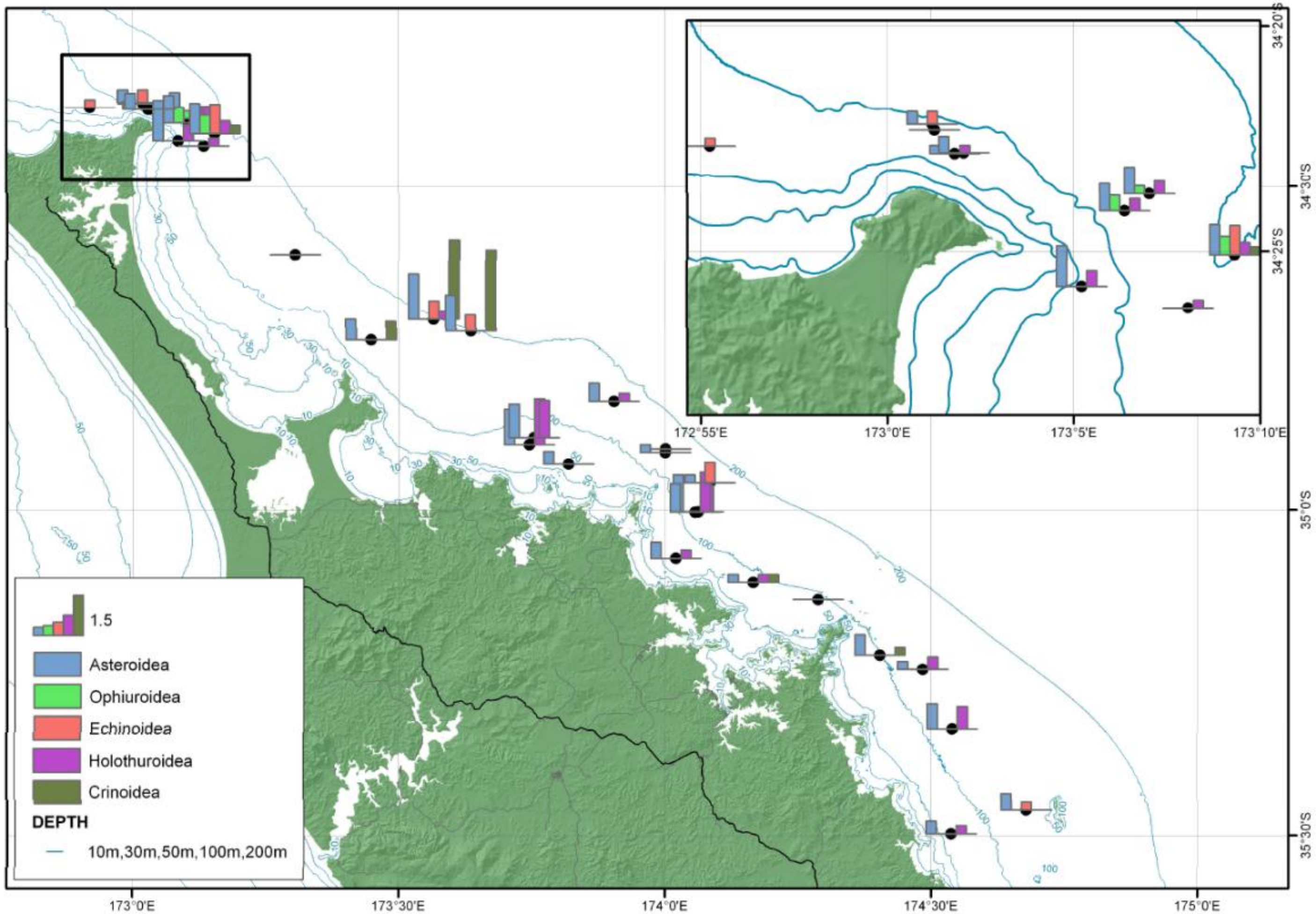


Figure 2.27: Echinoderm classes recorded by DTIS video on the NNCS, with enlarged inset off North Cape. Bars show the log10 transformed abundances of each class, so that double the length of a bar means the abundance is ten times greater (Bowden et al., 2010). Asteroidea are sea-stars; Ophiuriodea are brittle stars; Echinoidea are sea urchins; Holothuroidea are sea cucumbers; and Crinoidea are feather stars.

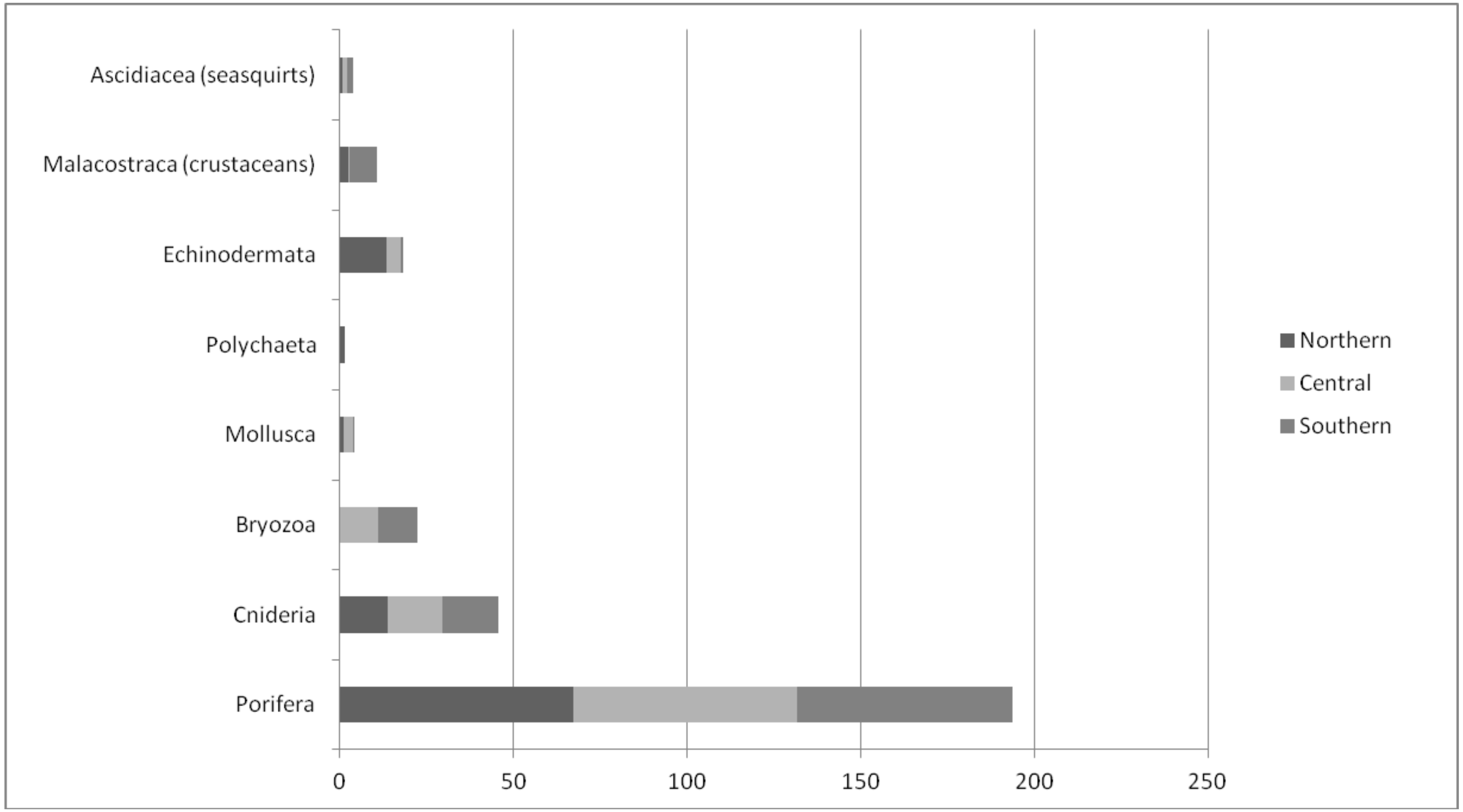


Figure 2.28: Number of benthic invertebrate taxa recorded in DTIS video transects from the northern, central and southern NNCS regions. Locations of the region divisions are shown in Figure 2.24. Constructed with raw data from Bowden et al. (2010).

2.4.3 Benthic algae

DTIS images were used to record the benthic algal population dynamics on the NNCS. The macroalgae were condensed into four groups consisting of erect brown algae, erect red algae, coralline encrusting red algae and low-relief mixed algal turfs (Figure 2.29). The general distribution of benthic algae are recorded in the BIO OS 20/20 Coastal Survey Reports (Chapter 9 Seafloor assemblage and habitat assessment using DTIS; Bowden *et al*., 2010) and summarised below.

Across the outer survey area all macroalgae apart from coralline encrusting red algae were uncommon, attributed to light limitations at depth ranges from 40-200 m. Coralline encrusting red algae were more commonly observed at these depths, probably due to transport by currents of broken algal thalli. Southeast of North Cape, north of Whangaroa Bay and east of Tutukaka Heads (at very shallow sites of 60-70 m with much exposed bedrock and coarse sediment) coralline encrusting red algae occur on the rocky substrates. This type of algae was the most frequently observed.

In the Bay of Islands the southeastern side of the bay had more abundant and diverse algae than the northwestern side, which could be due to greater sample depths on the northwestern side of the bay. The greatest algal diversity was recorded at Renown Anchorage, Te Rawhiti Inlet and to the north of Moturua Island (depths of 10-12 m). On the sand, gravel and shell hash substrates of these areas were developed rhodolith beds with attached macroalgae occurring on patches of boulders and on coarse mobile substrates.

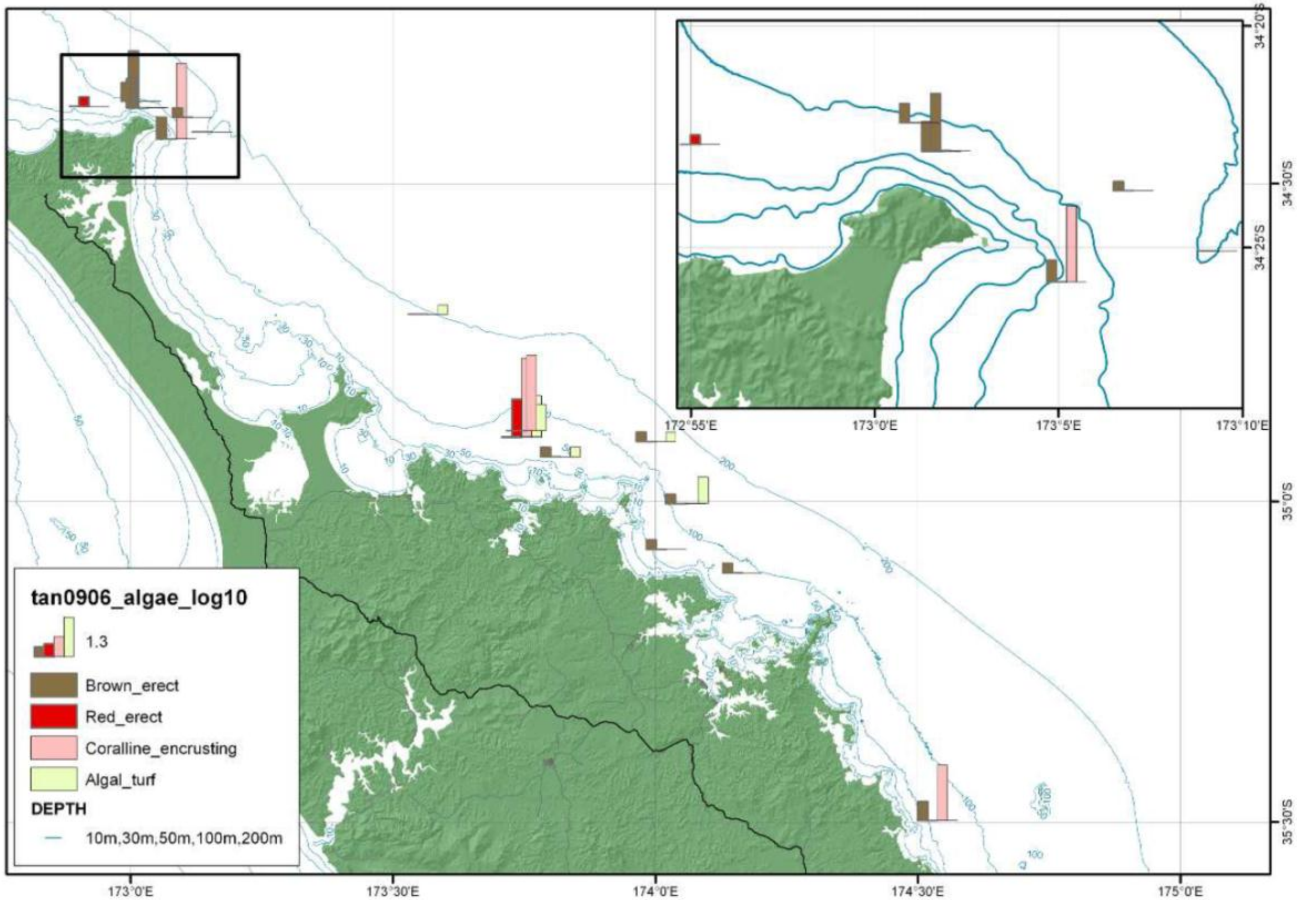


Figure 2.29: Benthic algae recorded by DTIS video on the NNCS, with enlarged inset off North Cape. Bars show the log10 transformed abundances of each class, so that double the length of a bar means the abundance is ten times greater (Bowden et al., 2010).

Chapter 3

METHODS

3.1 SAMPLE COLLECTION

96 sediment samples were collected for this study at NIWA, Wellington from archive storage of the sediment samples collected during the recent Bay of Islands Ocean Survey 20/20 voyages (KAH0907, KAH0906) and from various earlier oceanographic research cruises (402, 502, 538, 553, 9901, 533, 578, 1077). Sample locations are shown in Figure 3.1. These samples were split into two subsamples, one of which remained in the NIWA, Wellington archive store, and the other used for analysis in this study. Appendix A gives sampling details including voyage, station and site numbers of samples, gear used for collection, geographic coordinates and sample depths.

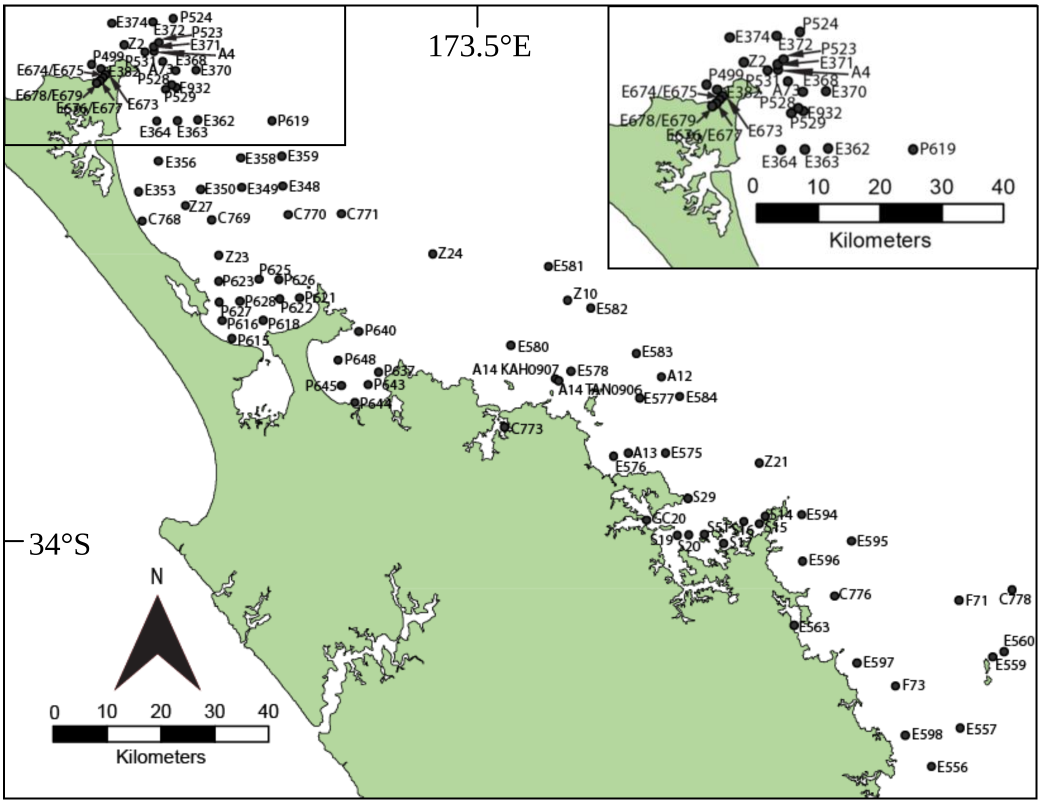


Figure 3.1: Surficial sediment sample locations in the NNCS study area. Inset shows slightly enlarged surficial sediment sample locations off North Cape.

3.2 GRAIN SIZE ANALYSIS

Grain size analysis was undertaken on 89 samples out of the 96 collected as 7 samples had insufficient sediment mass to undertake a full analysis. 17 samples had grain size analyses performed by Lisa Northcote at NIWA, Wellington. The percentages of gravel, sand and mud are detailed in Appendix B. At NIWA the samples were sieved over a 2 mm mesh sieve with the retained (if any) mass weighed. The mass passing 2 mm was then laser sized.

A representative split was taken of all samples for grain size analysis and then sieved over a 2 mm mesh screen. Dry sieve analysis was performed on the sediment grain sizes coarser than 2 mm (55 samples). The splits taken of the sediment in the coarser grained samples were washed through a 63 µm mesh sieve over a bucket. The sediment retained on the 63 µm mesh sieve was dried and then dry sieved, and the sediment passing 63 µm was kept wet and subject to laser sizing if there was sufficient mud material still available. Sediment samples with grain sizes less than 2 mm (i.e. had no gravel fraction) were laser sized only (17 samples). Sieving was not required for these samples due to the ability of the Laser Diffraction Particle Size Analyser to analyse sediment finer than 2 mm in size. The laser sizing results were made comparable to the dry sieve results by converting the volume percentages to weight percentages using a specifically designed spread sheet provided by Dr Willem de Lange in the Department of Earth and Ocean Sciences at the University of Waikato (provided in CD Appendix B).

3.2.1 Dry sieve analysis

20 l of washing solution was made by dissolving 1 g NaH_2CO_3 + 4 g $NaHCO_3$ in a beaker of deionised water on a hot plate with a stir bar. The carbuoy was filled with deionised water and dissolved washing solution was added. The sediment was subsampled and dried in an oven at 100°C. A numbered plastic bottle was tared, after which dried sediment was added and then weighed. The bottle was then filled with washing solution and agitated periodically until any clay had dispersed.

The sample was washed through a 63 µm mesh sieve mounted over a labelled plastic container, using a fine spray of washing solution. The container was then set aside to let the fine particles settle. The fraction >63 µm was rinsed onto labelled filter paper, removing all material from the sieve. The fraction >63 μm was dried in an oven at 60°C. It was then sieved over 2 mm, 500 μm, 250 μm, 125 μm and 63 μm mesh sieves and the mass retained on each sieve was recorded. The fractions for each sample were recombined and placed in labelled vials.

3.2.2 Laser sizing

A Beckman Coulter LS13320 Laser Diffraction Particle Size Analyser Instrument was used for laser size analysis of all the sediment samples. A minimum of approximately 0.25 g dry weight and ≥6 g for coarse material was subsampled for laser sizing. Nothing >2 mm size was put through the laser sizer by placing a 2 mm mesh sieve over the area where the sediment enters the machine, preventing the laser sizer getting clogged. The sample was agitated in an ultrasonic bath (Cole-Parmer 8891) for 10 seconds prior to laser sizing to disaggregate any mud/silt particle clusters. This also helped get better obscuration results which needed to be between 8 and 22% for accurate laser size results. The results were then uploaded into Gradistatv6 for statistical analysis (Laser sizing result charts are in CD Appendix B).

3.3 CARBONATE CONTENT

Calcium carbonate percentages were calculated by NIWA, Wellington from the acid digestion method outlined below for 19 of the samples sourced during the modern OS 20/20 Bay of Islands Coastal Survey Project (voyages KAH0907 and TAN0906) and 46 samples sourced from earlier NIWA voyages. Calcium carbonate percentages for the 31 remaining samples were calculated using a similar acid digestion method at The University of Waikato in the hope that it would eliminate some of the difficulties associated with the previous method (see below). These difficulties included the draining of fluid through the filter paper and the retention of sediment on the filter paper which often results in the loss of material. This loss was eliminated by keeping the sediment in the beaker rather than transferring it onto filter paper, although this can cause inaccuracies during the weighing process as a beaker is much heavier than filter paper. The method used at The University of Waikato was developed by Deborah Davey and is outlined below in section 3.3.2. The carbonate content calculations are detailed in Appendix C.

3.3.1 Acid digestion method used by NIWA, Wellington

A numbered glass beaker was tared and a representative sample of approximately 3 g of sediment added to the beaker. The weight of the sample and beaker number was then recorded. Hydrochloric acid (10%) was periodically added to the sediment in the beaker and agitated until fizzing stopped. The beaker was set aside to allow the fine particles to settle to the bottom, after which the acid was decanted from the beaker. The remaining sediment was washed with deionised water through folded, labelled filter paper which had been placed over a funnel to drain into another glass beaker. The sample was then set aside to allow the fluid to drain. Continued rinsing of the sediment with deionised water occurred until the acid was sufficiently washed from the sediment. The filter paper containing the acidified sediment was carefully removed from the funnel and dried in a 60°C oven. Once it was cooled, the filter paper was weighed with the acidified sample. The acidified sample weight was obtained by getting an average filter paper weight and deducting this from the total weight of the filter paper plus acidified sample.

3.3.2 Acid digestion method developed at the University of Waikato

A 600 ml beaker was labelled and weighed and on average 8-14 g of dried and whole powdered sediment was added to the beaker and weighed (except when dealing with samples with minimal sediment available for testing in which case only 1-5 g of sample was added to the beaker). 100-150 ml of 10% HCI were added to the beakers and thoroughly mixed. The samples were then left to digest for 2 hours. The samples were gently swirled after two hours and the ones that effervesced had another 50 ml of HCI added to them and were left for a further 2 hours. Water was then added to total 550 ml and samples were left to settle overnight. Using a 2 l Buchner flask the liquid was carefully suctioned off to leave about 2 cm of fluid above the sediment. The beakers were placed in a 70°C oven for 48 hours and removed and cooled at room temperature before weighing. The calcium carbonate percentage was calculated by subtracting the beaker weight from the final acidified sample weight and subtracting this weight from the original sample weight and then converting these numbers into percentages.

3.4 X-RAY DIFFRACTION (XRD)

Fast scan XRD was performed on 93 of the 96 powdered sediment samples (3 samples did not have sufficient material for analysis) to determine the bulk mineralogy of NNCS sediments. The fast scans were run from 12 to 45°2θ. Based on the availability of material, 86 out of 96 samples were further slow scanned to determine the calcite species types in the study area (all result charts are in CD Appendix D). The slow scans were run from 28 to 33°2θ. 6 samples were chosen to scan for clay mineral types. These were chosen on the basis that they showed clay peaks (although very low) in fast scan graphs, they contained sufficient clay material in the mud fraction for analysis, and they were well distributed across the study area. The various minerals were determined by scan peak positions (Figure 3.1 and 3.2). XRD counts (provided by High Score software) were used to semiquantify the mineralogy (Nelson and Cochrane, 1970; Hume and Nelson, 1986), and the chart of Chave (1952) used for determining the calcite species present in samples. The bulk mineralogy determinations are detailed in Appendix D.

Table 3.1: Common XRD mineral positions (e.g. Hume and Nelson, 1986)

Mineral	Window (°2θ, CuKα Radiation)	Range of D-Spacings (A)	Intensity Factor[a]
Amphibole	10.30–10.70	8.59– 8.27	2.50
Analcite	15.60–16.20	5.68– 5.47	1.79
Anatase	25.17–25.47	3.54– 3.50	0.73
Anhydrite	25.30–25.70	3.52– 3.46	0.90
Apatite	31.80–32.15	2.81– 2.78	3.10
Aragonite	45.65–46.00	1.96– 1.97	9.30
Augite	29.70–30.00	3.00– 2.98	5.00
Barite	28.65–29.00	3.11– 3.08	3.10
Calcite	29.25–29.60	3.04– 3.01	1.65
Chlorite	18.50–19.10	4.79– 4.64	4.95
Clinoptilolite	9.70– 9.99	9.11– 8.84	1.56
Cristobalite	21.50–22.05	4.13– 4.05	9.00
Dolomite	30.80–31.15	2.90– 2.87	1.53
Erionite	7.50– 7.90	11.70–11.20	3.10
Goethite	36.45–37.05	2.46– 2.43	7.00
Gypsum	11.30–11.80	7.83– 7.50	0.40
Halite	45.30–45.65	2.00– 1.99	2.00
Hematite	33.00–33.40	2.71– 2.68	3.33
Kaolinite	12.20–12.60	7.25– 7.02	2.25
K-Feldspar	27.35–27.79	3.26– 3.21	4.30
Magnetite	35.30–35.70	2.54– 2.51	2.10
Mica	8.70– 9.10	10.20– 9.72	6.00
Montmorillonite	4.70– 5.20	18.80–17.00	3.00
Palygorskite	8.20–8.50	10.70–10.40	9.20
Phillipsite	17.50–18.00	5.06– 4.93	17.00
Plagioclase	27.80–28.15	3.21– 3.16	2.80
Pyrite	56.20–56.45	1.63– 1.62	2.30
Rhodochrocite	31.26–31.50	2.86– 2.84	3.45
Quartz	26.45–26.95	3.37– 3.31	1.00
Sepiolite	7.00– 7.40	12.60–11.90	2.00
Siderite	31.90–32.40	2.80– 2.76	1.15
Talc	9.20– 9.55	9.61– 9.25	2.56
Tridymite	20.50–20.75	4.33– 4.28	3.00
Gibbsite	18.00–18.50	4.93– 4.79	0.95

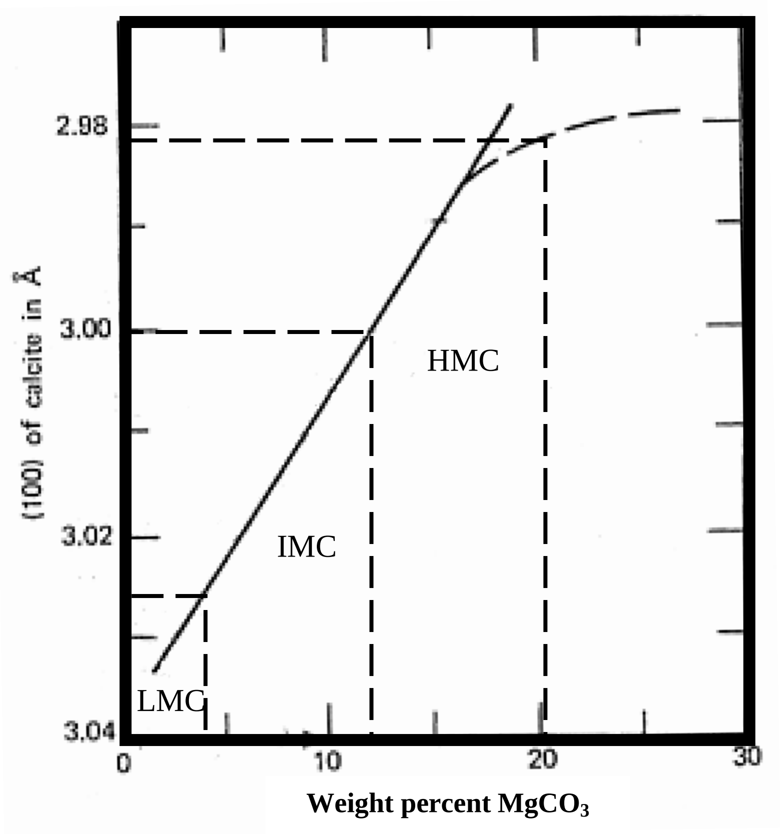


Figure 3.2: Chart used to determine calcite types (LMC=low-Mg calcite; IMC=intermediate-Mg calcite; HMC=high-Mg calcite). Weight percent MgCO3 incorporated diadochtically in a calcite type CaCO3 structure as a function of peak dislocation (from Chave, 1952).

3.5 THIN SECTIONS

A split was taken of 54 samples chosen for thin section analysis. These samples were chosen on the basis that they were well distributed over the study area and that they had relatively high carbonate contents. The gravel and mud fractions were removed by washing the sediment over 2 mm and 63 µm mesh sieves. The sand-sized sediment passing the 2 mm sieve and retained on the 63 µm sieve was used to make the sections. The sediment retained on the 2 mm sieve was saved for binocular skeletal identification of the gravel fraction. Small rectangular moulds were made from tin foil for each sample. About 10 g of material was split from the sand-sized sample and heated on a hot plate at 60 to 80°C. A resin mixture was prepared and heated at 60 to 80°C for 2 minutes while being continuously stirred to remove air bubbles before pouring into the tinfoil moulds. The sample was then added to the resin and gently pushed down and spread evenly across the mould to avoid the formation of air bubbles. A paper label was added to the glue and the sample was then left to set on the hotplate for 24 hours. Once the resin block was set the tinfoil was removed and the block ground on the bottom using a diamond lap wheel and then a glass plate with 600-grade carborundum powder. The blocks were then glued to a frosted slide with Hillquist Thin Section Epoxy and left for 24 hours to dry. The resin blocks were then cut off the slides using a discoplane saw and ground to the correct thickness for petrographic study with the discoplane.

3.6 SKELETAL IDENTIFICATION

The shape and form of the various skeletal grains in thin section under a petrographic microscope, and in the gravel fraction under a binocular microscope, were determined using the many skeletal illustrations provided by Scholle and Ulmer-Scholle (2003). The skeletal and siliciclastic component percentages were then estimated using comparative percentage circles (Figure 3.3) (Jones and Bloss, 1980). A percentage range scale was used to record the data (Table 3.2). The sorting and shape of skeletal grains and detrital mineral grains were estimated using sorting and roundness scales (Figure 3.4). The degree of abrasion of skeletal material was recorded using a scale from 1-5 with 1 being unabraded and 5 extremely abraded. Microborings were recorded used a scale ranging from some to moderate to very microbored. Alteration features which include limonite and glauconite infills were recorded using a scale from none to some to common infills. Petrographic summaries are listed in Appendix E.

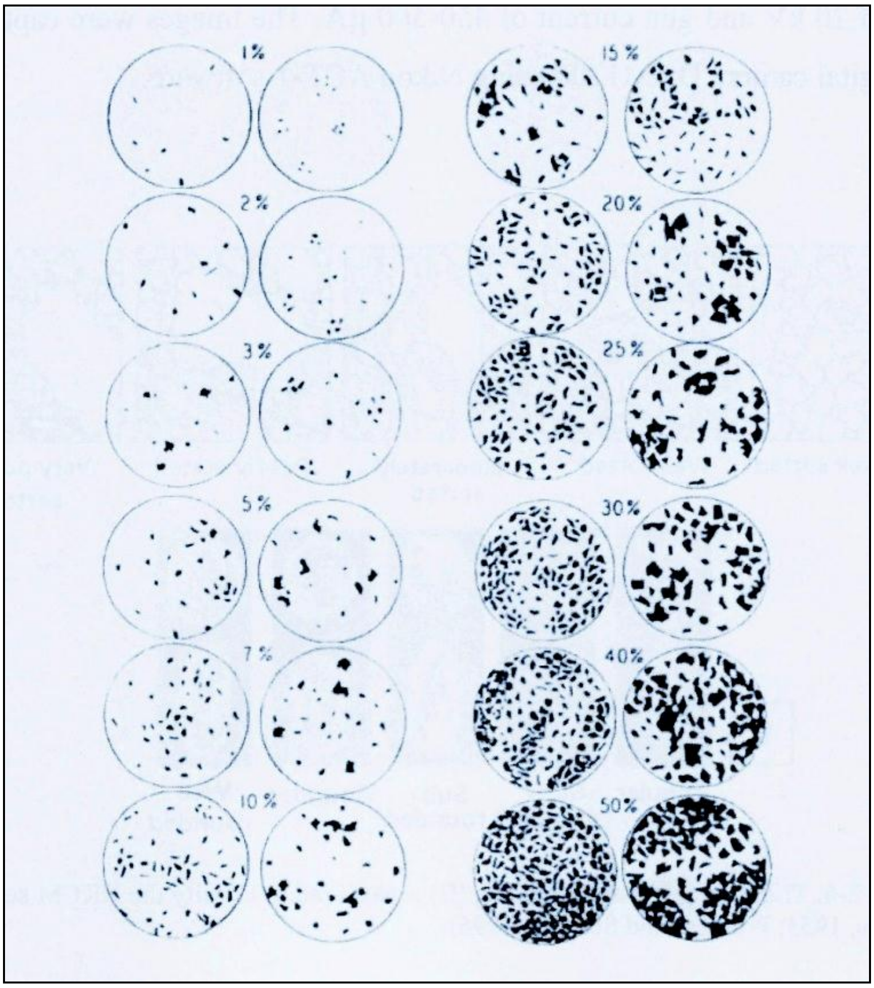


Figure 3.3: Comparative percentage circles to estimate the % of components in the total sediment (Jones and Bloss, 1980).

Table 3.2: Percentage ranges to describe components in the surficial bottom sediments on the NNCS.

Classification	% Component
Rare	<1
Some	1-5
Many	5-15
Common	15-25
Very common	25-50
Abundant	50-75
Very abundant	75-100

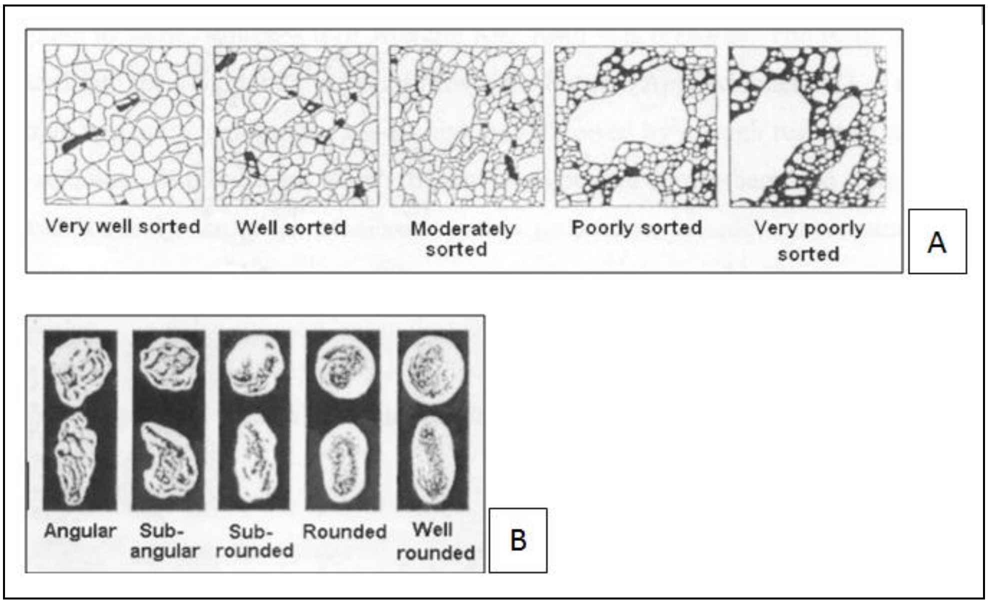


Figure 3.4: Sorting (A) and roundness (B) scales used for the NNCS sediments (Powers, 1953; Prothero and Schwab, 1996).

3.7 DIGITAL APPENDICES

The main data reported in the text of this study are contained in the Appendices at the end of the thesis (p. 207 and following). Additional data from this study is included on the CD accompanying this thesis as the CD Appendices, as follows:

CD Appendix A - Sample locations and descriptions

CD Appendix B - Textural data (including laser sizing result charts and spreadsheet calculations)

CD Appendix C - Carbonate content

CD Appendix D - XRD data (including all result charts)

CD Appendix E - Petrography (including photomicrographs of petrographic samples)

Chapter 4

SEDIMENT TEXTURE

4.1 DISTRIBUTION OF GRAVEL, SAND AND MUD FRACTIONS

This section describes the distribution of weight percentages of gravel (>2 mm), sand (0.063-2 mm) and mud (<0.063 mm) sized sediment on the NNCS. The bulk gravel, sand and mud (which includes both silt and clay sizes) percentages for each sample, as well as the depth at which each sample was collected at, are recorded in Table 4.1. The NNCS sediments are mainly dominated by sand-sized sediment over mud and gravel sized. In the mud fraction clay-sized sediment is negligible in most samples (Table 4.1).

The proportions of gravel, sand and mud at the various sample locations can depend on the water depths of these sites. Sediment usually becomes finer in an offshore direction due to the concentration of higher energy at the coast which contributes to coarse and sometimes more poorly sorted sediment nearshore and finer often better sorted sediment further offshore. However, the NNCS has a variety of bays and harbours as well as many rocky outcrops in deeper shelf and slope waters which could contribute to the accumulation of fine sediments nearshore in mangroves and inlets and the presence of coarse shell hash and gravels in deeper waters on rocky outcrops.

Table 4.1: Sample number, water depth and weight percentages of gravel, sand and mud (which is differentiated into silt plus clay) in the NNCS surficial bottom sediments. Pink highlighted cells were not laser sized due to their paucity of mud and therefore show no weight percentages for silt and clay. Blue highlighted cells had insufficient material for textural analysis.

Number	Sample #	Depth (m)	Wt % Gravel	Wt % Sand	Wt % Mud	Wt % Silt	Wt % Clay
1	S17	~20	0.0	36.3	63.7	54.7	9.0
2	S20	30	0.0	68.6	31.4	27.7	3.7
3	S51	29	21.9	77.0	1.1	1.0	0.1
4	S14	42	0.0	79.4	20.6	18.3	2.3
5	S29	37	51.4	46.6	2.0	1.7	0.3
6	S15	34	0.0	85.2	14.8	13.5	1.3
7	S16	12	0.0	76.4	23.6	19.2	4.4
8	S19	23	0.0	78.8	21.2	18.3	2.9
9	GC20	12	61.9	38.0	0.1	0.1	0.0
10	Z23	50	0.0	98.5	1.5	1.2	0.3
11	Z10	156	0.0	77.1	22.9	19.4	3.5
12	A14	55	0.0	67.0	33.0	28.7	4.4
13	Z21	118	0.0	76.7	23.3	19.8	3.5
14	A14	55	0.0	67.7	32.3	27.3	4.9
15	Z2	88	26.4	59.1	14.5	12.5	2.0
16	Z27	71	44.6	49.2	6.2	5.4	0.7
17	Z24	170	0.0	89.9	10.1	8.5	1.6
18	A12	148	0.0	86.6	13.4	11.6	1.8
19	A13	65	32.0	64.6	3.4	2.9	0.5
20	A4	47					
21	A73	69					
22	C768	24	0.0	100.0	0.0	0.0	0.0
23	C769	77	1.7	93.6	4.7	4.6	0.1
24	C770	134	13.2	83.9	3.0	3.0	0.0
25	C771	188	0.0	88.5	11.5	11.0	0.4
26	C773	26	64.7	32.4	2.9	2.8	0.1
27	C776	77	3.3	74.8	21.9	21.4	0.5
28	C778	187	2.0	86.7	11.4	11.1	0.3
29	E348	150	1.5	90.3	8.2	8.1	0.1
30	E349	121	5.7	78.9	15.4	15.0	0.4
31	E350	102	0.9	79.0	20.1	19.7	0.4
32	E353	27	3.0	95.3	1.7		
33	E356	68	1.1	93.9	5.0	4.9	0.1
34	E358	143	13.7	63.3	23.0	22.7	0.3
35	E359	172	9.2	82.1	8.7	8.5	0.2
36	E362	135	0.0	70.4	29.6	29.1	0.4
37	E363	110	0.6	63.5	35.9	35.2	0.6
38	E364	73	3.0	88.9	8.0	7.9	0.1
39	E368	126	5.7	82.4	11.9	11.7	0.2
40	E370	146	29.3	59.8	10.9	10.7	0.2
41	E371	121	6.6	76.1	17.4	17.1	0.3
42	E372	135	3.8	86.6	9.6	9.5	0.1
43	E374	117	0.0	85.4	14.6	13.1	1.5
44	E382	29	5.9	91.9	2.1		
45	E556	88	1.0	72.7	26.3	26.0	0.4
46	E557	106					

Table 4.1 continued.

Number	Sample #	Depth (m)	Wt % Gravel	Wt % Sand	Wt % Mud	Wt % Silt	Wt % Clay
47	E559	106	24.2	65.9	9.9	9.7	0.2
48	E560	154	17.5	68.8	13.7	13.5	0.2
49	E563	9	34.6	56.9	8.5	8.4	0.1
50	E575	77					
51	E576	38	0.0	96.4	3.6	3.0	0.6
52	E57	108					
53	E578	62					
54	E580	84					
55	E581	198	0.0	87.3	12.7	12.4	0.3
56	E582	190	0.0	16.3	83.7	67.4	16.3
57	E583	179	1.9	91.1	6.9	6.8	0.1
58	E584	150	1.5	90.3	8.2	8.1	0.2
59	E594	93	10.3	87.9	1.7	1.7	0.0
60	E595	128	0.0	61.0	39.0	35.4	3.6
61	E596	73	0.0	100.0	0.0	0.0	0.0
62	E597	46	0.0	92.4	7.6	6.5	1.1
63	E598	68	0.0	61.4	38.6	34.1	4.5
64	E673	0	0.4	94.2	5.4		
65	E674	0	0.0	99.5	0.5	0.5	0.1
66	E675	0	52.1	46.7	1.2		
67	E676	0	0.0	100.0	0.0	0.0	0.0
68	E677	0	5.6	93.3	1.1		
69	E678	0	17.7	80.8	1.5		
70	E679	0	0.0	99.4	0.6	0.5	0.1
71	F71	150	5.7	81.6	12.7	12.3	0.4
72	F73	79	38.6	48.2	13.2	12.9	0.3
73	F932	113	42.3	50.5	7.2	7.0	0.2
74	P499	30	12.2	85.0	2.8		
75	P523	210	6.3	86.3	7.3	7.2	0.2
76	P524	134	18.0	62.4	19.6	19.4	0.3
77	P528	115	18.5	68.1	13.4	13.0	0.3
78	P529	97	3.0	85.8	11.2	11.1	0.2
79	P531	112	17.3	63.1	19.6	19.3	0.3
80	P615	18	0.0	99.1	0.9	0.9	0.0
81	P616	16	3.2	95.0	1.8		
82	P618	21	0.0	98.5	1.5	1.2	0.3
83	P619	19	2.1	96.1	1.8		
84	P621	18	62.6	34.5	2.8		
85	P622	28	0.3	96.8	2.9		
86	P623	41	4.1	92.7	3.2	3.1	0.0
87	P625	42	0.0	93.3	6.7	6.3	0.4
88	P626	40	15.5	83.5	1.0		
89	P627	22	0.0	99.4	0.6	0.6	0.0
90	P628	30	12.2	86.1	1.7		
91	P637	28	74.5	24.6	0.9		
92	P640	57	3.2	85.9	10.9	10.7	0.2
93	P643	22	61.7	35.8	2.5		
94	P644	12	0.0	88.5	11.5	10.5	1.0
95	P645	21	0.0	95.6	4.4	4.0	0.5
96	P648	25	0.7	69.1	30.2	29.7	0.5

Figure 4.1 plots water depth (ranging from 0-210 m) against the percentage of gravel (A), sand (B), mud (C), silt (D) and clay (E). Gravel percentages generally increase towards the shoreline although some gravel does occur throughout the entire depth range (Figure 4.1A). A moderate number of samples contain no gravel. High sand percentages (60-100%) occur throughout the depth ranges on the NNCS, although for several samples there is a prominent trend of decreasing sand content towards the coastline (Figure 4.1B). Mud contents mainly range from 0-40% on the NNCS, and there is a cluster of samples with very low mud percentages at 0-50 m water depths (Figure 4.1C). Silt contents mimic the mud percentages because silt sizes completely dominate the mud fraction (Figure 4.1D). Clay percentages are consequently very low, typically < 2% (Figure 4.1E).

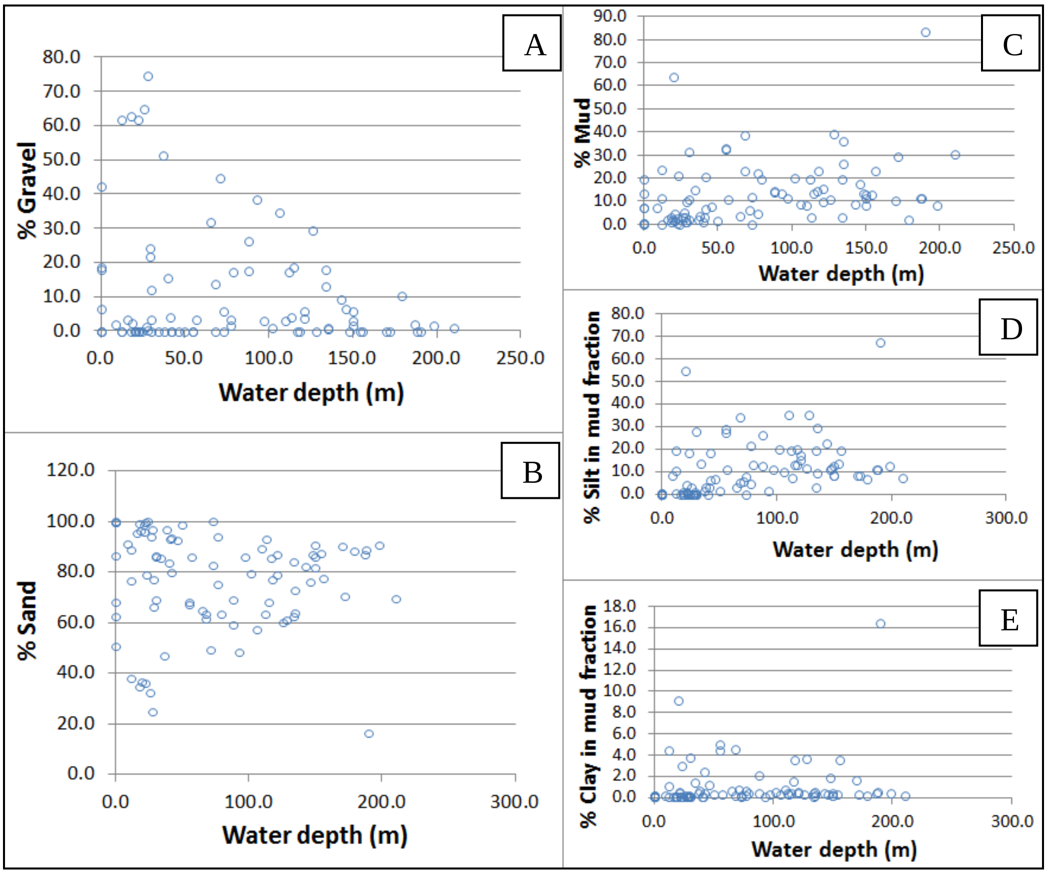


Figure 4.1: Plots of water depth versus weight percentage gravel, sand, mud, silt and clay in the NNCS sediments.

In Figure 4.3 the gravel, sand and mud percentages are plotted against water depth along the eight transects (A-H) shown in Figure 4.2. The gravel fraction shows an erratic pattern with patches containing no gravel and patches containing significant gravel on the same transect. High gravel percentages generally occur at depths from 0-30 m in transects A, D, E, F and G, but gravel is also significant in water depths from 30-100 m in transects B, C, D and H.

Sand is the dominant fraction across all eight transects and shows no clear pattern of increase or decrease in an offshore direction. In profile C, the outermost surficial sediment sample (P619) shallows to a depth of 19 m which may be due to a rocky outcrop not recorded in the bathymetric data. This is backed up by the acoustic backscatter data (Figure 2.23) which show a hard substrate in the location of sample P619, despite the surface sediment consisting almost entirely of sand.

Mud percentages are highest in transects F and G off Whangaroa Harbour and Bay of Islands. Mud percentages are particularly low in transects A, D and E off Tom Bowling, Rangaunu and Doubtless Bays. Mud generally increases offshore except in transects G and H where there is a significantly higher percentage of mud at shallower depths (12-42 m in transect G and 88 m in transect H). Transect E shows slightly higher mud percentages on the inner shelf (12 m) and the outer shelf (170 m) compared to mid-shelf depths. Overall there is not a well defined pattern of increasing mud and decreasing gravel content moving offshore on all of the eight transects, as is usually anticipated in coastal shelf to slope environments, but rather there exists a quite complex distribution of gravel, sand and mud-sized sediment across the NNCS, and between transects.

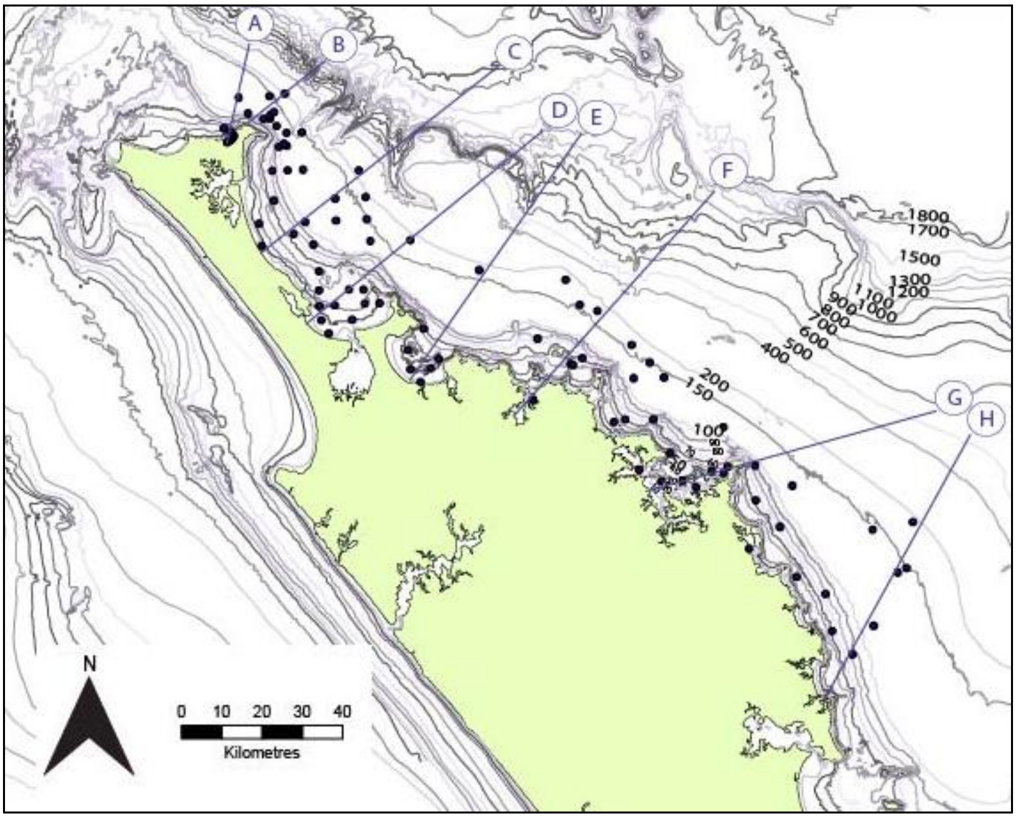


Figure 4.2: Location of 8 bathymetric transects (A-H) off northeastern Northland. See Figure 4.3 for bottom sediment textural types along these transects.

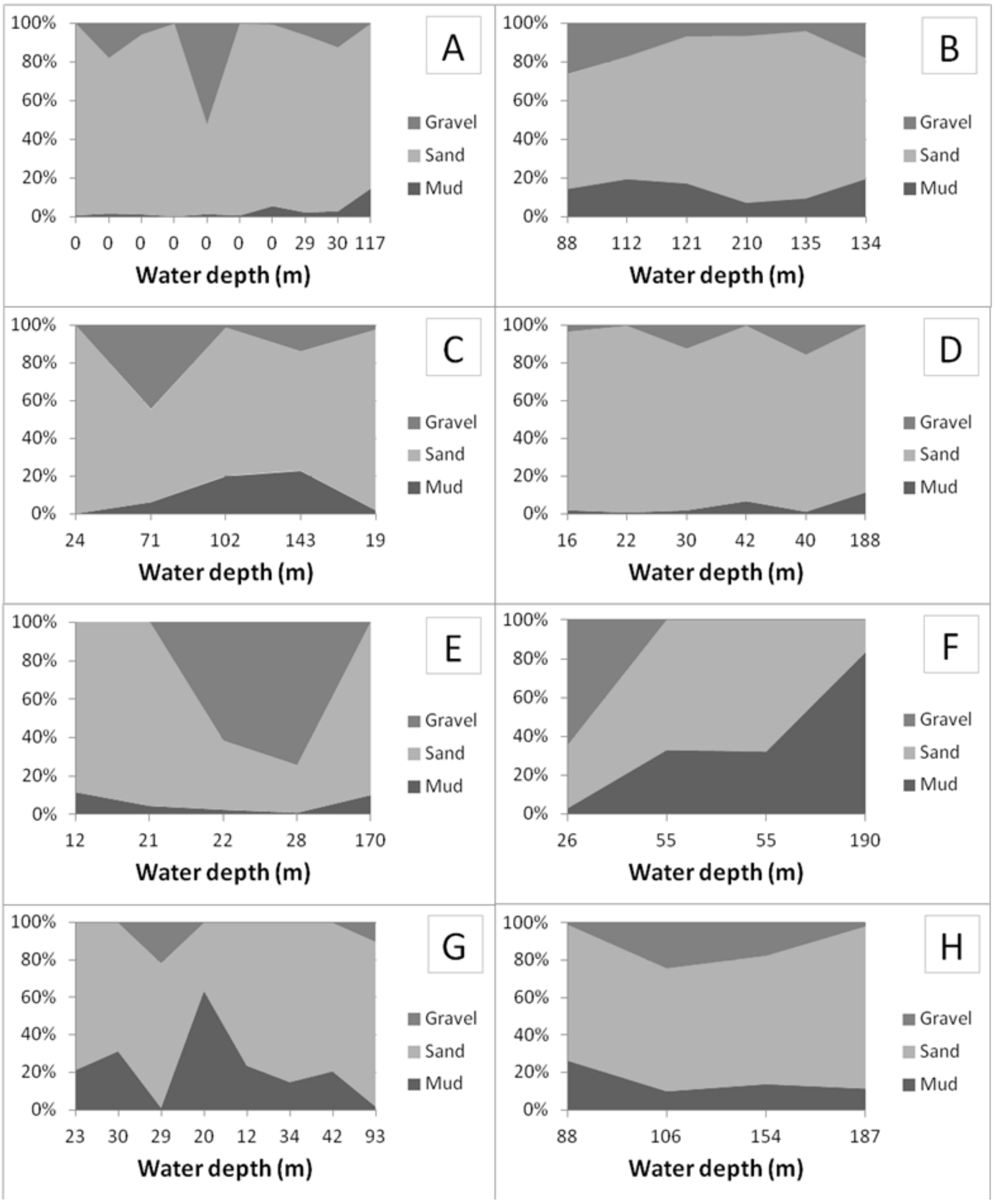


Figure 4.3: Distribution of gravel, sand and mud fractions in bottom sediments across the 8 transects (A-H) on the NNCS (see Figure 4.2). Note: transect A intersects land and seven of the samples were collected from the beach; transect C decreases to 19 m water depth offshore due to a bank or rocky outcrop in the bathymetric data; the samples in transect G have irregular water depths due to the many islands off the Bay of Islands region.

Sediment size distribution maps for the NNCS are presented in Figure 4.4 to 4.9 for % gravel, % sand and % mud, and for modal size classes for these textures. Gravel percentages of 0-5% occur throughout most of the NNCS sediments from coastal settings to the outer shelf (Figure 4.4). High gravel percentages (40-75%) are observed nearshore at North Cape, in isolated areas in Great Exhibition and Rangaunu Bay, and in Whangaroa Harbour and Bay of Islands. Moderate gravel percentages of 20-40% are also observed nearshore off North Cape and in and to the south of the Bay of Islands region. Lower percentages (0-20%) are found in deeper waters of the mid- to outer-shelf. Overall, gravel in the surficial NNCS sediments significantly decreases in an offshore direction.

The modal sizes for gravel were simply divided into pebbles (4-64 cm) and granules (2-4 cm) (Figure 4.5). Pebble-sized sediment occurs almost exactly where high gravel percentages (40-75%) exist on the NNCS. The high gravel percentages and pebble sized sediment found off North Cape and in the deeper outer shelf waters off Great Exhibition Bay correlate with the acoustic backscatter information (Figure 2.23), suggesting the existence of some hard substrates, likely rock outcrops in these areas. Granule-sized sediment occurs off North Cape, Rangaunu Bay, Bay of Islands regions and in deeper waters adjacent to the pebble-sized sediment at Sandy Bay.

Sediment with sand contents over 50 % occur almost everywhere over the NNCS (Figure 4.6). Sediment with lower sand percentages are rare, being recorded in one sample in Great Exhibition Bay, the eastern side of Doubtless Bay, Whangaroa Harbour, northern Bay of Islands and a sample in Ngurauru Bay south of the Bay of Islands.

The sand modal size distribution map shows a very mosaic pattern with mixed sand modal sizes throughout the NNCS (Figure 4.7). Sediments consisting of very coarse sand and coarse sand dominate the Bay of Islands and surrounding area. However, they are also found in the North Cape region, in mid-shelf depths off Great Exhibition Bay, northern Rangaunu and Doubtless Bay, and south of the Bay of Islands at mid- to outer-shelf depths. Medium sand is rare and found only in Rangaunu Bay and the Bay of Islands. Fine sand occurs throughout the NNCS and very fine sand dominates in Great Exhibition Bay, Whangaroa Harbour and south of the Bay of Islands.

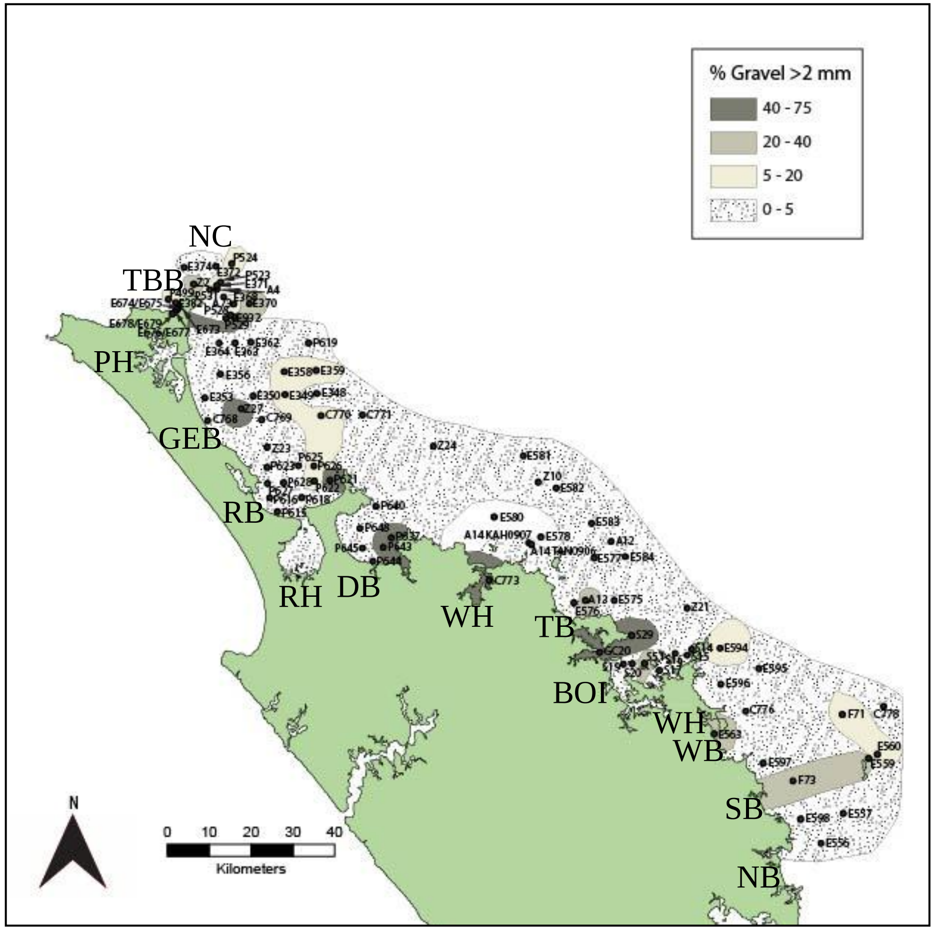


Figure 4.4: Distribution of percent gravel sized grains in the surficial sediments on the NNCS. Locality name codes are defined in Figure 1.2.

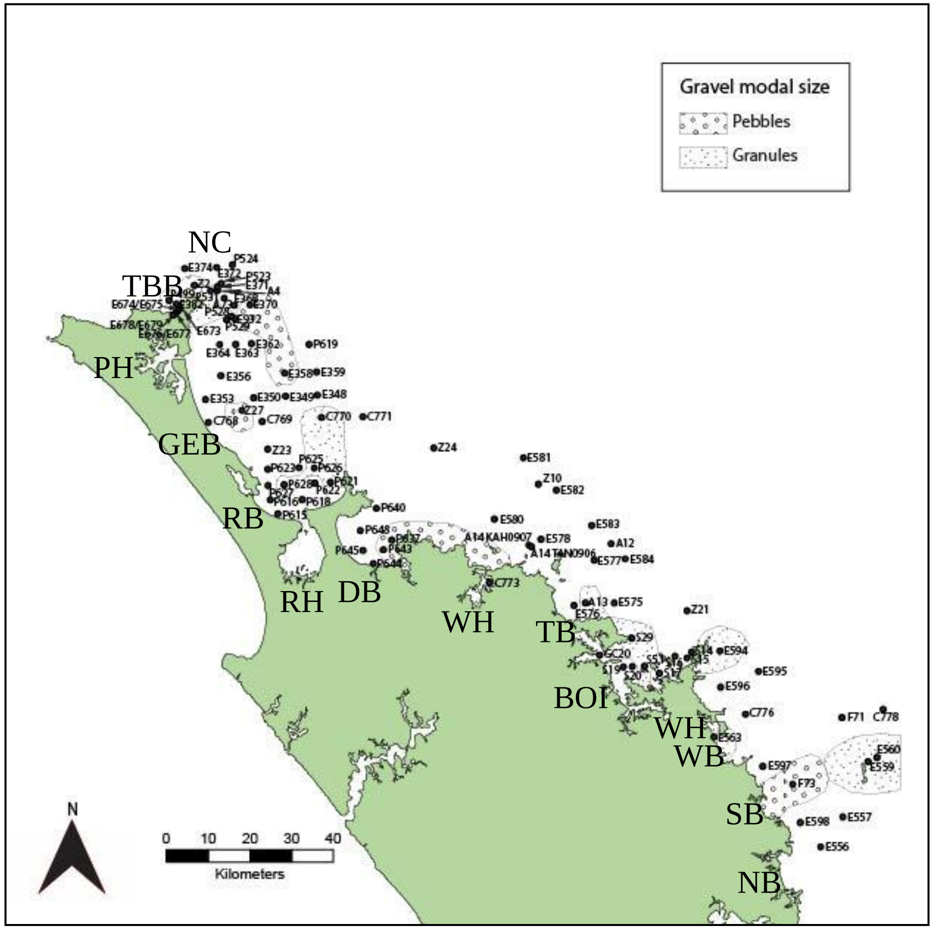


Figure 4.5: Distribution of the gravel modal size classes in the surficial sediments on the NNCS. Pebbles are sized 4-64 mm and granules 2-4 mm. Locality name codes are defined in Figure 1.2.

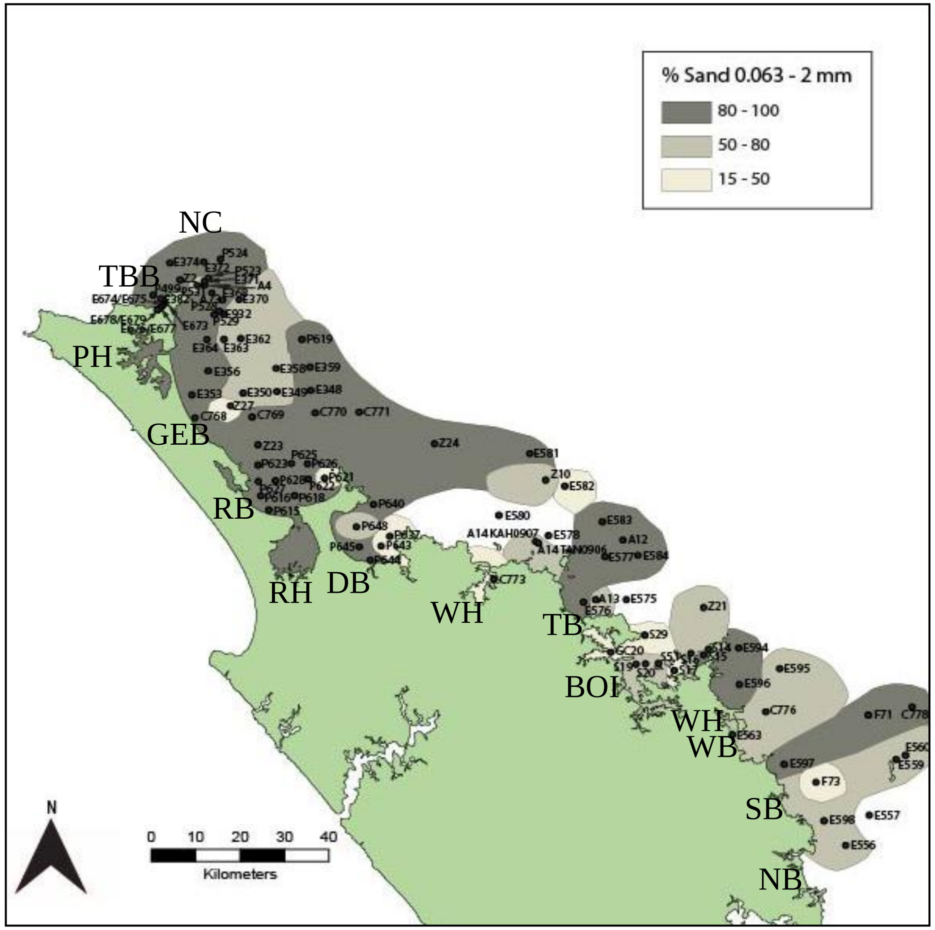


Figure 4.6: Distribution of percent sand sized grain in the surficial sediment on the NNCS. Locality name codes are defined in Figure 1.2.

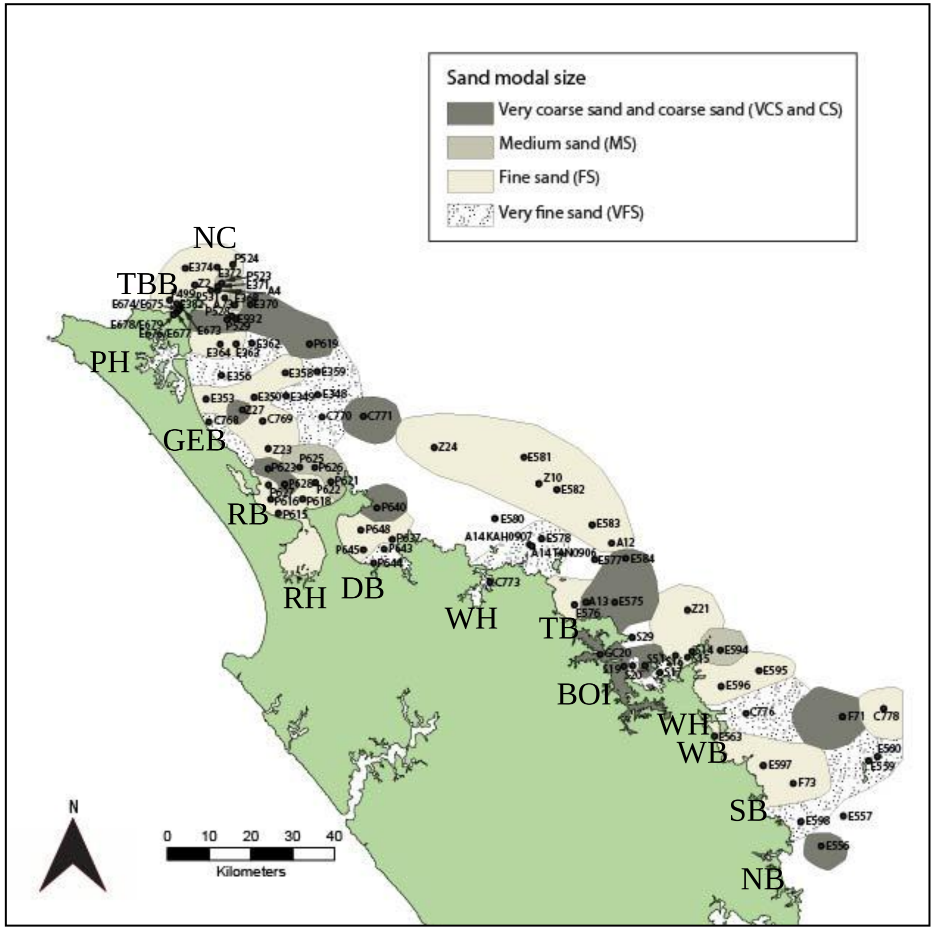


Figure 4.7: Distribution of the sand modal size classes in the surficial sediments on the NNCS. VCS are 1 – 2 mm, CS are 0.5 – 1 mm, MS are 0.25 – 0.5 mm, FS are 0.25 – 0.125 mm, VFS are 0.125 – 0.063 mm. Locality name codes are defined in Figure 1.2.

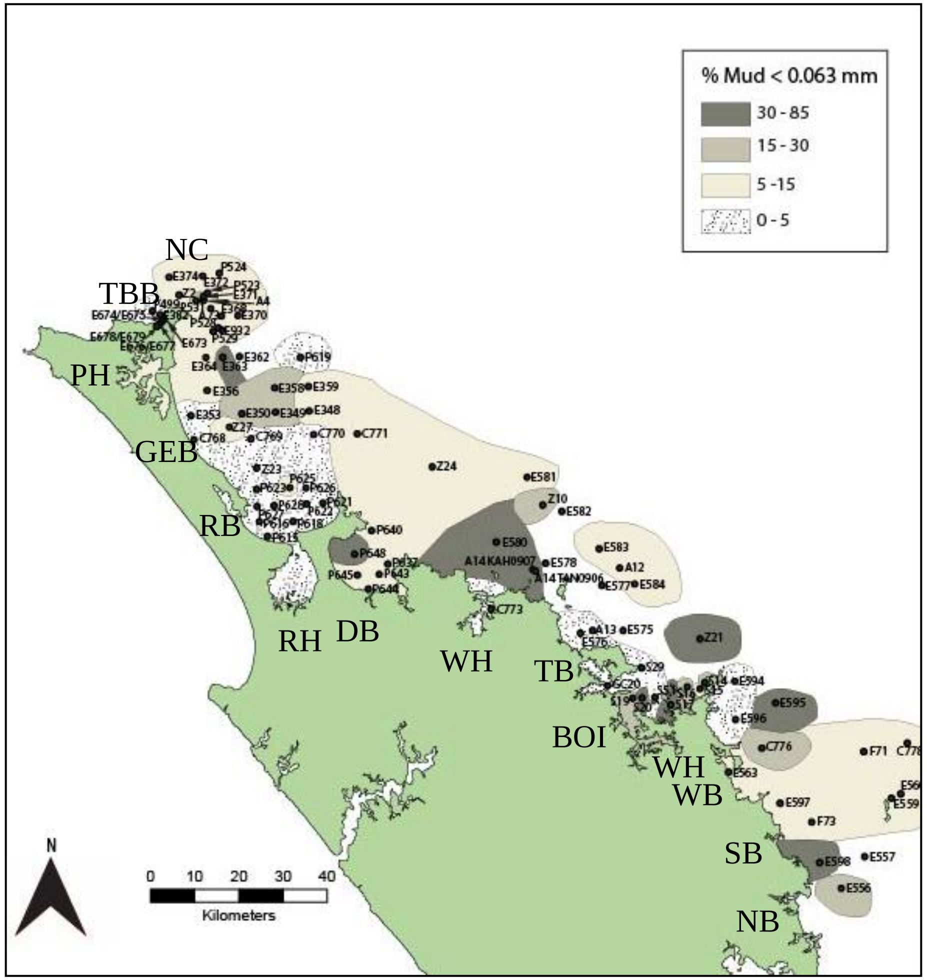


Figure 4.8: Distribution of percent mud sized grains in the surficial sediment on the NNCS. Locality name codes are defined in Figure 1.2.

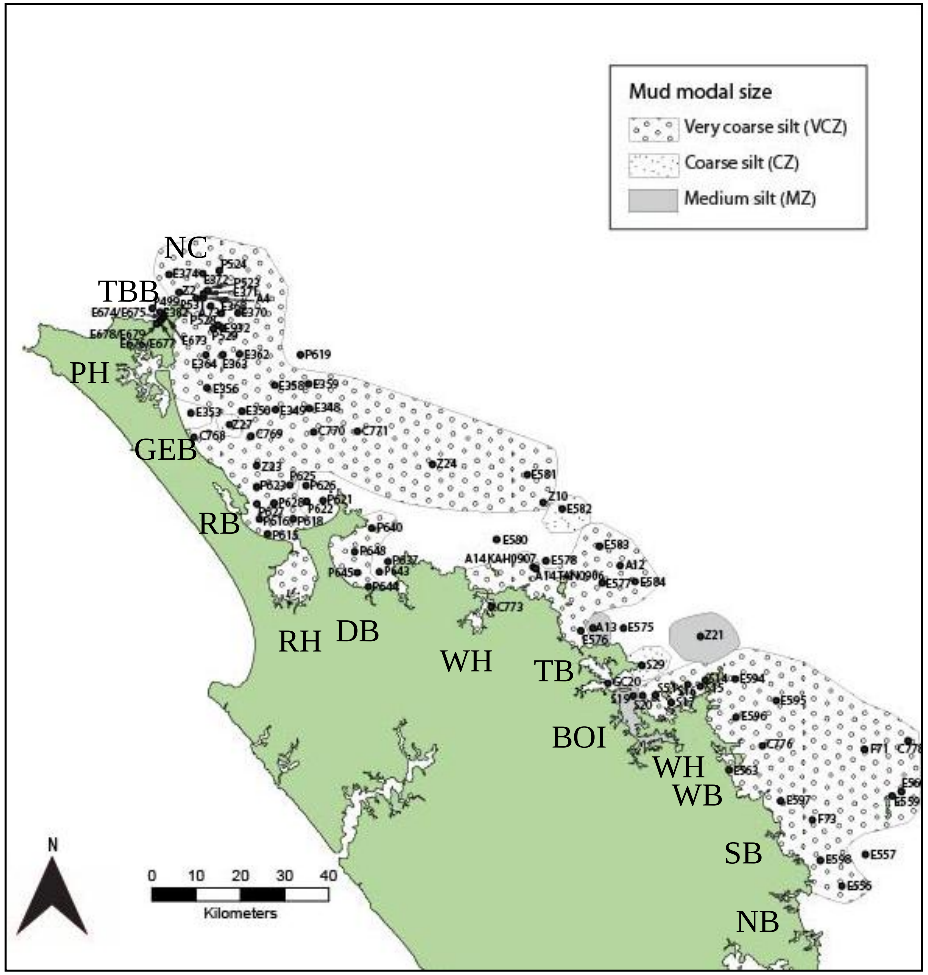


Figure 4.9: Distribution of mud modal size classes in the surficial sediments on the NNCS. VCZ is 125 - 41.7 µm, CZ is 41.7 - 31.25 µm, MZ is 31.25 - 15.63 µm. Locality name codes are defined in Figure 1.2.

Mud-sized sediment is not particularly common on the NNCS, comprising <30% throughout most of the study area (Figure 4.8). Sediment with higher mud percentages (30-85%) occurs in Doubtless Bay, mid-shelf depths adjacent to Whangaroa Harbour, in the Bay of Islands and at mid-shelf depths offshore and south of the Bay of Islands.

The mud modal size distribution map show that only silt-sized sediment occurs on the NNCS with no modes in clay sizes (Figure 4.9). The silt modes range from very coarse silt to medium silt. Very coarse silt dominates throughout most of the study area which is indicative of the coarseness of the mud-sized fraction. The finest mud modal size is medium silt which is only present rarely in Takou Bay, the Bay of Islands and at outer-shelf depths off the Bay of Islands.

4.2 SEDIMENT CLASSIFICATION

The textural classification of the NNCS sediments is generated by plotting the gravel, sand and mud percentage data onto a ternary diagram (Figure 4.10). A large proportion of the NNCS samples fall into the sand section of the ternary diagram, particularly the muddy sand and sand textural classes. Many samples fall into the gravel section of the plot, in the sandy gravel and muddy sandy gravel textural classes. Only two samples fall into the mud textural class, both as sandy muds.

The sediment can also be further classified by plotting the sand, silt and clay percentages for samples without any gravel into a ternary diagram (Figure 4.11). The sand-silt-clay ternary diagram shows that the samples consist mostly of sand and silty sand, with very rare sandy silt. There are no samples in the clay section or the mud section (which consists of a relatively equal mixture of silt and clay) of the diagram, indicating that clay-sized sediment is particularly rare in the NNCS sediments.

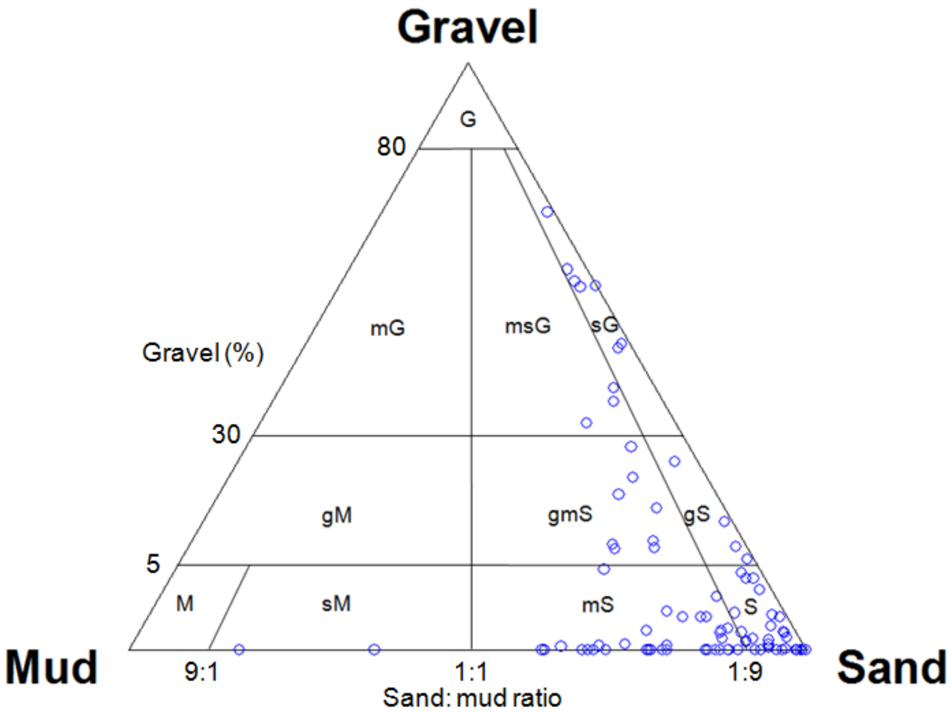


Figure 4.10: Gravel-sand-mud ternary diagram showing the total sediment textural classification (after Folk, 1968) for the NNCS sediments. G=gravel, S=sand, M=mud, g=gravelly, s=sandy, m=muddy.

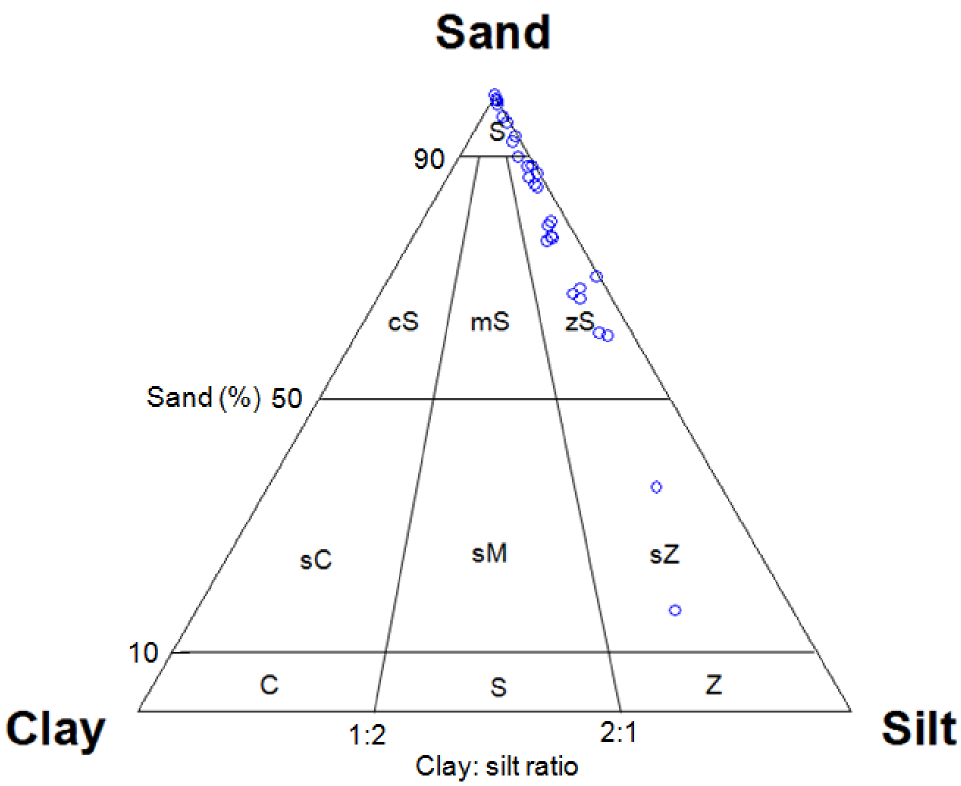


Figure 4.11: Sand-silt-clay ternary diagram showing the textural classes (after Folk, 1968) for the NNCM sediments. S=sand, M=mud, Z=silt, C=clay, s=sandy, m=muddy, z=silty, c=clayey.

The textural classes derived from the gravel-sand-mud ternary diagram (Figure 4.10) have been mapped across the NNCS and are shown in Figure 4.12. The group consisting of muddy sand and gravelly muddy sand, closely followed by that consisting of gravelly sand and sand, are the dominant textural classes on the NNCS. Sandy gravel and muddy sandy gravel are the coarsest textural classes and found mostly nearshore in the bays and harbours from Doubtless Bay southwards. Gravelly sand and sand are most common in the northern sector from North Cape to Rangaunu Harbour from coastal to outer shelf depths. Muddy sand and gravelly muddy sand are most common south of Doubtless Bay but also occur off North Cape and Great Exhibition Bay from coastal to outer shelf depths. Sandy mud is the finest textural class in the NNCS surficial sediments and is found in the Bay of Islands and on the outer-shelf off Whangaroa Harbour and Ngurauru Bay.

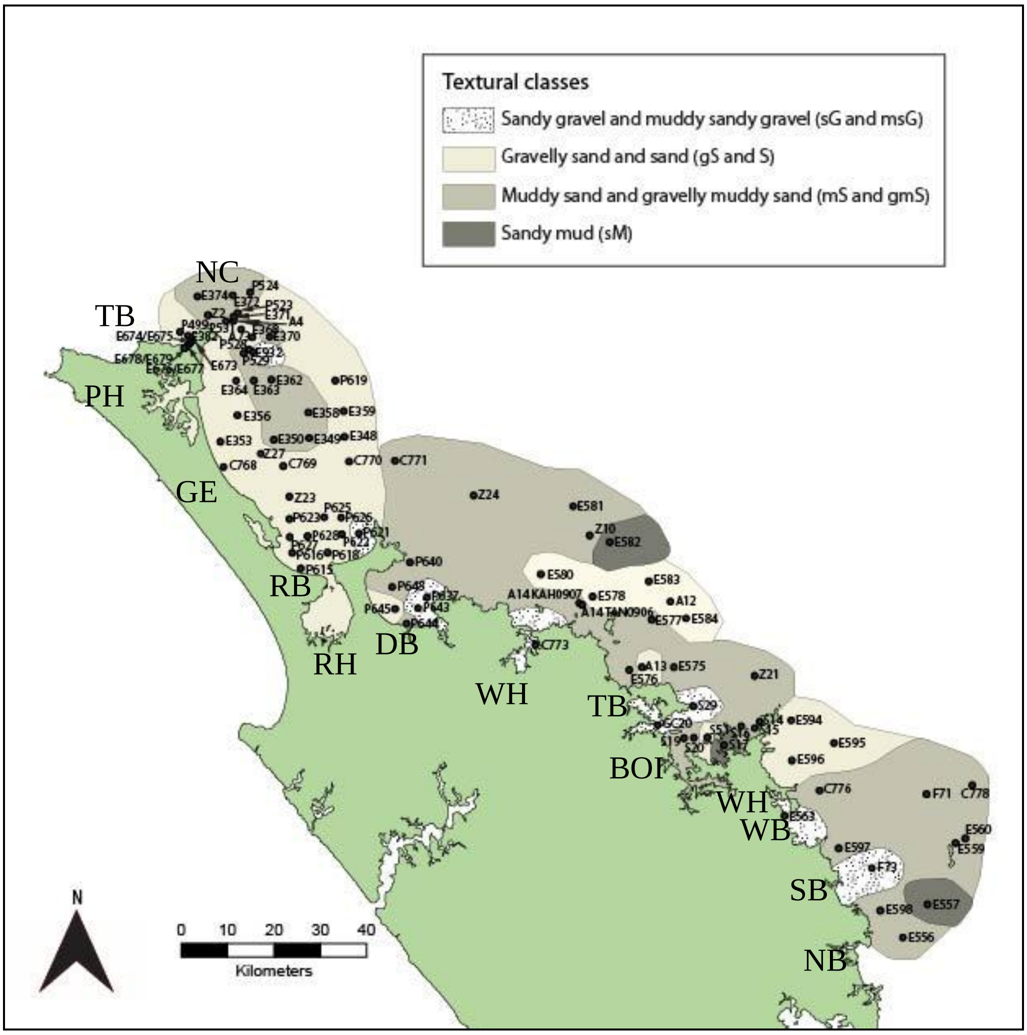


Figure 4.12: Distribution of textural classes from the gravel-sand-mud diagram in the surficial sediments across the NNCS (data from Figure 4.10). Locality name codes are defined in Figure 1.2.

The textural classifications from the sand-silt-clay diagram (Figure 4.11) for sediments that contained no gravel were also mapped across the NNCS and are shown in Figure 4.13. Silty sand is the most common textural class, occurring mostly in outer-shelf depths and in the Bay of Islands. Sand is common in Great Exhibition Bay, Rangaunu Bay and at inner-shelf depths south of the Bay of Islands. Sandy silt is the finest textural class represented in the gravel-free sediments and is only found in one sample at an outer-shelf depth off Whangaroa Harbour. Note that due to the absence of mud, textural classes in the gravel-sand-mud diagram (Figure 4.10) of sand, muddy sand and sandy mud are equivalent to textural classes of sand, silty sand and sandy silt in the sand-silt-clay diagram (Figure 4.11). This is reflected in the distribution maps in Figure 4.12 and 4.13.

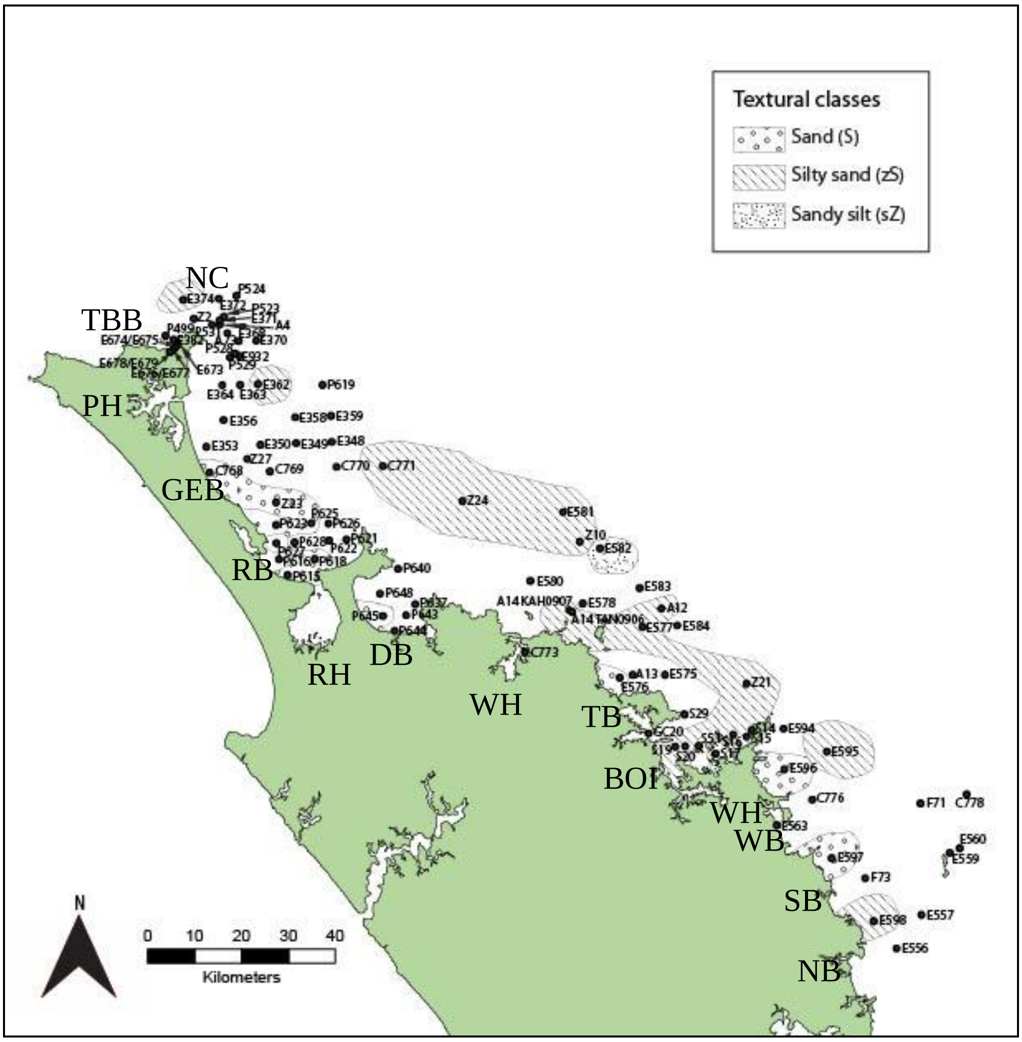


Figure 4.13: Distribution of textural classes from the sand-silt-clay diagram in the surficial sediments, without gravel, from the NNCS (data from Figure 4.11) Locality name codes are defined in Figure 1.2.

4.3 SORTING

Sorting for the NNCS surficial sediments is mapped in Figure 4.14. It shows a highly mosaic pattern that reflects the complex nature of this coastal-shelf regime. Off North Cape sorting values are mixed, ranging from very poorly sorted to very well sorted. Very well sorted and well sorted sediments are dominant off Parengarenga Harbour and Great Exhibition Bay with the odd moderately to poorly sorted sample. Sediment in Rangaunu Harbour, Whangaroa Harbour, Bay of Islands and bays south of the Bay of Islands consist of poorly sorted to very poorly sorted sediments. Doubtless Bay has very well sorted sediments on its western side but very poorly sorted sediments on the eastern side. South of the Bay of Islands there is mix of contrasting very well sorted sediments and very poorly sorted sediments. There is no clear pattern of any offshore increase in sorting as occurs in some coastal shelf environments. Poorly and very poorly sorted sediments occur in bays and harbours south of Rangaunu Bay, but they also occur in outer-shelf depths indicating that there are no particular sorting trends for the NNCS sediments.

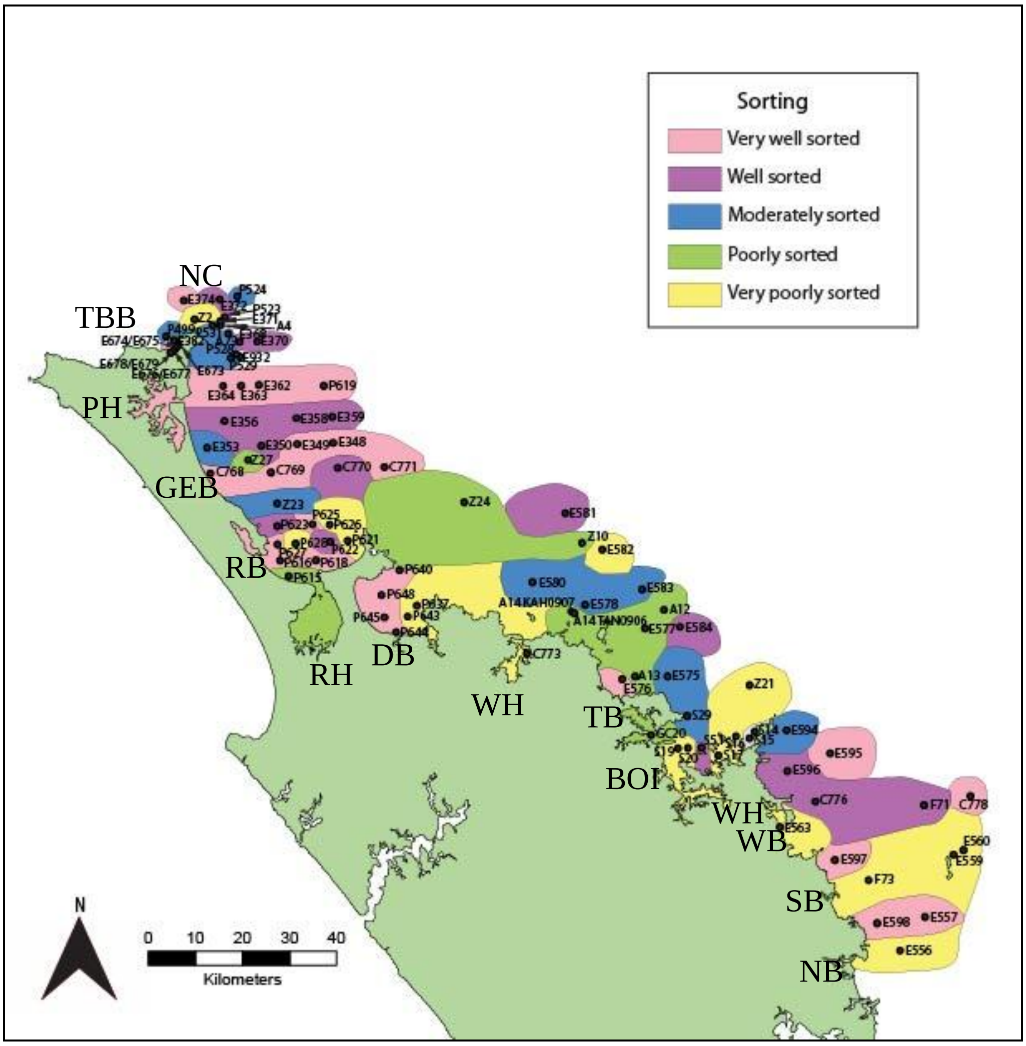


Figure 4.14: Distribution of surficial sediment sorting values on the NNCS. Sorting values obtained using the comparative sorting chart in Figure 3.4 A. Locality name codes are defined in Figure 1.2.

Chapter 5

BULK SEDIMENT COMPOSITION AND MINERALOGY

5.1 CARBONATE CONTENT

The calcium carbonate content in surficial sediments on the NNCS ranges from 0-84% and exhibits a prominent mosaic pattern throughout the study area (Figure 5.1). Based on the bathymetric map in Figure 5.2, high carbonate contents (50-85%) occur at depths from 0-150 m, mostly near shore in bays and harbours but also in mid-shelf areas adjacent to these. These areas include North Cape, depths of 100-150 m off Great Exhibition Bay, northeastern Rangaunu Bay, shallower depths (0-100 m) off Doubtless Bay, Whangaroa Harbour, depths of 80-130 m off Takou Bay, the Bay of Islands, and between Sandy and Ngurauru Bay in the southern sector.

Sediment with moderate carbonate contents (30-50%) occurs mostly in water depths of 100-200 m on the outer shelf and slope from Great Exhibition Bay to the southern end of the NNCS study area. They also occur at depths of 0-100 m in the southern sector at Takou Bay, northern Bay of Islands, Whangaruru Harbour region, Sandy Bay and Ngurauru Bay.

Sediment with low carbonate contents (0-30%) occurs mostly in the northern sector at depths ranging from 0-150 m. These areas include Parengarenga Harbour down through Great Exhibition Bay and western Rangaunu Bay, the whole of Rangaunu Harbour, and northern Doubtless Bay. The only sediment in the southern sector with low carbonate contents, at coastal and deeper shelf and slope depths from 0-200 m, is off Whangaruru Bay.

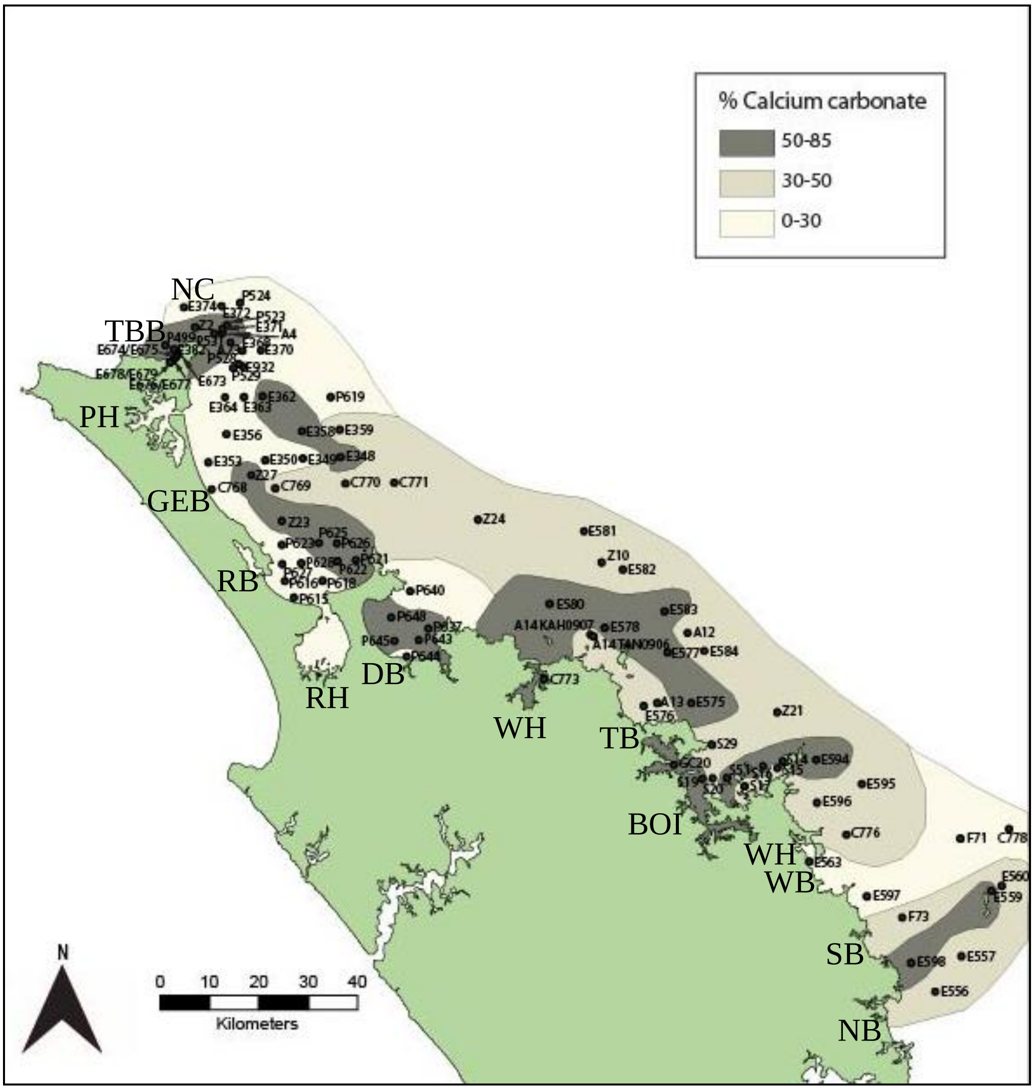


Figure 5.1: Distribution of calcium carbonate content in bulk surficial sediments on the NNCS. Locality name codes are defined in Figure 1.2.

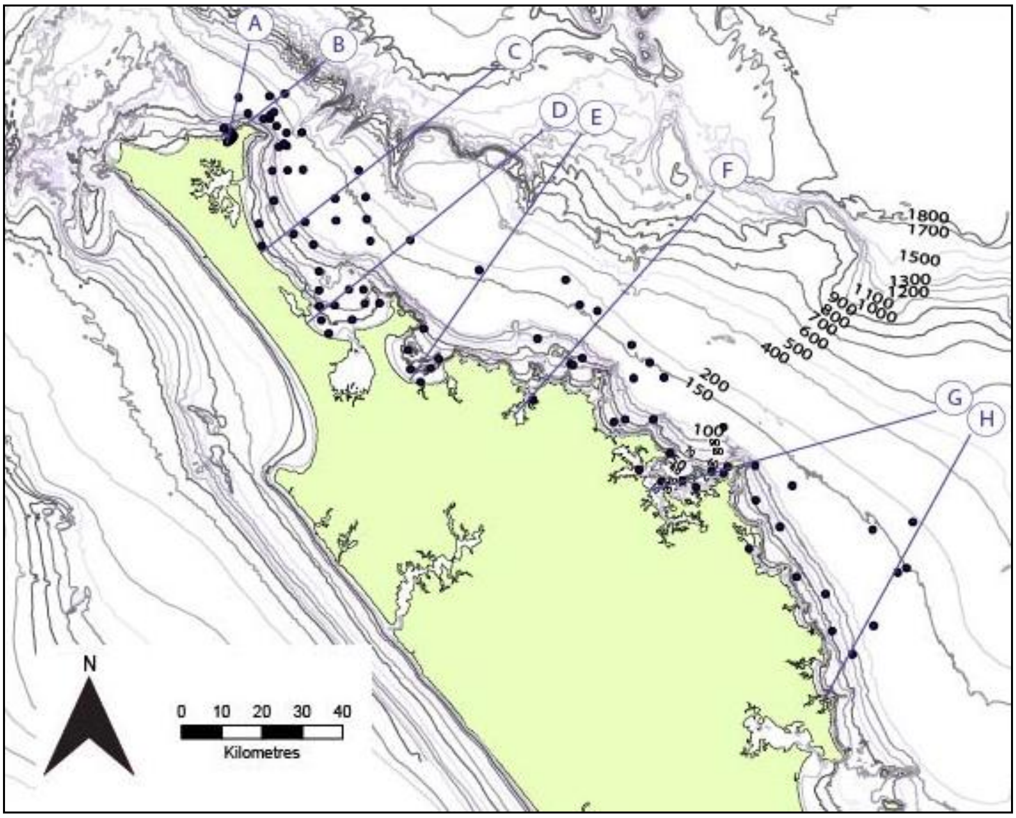


Figure 5.2: Bathymetric map for the northeastern Northland continental margin showing the transect lines A-H for which bathymetric profiles were reproduced in Figure 2.13 and 2.14.

5.2 SILICICLASTICS

Siliciclastic minerals in the NNCS sediments include mainly quartz and feldspar (Section 5.2.1), but also heavy minerals (Section 5.2.2) and rock fragments (Section 5.2.3).

5.2.1 Quartz and feldspar

Quartz and feldspar are the dominant siliciclastic minerals in the sediments on the NNCS. Many of the quartz and feldspar grains appear dirty and have limonite staining in fractures and on surfaces. Due to the degraded nature and significant rounding of these siliciclastic grains, differentiating quartz from feldspar was near impossible. Therefore XRD data (XRD peak height counts) were mainly used to semi-quantify their abundances and distribution. Petrographic analysis does, however, reveal that the abundance of quartz and feldspar in the NNCS surficial sediments ranges from 0-85%. Both quartz and feldspar grains are subrounded and well sorted with a dominant modal size of 0.15-0.20 mm (fine sand) (Plate 5.1 A-H).

The general distribution of quartz and plagioclase is mapped in Figure 5.3 and 5.4 based on XRD peak counts. Quartz grains are most abundant (>1000 counts) in inner-shelf environments at water depths of <100 m at Great Exhibition Bay, Rangaunu Harbour and the southern part of its harbour, and Takou Bay. Moderate quartz contents (200-1000 counts) are present at water depths from 0-200 m in the northern sector of the NNCS, and in inner-shelf depths from 50-90 m in the very southern sector at Whangaruru and Ngurauru Bay. Most of the sediment on the NNCS, however, contains low quartz contents (0-200 counts) from mid to southern parts of the NNCS at 0-210 m water depth, including Whangaroa Harbour, Bay of Islands and other southern bays and inlets. Overall quartz grains tend to be more abundant nearshore and in the north, often decreasing in abundance in an offshore direction.

High feldspar abundances (>500 counts), dominated by plagioclase, are common throughout the NNCS and occur more often in mid- to outer-shelf depths at >50 m water depth in the northern sector, off Bay of Islands, and near Whangaruru Bay. Moderate feldspar abundances (200-500 counts) occur commonly at coastal and inner-shelf depths of <100 m in the northern sector, and in a patchy distribution at mid- to outer-shelf water depths of >50 m in the southern sector. Low feldspar abundances (<200 counts) are present in water depths ranging from 0-210 m patchily throughout the NNCS off Great Exhibition Bay, Whangaroa Harbour, Bay of Islands region, and between Sandy Bay and Ngurauru Bay.

PLATE 5.1

Photomicrographs of quartz and feldspar rich NNCS sediments

A Quartz and feldspar rich sample E382 (transect A; 29 m depth). The quartz and feldspar grains are well sorted and subrounded, and most are dusty looking and limonite stained. Opaque heavy minerals and scattered broken and altered shell fragments are also present.

B Quartz and feldspar rich sample E382 (transect A; 29 m depth). The subrounded and dusty appearance of grains is again evident, although here the limonite staining is more apparent as indicated by bright orange coloured quartz and feldspar grains. A small gastropod shell (2.5 mm) is present amongst smaller fragmented shell material and heavy minerals.

C Sample E580 (near transect F; 84 m depth) with small to moderate amounts of quartz and feldspar and common broken, microbored and limonite stained skeletal fragments (mostly of foraminifera, gastropods and bryozoans). Occasional carbonate grains are altered to glauconite and heavy minerals are present.

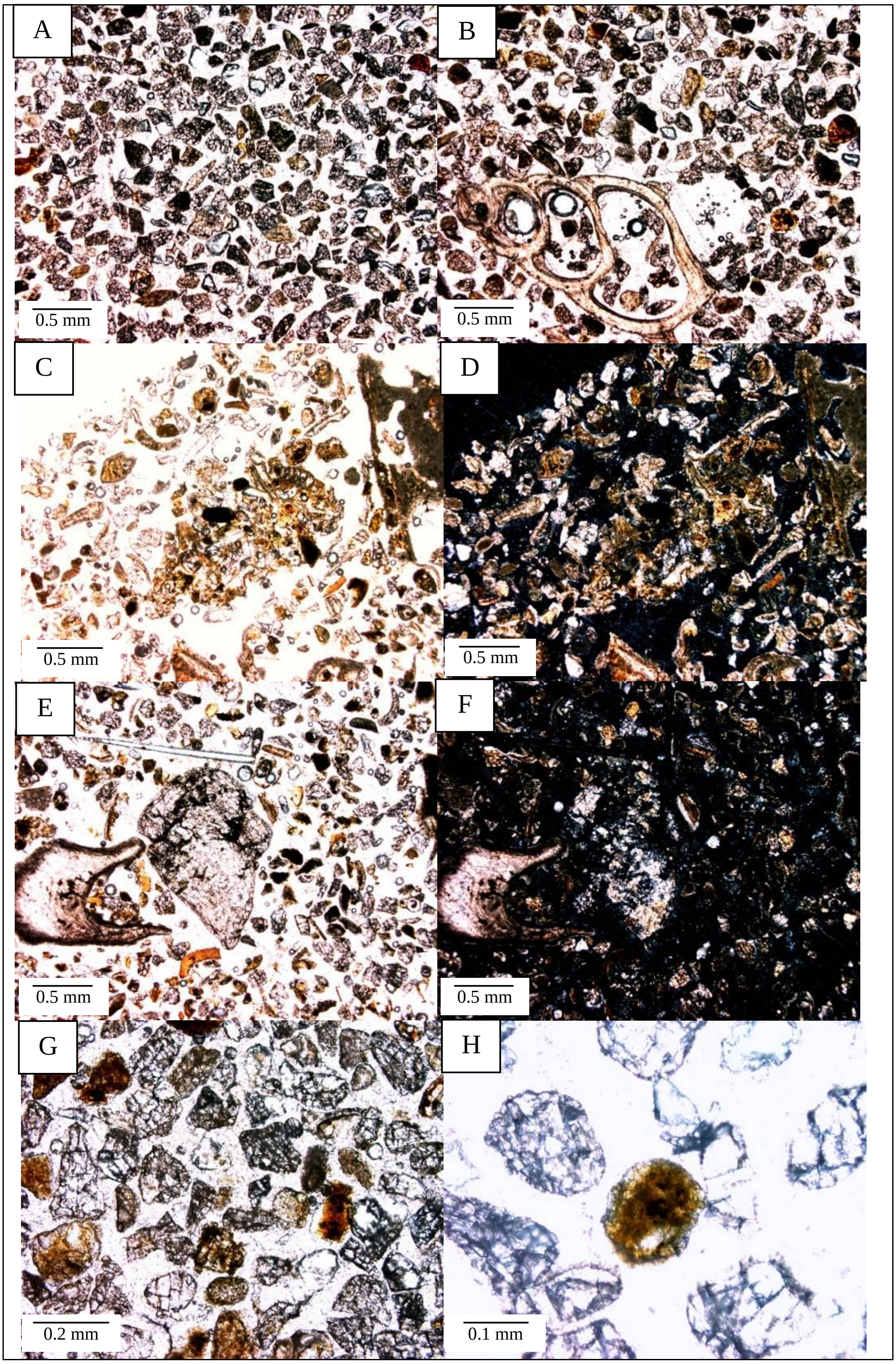
D As for C except viewed under cross-polarised light (XPL), displaying the limonite and glauconite staining in the skeletal grains and the light coloured quartz and feldspar grains.

E Sample C770 (near transect D; 134 m depth) with moderate amounts of quartz and feldspar grains and predominantly very poorly sorted, broken, microbored and limonite stained skeletal fragments (mostly from bivalves). Also seen is a large sponge spicule (top left), a barnacle fragment (mid left), a rock fragment (middle), and opaque heavy minerals.

F As for E except under XPL displaying the limonite staining in the skeletal grains and the lighter coloured quartz and feldspar grains.

G Quartz and feldspar rich sample P623 (near transect D; 41 m depth) at higher magnification (10x) showing the surface fractures and limonite staining of grains.

H Quartz and feldspar rich sample C768 (transect C; 24 m depth) at very high magnification (20x) showing the dusty appearance, subrounded nature, surface fractures and limonite staining (central grain) of grains.


A
B
C
D
E
F
G
H
0.5 mm
0.5 mm
0.5 mm
0.5 mm
0.5 mm
0.5 mm
0.2 mm
0.1 mm

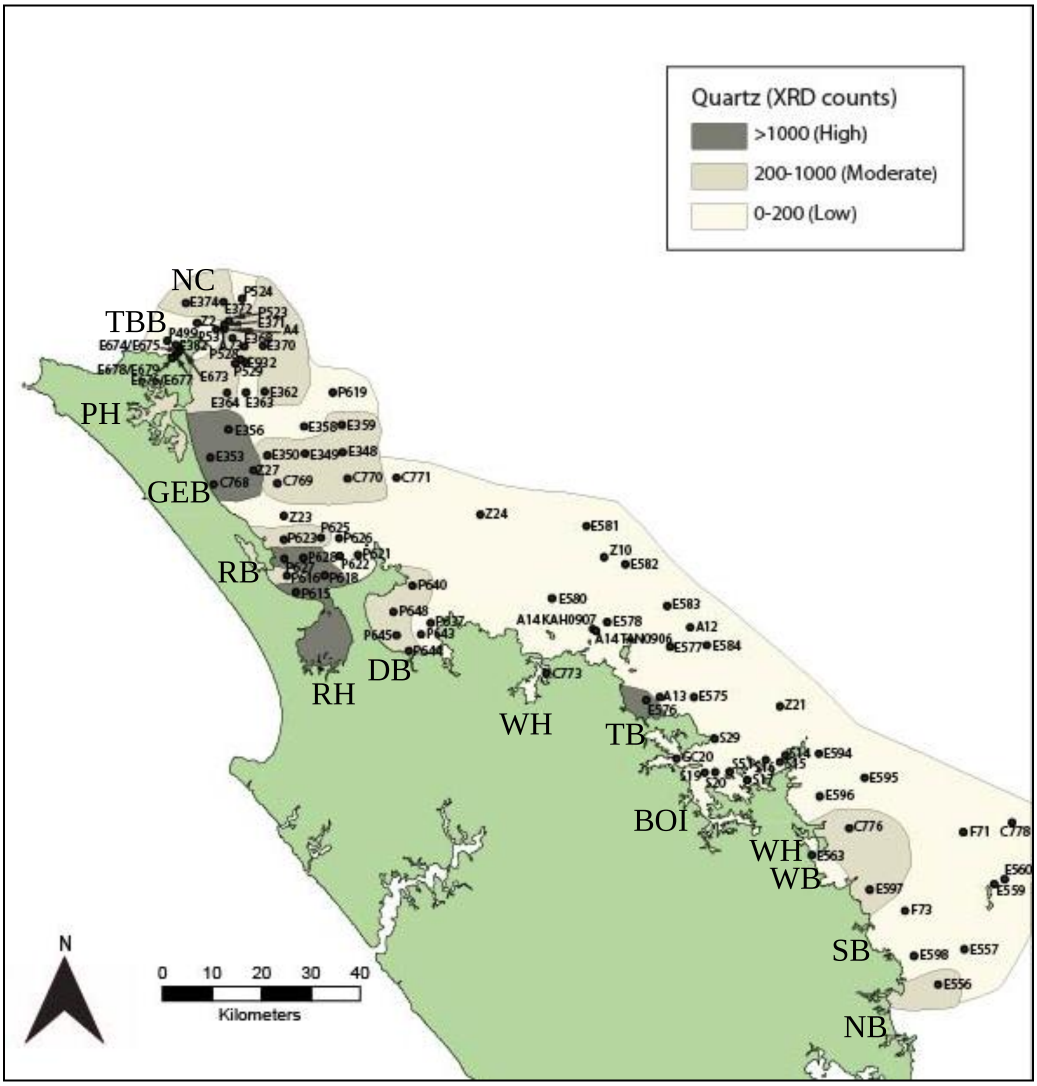


Figure 5.3: Relative abundance of quartz in surficial sediments on the NNCS based on X-ray diffraction (XRD) counts. Locality name codes are defined in Figure 1.2.

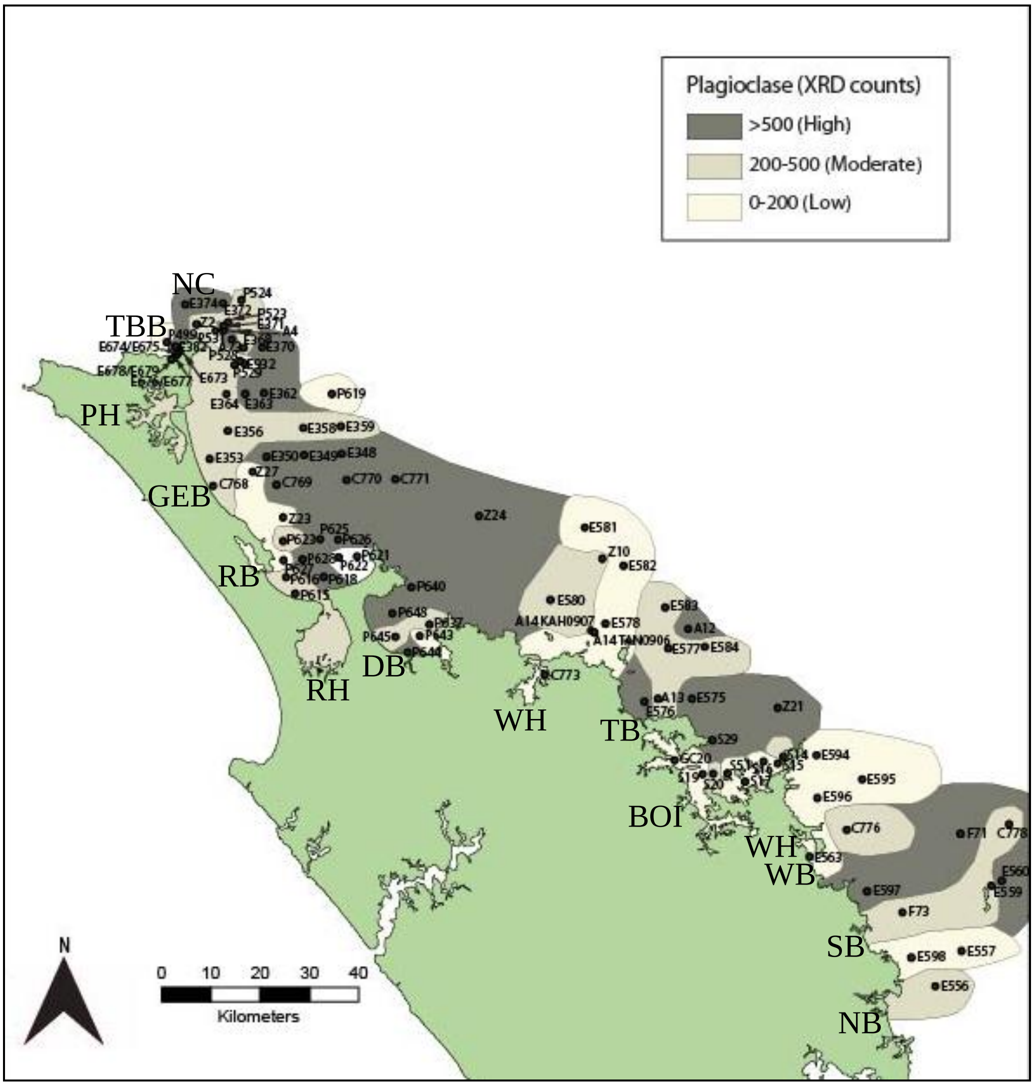


Figure 5.4: Relative abundance of feldspar (plagioclase) in the surficial sediments on the NNCS based on X-ray diffraction (XRD) counts. Locality name codes are defined in Figure 1.2.

5.2.2 Heavy minerals

Specific heavy mineral analysis was not performed in this study, although it was done so off Parengarenga Harbour and northwards in 'the eastern province' by Summerhayes (1969a) (Table 5.1). His method involved removing organic matter, light material, carbonates and iron oxides so that only heavy minerals remained, from which slides were made. Minerals were counted using a petrographic microscope along adjacent gridlines to reach a total of 100 grains to determine the proportions of altered, opaque and non-opaque heavy minerals (note altered heavy minerals are not included in Table 5.1). The non-opaque heavy minerals types were then counted until the total number of non-opaque grains reached 100 (note unidentifiable minerals were not included in Table 5.1). From this data it can be assumed for the majority of the northern sector of the NNCS that non-opaque heavy minerals dominate over opaque heavy minerals. Non-opaque minerals in the NNCS include (in order of highest to lowest abundance) epidote, hypersthene, green hornblende, brown hornblende, enstatite and some augite (Table 5.1).

Table 5.1: Heavy mineral grain count data (modified from Summerhayes, 1969a).

Station-#	Opaque	Non-opaque	Epidote	Green Horne-blende	Brown Horne-blende	Hypers-thene	Enstatite	Augite
E348	13	75	39	20	6	31	3	-
E349	8	79	33	28	3	22	7	-
E353	60	22	52	15	7	19	7	-
E356	17	56	53	17	3	24	-	3
E358	5	84	17	28	5	30	5	5
E359	14	73	34	27	5	25	6	3
E362	6	82	38	18	8	31	3	2
E364	12	64	47	24	7	18	1	2
E368	18	62	58	12	1	27	1	-
E370	8	81	29	25	11	25	8	2
E372	24	64	32	19	3	37	5	1
E382	16	62	57	3	1	35	4	-

Opaque heavy minerals grains in the NNCS sediments were mainly rounded to subangular in shape indicating that they were most likely transported (Plate 5.2 A-D). They are well sorted and commonly 0.1-0.3 mm in size (Plate 5.2 A-D). The grains having an abraded to rounded octahedral shape are likely to be (titano)magnetite, while those with a more elongated shape are possibly ilmenite.

Opaque grains in the NNCS surficial sediments are rare (<1%) throughout much of the study area (Figure 5.5). They are most concentrated at 5-15% at mid-shelf depths of 100-150 m off Parengarenga Harbour in the north, and inner shelf depths of 0-50 m off Whangaruru Bay in the south. Opaque heavy mineral grains at 1-5% are present off Tom Bowling Bay, in coastal to outer-shelf water depths from 0-200 m off Great Exhibition Bay, western Doubtless Bay, Takou Bay, and coastal to inner-shelf depths from 0-50 m off Whangaruru Harbour.

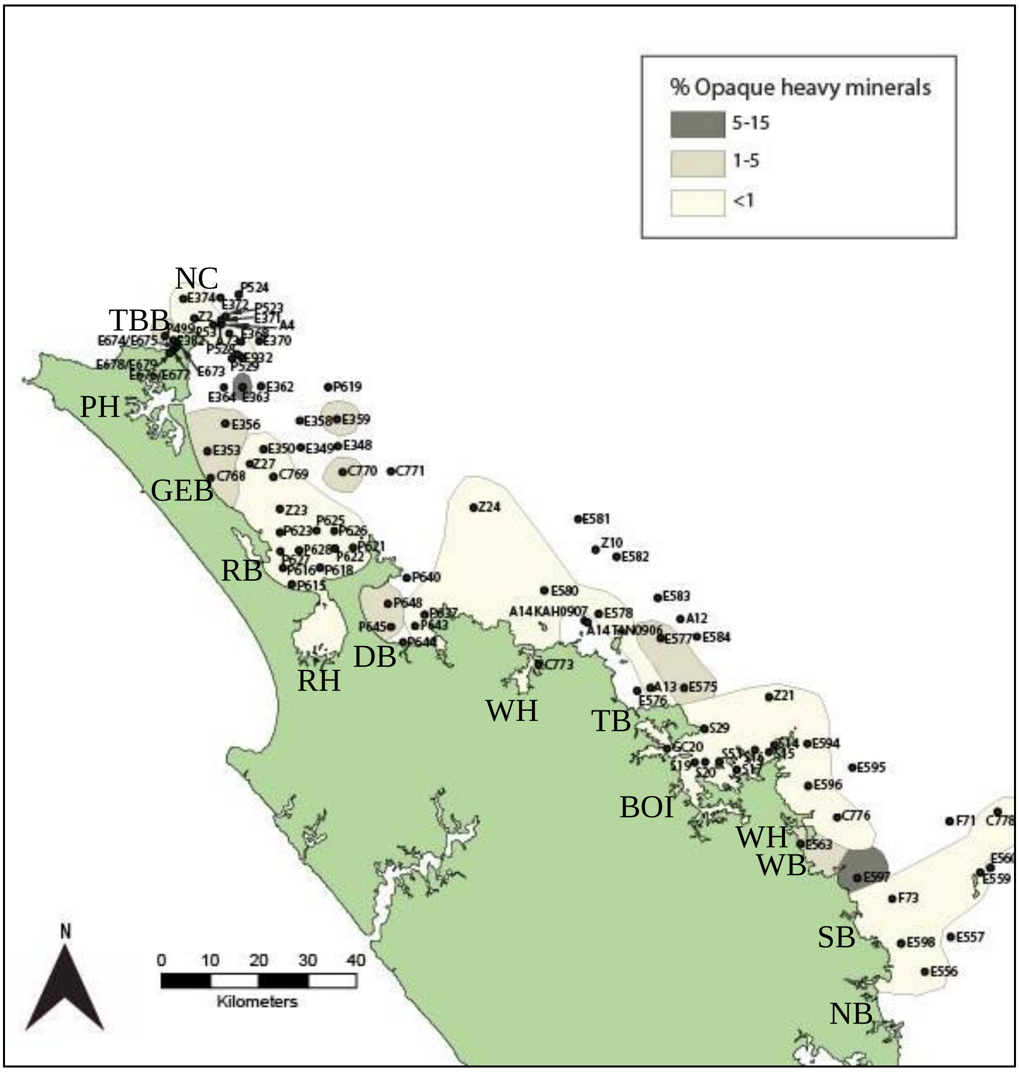


Figure 5.5: Distribution of opaque heavy minerals dominated by (titano)magnetite-ilmenite in the NNCS surficial sediments. Locality name codes are defined in Figure 1.2.

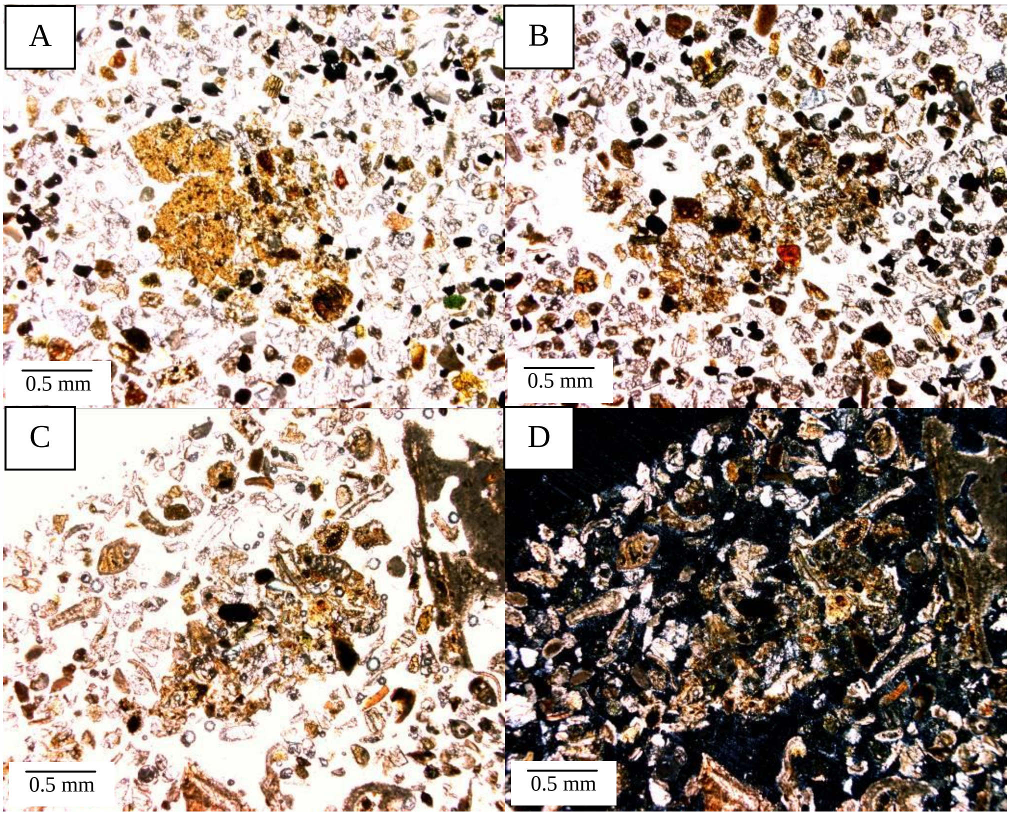
PLATE 5.2

Photomicrographs of some opaque heavy mineral grains and sedimentary rock fragments type 2 in NNCS sediments

A, B Heavy mineral rich sample E597 (near transect H; 46 m depth). Dark heavy minerals are (titano)magnetite (up to 15%). Dirty limonite stained quartz and feldspar grains dominate the sample and, along with heavy mineral grains, are contained in poorly-lithified mixed siliciclastic-carbonate sedimentary rock fragments type 2. These also contain broken, unidentifiable, limonite altered skeletal carbonate grains (possibly *Homotrema*, a benthic encrusting foraminifera in this sample) and have very irregular shapes and sizes. A glauconite grain is present at bottom right of the photomicrograph.

C Sample E580 (near transect F; 84 m depth) contains dirty limonite stained quartz and feldspar grains and often broken and unidentifiable limonite stained skeletal carbonate grains. A sedimentary rock fragment type 2 is present in the centre of the photomicrograph and is composed of poorly-lithified siliciclastic-carbonate grains, involving quartz and feldspar, (titano)magnetite, benthic foraminifera, sponge spicules and other broken carbonate grains.

D As for C, but under XPL showing the quartz and feldspar and skeletal carbonate grains with clear limonite staining. The (titano)magnetite grains in sedimentary rock fragment type 2 remain dark (opaque) under XPL.


A
B
C
D
0.5 mm
0.5 mm
0.5 mm
0.5 mm

5.2.3 Rock fragments

Three main types of rock fragments occur in the NNCS surficial sediments, namely volcanic rock fragments, sedimentary rock fragments type 1, and sedimentary rock fragments type 2.

Volcanic rock fragments in the NNCS sediments tend to be rounded to subangular, poorly sorted grains of basaltic composition typically 1.0-3.0 mm in size (Plate 5.3 A-H). They have a porphyritic texture involving lath shaped plagioclase from about 0.1-0.5 mm in size (Plate 5.3 A-F), and irregularly shaped pyroxene, olivine and sometimes augite phenocrysts 0.25 mm in size (Plate 5.3 B, C and D), set in a glassy groundmass. The rock fragments show a variolitic texture of fine, radiating fibres of plagioclase or pyroxene (Plate 5.3 B), a fabric common in submarine basalts during rapid quenching in seawater (McPhie *et al*., 1993). The volcanic grains have a medium to dark grey-brown, probably devitrified, glassy groundmass, which is typical of submarine basalts.

Volcanic rock fragments are relatively rare in NNCS sediments, making up <1% of the sediment components throughout most of the study area. Exceptions include eastern Doubtless Bay and the Bay of Islands region where contents range from 1-5%, and off Whangaroa Harbour with values from 5-15% (Figure 5.6).

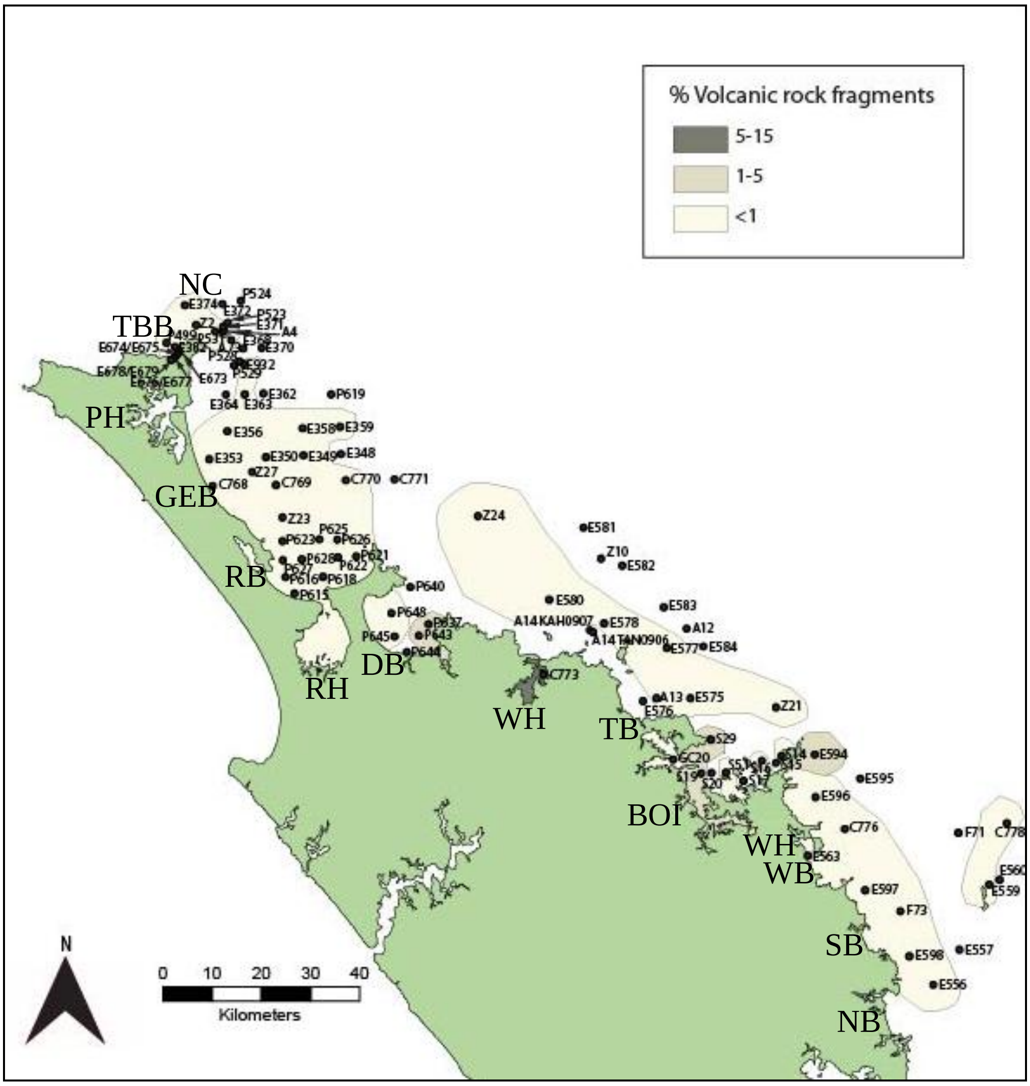


Figure 5.6: Abundance of volcanic rock fragments in whole samples of the NNCS surficial sediments. Locality name codes are defined in Figure 1.2.

PLATE 5.3

Photomicrographs of volcanic rock fragments in NNCS sediments

A Sample A4 (transect B; 132 m depth) showing a basaltic fragment with lath-shaped colourless plagioclase, green olivine and yellow-brown pyroxene phenocrysts set in a very dark glassy groundmass.

B Sample P637 (transect E; 28 m depth) showing a basaltic with a variolitic texture of radiating fibres of plagioclase, green olivine and yellow-brown pyroxene in a dark-brown to black glassy groundmass.

C Sample C773 (transect F; 26 m depth) showing a basaltic fragment with lath-shaped colourless plagioclase, irregularly shaped light yellow-brown pyroxene, and colourless olivine phenocrysts set in a very dark, glassy groundmass. A bivalve fragment is present on left side of image.

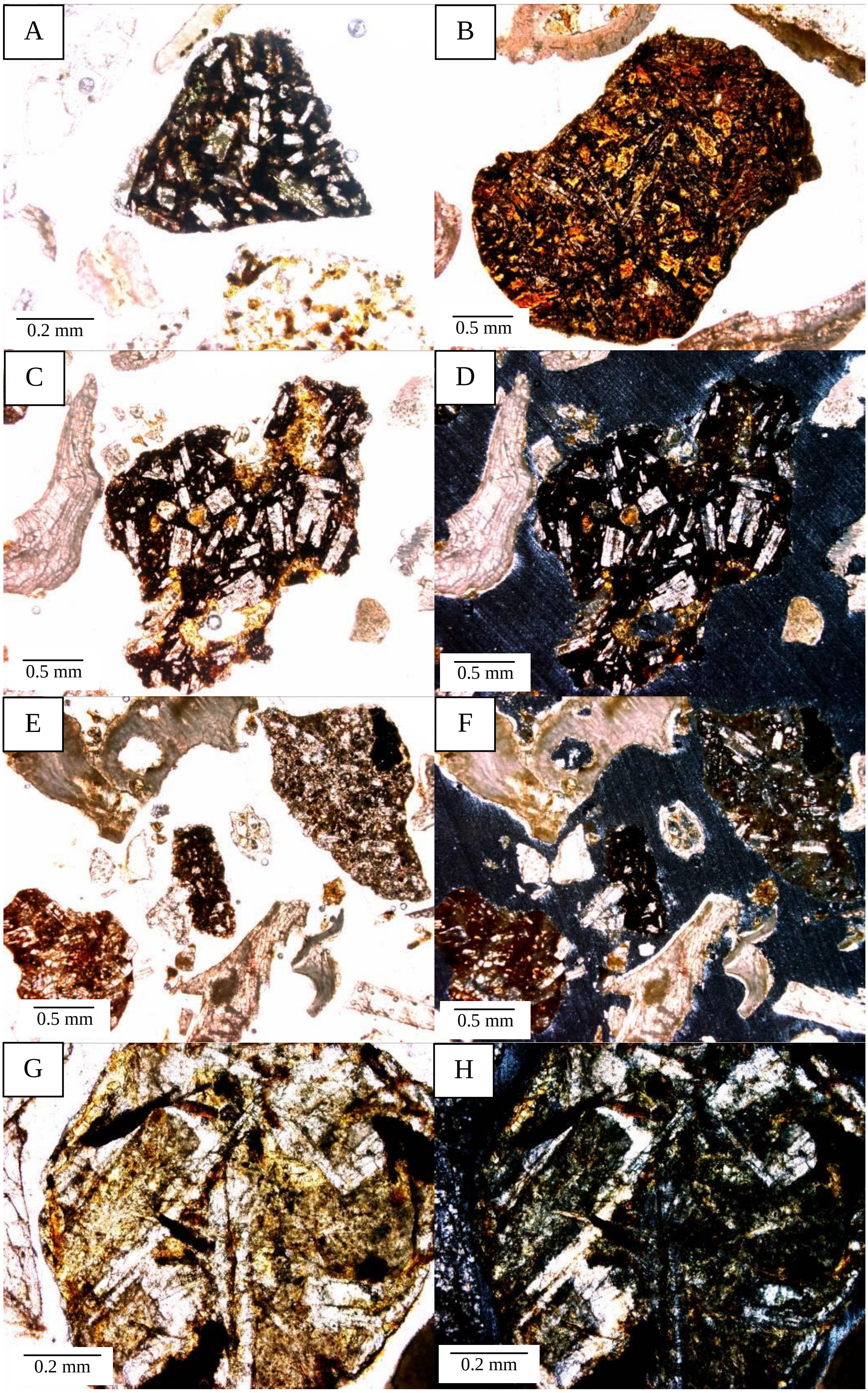
D As for C but under XPL showing that the light yellow-brown pyroxene crystals remain the same colour under XPL.

E Sample C773 (transect F; 26 m depth) showing basaltic grains with dark red-brown glassy groundmass containing often lath shaped colourless plagioclase and irregularly shaped yellow-brown pyroxene and colourless olivine phenocrysts. Bivalve fragments also present.

F As for E but under XPL.

G Sample S29 (near transect G; 37 m depth) showing a basaltic grain mostly of zoned colourless plagioclase, light brown to yellow-green pyroxene and yellow-green olivine. The dark groundmass is not so visible in this example.

H As for G but under XPL. Note the greenish hue from the pyroxene and olivine under XPL.


A
0.2 mm
B
0.5 mm
C
0.5 mm
D
0.5 mm
E
0.5 mm
F
0.5 mm
G
0.2 mm
H
0.2 mm

Sedimentary rock fragments type 1 consists mainly of what appear to be greywacke and/or argillite lithologies (Plate 5.4 A-F). Sedimentary rock fragments type 1 often have a red-brown colour, but can also have a greenish tinge due to chlorite (Plate 5.4 A-F). They are typically subrounded, poorly sorted and range in size from about 1.0-3.0 mm (Plate 5.4 A-F). The highest contents of 50-75% of sedimentary rock fragments type 1 occur locally in mid-shelf depths from 100-150 m off Parengarenga Harbour, and at inner to mid shelf depths from 0-150 m off Takou Bay and Bay of Islands (Figure 5.7). Contents of 15-50% occur in inner-shelf depths from 0-50 m off northeastern Doubtless Bay and the Bay of Islands. Lower contents of 1-15% and <1% clearly dominate the NNCS sediments and are found throughout the study area from North Cape to Ngurauru Bay.

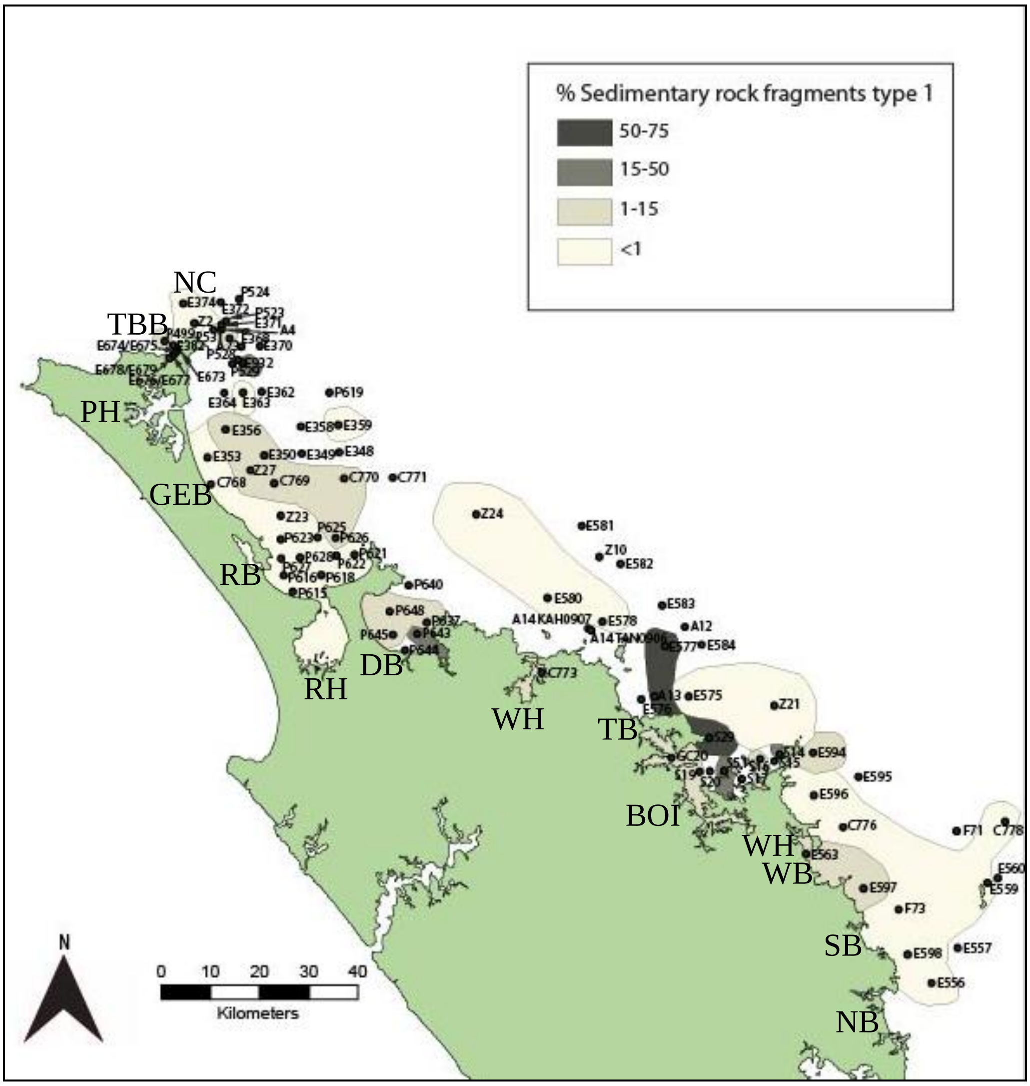


Figure 5.7: Abundance of sedimentary rock fragments type 1 in whole samples of NNCS surficial sediments. Locality name codes are defined in Figure 1.2.

PLATE 5.4

Photomicrographs of sedimentary rock fragments type 1 in NNCS sediments

A Sample A13 (between transect G and F; 65 m depth) showing a rounded, red-brown argillite fragment containing very fine grained quartz and plagioclase grains. Barnacle fragments also present.

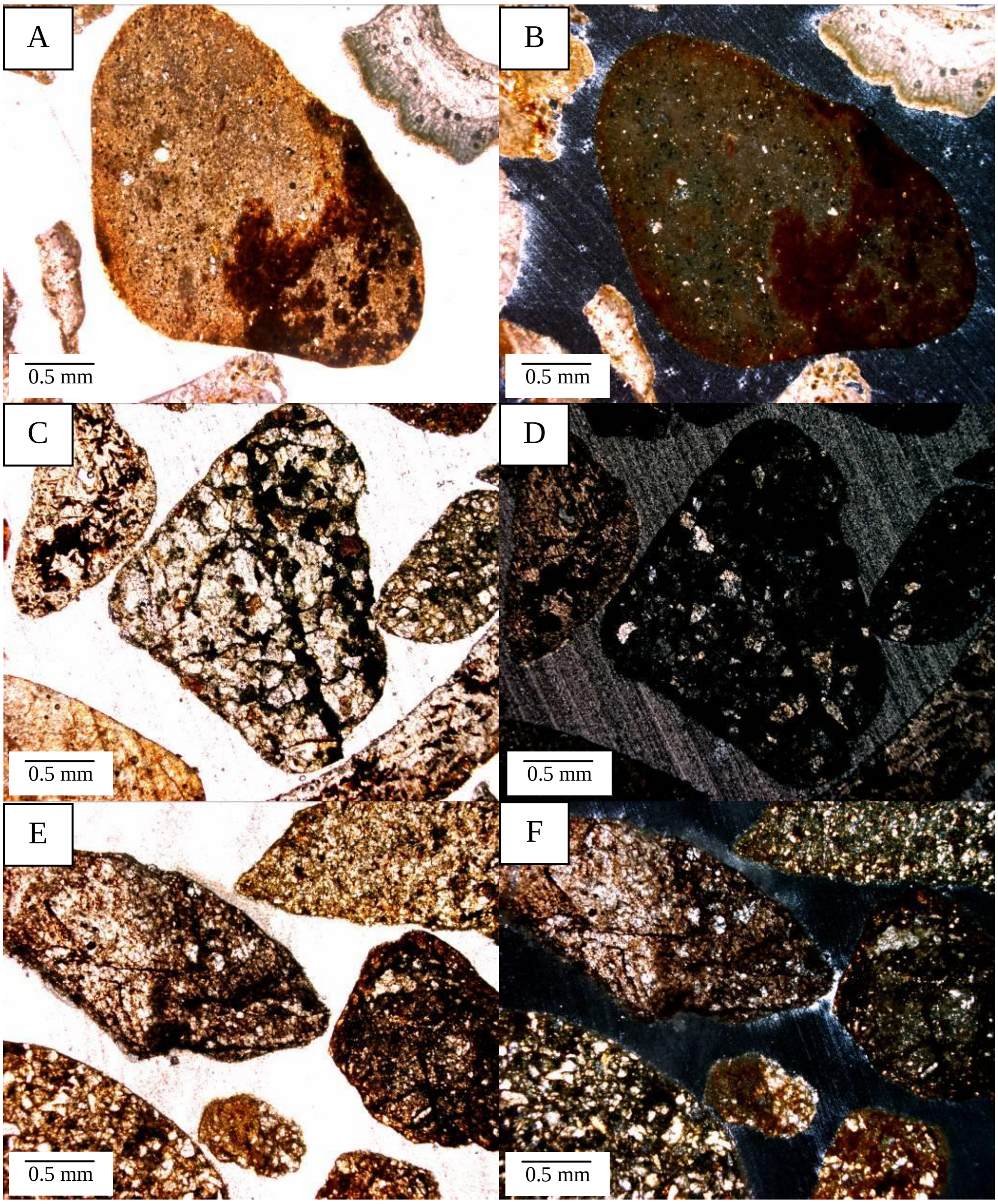
B As for A, but under XPL which emphasises the iron staining.

C Sample P637 (transect E; 28 m depth) shows light to dark red-brown greywacke sandstone containing quartz and plagioclase grains about 0.25 mm in size and green minerals which are probably chlorite.

D As for C, but under XPL.

E Sample S29 (near transect G; 37 m depth) shows several red-brown to green-brown greywacke grains. The green colour is likely to be chlorite.

F As for E, but under XPL. Note the greenish yellow hue to the rock fragments under XPL.


A
0.5 mm
B
0.5 mm
C
0.5 mm
D
0.5 mm
E
0.5 mm
F
0.5 mm

Sedimentary rock fragments type 2 is composed of more poorly-lithified mixed siliciclastic-carbonate grains (Plate 5.2 A-D). They are limonite stained and are poorly sorted, and irregular in shape and size (Plate 5.2 A-D). They are typically composed of (titano)magnetite and dirty limonite stained quartz and feldspar grains, glauconite grains and often unidentifiable, broken and limonite altered skeletal carbonate grains. They are more common in the central and southern sectors of the NNCS ranging from 15-50% in mid-shelf depths of 50-100 m off Whangaroa Harbour, and inner-shelf depths of 0-50 m from the eastern edge of Bay of Islands to the very southern parts of the NNCS (Figure 5.8). Contents of 1-15% of sedimentary rock fragments type 2 occur in the North Cape region, and in outer shelf depths of 150-200 m off Great Exhibition Bay. However, sedimentary rock fragments type 2 mainly comprise only of a percent or two of most NNCS sediments.

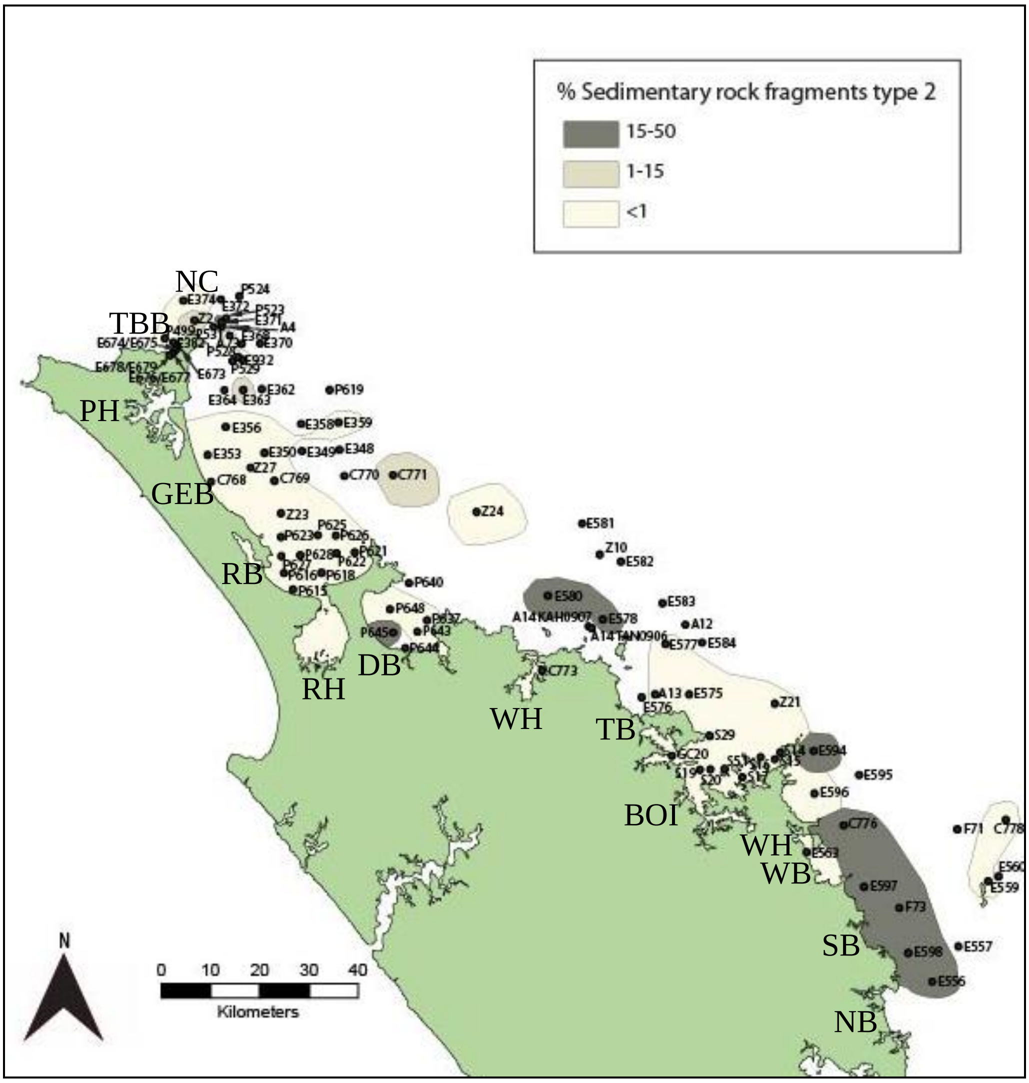


Figure 5.8: Abundance of sedimentary rock fragments type 2 in whole samples of the NNCS surficial sediments. Locality name codes are defined in Figure 1.2.

5.3 CALCICLASTIC (SKELETAL) TYPES

The calciclastic (or bioclast/skeletal content) of the NNCS sediments shows a strongly mosaic pattern with typically lower contents nearshore in the northern sector of the NNCS, and higher contents nearshore in the southern sector of the NNCS from Whangaroa Harbour and eastern parts of Doubtless Bay (Figure 5.9). The highest contents of 75-100% are present off North Cape, at inner-shelf depths of 0-50 m off Rangaunu Bay, at mid-shelf depths of 50-100 m off Whangaroa Harbour, and 0-200 m depths off the Bay of Islands and Sandy Bay. Contents of 50-75% occur in sediment at inner-shelf depths of 0-50 m off Great Exhibition Bay, northern Doubtless Bay, Whangaroa Harbour, Bay of Islands, Whangaruru Bay, and in a sample off Whangaruru Bay from outer-shelf depths of 150-200 m. Contents of 25-50% are randomly distributed from the north to south of the NNCS, and contents of 0-25% occur in inner-shelf depths of 0-50 m off Great Exhibition Bay, Rangaunu Harbour, Takou Bay and northwestern Bay of Islands.

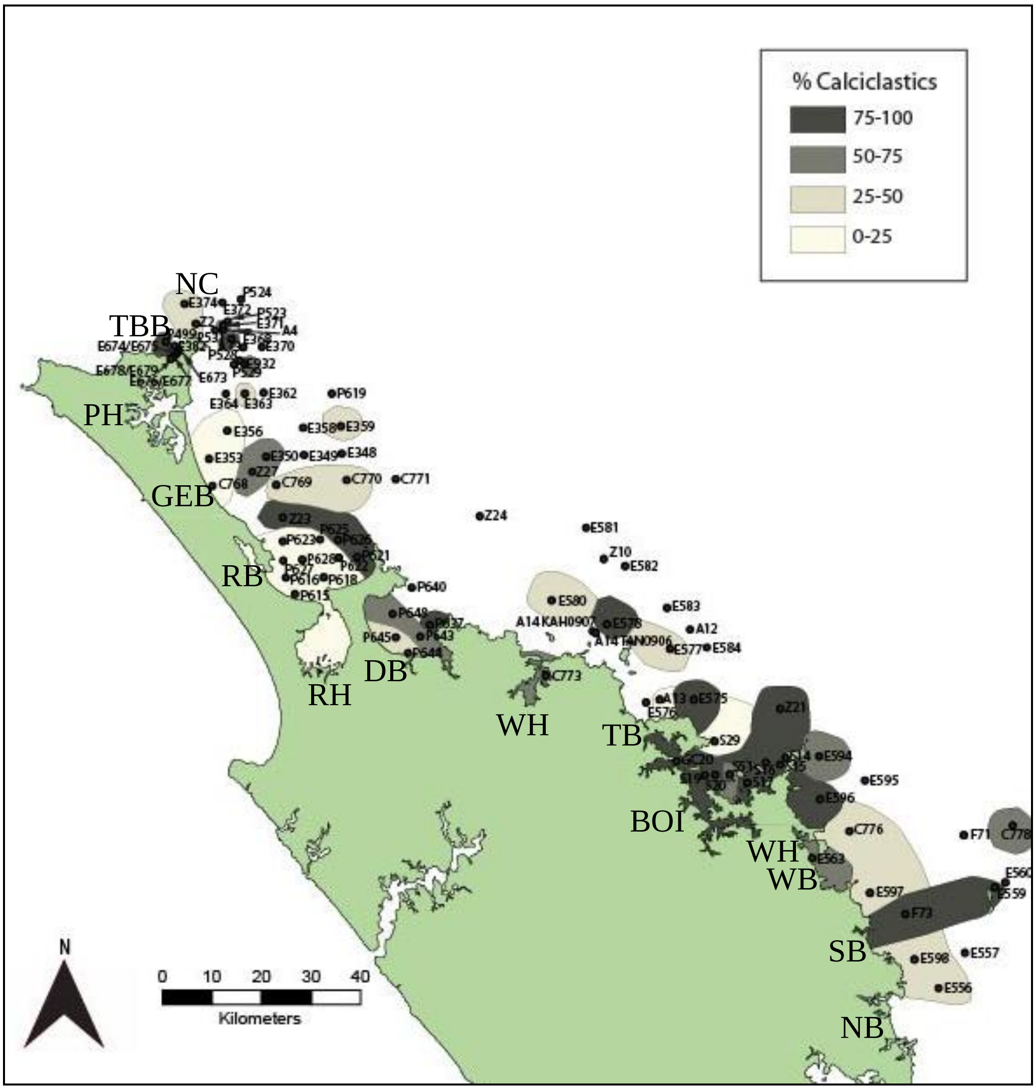


Figure 5.9: Abundance of calciclastics (skeletal grains) in NNCS surficial sediments. Locality name codes are defined in Figure 1.2.

In Figure 5.10 the dominant skeletal types are mapped. Calciclastic grains in NNCS surficial sediments are typically highly fragmented, abraded, microbored and limonite stained, often making them particularly difficult to identify. Therefore, only the dominant skeletal types are represented in this map. The dominant skeletal type is bivalves (Plate 5.5 D) which extend over much of the northern sector of the NNCS in inner- to outer-shelf depths of 0-200 m off North Cape, Great Exhibition Bay, and Rangaunu Harbour, and outer-shelf depths of 100-200 m off Doubtless Bay through to Whangaroa Harbour. Barnacles (Plate 5.5 A) dominate in inner- to mid-shelf depths of 0-150 m in the central sector of the NNCS off Great Exhibition Bay, eastern Doubtless Bay, Whangaroa Harbour and Bay of Islands region. Bryozoans (Plate 5.5 C) dominate in the southern sector in mid-shelf depths of 50-100 m in and around the Bay of Islands.

Calcareous red algae (Plate 5.5 B) also dominate in mid-shelf depths of 50-100 m off Rangaunu Bay, Bay of Islands, and from 0-50 m depth off Sandy Bay. Gastropods (Plate 5.1 B) dominate only in the northern sector of NNCS in 0-150 m depths off North Cape, Great Exhibition Bay and northern Rangaunu Bay. Planktic foraminifera (Plate 5.5 E) only dominate in the very south of the NNCS in 50-100 m water depths, along with mixed bivalves/benthic foraminifera (benthic forams in Plate 5.5 F) in deeper waters of 150-200 m. Endolithic boring of the main skeletal grains (predominantly bivalves and barnacles) is common throughout the NNCS surficial sediments. These borings are often filled with limonite (Plate 5.5 A) and sometimes glauconite. Limonite and glauconite infills are also common within foraminiferal tests, along with mud/clay infills.

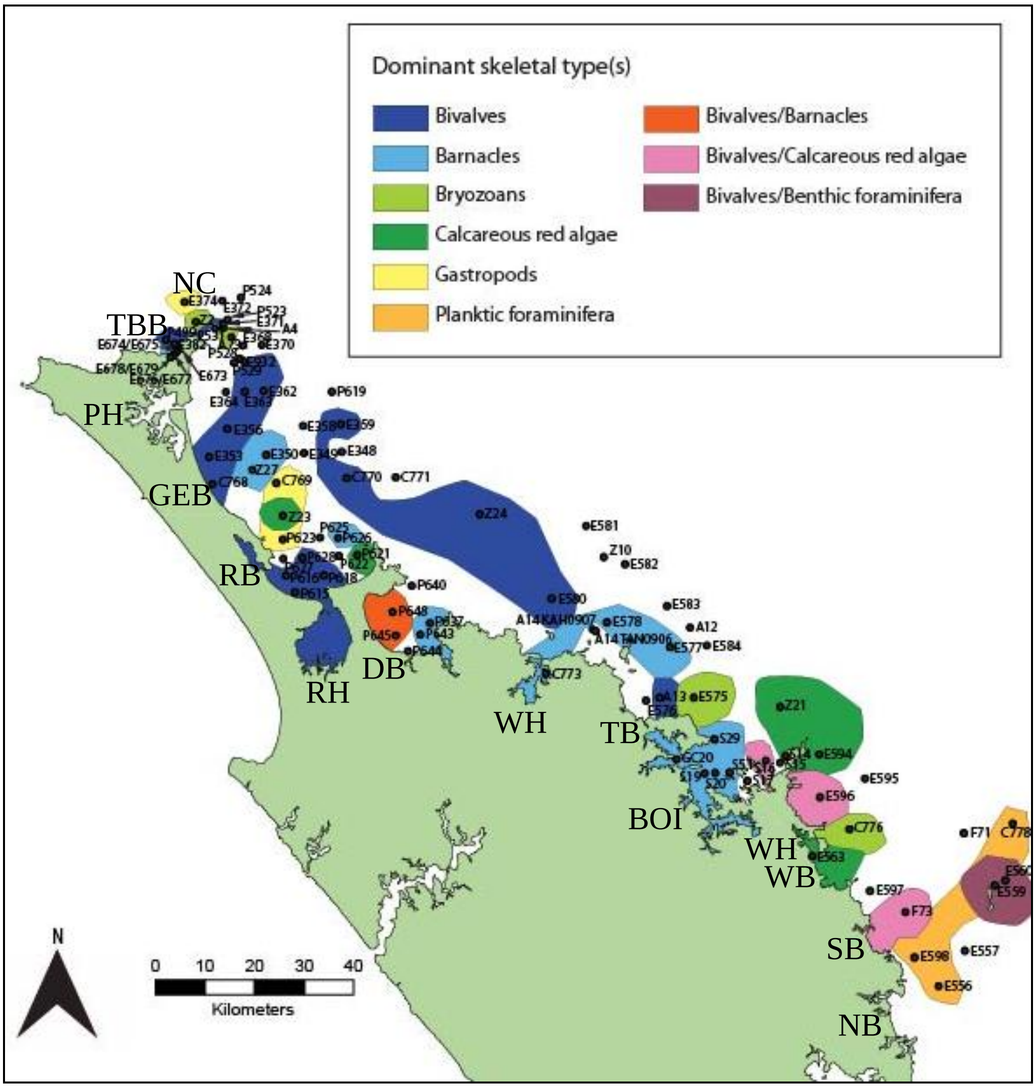


Figure 5.10: Distribution of dominant skeletal type(s) in NNCS surficial sediments. Locality name codes are defined in Figure 1.2.

PLATE 5.5

Photomicrographs of some skeletal fragments in NNCS sediments

A Very microbored, altered and limonite stained barnacle in sample E371 (transect B; 121 m depth).

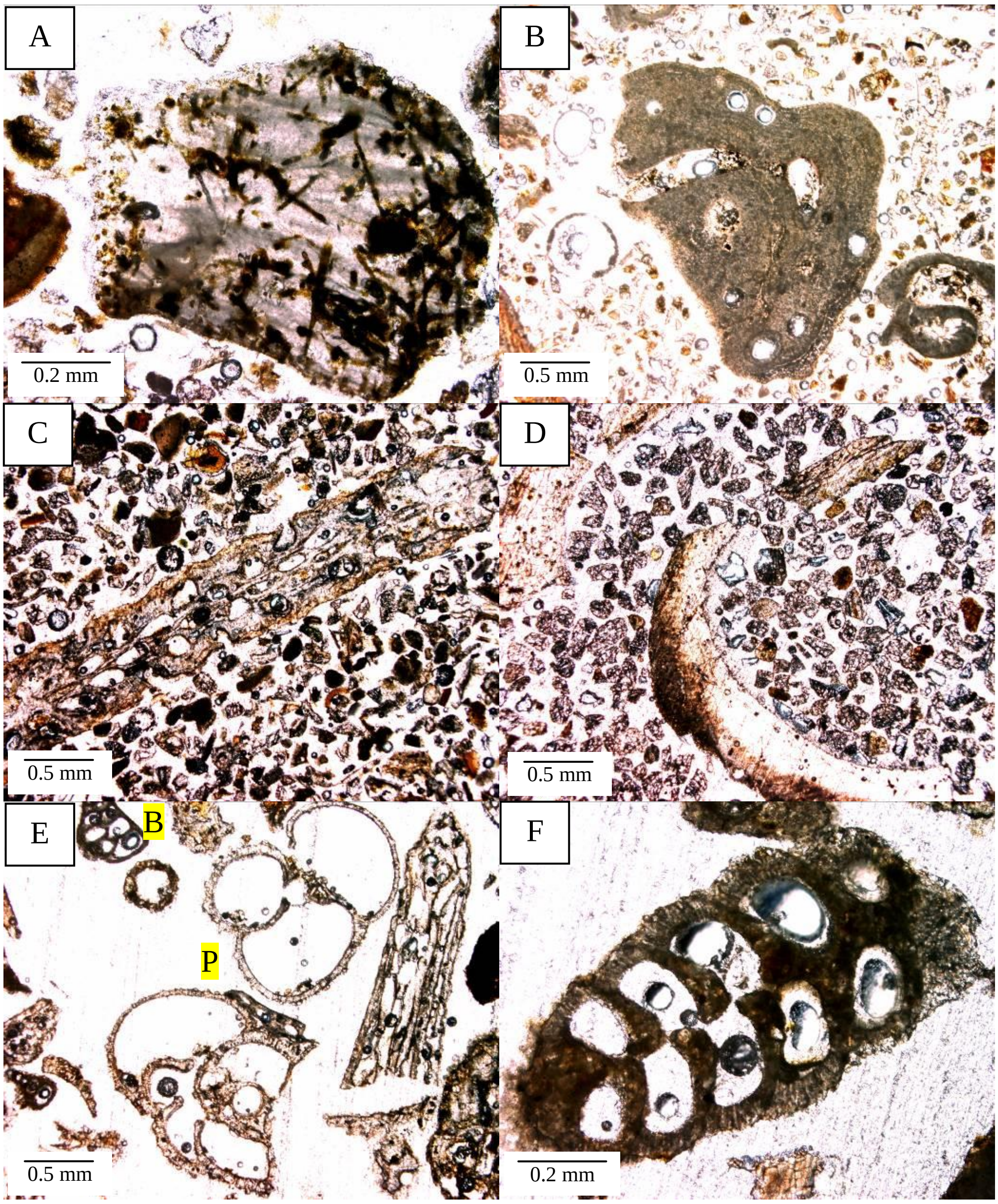
B Calcareous red algal grain in sample E356 (near transect C; 9 m depth) surrounded by quartz and feldspar grains and broken, very altered and unidentifiable carbonate material.

C Elongated bryozoan fragments in sample E580 (near transect F; 84 m depth) surrounded by a few quartz and feldspar grains, broken and altered, unidentifiable carbonate grains and rock fragments. Note minor microborings and limonite staining.

D Bivalve fragments in sample P616 (transect D; 16 m depth) surrounded by dirty and limonite stained quartz and feldspar grains. Note minor microborings and limonite staining.

E Planktic foraminifera (P) in sample E559 (transect H; 106 m depth) surrounded by benthic foraminifera (B) and other broken skeletal grains

F Benthic foraminifera in sample E559 (transect H; 106 m depth) altered to limonite in centre of the grain where its colour takes on a blurred orange hue.


A
0.2 mm
B
0.5 mm
C
0.5 mm
D
0.5 mm
E
B
P
0.5 mm
F
0.2 mm

5.4 GLAUCONITE

Glauconite, although rare, occurs in some of the NNCS sediments. Grains are mostly well rounded and well sorted, ranging in size from 0.1-0.2 mm (Plate 5.4 A). Contents of 5-15% occur only in the northern sector in outer-shelf depths from 150-200 m in scattered samples off North Cape, Great Exhibition Bay, Doubtless Bay and Whangaroa Harbour (Figure 5.11). Contents of 1-5% also occur only in the northern sector in inner- to outer-shelf depths from 0-200 m off Great Exhibition Bay, Rangaunu Bay and western Doubtless Bay (Figure 5.11). The entire southern sector of the NNCS and most of the sediments in the northern sector contain <1% glauconite (Figure 5.11).

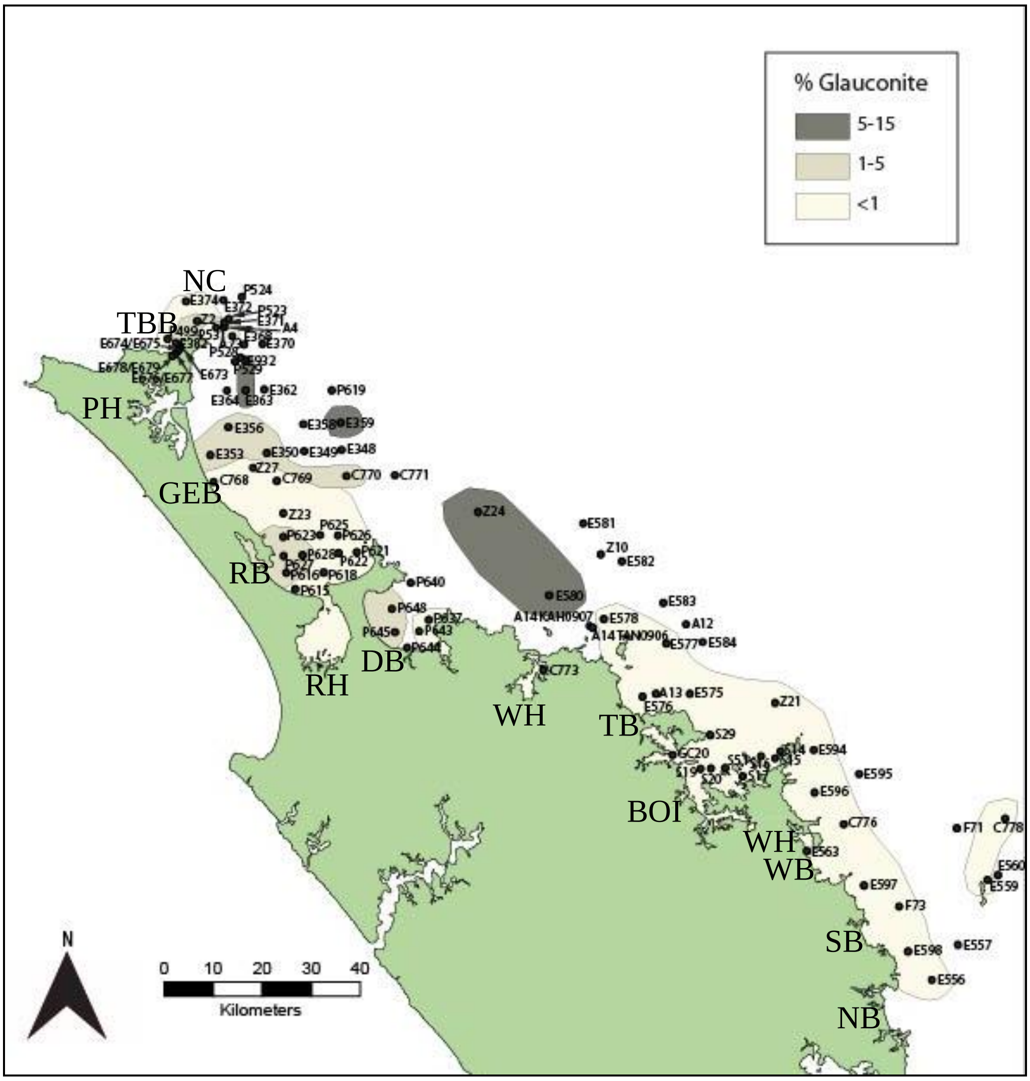


Figure 5.11: Abundance of glauconite in NNCS surficial sediments. Locality name codes are defined in Figure 1.2.

Chapter 6

SKELETAL TYPES

6.1 INTRODUCTION

This chapter concentrates solely on descriptions of the skeletal carbonate types in the NNCS surficial sediments. The distribution of the dominant skeletal type(s) in the NNCS sediments was noted in Section 5.3 and shown in Figure 5.10, and that information is not repeated here. The skeletal taxa and species identification was performed during petrographic analysis of the gravel and sand fractions. Individual species identification was difficult due to the fragmented and microbored nature of the NNCS sediments (particularly for bivalves and barnacles). Most of the borings in skeletal grains contained limonite and sometimes glauconite infills, and some foraminiferal tests also contained mud/clay infills, further contributing to the difficulty of making individual species identifications. Consequently, individual species were only identified for skeletal taxa when possible. This chapter is divided into a comparison of the gravel and the sand fraction in relation to the different skeletal taxa found (Section 6.2), the major skeletal taxa and some of the species identified in these taxa (Section 6.3), and any relation of the skeletal types to the bathymetry of the NNCS (Section 6.4). The chapter continues to describe the preservation and microboring and alteration features of the skeletons (Section 6.5), followed by their mineralogy (Section 6.6), which includes the calcite and aragonite distribution and the calcite species types in the NNCS sediments.

6.2 GRAVEL AND SAND FRACTION

The gravel and sand fraction in sediment samples on the NNCS contained different but relatively comparable abundances of skeletal taxa due to the size ranges of particular skeletal types (Figure 6.1). In the gravel fraction bivalves are the dominant skeletal type at 41%, compared to 15% in the sand fraction. Bivalves in the gravel fraction are followed by barnacles 21%, gastropods 11%, red algae 8% and bryozoans 7%. In the sand fraction the dominant skeletal type is barnacles at 23%, followed by red algae 17%, bivalves 15% and bryozoans 12%, with gastropods only 5%. Benthic and planktic foraminifera are most abundant in the sand fraction due to their small size ranges.

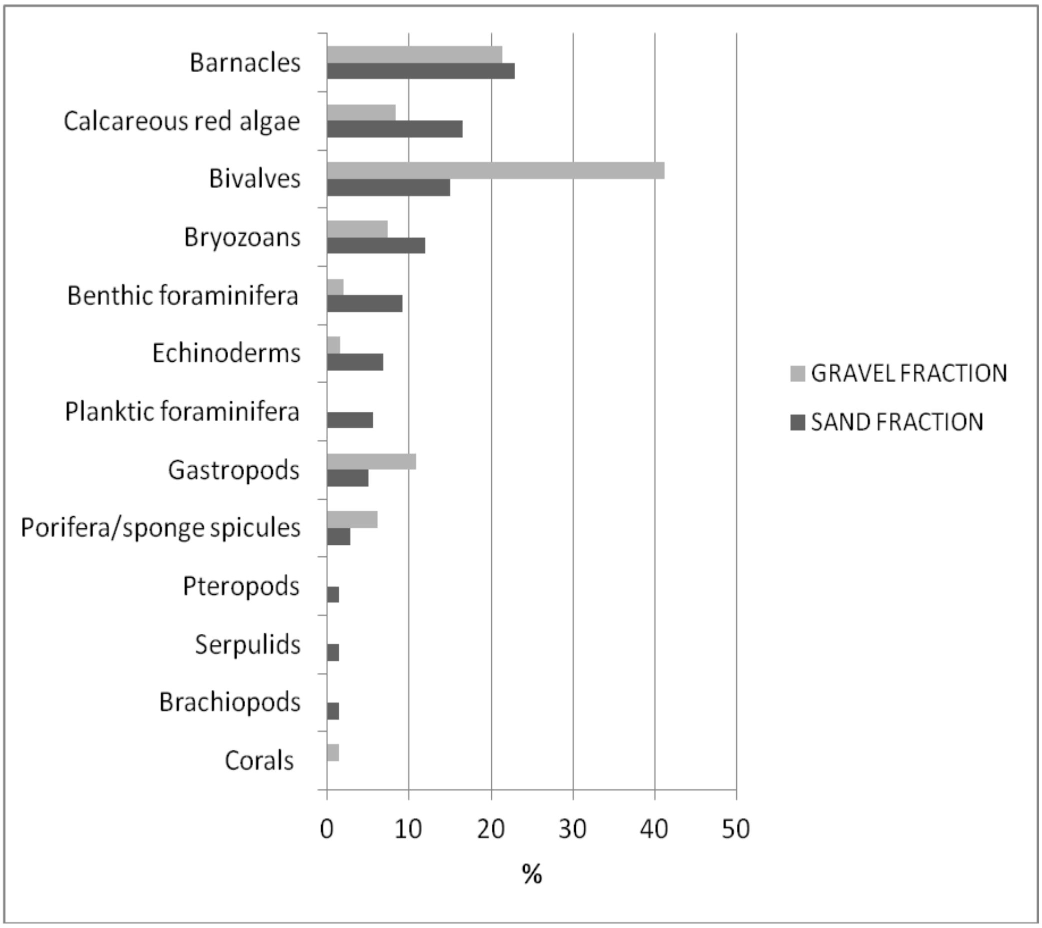


Figure 6.1: The overall skeletal composition in the sand (0.063-2 mm) and gravel fraction (>2 mm) of the NNCS surficial sediments.

6.3 MAJOR SKELETAL TYPES AND INDIVIDUAL SPECIES IDENTIFICATION

6.3.1 Mollusca

6.3.1A Bivalves

The bivalves in the NNCS sediments are usually over 1 mm in size and their shells are only found in fragmented pieces in the sand fraction (Plate 5.5 D). In the gravel fraction, bivalve shells range from whole, modern and fresh looking grains to fragmented, relict, abraded and microbored grains. The dominant bivalve species in the NNCS surficial sediments include *Perrierina perstriata, Tawera spissa, Tawera marionae, Maorithyas flemingi and Sphaerium* sp. (Plate 6.1 A-F).

Bivalves dominate only in the northern sector in inner- to outer-shelf depths of 0-200 m (Figure 5.10).

6.3.1B Gastropoda

Gastropods are highly fragmented throughout the NNCS making identification of the species involved unachievable in both the gravel and sand fraction. Gastropod fragments were sometimes microbored and these borings contained limonite infills (Plate 5.1 B). The internal axial whorl of gastropods is commonly scattered throughout the gravel fraction of the NNCS surficial sediments following the abrasion/erosion of the outer shell (Plate 6.2 A and B). Gastropods dominate only in the northern sector in inner- to mid-shelf depths of 0-150 m (Figure 5.10).

PLATE 6.1

Some of the dominant bivalve species in NNCS sediments

A Sample Z2 (transect B) showing a very microbored *Perrierina perstriata*.

B Sample E353 (near transect C) showing *Tawera spissa* (top and bottom left) and *Tawera marionae* (bottom right).

C Sample C768 (transect C; 24 m depth) showing *Tawera spissa*.

D Sample P645 (transect E; 21 m depth) showing *Tawera spissa* (left) and unknown microbored and corroded bivalve shell (right).

E Sample S19 (transect G; 27 m depth) showing *Maorithyas flemingi*.

F Sample F73 (near transect H; 79 m depth) showing possible *Sphaerium* sp.

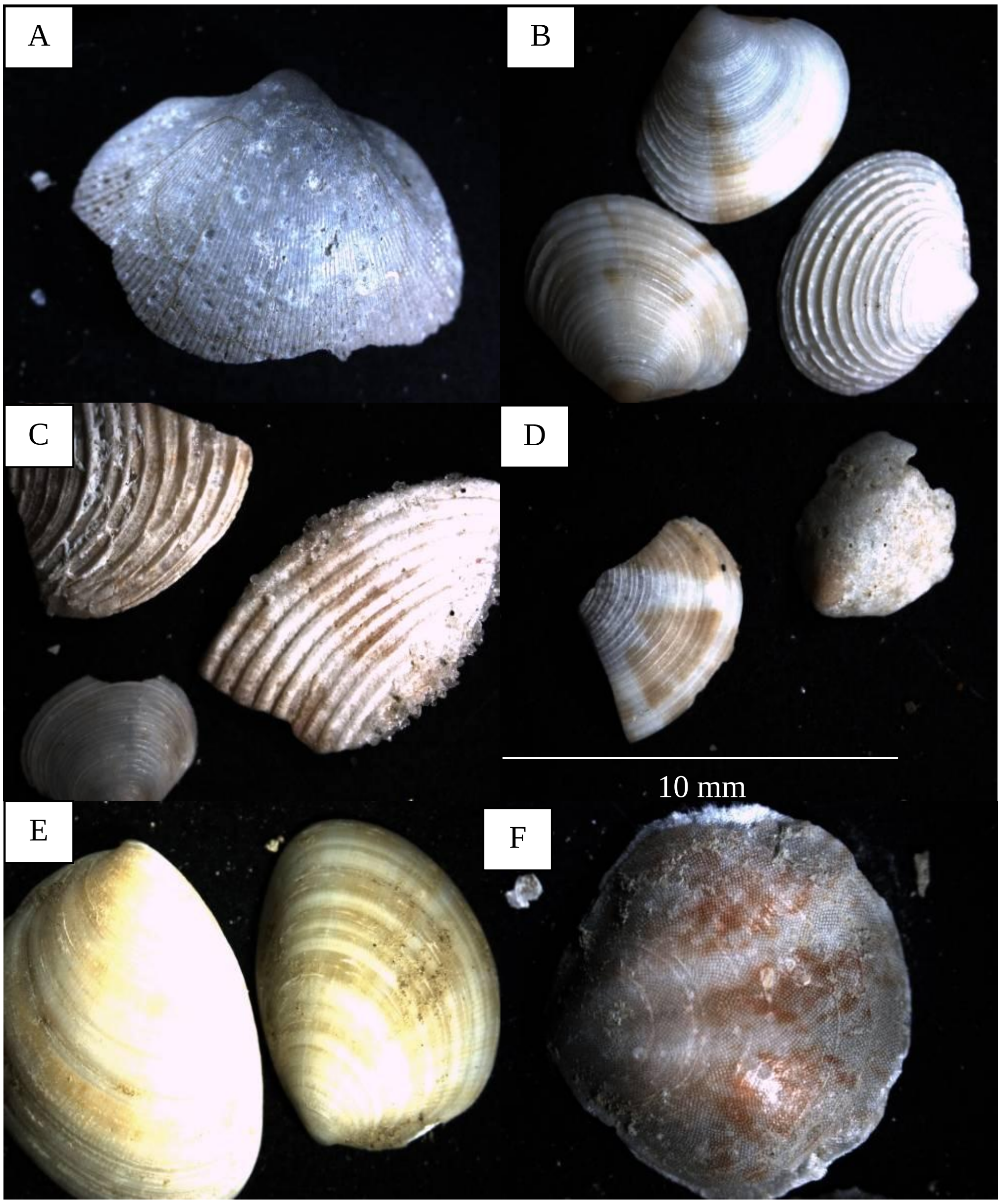

A
B
C
D
10 mm
E
F

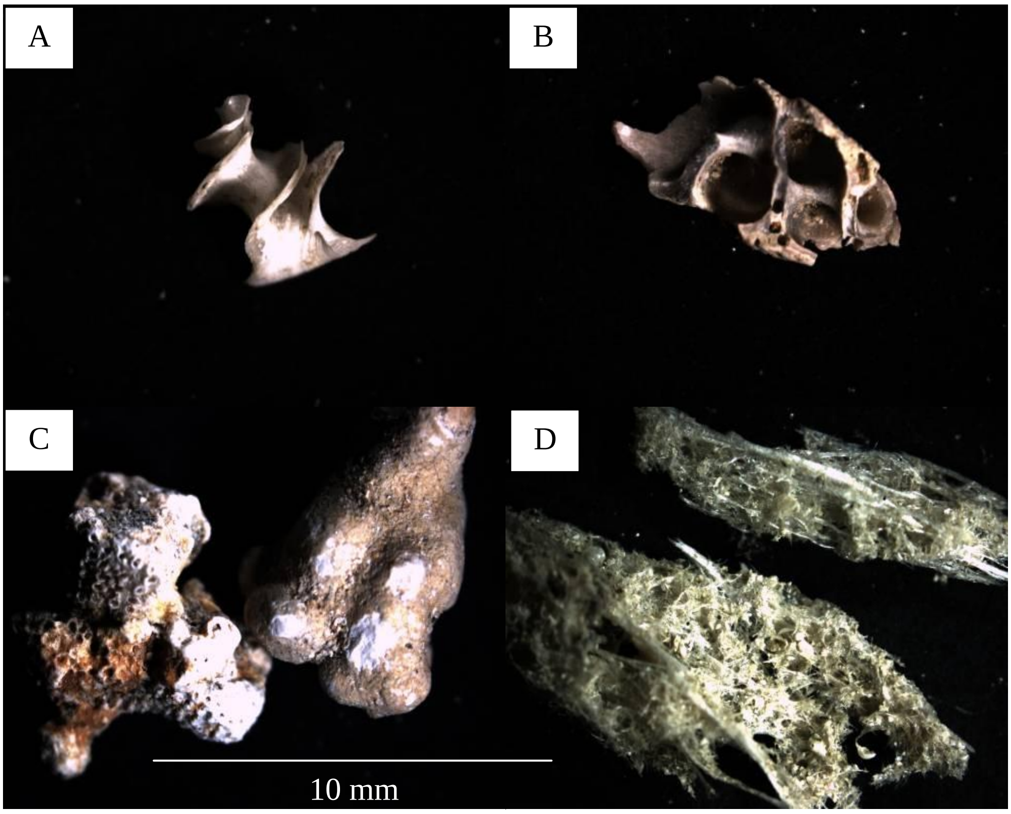
PLATE 6.2

Example of some gastropod fragments, red algal grains and sponge baskets from the NNCS sediments.

A, B Inner structure of gastropod shells from samples E559 (A, transect H; 106 m depth) and E563 (B, between transect G and H; 9 m depth).

C Very abraded and microbored red algal grains from sample E563 (between transect G and H; 9 m depth).

D Sponge basket structures from sample A73 (near transect B; 69 m depth).


A
B
C
D
10 mm

6.3.2 Arthropoda

6.3.2A Barnacles

Barnacles are sessile suspension feeders and generally occur in shallow and tidal waters. Species identification was not performed on barnacles, although *Notobalanus vestitus* is likely to be present as these species have been recorded in sediments off North Cape (Keane, 1986) and are regarded as inner- to outer-shelf species from the shore to 400 m throughout New Zealand waters (Foster, 1978). Barnacles in the NNCS dominate in the central sector in inner- to mid-shelf depths of 0-150 m (Figure 5.10). Their various appearances are shown in Plate 6.3 A-F. Plate 6.3 G shows highly polished barnacle fragments and Plate 6.3 H shows very abraded, microbored and relict looking barnacle fragments.

6.3.3 Bryozoans

Bryozoans are the dominant skeletal type in few scattered locations throughout the NNCS including North Cape, east of Takou Bay and Whangaruru Harbour in inner- to mid-shelf depths of 0-100 m (Figure 5.10). There are four types of bryozoan growth forms observed in the NNCS sediments, namely free living, erect rigid, erect rigid fenestrate and erect rigid radiate types (Plate 6.4 A-D). Bryozoans in the gravel fraction are mostly modern, fresh looking and well preserved fragments ranging in size from 4-20 mm. In the sand fraction they range from fresh looking and well preserved to poorly preserved, microbored and limonite stained grains such as in Plate 5.5 C.

6.3.4 Foraminifera

Both planktic and benthic foraminifera are common in the southern sector of the NNCS (Figure 5.10). Planktic foraminifera, including *Globigerina* sp. and *Globorotalia* sp., occur throughout the NNCS but are the dominant skeletal type in mid- to outer-shelf depths ranging from 50-200 m off Sandy Bay and Ngurauru Bay. Benthic foraminifera occur in much of the sediment throughout the NNCS but are the dominant skeletal type in combination with bivalves in mid-shelf depths of 100-150 m off Sandy Bay. The dominant benthic foraminiferal species in the NNCS sediments are *Homotrema* sp., *Bulimina* sp., *Textularia* sp., *Notorotalia* sp. and *Nonionellina flemingi* (Plate 6.5 A-F)

PLATE 6.3

Barnacle plates and fragments from the NNCS sediments.

A-F Relatively intact barnacle plates from samples P626 (A and B, transect D; 40 m depth), P637 (C, transect E; 28 m depth), S29 (D, near transect G; 37 m depth), S19 (E, transect G; 23 m depth) and E594 (F, transect G; 93 m depth).

G Highly polished, smooth and glossy barnacle fragments from sample E678 (transect A; beach sample)

H Very abraded and microbored barnacle fragments from sample A13 (between transect F and G; 65 m depth).

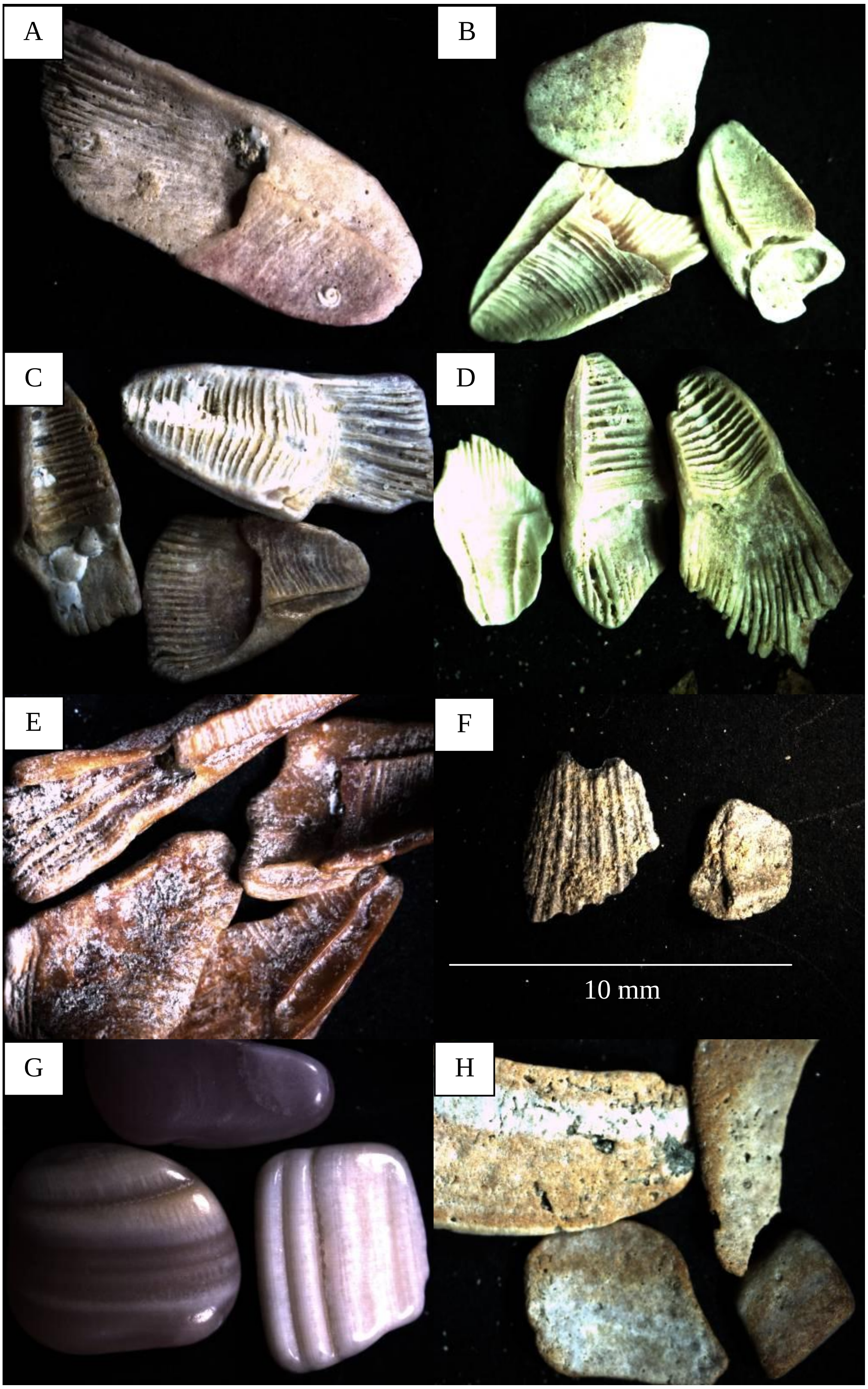

A
B
C
D
E
F
10 mm
G
H

PLATE 6.4

Dominant bryozoan types from the NNCS sediments.

A Free living bryozoans in sample Z2 (transect B; 88 m depth).

B Erect rigid bryozoans fragments in sample Z2 (transect B; 88 m depth).

C Erect rigid fenestrate bryozoan fragments in sample Z2 (transect B; 88 m depth).

D Erect rigid radiate bryozoan fragment in sample E575 (near transect G; 77 m depth).

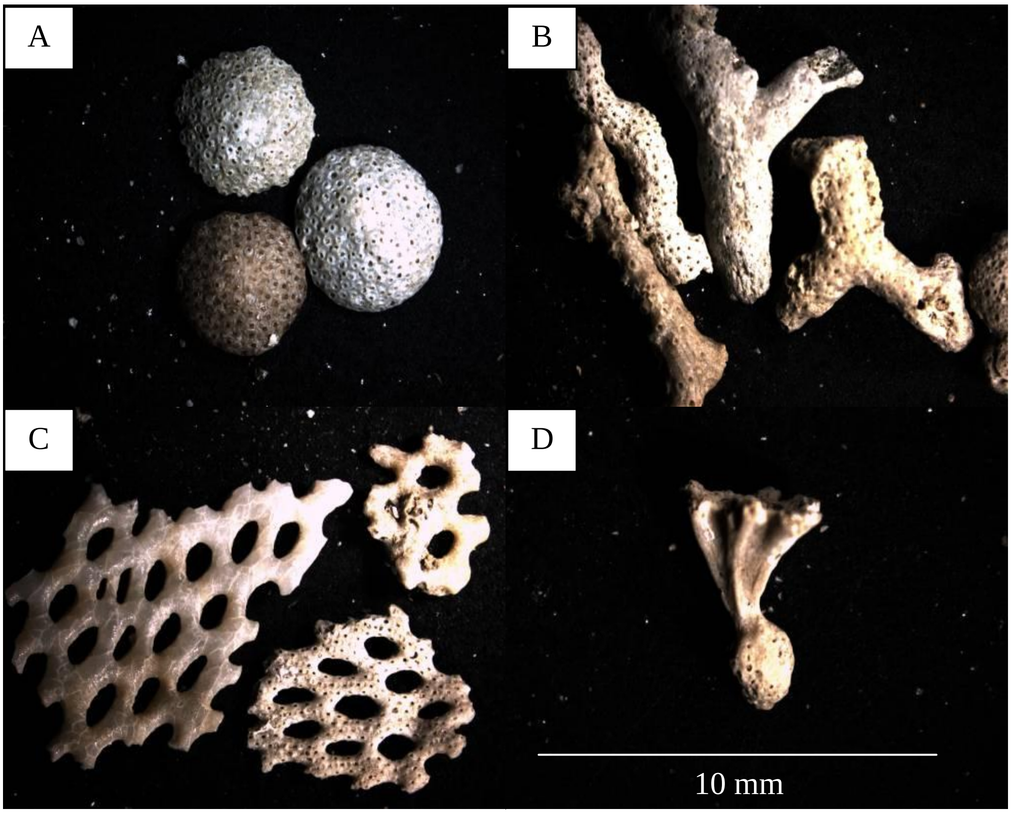

A
B
C
D
10 mm

PLATE 6.5

Some benthic and planktic foraminifera in the NNCS sediments.

A Sample E559 (transect H; 106 m depth) containing relatively modern looking *Bulimina* sp. (benthic foraminifera)

B Sample E559 (transect H; 106 m depth) containing *Textularia* sp. (benthic foraminifera). Note limonite staining of skeletal structure.

C Sample Z24 (transect E; 170 m depth) containing *Notorotalia* sp. (benthic foraminifera). Note dark brown to black mud infills within the test chamber.

D Sample Z24 (transect E; 170 m depth) containing *Nonionellina flemingi* (benthic foraminifera). Note glauconite and mud infills within the test chamber.

E Sample E559 (transect H; 106 m depth) containing *Homotrema* sp. (encrusting benthic foraminifera). Note orange limonite staining to orange.

F Sample E559 (transect H; 106 m depth) containing *Homotrema* sp. (encrusting benthic foraminifera). Note orange limonite staining and dark brown clay infills inside pores of skeletal fragments.

G Sample E559 (transect H; 106 m depth) containing *Globigerina* sp. (planktic foraminifera). Note orange limonite staining.

H Sample E598 (near transect H; 68 m depth) containing *Globigerina* sp. (A) and *Globorotalia* sp. (B) (planktic foraminifera). Note alteration to limonite/glauconite and clay infills.


A
10 mm
B
0.2 mm
C
0.2 mm
D
0.2 mm
E
0.5 mm
F
0.5 mm
G
0.5 mm
H
B
A
0.5 mm

6.3.5 Rhodophyta

Calcareous red algal material dominates in the southern sector of the NNCS in inner- to mid-shelf depths of 0-100 m (Figure 5.10). Red algae occur in both the gravel and sand fractions. In the gravel fraction they range from modern and intact skeletal grains to relict, fragmented and microbored skeletal grains (Plate 6.3 C). In the sand fraction their pores often contain limonite infills making them difficult to identify, but they mainly appear modern and unaltered (Plate 5.5 B).

6.3.6 Porifera

Siliceous sponge spicules usually form <1% of the skeletal fraction in NNCS sediments. They occur in the gravel fraction as sponge baskets (Plate 6.3 D), and in the sand fraction they usually occur as simple sponge spicules, typically with one arm (Plate 5.1 E) but sometimes up to 3 arms.

6.4 RELATION OF SKELETAL SPECIES TO BATHYMETRY

6.4.1 Bivalvia

Bivalves are mostly found in water depths >200 m on the North Kaipara margin on the west coast of Northland (Payne, 2010). The expected depth ranges of some dominant bivalve species and the depths they were found in the NNCS sediments are shown in Figure 6.2. All occur within their expected depth ranges except for *Perrierina perstriata* which is found in deeper waters of 50-88 m rather than the expected 27-46 m. This could be because the species has a greater depth range than recorded in the literature or the shells may have been reworked by tide, storm wave or coastal currents. *Perrierina perstriata* could also represent relict shell material deposited in the Last Glaciation during periods of lowered sea level and would have therefore been stranded at greater depths than expected. This is supported by the microborings, bleached colour and relict appearance of these shell fragments (Plate 6.1 A).

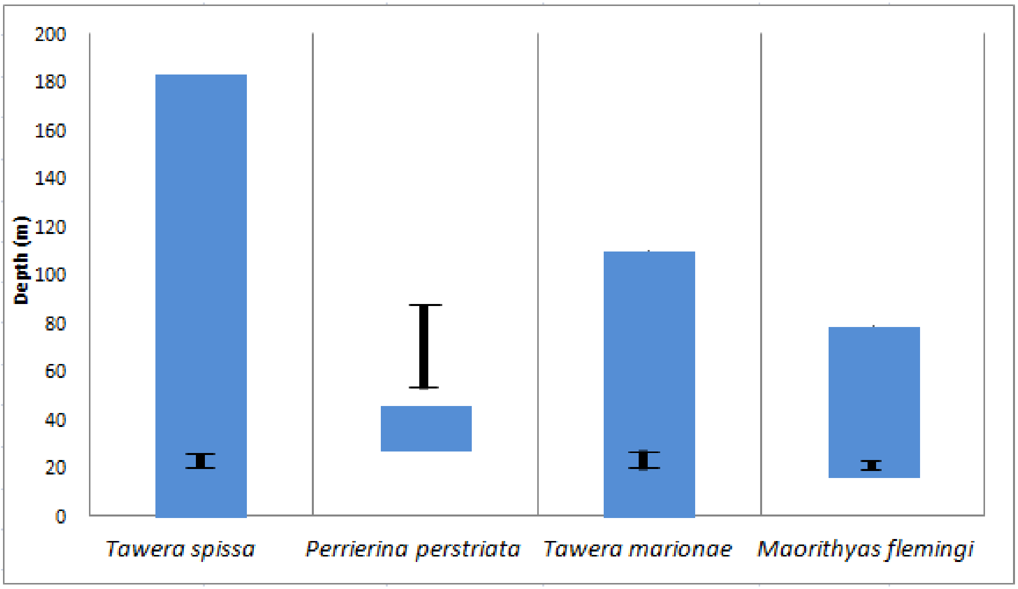


Figure 6.2: The expected depth range (m) of some bivalve species found within skeletal samples from the NNCS (depth ranges based on Powell, 1979). The blue bars are the expected depths and the black bars are the depths at which the species have been recorded in the present sample set.

6.4.2 Benthic foraminifera

The expected depth ranges of some dominant benthic foraminiferal species and the depths they were found in NNCS sediments are shown in Figure 6.3. The benthic foraminifera identified were not found outside their depth ranges. This suggests that little reworking of shell material has occurred in the southern half of the NNCS where benthic foraminifera are most common.

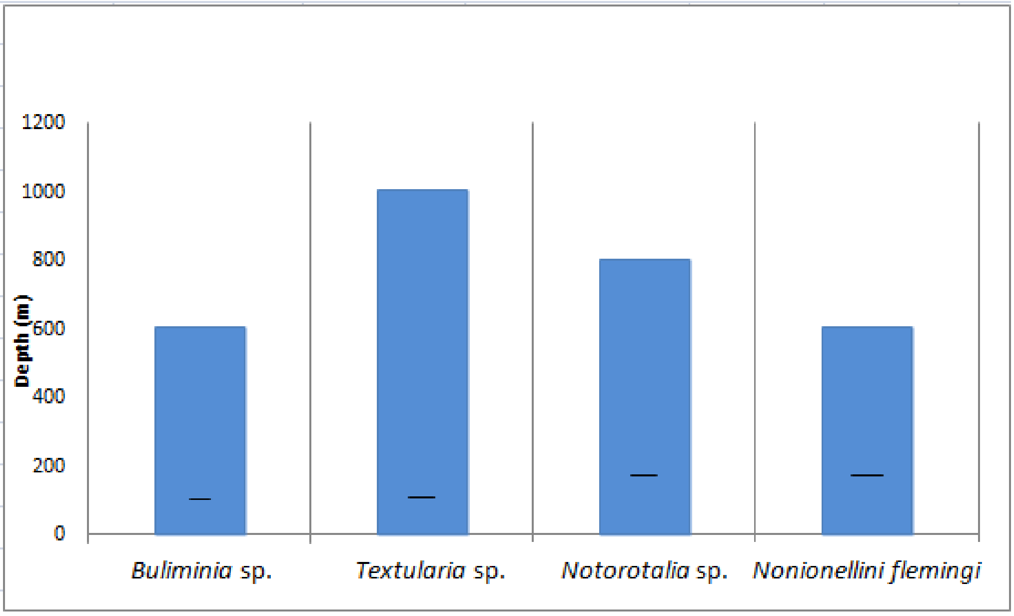


Figure 6.3: The expected depth range (m) of some benthic foraminifera species found within skeletal samples from the NNCS (depth ranges based on Hayward *et al.*, 1999). The blue bars are the expected depths and the black bars are the depths at which the species have been recorded in the present sample set.

6.5 PRESERVATION

The bottom sediments on the NNCS can include well, moderately or poorly preserved shell material. The break down, bleaching, boring and degree of alteration of the shell material was assessed during petrographic analysis using the grading system in Table 6.1 and Plate 6.6 A-F.

Table 6.1: Description of three grades of preservation used for the skeletal samples from the NNCS.

GRADE	DESCRIPTION	NAME
1	Shells fresh, mostly whole with a brightly coloured, non-microbored or altered surface	Well preserved
2	Shells mostly broken with a faded colour, moderate microboring and some alteration features (limonite)	Moderately preserved
3	Shells appear relict and are all broken, bleached in colour and very microbored with common alteration features (limonite and glauconite)	Poorly preserved

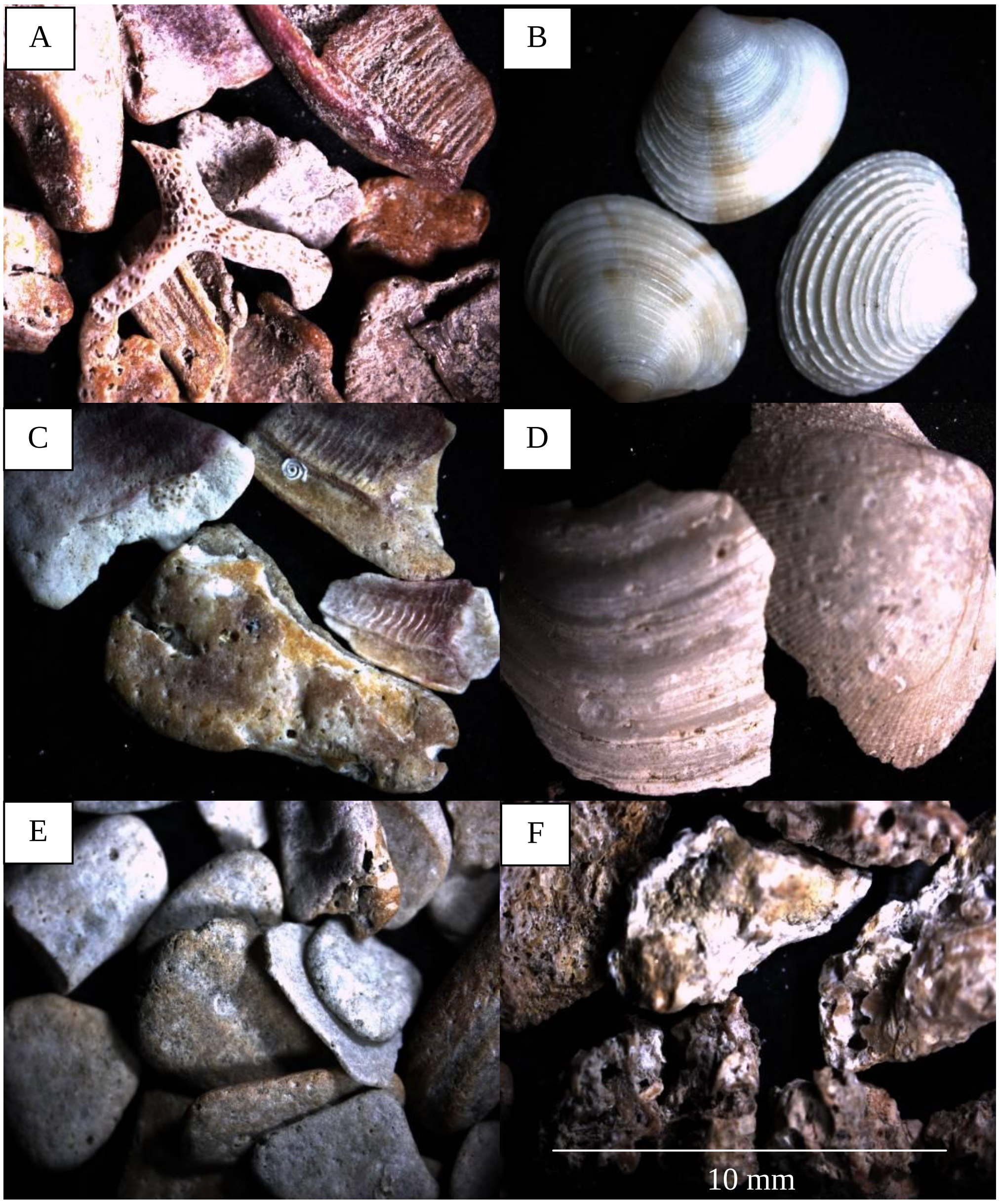
PLATE 6.6

Grades used to assess the preservation of skeletal material

A, B Grade 1: Well preserved = shells appear fresh, are often whole and brightly coloured with a smooth non-microbored and shiny surface. A = S19; 23 m depth. B = E353; 27 m depth.

C, D Grade 2: Moderately preserved = shells are more broken, faded in colour, and show signs of microboring. C = P499; 30 m depth. D = Z2; 88 m depth.

E, F Grade 3: Poorly preserved = shells appear relict, are all broken, abraded and bleached of colour with common microborings. Shell structure is lost and identification is impossible. E = Z27; 148 m depth. F = E578; 62 m depth.


A
B
C
D
E
F
10 mm

Shell preservation in the NNCS sediments is mapped in Figure 6.4 and shows a very general trend of worse preservation with increasing water depth, except in the very southern sector of the NNCS where the shells are poorly preserved in shallow inner-shelf waters of <100 m water depth and moderately preserved in deeper waters from 100-200 m.

Well preserved skeletal material predominantly occurs in and north of the Bay of Islands region in inner- to mid-shelf water depths of <100 m. Well preserved grains are common off the bays and harbours, particularly off part of Great Exhibition Bay, Rangaunu Bay and Rangaunu Harbour, Whangaroa Harbour and the Bay of Islands. A sample off Great Exhibition Bay at 134 m water depth also contains well preserved grains which could be due to the high hydraulic regime of the area. The NNCS sediments containing well preserved skeletal material represent areas with high bivalve and barnacle production.

Moderately preserved skeletal material occurs in water depths ranging from 0-100 m in the northern half of the NNCS and in depths ranging from 80-200 m in the southern sector of the NNCS. Therefore they are not necessarily restricted to a particular depth but tend to occur in greater depths than the well preserved skeletal grains. The areas containing moderately preserved skeletal material correspond to regions with high production rates of almost all skeletal types in the NNCS, including bivalves, barnacles, bryozoans, red algae, gastropods and benthic foraminifera.

Poorly preserved skeletal material dominates in areas of >100 m water depth in the northern sector, and occurs in depths ranging from 50-100 m south of the Bay of Islands in the southern sector of the NNCS. The poorly preserved material in the northern sector of the NNCS represents areas of high bivalve and barnacle production indicating that bivalve and barnacle fragments can range from well to poorly preserved. The sediment dominated by poorly preserved material in the southern sector has high production rates of calcareous red algae, bivalves and planktic foraminifera.

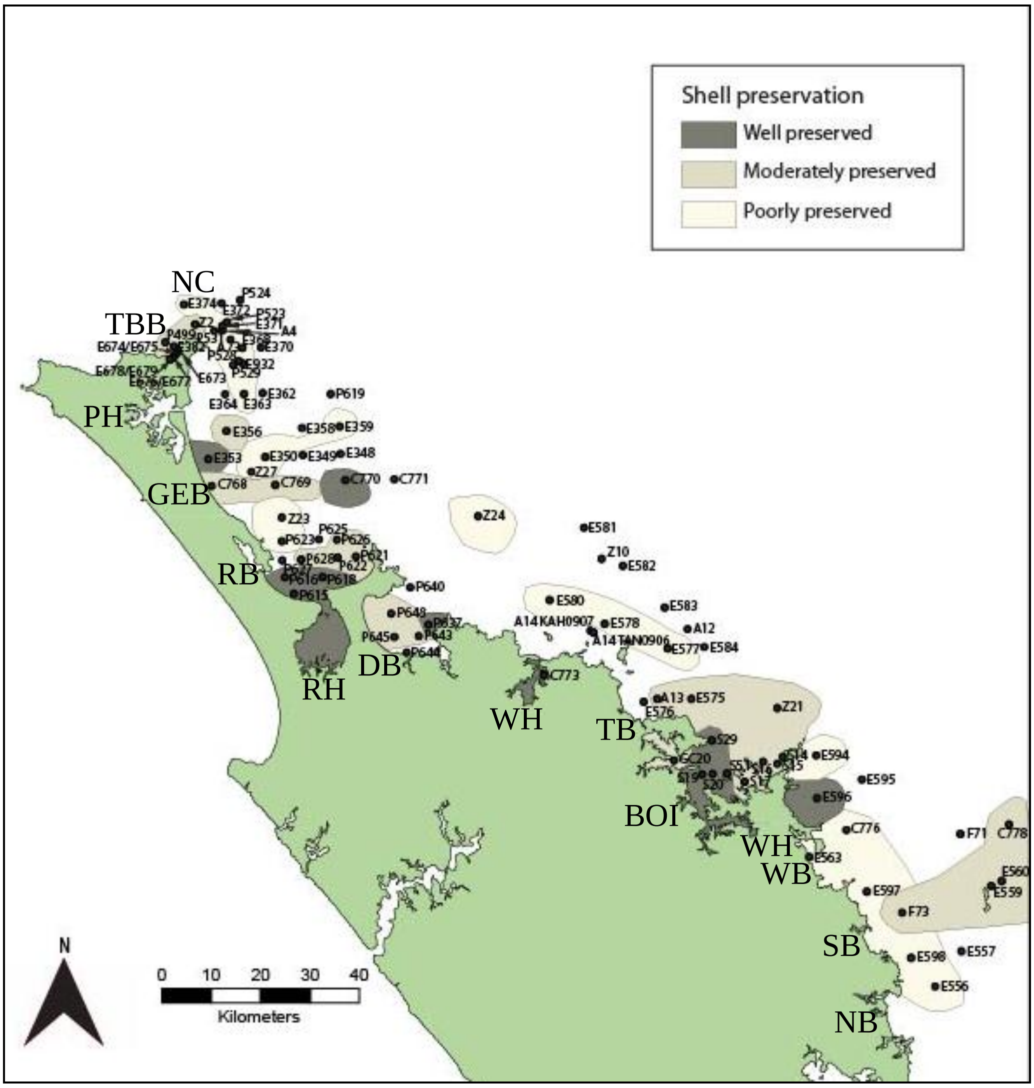


Figure 6.4: Distribution of well, moderately and poorly preserved skeletal grains in the NNCS surficial sediments. Locality name codes are defined in Figure 1.2.

6.6 MINERALOGY

The major carbonate minerals that comprise skeletal grains in this study are divided into aragonite and calcite of either low-Mg calcite (<4 wt% $MgCO_3$), intermediate-Mg calcite (4-12 wt% $MgCO_3$) or high-Mg calcite (>12 wt% $MgCO_3$) type. Table 6.2 notes which skeletal types secrete which carbonate minerals, including the stability of the carbonate minerals. The relative abundance of aragonite, calcite and calcite species types is mapped in Figure 6.5, 6.6 and 6.7.

Table 6.2: Relative stability of carbonate minerals and the carbonate minerals that the main skeletal types in the NNCS sediments are composed of (modified from Keane, 1986b).

STABILITY	CARBONATE MINERALS	SKELETAL TYPES
More stable ↓	Low-Mg calcite (<4 wt% $MgCO_3$)	➢ Epifaunal bivalves ➢ Most foraminifera (benthic and planktic)
	Aragonite	➢ Infaunal bivalves ➢ Gastropods
Less stable	Intermediate (4-12 wt% $MgCO_3$) and high-Mg calcite (>12 wt% $MgCO_3$)	➢ Infaunal bivalves ➢ Bryozoans ➢ *Homotrema* sp. of benthic foraminifera ➢ Echinoderms

The bulk mineralogy of the NNCS sediments is dominated by calcite with the majority of the sediments consisting of >600 X-ray diffraction (XRD) counts for calcite, compared to aragonite where most of the sediment ranges from 0-100 XRD counts. Aragonite contents are highest (>300 XRD counts) off Great Exhibition Bay from 0-150 m water depth and in Whangaroa Harbour. Moderate aragonite contents (100-300 XRD counts) occur off North Cape, Great Exhibition Bay and Rangaunu Bay, Doubtless Bay (<50 m water depth), Takou Bay, in the Bay of Islands (>50 m water depths), Whangaruru Bay and Harbour (<100 m water depth) and Sandy Bay through shelf water depths ranging from 0-200 m. Low aragonite contents also occur throughout shelf water depths ranging from 0-

200 m. These dominate in the NNCS sediments, especially south of Rangaunu Bay outside of the bays and inlets in shelf water depths >50 m.

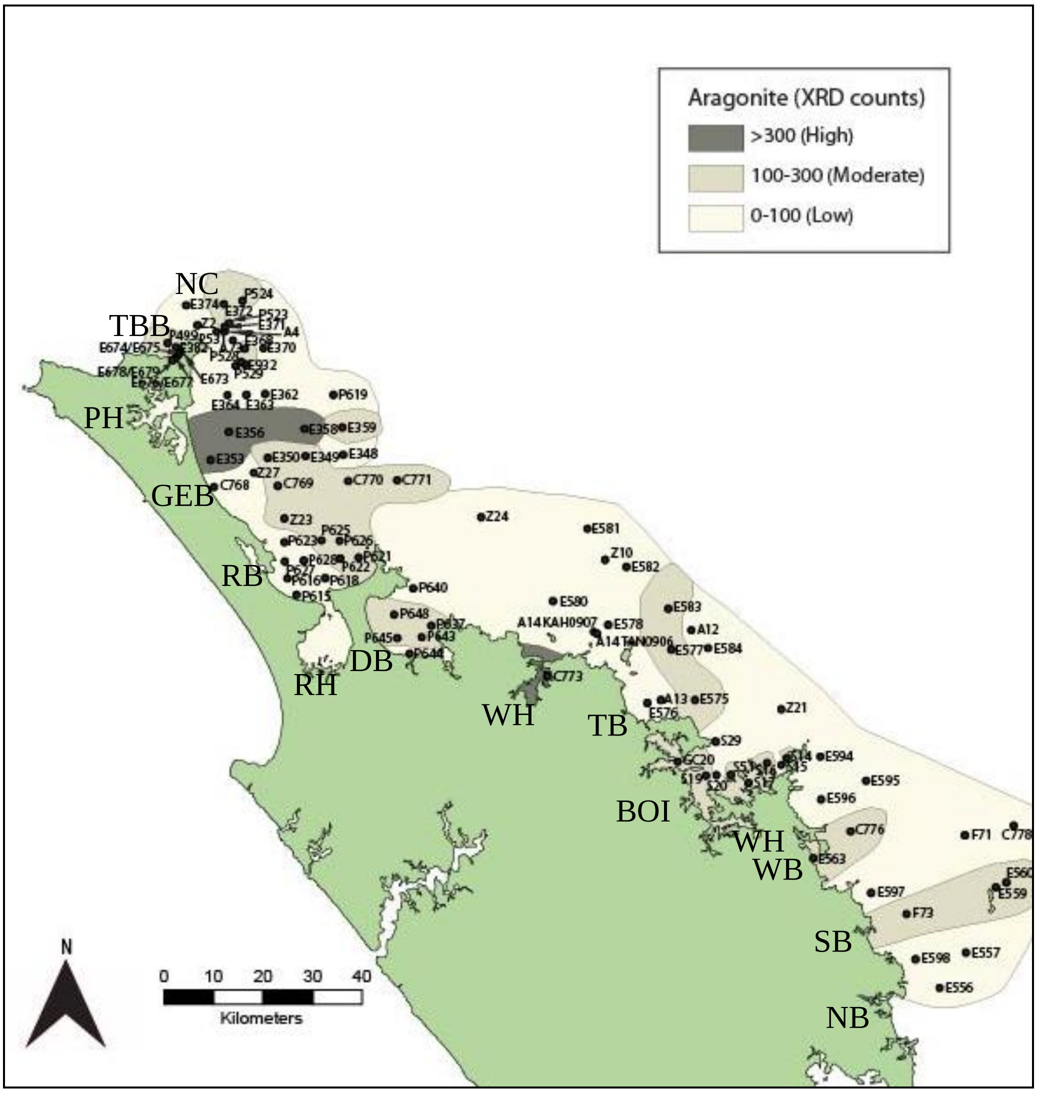


Figure 6.5: Relative abundance of aragonite based on X-ray diffraction (XRD) counts in the NNCS sediments. Locality name codes are defined in Figure 1.2.

Calcite contents generally increase with water depth in the NNCS sediments. Higher calcite contents (>600 XRD counts) are dominant in depths >100 m throughout the northern sector of the NNCS, in depths <50 m in the Bay of Islands, and 0-200 m southwards of the Bay of Islands. Moderate calcite contents (200-600 XRD counts) occur in the northern sector in the North Cape at water depths ranging from 0-200 m, off Parengarenga Harbour and Great Exhibition Bay ranging from 50-150 m water depth, and <100 m off Doubtless Bay and Whangaroa Harbour. Moderate calcite contents occur most often in water depths >70 m throughout the southern sector. Low calcite contents (<200 XRD counts) occur mostly in <50 m water depths off Great Exhibition Bay, Rangaunu Bay and Harbour, Takou Bay and between Whangaruru Harbour and Sandy Bay.

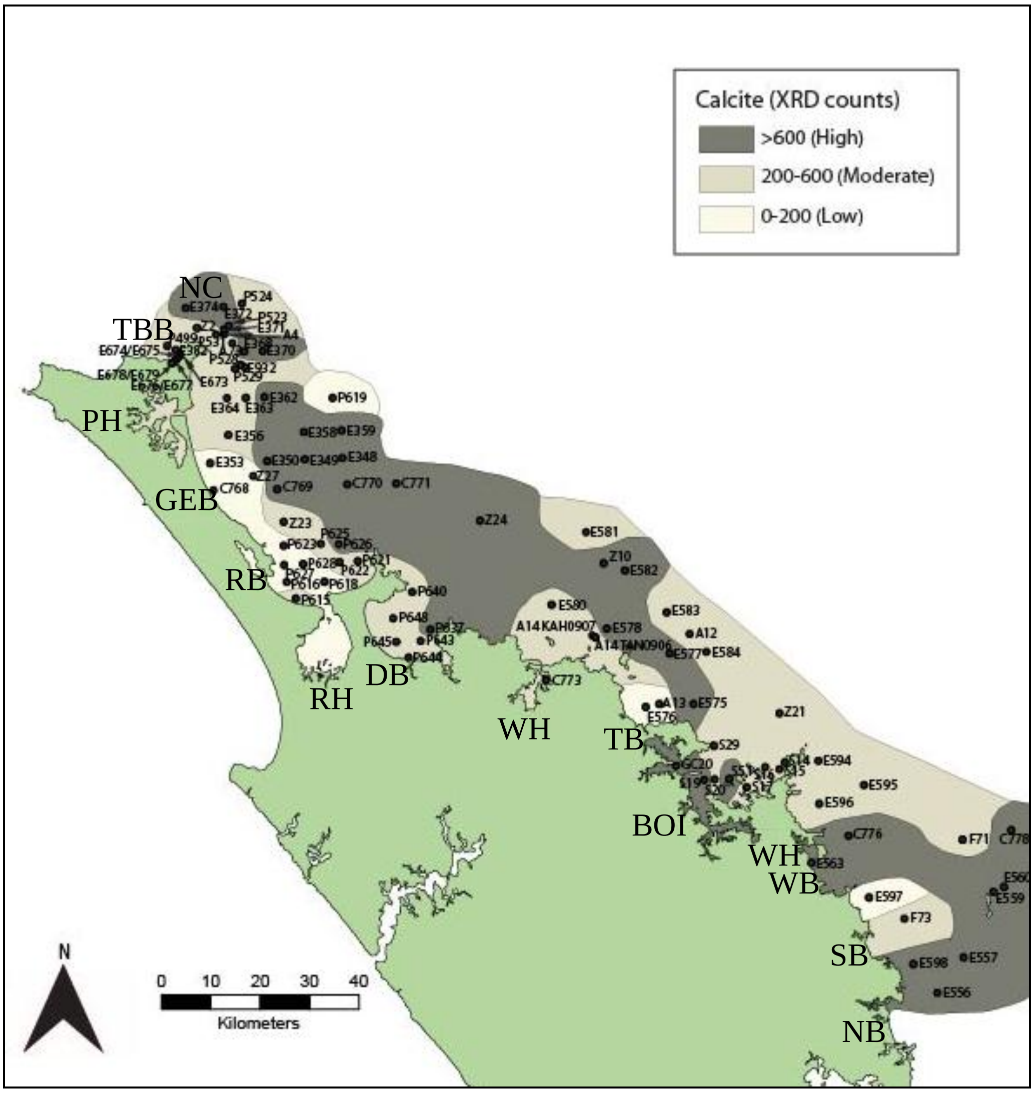


Figure 6.6: Relative abundance of calcite based on X-ray diffraction (XRD) counts in the NNCS sediments. Locality name codes are defined in Figure 1.2.

The distribution of calcite species is mapped for the NNCS sediments in Figure 6.7. The distribution of calcite species shows a very mosaic pattern with high-Mg calcite being the most common, followed by high>intermediate-Mg calcite. Both of these calcite species occur at depths ranging from 0-200 m and are randomly distributed throughout the NNCS. High-intermediate-Mg calcite occurs in only three samples in depths ranging from 80-210 m off Parengarenga Harbour, Bay of Islands and Sandy Bay. High>low-Mg calcite occurs in depths <100 m off North Cape, Parengarenga Harbour, Rangaunu Bay and the Bay of Islands. High<low-Mg calcite only occurs off Great Exhibition Bay at depths <100 m.

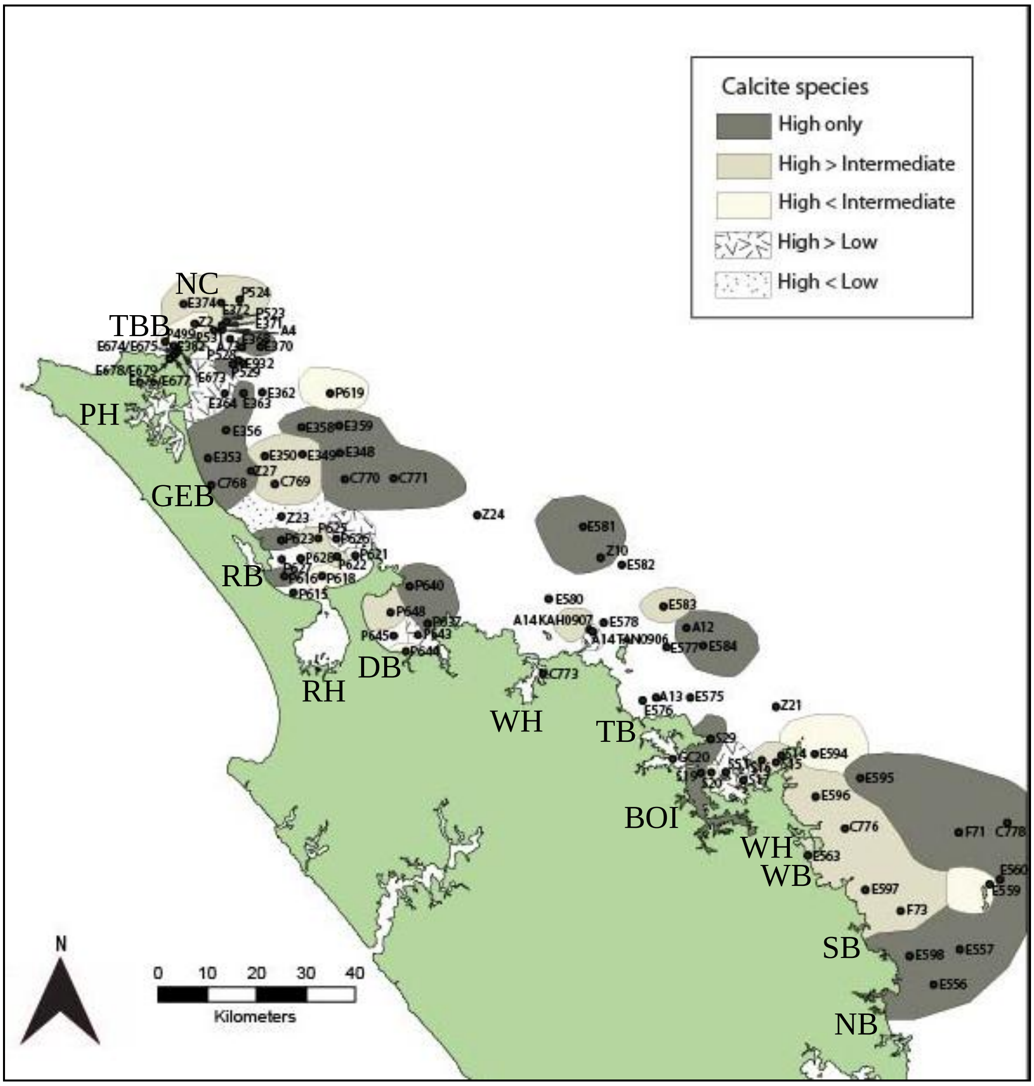


Figure 6.7: Relative abundance of high-Mg calcite (>12% $MgCO_3$), intermediate-Mg calcite (4-12% $MgCO_3$) and low-Mg calcite (<4% $MgCO_3$) in the NNCS sediments. Locality name codes are defined in Figure 1.2.

Chapter 7

DISCUSSION

7.1 INTRODUCTION

This chapter first addresses some of the important controls on sedimentation (Section 7.2) which include sediment provenance, hydrodynamics, substrate types and glacio-eustatic sea level changes. The next section on skeletal carbonates (Section 7.3) suggests an explanation for the variable preservation of the skeletal material and compares the NNCS skeletal types to the modern ecology. A sedimentary facies model is then proposed for the NNCS (Section 7.4) which classifies the sediments into five facies types based on their textural and compositional characteristics. Interpretations of facies origins are made including the environmental and depositional processes involved. Chapter 7 concludes with an account of temperate carbonate sedimentation elsewhere about the North Island, New Zealand (Section 7.5), comparing the NNCS sediments to a basic temperate carbonate textural sedimentation model and with other North Island examples, including the Three Kings region, North Kaipara margin, Wanganui shelf, and Hauraki Gulf. Lastly, the place of the NNCS sediments in the temperate carbonate model is established.

7.2 CONTROLS ON SEDIMENTATION

7.2.1 Provenance of siliciclastic material

7.2.1A Quartz and feldspar

Quartz and feldspar grains typically dominate the siliciclastic fraction of much of the NNCS sediment (Figure 5.3 and 5.4) but definitively determining their provenance is difficult as they are common mineral components in a wide range of rock types. The Northland onland volcanic and sedimentary deposits are obvious potential local sources of quartz, but so too are more distant sources such as the silicic volcanics on Coromandel Peninsula and the Taupo Volcanic Zone. The onland geology in the northern sector of the NNCS comprises widespread occurrences of unconsolidated coastal dune sands of the Quaternary Karioitahi Group that are certainly quartz rich (Issac *et al*., 1994; Issac, 1996; Edbrooke, 2001). For example, Rickets (1979) favoured the quartz rich sand in Great

Exhibition Bay to be sourced from the reworking of such Pleistocene deposits (Figure 7.1). Schofield (1969), on the other hand, suggested that the quartz rich 'Parengarenga Sand Facies', occurring between Parengarenga Harbour and Doubtless Bay, is modern sediment sourced from nearby podsols. These podsols are formed by leaching processes, often enhanced by certain vegetation types that remove feldspar and other minerals from the soil producing quartz rich sands (Schofield, 1969). He based this conclusion on two facts: 1) the 'Parengarenga Sand Facies' occurs only where mature sandy podsols are prevalent, and 2) the high angularity of the quartz rich sand suggests it has not been sorted to the extent required to separate quartz from other rocks derived from the onland geology.

In the southern sector of the NNCS the Mesozoic basement rocks of the Mount Camel Terrane and Waipapa Terrane (Figure 7.1) comprise indurated sandstone and siltstone, typically greywacke and argillite, and local submarine basalt and basaltic andesite lavas (Hayward, 1993; Issac *et al*., 1994; Issac, 1996; Herzer *et al*., 1997). The greywacke and argillite lithologies are likely sources of at least a proportion of quartz in the NNCS sediments.

Other local onland sources could be Oligocene Ruatangata Sandstone (Te Kuiti Group) that contains about 20-30% quartz and the Late Cretaceous Punakitere Sandstone (Northland Allochthon) with some quartz, in both cases of monocrystalline type (Gilbert *et al*., 1989).

Other more distant sources of quartz grains include the Coromandel Volcanic Zone and especially the Taupo Volcanic Zone (TVZ), as well as central North Island axial range greywackes (Figure 7.2). The TVZ, with its huge erupted volumes (16000-20000 km^3) during the last 1.6 Myrs of quartz-rich rhyolitic/silicic volcanic material (Houghton *et al*., 1995) is a viable source of reworked volcanic quartz grains in the NNCS sediments. North Island greywackes of Permian-Jurassic Torlesse (15-25% of monocrystalline quartz) occur in north to south trending ranges in central to southern North Island (Figure 7.2) and may have also additionally contributed minor amounts of quartz to the NNCS (Stokes and Nelson, 1991; Hudson, 1996; Briggs *et al.*, 2004). The cool temperatures and strong westerly winds associated with the last glaciation may have provided an optimum environment for erosion of these distal sources producing quartzofeldspathic sands (Schofield, 1969).

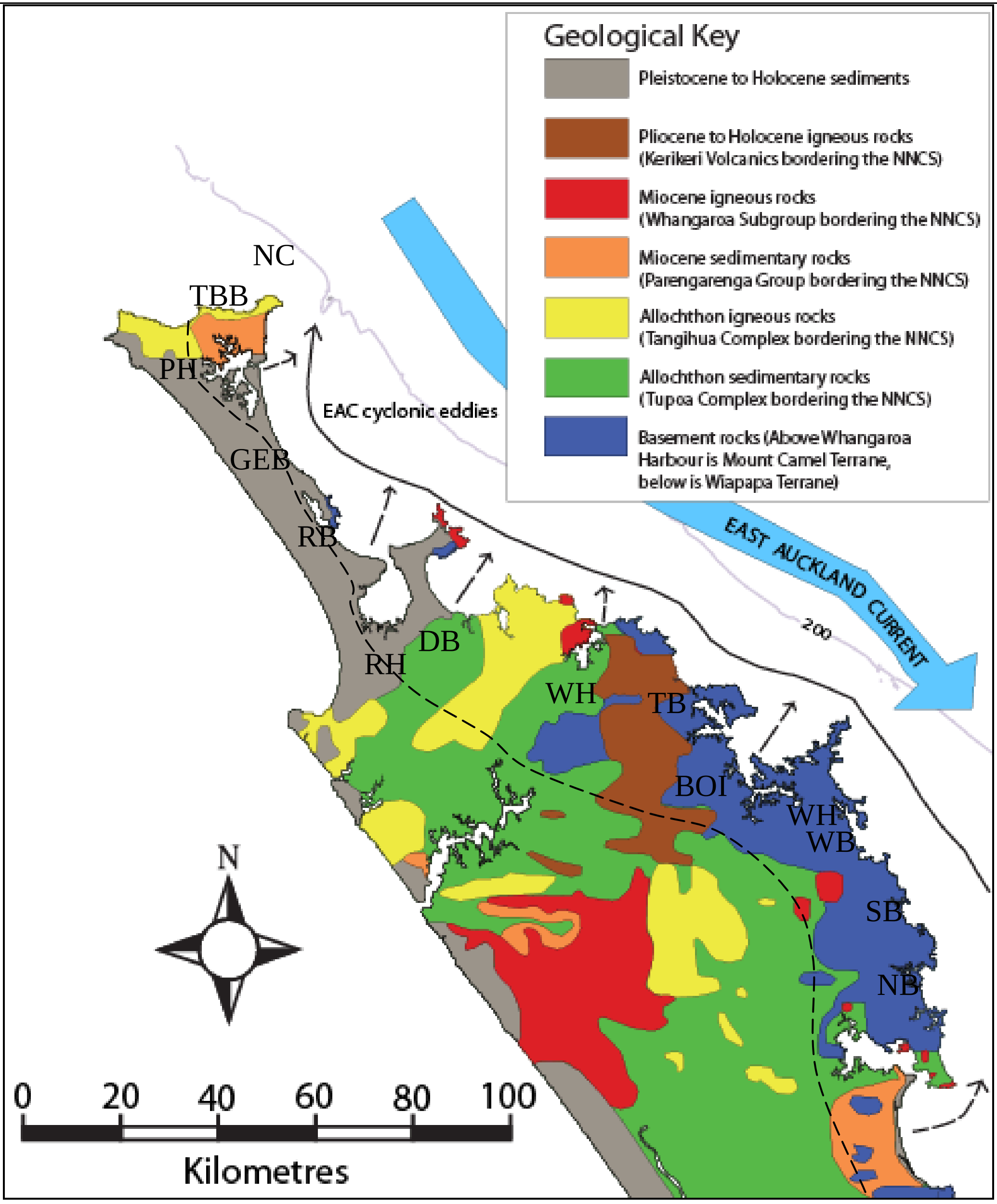


Figure 7.1: Sediment transport pathways for the NNCS sediments in relation to local source rock types (modified from Summerhayes, 1969a; Issac *et al*., 1994; Isaac, 1996; Rait, 2000; Edbrook, 2001; Spörli and Harrison, 2004). Locality name codes are defined in Figure 1.2. The dashed line onland is the approximate catchment divide between east and west flowing rivers/streams.

The high energy hydraulic environment that existed during lowered sea level may have contributed to the reworking of these distal sources of quartzofeldspathic sand in a northward direction by eddies to reach the NNCS. Progradation was also favoured during periods of lowered sea level on the eastern Northland shelf, possibly enhancing the accumulation of sediment further northwards. However, both Schofield (1970) and Summerhayes (1969a) favour a more local source for the quartzofeldspathic sands and Schofield (1970) suggests progradation plays only a small part on the eastern shelf of Northland compared to the western shelf due to the relative paucity of sediment supply and lesser wave energy along the east coast.

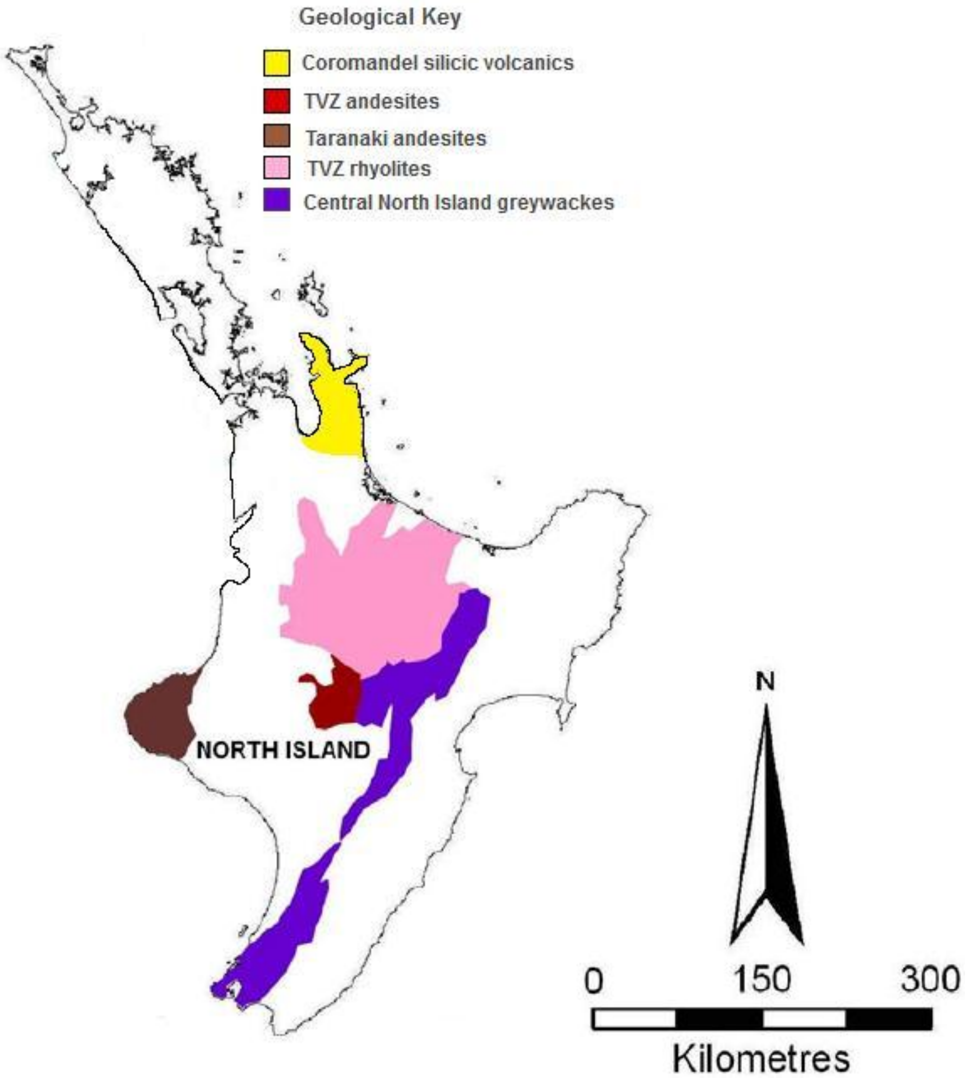


Figure 7.2: Location map of possible distal sources in the North Island for the NNCS sediments (modified from Hudson, 1996; Stokes and Nelson, 1991). TVZ = Taupo Volcanic Zone.

The bulk mineralogy determined by X-ray diffraction (XRD) indicates that plagioclase feldspar greatly dominates over orthoclase (K) feldspar in the NNCS sediments (see Appendix D, Table D.1). However, the XRD results do include plagioclase feldspar phenocrysts in volcanic rock fragments, making this approach less accurate for semi-quantifying the discrete plagioclase feldspar mineral content. Plagioclase feldspar is the most abundant phenocrystic mineral in the majority of Northland basaltic and andesitic rocks, and can also be common in silicic volcanic rocks, so that both local and more distal volcanic sources could account for the plagioclase in the NNCS sediments, as for the quartz grains. Also the Mesozoic basement greywacke and argillite are potential sources of small amounts of plagioclase grains (Hudson, 1996), both from onshore in the southern sector of the study region (Figure 7.1) and from further afield in the central North Island (Figure 7.2).

7.2.1B Sedimentary and volcanic rock fragments

Rock fragments represent miniature hand specimens of the source rock types feeding a sedimentary system. Sedimentary and volcanic rock fragments typically form <15% of the NNCS sediment composition. They are dominated by submarine basaltic, argillite and greywacke-type lithologies all of which can be sourced from the local onland geology (Figure 7.1). In particular, the greywacke and argillite fragments (sedimentary rock fragments type 1), but also the basaltic fragments, can be derived from the Mesozoic basement rocks (Figure 7.1). Submarine basalts could also be derived from the Tangihua Complex and Pliocene to Holocene Kerikeri Volcanics (Ashcroft, 1986) (Figure 7.1). Sedimentary rock fragments type 2 (composed of poorly-lithified mixed siliciclastic-carbonate grains) often contain authigenic glauconite commonly found in New Zealand Tertiary rocks. The New Zealand Tertiary rock record consists of marine sedimentary, coastal plain and deltaic rocks which were deposited during a tectonically driven transgressive-regressive marine cycle (Dodd and Nelson, 1998). The maximum period of subsidence in the Oligocene and Early Miocene was associated with the development and deposition of limestone as well as glauconite, often contained within the limestone (Dodd and Nelson, 1998). The sedimentary rock fragments type 2 can be sourced from any of the Oligocene (Te Kuiti Group) or Miocene (Waitemata/Parengarenga Group) Northland Allochthon sedimentary rocks in the onland geology of the NNCS (Figure 7.1).

7.2.1C Heavy minerals

The dominant heavy minerals in the NNCS sediments, from highest to lowest abundance, are epidote, hypersthene, green hornblende, brown hornblende, enstatite and some augite and (titano)magnetite (Table 5.1). Igneous rocks are the dominant source of most of these heavy mineral types in the NNCS, with hornblende, hypersthene, augite and magnetite typically derived from basaltic and/or andesitic rocks (Deer *et al*., 1992). The closest sources of these heavy minerals in the NNCS include: a) Pliocene to Holocene Kerikeri Volcanics, b) Miocene volcanics of the Whangaroa Group, c) submarine basalts and basaltic andesite lavas inerbedded within the Mesozoic basement rocks, d) local Tangihua volcanics of Cretaceous age within the Early Miocene Northland Allochthon unit (Summerhayes, 1969a), and e) the more distal Taupo Volcanic Zone (Figure 7.1 and 7.2).

Epidote, often the most abundant heavy mineral in the NNCS sediment, is most likely sourced from the Waipapa Terrane Mesozoic basement rocks in the south of the study area (Jennings, 1989). Hypersthene and augite predominate in TVZ rhyolites and andesites, with rare hornblende and opaque minerals also present (Stokes and Nelson, 1991; Hudson; 1996).

7.2.1D Provenance overview for the NNCS sediment

Local onland sources can largely account for the siliciclastic components in the NNCS sediments. Given the relative weakness of any persistent longshore current system in the inner NNCS compared to that on the western and northern side of the Northland Peninsula (Summerhayes, 1969a), the effect of local sources should be enhanced. Local sources of siliciclastic material from the onland geology of the NNCS are described below:

a) The southern sector is dominated by Mesozoic basement rocks (greywacke, argillite and local submarine basalts), which contribute common sedimentary rock fragments type 1 and quartz, some plagioclase feldspar, and minor amounts of heavy minerals.

b) The central sector is dominated by Early Miocene Northland Allochthon deposits from which the Tangihua Complex, in particular, is a local source of submarine basaltic rock fragments and heavy minerals, while the sedimentary Tupoa Complex can account for some of the sedimentary rock fragment (type 2) grains and some quartz, plagioclase and heavy minerals. Pliocene to Holocene Kerikeri Volcanics could also contribute minor to moderate amounts of basaltic rock fragments.

c) The northern sector is dominated by Quaternary quartzofeldspathic beach, dune and terrace deposits (Karioitahi Complex), an obvious major source of quartz and plagioclase grains.

More distant sources for quartz, feldspar, volcanic rock fragments and heavy minerals could be the TVZ and Coromandel andesites and silicic volcanics and the Taranaki andesites (Figure 7.2).

The major sources of sediment to the NNCS are therefore concluded to be local ones involving in approximate order of importance: the Mesozoic basement rocks, the Northland Allochthon deposits, particularly the Tangihua Complex, the Pleistocene to Holocene sediments of the Karioitahi Group and the Miocene sedimentary rocks of the Parengarenga Group. The TVZ andesites and rhyolites, the silicic volcanics from the Coromandel peninsula and the Taranaki andesites (Figure 7.2) are unlikely to supply much material to the NNCS due to difficulties in transportation.

7.2.2 Hydrodynamics and sediment transport

The source rocks of the major siliciclastic sediment components in the NNCS sediments generally occur in the onland bordering geology. The supply of these minerals to the coastline is via river/stream action and coastal erosion. Some sediment components may have also been transported from other coastal settings such as North Kaipara and Cape Reinga through littoral drift or oceanic currents.

Many of the bays and inlets bordering the NNCS receive relatively low fresh water runoff except for the Bay of Islands which receives an annual average fresh water runoff of 46 m^3s^{-1} (Table 2.1). The few rivers associated with this runoff are likely to have transported sediment components from local onland sources, including Mesozoic basement rocks, Northland Allochthon rocks, Miocene sedimentary rocks and Quaternary sand deposits (see Section 7.2.1D).

From the coastline it is possible that grains tend to be transported northwards within cyclonic eddies that originate from the East Auckland Current (Schofield, 1969; Summerhayes, 1969a). Some evidence for this comes from a composite dispersal chart using hornblende directional indicators to show the influence of currents on sediment distribution (Summerhayes, 1969a). Hornblende data off the northeastern part of the NNCS reflect a northwards current transport direction deflected to the east due to contact with North Cape , a scenario supported by the bathymetric profile off North Cape (Schofield, 1969; Summerhayes, 1969a) (Figure 5.2). Summerhayes (1969a) suggested that coastal profiles do not indicate any particular longshore drift directions symptomatic of currents that are weaker in northeastern Northland than on the northwestern and northern shelves. He and Schofield (1969) also suggested that the southeast flowing East Auckland Current produces fine-scale current activity and that eddies derived from this current are responsible for the inshore local sediment transport in the opposite direction. A sediment transport scheme is shown in Figure 7.1 that links the generalised onland source geology bordering the NNCS with the proposed hydrodynamic regime.

7.2.3 Substrate types

Hard substrates recorded in the acoustic backscatter map (Figure 2.23) occur in areas consisting of bedrock and gravel sized sediment including boulders, cobbles and pebbles (Figure 2.24). It was also determined in Chapter 4 (Section 4.1) that hard substrates (Figure 2.23) correlate well with areas of high gravel contents (Figure 4.4). Many organisms, such as red algae and barnacles, attach themselves to hard substrates leading to the preferential accumulation of coarse grained carbonate material on hard substrates rather than in soft substrates. Figure 7.3 compares the acoustic backscatter image of the NNCS with the distribution of carbonate contents in the NNCS sediments. Most typically it is evident that the areas of highest calcium carbonate contents coincide with hard substrate areas. In Figure 7.4 the acoustic backscatter is compared to the calciclastic or skeletal content in the NNCS sediments and expectedly the areas with the highest skeletal contents also correspond broadly to those with hard substrates.

Sediments that contain high amounts of sand and mud (Figure 2.24) do not always correlate with soft substrates recorded in the acoustic backscatter map (Figure 2.23), in agreement with the mud and sand textural data reported in Chapter 4. Both mud and sand are found in depths ranging from 0-210 m with high sand contents occurring throughout the majority of the study area and high mud contents (consisting almost entirely of very coarse silt) occurring mainly in the southern sector due to accentuated supply from bays and inlets, especially from the Bay of Islands. Sediment usually becomes finer in an offshore direction due to higher energy at the coast which contributes to coarse and sometimes more poorly sorted sediment nearshore and finer often better sorted sediment further offshore. This relationship may relate partly to the apparent paucity of finer silt and clay sizes in the NNCS sediments, which could be due to a dearth of such sizes supplied from source or to bypassing beyond the shelf. Also, this fine sediment may become trapped in bays and inlets or by mangroves or sea grass which are common in the coastal embayments (Adams, 1979; Hayward, 1981; Pickrill, 1986; Pickrill *et al*., 1986).

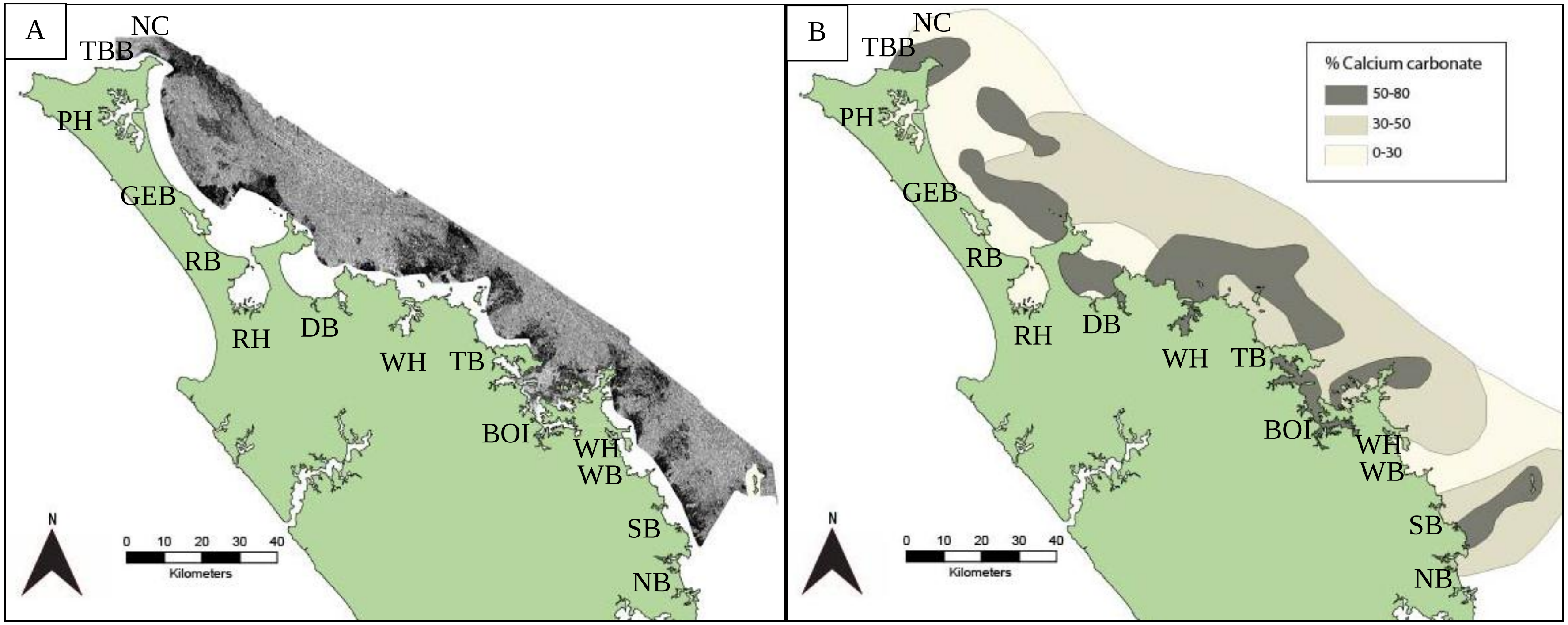


Figure 7.3: Comparison of acoustic backscatter image over portions of the NNCS (A) with the distribution of calcium carbonate content in bulk sediments on the NNCS (B). Dark areas on acoustic backscatter image represent hard substrates and light areas represent soft substrates. Locality name codes are defined in Figure 1.2.

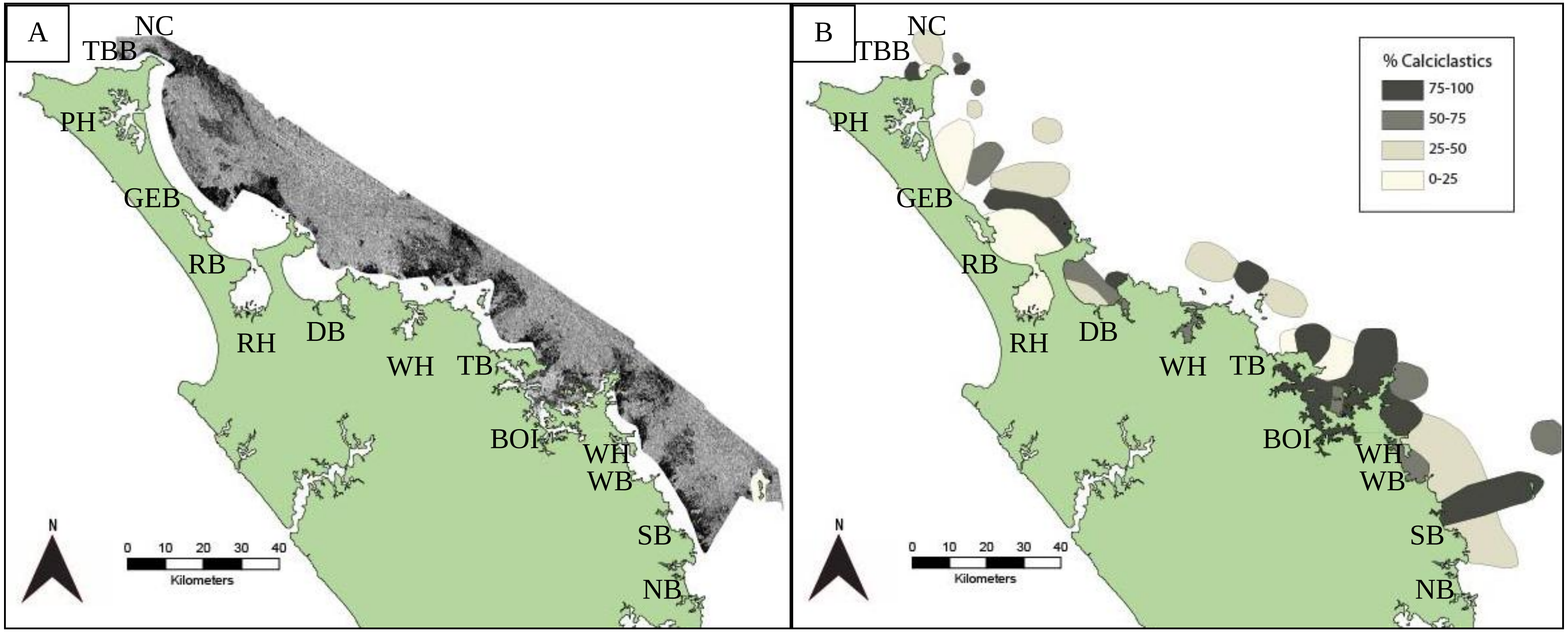


Figure 7.4: Comparison of acoustic backscatter image over portions of the NNCS (A) with the distribution of calciclastics (skeletal grains) in NNCS surficial sediments (B). Dark areas on acoustic backscatter image represent hard substrates and light areas represent soft substrates. Locality name codes are defined in Figure 1.2.

7.2.4 Glacio-eustatic sea level changes

Sea level is reported to have fallen 120 m below its current level during the peak of the last Glaciation, approximately 20 000 years ago (Carter, 1975). During this period of lowered sea level carbonate secreting organisms established themselves in their usual preferred water depths thus contributing skeletal carbonates to the immediately local sediment. Likewise, the distribution of terrigenous material was also affected by the new hydraulic regime. Once post-glacial melting of the Antarctic and northern hemisphere ice sheets occurred, sea level rose and the carbonate and/or terrigenous material was potentially left stranded 120 m below their usual environmental and depositional depths. During sea level rise sediment facies progressively moved towards the shoreline.

Evidence for lowered sea level on the NNCS is reflected in the following sediment characteristics:

- Moderately and poorly preserved skeletal material occurs in sediment in outer-shelf depths. This likely relict skeletal material may have been left at these depths during periods of lowered sea level.
- Rounding and sorting of many of the glauconite grains in the NNCS sediments in mid- to outer-shelf depths suggest that glauconite may have been deposited or formed during relatively higher energy conditions associated with periods of lowered sea level.
- Poorly preserved bivalves and barnacle fragments, the latter usually requiring hard substrates on which to form, occur on soft sandy substrates in mid- to outer-shelf depths on the NNCS. These skeletal fragments could easily have been reworked by strong currents or could have formed in these once near shore depths during periods of lowered sea level. This is supported by DTIS video imagery which indicates very low amounts or an absence of live bivalves and barnacles in mid- to outer-shelf depths, so suggesting some relict source.

7.3 SKELETAL CARBONATES

7.3.1 Preservation and age of skeletal grains

Shell preservation in the NNCS sediments shows a very general trend of worse preservation with increasing water depth (Figure 6.4). This suggests that some proportion of the skeletal material in outer-shelf depths of the NNCS may have been deposited during lowered sea levels accompanying last glacial and post-glacial times (Payne, 2010). Consequently they would be significantly older than their modern counterparts, and therefore potentially far more abraded, microbored and altered. The presence of poorly preserved and relict appearing skeletal grains may also represent skeletal material that has been degraded much faster due to a high energy environment and being composed of less stable carbonate minerals such as aragonite or high-Mg calcite (Nelson *et al*., 1982).

The occurrence of well to poorly preserved grading of sediments in an offshore direction suggests that modern sediment is being supplied primarily by ‘carbonate factories’ occurring at inner-shelf depths and in bays and inlets, and from some deeper areas of rocky outcrops. This is supported by both the calcium carbonate and calciclastic contents decreasing with increasing water depth and occurring in areas with harder substrate types (Figure 7.2 and 7.3).

Endolithic boring of the main skeletal grains (predominantly bivalves and barnacles) is common throughout the NNCS surficial sediments. These borings are often filled with limonite and sometimes glauconite. Limonite and glauconite infills are also common within foraminiferal tests, along with mud/clay infills. Individual glauconite grains also occur in the NNCS sediments with the highest contents (5-15%) in mid- to outer-shelf depths in the northern sector of the NNCS (Figure 5.11). The glauconite grains are often well rounded and well sorted indicative of transportation from elsewhere or possibly through being subjected to high energy environments or strong currents in these localities near the shelf edge (e.g. Sverdrup *et al*., 1942; Kuenen, 1950). Glauconite formation requires slightly reducing environments often associated with slow or negligible sedimentation, typically associated with relict sediment (McRae, 1972). Nutrient rich waters, caused by upwelling and high energy environments, are also favourable for glauconite evolution and this is consistent with the occurrence of glauconite in mid- to outer-shelf depths where strong currents and upwelling prevail (Summerhayes, 1969a).

The presence of glauconite in mid- to outer-shelf depths may be linked to the presence of poorly preserved and relict appearing grains also occurring at these depths. Glauconite requires at least 100 000 years to evolve (Odin and Fullagar, 1988) which suggests that the glauconite grains are relatively old. The time required for glauconite to evolve and the rounding and sorting of many of the glauconite grains in the NNCS sediments in mid- to outer-shelf depths indicate that glauconite may have been deposited or formed during relatively higher energy conditions associated with periods of lowered sea level (see Section 7.2.4).

Radiocarbon dates were obtained by Nelson *et al.* (1982) for five relict appearing skeletal samples in the Three Kings region on the northwestern shelf of Northland (Figure 1.2). The ages ranged from 5000 to 10500 year B.P. (Table 7.1). NNCS sediments are likely to have similar ages to the Three Kings sediments. Interestingly, the most relict appearing sediment yielded the youngest date and the freshest appearing sediment yielded the oldest date, suggesting that grain appearance is more, or as much, a function of environmental and mineralogical characteristics than of age (Nelson *et al.*, 1982).

Table 7.1: Radiocarbon dates for carbonate sediments off northern New Zealand (from Nelson *et al.*, 1982).

Sample No.	Station No.	U.W. ^{14}C No.[a]	Age yr ± 1σ B.P.	Depth (m)	Sample Description
1	P450A	Wk206	7900 ± 80	120	Slightly discolored and corroded-looking bryozoan-bivalve gravel concentrate
2	P450B	Wk207	9260 ± 70	120	Slightly discolored and worn bryozoan-bivalve coarse and very coarse sand concentrate
3	P509	Wk208	10520 ± 95	80	Fresh-looking bivalve gravel concentrate
4	P590	Wk209	10270 ± 100	110	Slightly discolored and corroded-looking bryozoan-bivalve gravelly sand from base of 2.2-m-long core near station P450
5	P555	Wk210	5120 ± 70	516	Discolored and strongly corroded-looking ahermatypic coral fragments

7.3.2 Comparison of skeletal types with modern ecology

Dominant skeletal types in the NNCS include bivalves, barnacles, bryozoans, calcareous red algae, gastropods and benthic and planktic foraminifera (Figure 7.5). These are significantly different from the dominant live organisms observed during DTIS video imagery (Figure 7.6) which include porifera (sponges), cnidaria (anthozoa – corals, anemones and sea pens; hydrozoa – hydroids), bryozoans and echinoderms. The situation could partly reflect: a) the absence of DTIS video imagery in large sections of the NNCS, particularly the northern sector, b) the inability of DTIS to provide detailed imagery of small organisms (such as foraminifera) and c) the contribution from relict carbonate material (particularly bivalves and barnacles) associated with former lowered sea levels. The high energy and associated high nutrients during periods of lowered sea level implies that the biological ecosystem allowed for higher abundances of barnacles and bivalves during these periods and this may have changed over time with sea level rise in these areas reducing their population in more recent times.

Porifera, particularly in the form of sponge spicules in the sand fractions and occasional sponge baskets in the gravel fraction, are never a dominant skeletal type in the NNCS sediments but were still ubiquitously scattered throughout most of the shelf. This likely reflects the paucity of hard parts other than (siliceous) spicules in the sponge structure. Moreover, because of the small and light weight nature of the spicules they are probably prone to reworking off the shelf into deeper slope depths or being distributed in suspension in northward flowing eddies.

Live cnidaria (anthozoa – corals, anemones and sea pens; hydrozoa – hydroids) are dominant in outer-shelf depths (100-200 m) on the NNCS, however, skeletal material from these organisms was not observed in the NNCS sediments. This probably reflects the non-calcifying nature of the majority of the cnidaria, their soft tissues not remaining intact post-mortem.

The only dominant skeletal type found in the NNCS sediments that was also dominant in DTIS video imagery is bryozoans. Living bryozoans were observed only off Takou Bay in the central sector which corresponds to the skeletal material that occurs off Takou Bay, but bryozoan skeletal material also occurs off North Cape and Whangaruru Harbour.

As bryozoan material is presently being supplied to the sediment and bryozoan skeletal material is mostly well preserved and fresh looking, they are probably a relatively modern skeletal component recently contributed to the NNCS sediment. However, after reviewing radiocarbon dates for the sediment off northern New Zealand it is apparent that the appearance of skeletal grains does not always reflect their age. Therefore, the bryozoan skeletal material outside of Takou Bay could also represent relict, but well preserved, material that was supplied to the sediment during periods of lowered sea level.

Echinoderms, although never a dominant skeletal component in the NNCS sediment, are scattered as a minor contributor throughout samples. Live echinoderms were dominant in inner-shelf depths and in very outer-shelf depths so are not restricted to a particular depth on the NNCS shelf. Therefore their scattered occurrences are likely to be modern skeletal components recently contributed to the NNCS sediments.

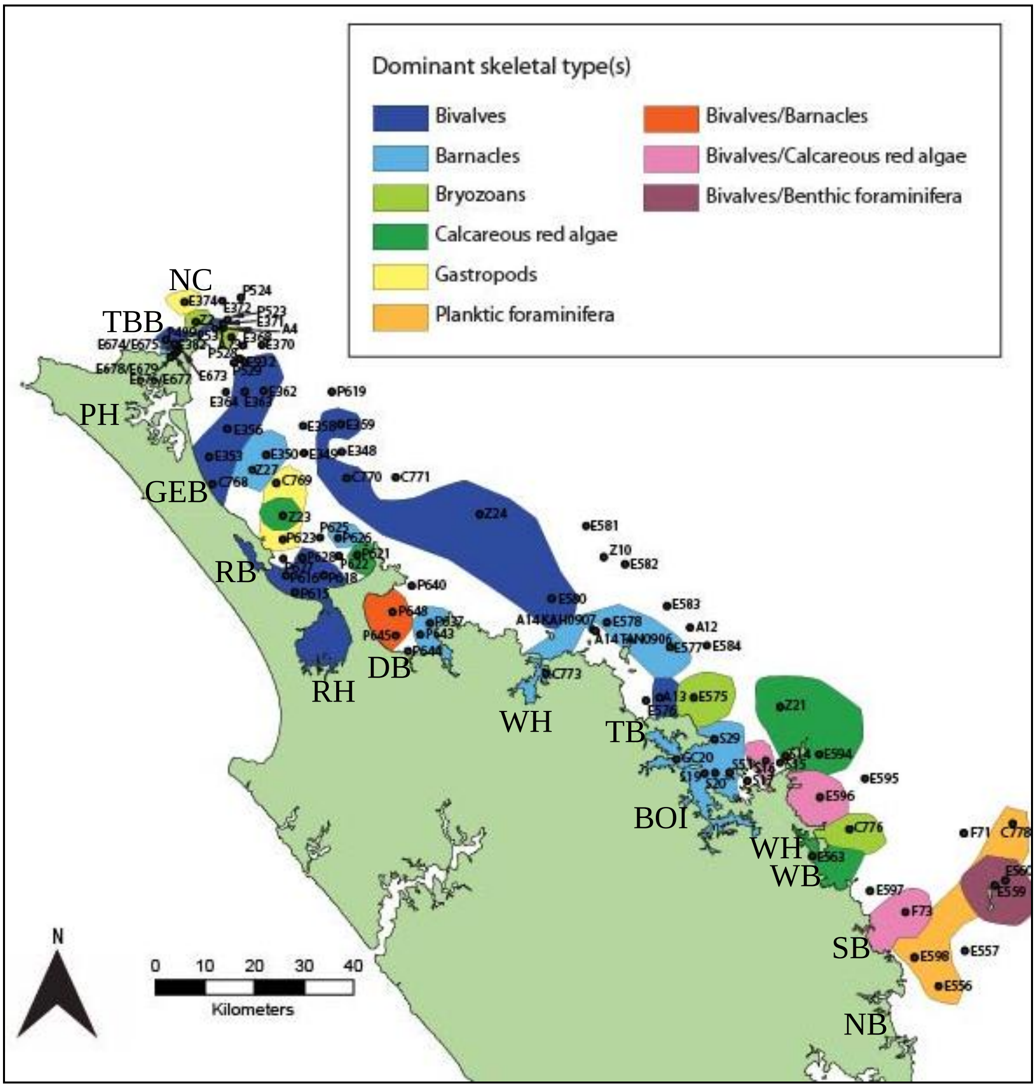


Figure 7.5: Distribution of dominant skeletal type(s) in NNCS surficial sediments. Locality name codes are defined in Figure 1.2.

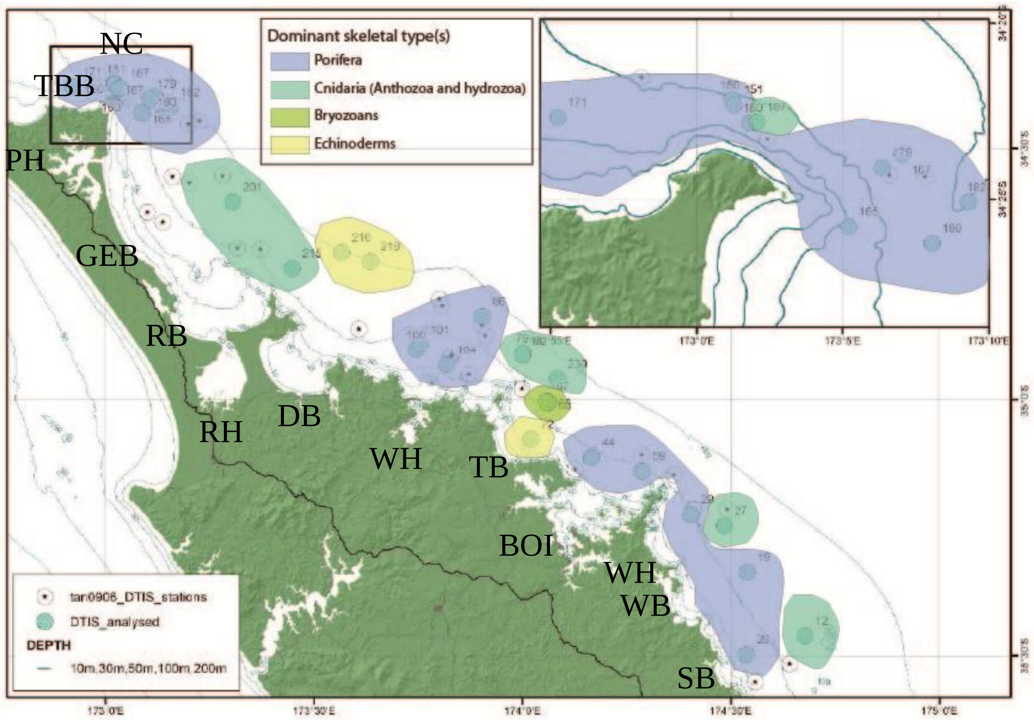


Figure 7.6: Distribution of dominant live organisms in NNCS surficial sediments based on DTIS video imagery (data from Bowden *et al*., 2010). Locality name codes are defined in Figure 1.2. Inset map shows the area around North Cape enlarged. The black line on land is the E-W catchment divide position in northern Northland.

7.4 SEDIMENTARY FACIES MODEL FOR THE NNCS

7.4.1 Major facies identified in the NNCS sediments

Five distinctive surficial sediment facies types have been defined for the sediments on the NNCS based on their textural characteristics and skeletal and siliciclastic composition. These facies are mapped in Figure 7.7 and described below, and their essential properties are compared in Table 7.2.

- Facies 1: Siliciclastic quartzofeldspathic sand – Quartzofeldspathic sands (gravelly sand to muddy sand) containing scattered bivalve and sometimes gastropod material.

- Facies 2: Mixed barnacle-siliciclastic gravel and sand – Gravels and sands (sandy gravel to muddy sand) generally dominated by barnacles with admixed sedimentary and volcanic rock fragments.

- Facies 3: Mixed calcareous red algae and bivalve-siliciclastic gravel and sand – Gravels and sands (sandy gravel to muddy sand) dominated by calcareous red algae and bivalves with admixed sedimentary rock fragments.

- Facies 4: Mixed foraminiferal-siliciclastic sand and mud – Sands (muddy sand, gravelly muddy sand and sandy mud) dominated by foraminifera with admixed quartzofeldspathic siliciclastic material and sedimentary rock fragments (type 2).

- Facies 5: Mixed bryozoan-siliciclastic sand – Sand (gravelly sand to muddy sand) dominated by bryozoans admixed with some quartzofeldspathic grains and sedimentary rock fragments (type 2).

Table 7.2: Summary of essential properties of the six facies defined for the NNCS sediments. Abbreviations are: v. = very, mod. = moderately.

Facies	Sediment texture	Sorting	Siliciclastics	Calciclastics	Preservation	Dominant skeletal types
1a/b	Sand	Well	>75%	<25%	Well to poorly	Bivalves
2	Gravel and sand	V. well to v. poorly	<25%	>75%	Well to poorly	Barnacles
3	Gravel and sand	V. well to v. poorly	<50%	>50%	Well to poorly	Calcareous red algae and bivalves
4a	Sand	V. poorly	25-50%	50-75%	Mod.	Benthic foraminifera
4b	Sand and mud	V. well to v. poorly	<50%	>50%	Mod. to poorly	Planktic foraminifera
5	Sand	Mod. to well	<40%	>60%	Mod. to poorly	Bryozoans

Facies 1: Siliciclastic quartzofeldspathic sand

Facies 1 occurs only in the northern sector of the NNCS from North Cape through Great Exhibition Bay, at depths ranging from 0-210 m, in western Rangaunu Bay and Doubtless Bay and off these Bays out to depths of 210 m (Figure 7.7). Facies 1 consists of well sorted quartzofeldspathic sand (Plate 7.1 A). The majority of the sediment comprises >75% siliciclastics and <25% calciclastics (Table 7.2). Non-opaque heavy minerals are common and opaques range from 1-5% and occasionally 5-15% (Figure 5.5). Glauconite is at its highest abundance in Facies 1 and although usually only a few %, can range up to 15% (Figure 5.11) Volcanic and sedimentary rock fragments (type 1 and 2) are rare and mostly <1% (Figure 5.6, 5.7 and 5.8). Scattered bivalve fragments/shells are common and are usually the dominant skeletal type in Facies 1, although occasionally gastropod material dominates. Facies 1 is divided into subfacies 1a quartzofeldspathic sand (Q>F) and subfacies 1b quartzofeldspathic sand (F>Q) (Figure 7.7).

Facies 2: Mixed barnacle-siliciclastic gravel and sand

Facies 2 occurs off Tom Bowling Bay, in mid Great Exhibition Bay out to depths of 200 m, in northeastern Rangaunu Bay, eastern Doubtless in Whangaroa Harbour out to depths of 108 m, and in the Bay of Islands (Figure 7.7). Facies 2 involves mostly well and very well sorted sediment in the north and poorly to very poorly sorted sediment in the south. The skeletal content forms >75% of the sediment and is dominated by barnacle fragments while siliciclastic material is generally <25% (Table 7.2) (Plate 7.1 B, C). Heavy minerals are rare with opaques mostly <1% (Figure 5.5). The barnacles range from fresh looking to relict and altered grains and are often very abraded and polished. Volcanic rock fragments are most common in Facies 2, ranging from 5-15% off Whangaroa Harbour and 1-5% in eastern Doubtless Bay and the Bay of Islands (Figure 5.6). Sedimentary rock fragments type 1 are common at 1-15% off Tom Bowling Bay, Great Exhibition Bay and western Bay of Islands, 15-50% in southern Doubtless Bay and central Bay of Islands and 50-75% in Takou Bay and off northern Bay of Islands (Figure 5.7). Glauconite is rare in Facies 2 at <1% (Figure 5.11).

Facies 3: Mixed calcareous red algae and bivalve-siliciclastic gravel and sand

Facies 3 occurs in the southern sector only, in and around eastern Bay of Islands out to depths of 128 m, and through Whangaruru Harbour and Bay to Sandy Bay at depths <80 m (Figure 7.7). Facies 3 is very poorly to very well sorted and consists of >50% calciclastics and is typically poor in siliciclastic material at <25% (Table 7.2) (Plate 7.1 D, E). Heavy minerals are rare with opaques contributing <1% most often (Figure 5.5). Volcanic rock fragments contribute <1% in most of the sediment (Figure 5.6) while sedimentary rock fragments type 1 and 2 are generally <15% but sedimentary rock fragments type 2 can locally reach up to 50% (Figure 5.7 and 5.8). Glauconite is also rare at <1% (Figure 5.11).

Facies 4: Mixed foraminiferal-siliciclastic sand and mud

Facies 4 occurs in the very southern sector of the NNCS and is divided into subfacies 4a, consisting of a mixed benthic foraminiferal-siliciclastic sand, and subfacies 4b, a mixed planktic foraminiferal-siliciclastic sand and mud. Subfacies 4a occurs off Sandy Bay in water depths ranging from 100-150 m (Figure 7.7). It comprises 50-75% calciclastics/skeletal material typically dominated by benthic foraminiferal tests, and 25-50% siliciclastics (Table 7.2) with moderate amounts of quartz and plagioclase, the latter sometimes dominating over quartz (Figure 5.3 and 5.4) (Plate 7.1 F). Benthic foraminifera are moderately preserved skeletal grains. Heavy minerals, volcanic rock fragments and sedimentary rock fragments (type 1 and type 2) are rare in subfacies 4a (Figures 5.5 to 5.8). Glauconite contents are also negligible in subfacies 4a at <1% (Figure 5.11).

Subfacies 4b occurs between Sandy Bay and Ngurauru Bay from mid to outer-shelf depths ranging from 50-200 m (Figure 7.7). Subfacies 4b contains >50% siliciclastics consisting of low to moderate amounts quartz and feldspar (Figure 5.3 and 5.4) and <50% calciclastics (Table 7.2) dominated by planktic foraminifera (Plate 7.1 G). Planktic foraminifera are poorly preserved and contain limonite and glauconite infills within test chambers. Heavy minerals, volcanic rock fragments and sedimentary rock fragments type 1 are all <1% (Figure 5.5, 5.6 and 5.7) but sedimentary rock fragments type 2 are relatively abundant at 15-50% in water depths at <100 m (Figure 5.8).

Facies 5: Mixed bryozoan-siliciclastic sand

Facies 5 has a limited and scattered distribution off North Cape, east of Takou Bay and off Whangaruru Harbour at water depths of 50-100 m (Figure 7.7). Siliciclastic material is <40% with low to high relative abundances of quartz and feldspar (Figure 5.3 and 5.4) and calciclastics are >40% and dominated by bryozoan material (Table 7.2) (Plate 7.1 H). Poorly preserved bryozoan grains occur off North Cape and Whangaruru Harbour and well preserved bryozoan grains occur near the Bay of Islands east of Takou Bay (Figure 6.4). Heavy minerals are relatively low with opaques at <1% except east of Takou Bay near the Bay of Islands where they range from 1-5% (Figure 5.5). Both volcanic and sedimentary rock fragments (type 1 and 2) are rare at <1% except off Whangaruru

Harbour where sedimentary rock fragments type 2 range from 15-50% (Figure 5.6, 5.7 and 5.8). Once again glauconite is negligible at <1% (Figure 5.11).

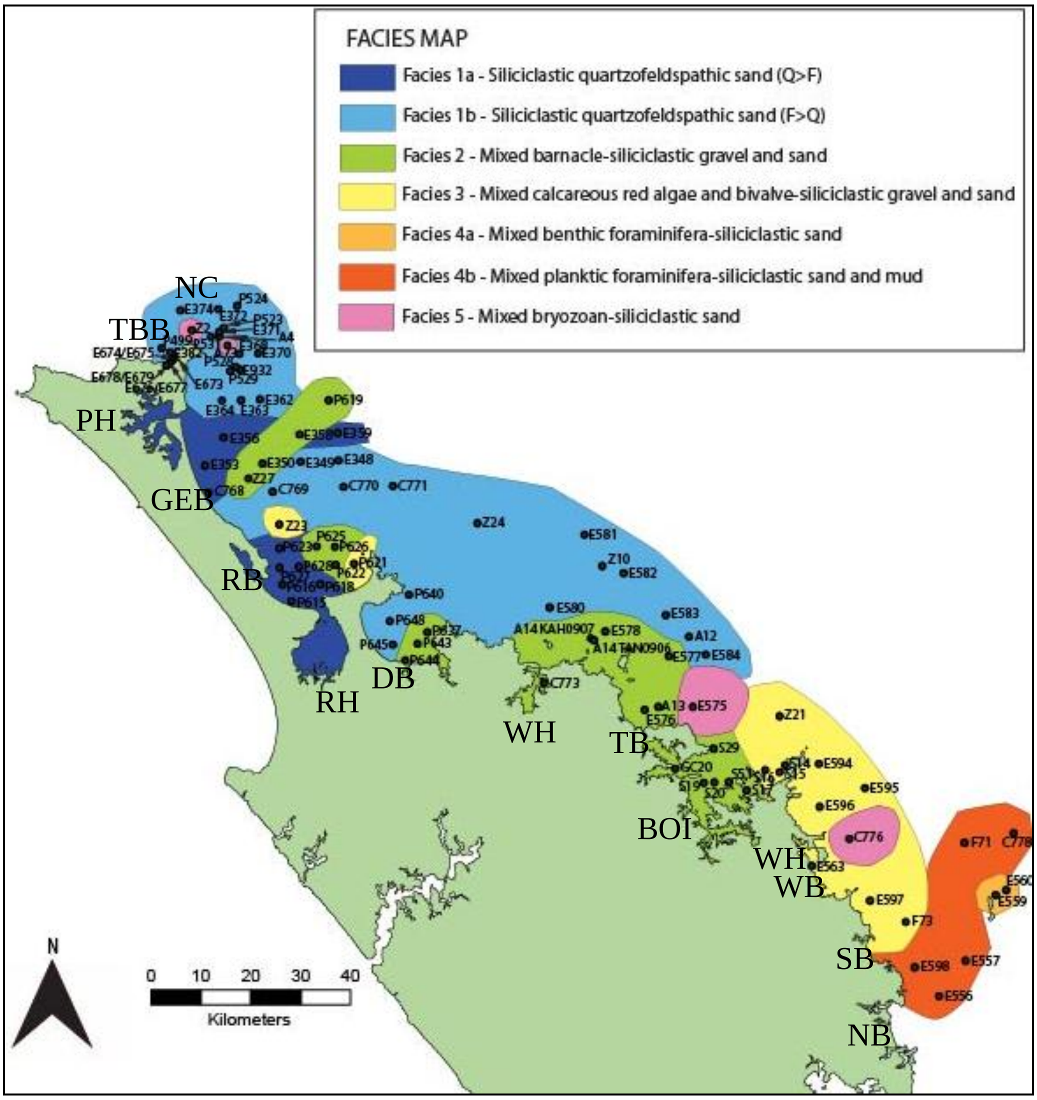


Figure 7.7: Distribution of surficial sediment facies on the NNCS. Locality name codes are defined in Figure 1.2. The 'Parengarenga Sand Facies' occurs approximately within the boundaries of Facies 1a.

PLATE 7.1

Photomicrograph examples of Facies 1 to 5 (see Table 7.2).

A Facies 1 siliciclastic quartzofeldspathic sand of sample P616 (transect D; 16 m water depth) showing well sorted quartzofeldspathic grains and some bivalve fragments.

B Facies 2 mixed barnacle-siliciclastic gravel and sand of sample C773 (transect F; 26 m water depth) showing a volcanic rock fragment (centre) and a barnacle fragment (left).

C Facies 2 mixed barnacle-siliciclastic gravel and sand of sample S29 (near transect G; 37 m water depth) showing a range of sedimentary rock fragments type 1 including red-brown sandstones (greywacke) and a mudstone (argillite) at bottom right corner.

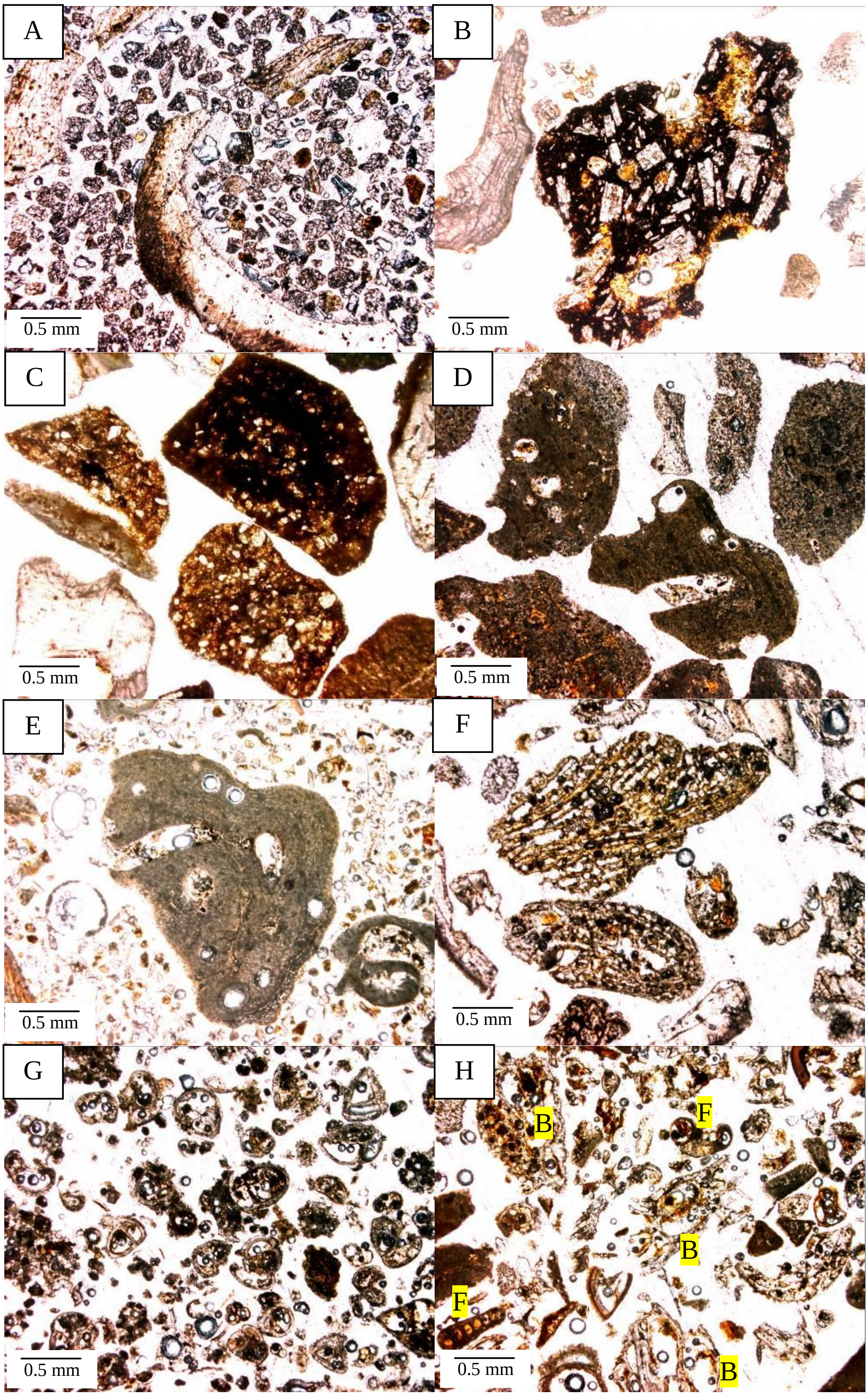
D Facies 3 mixed calcareous red algae and bivalve-siliciclastic gravel and sand of sample P621 (near transect D; 18 m water depth) showing several calcareous red algal grains but an absence of siliciclastic grains.

E Facies 3 mixed calcareous red algae and bivalve-siliciclastic gravel and sand of sample E563 (between transect G and H; 9 m water depth) showing a central calcareous red algal grain amongst fine grained broken and altered carbonate grains and some siliciclastic grains.

F Subfacies 4a mixed benthic foraminiferal-siliciclastic sand of sample E559 (transect H; 106 m water depth) showing the encrusting benthic foraminifera *Homotrema* sp. surrounded by broken and altered carbonate grains.

G Subfacies 4b mixed planktic foraminiferal-siliciclastic sand and mud of sample E598 (near transect H; 68 m water depth) showing planktic foraminifera rich sediment. The planktic foraminifera are altered and contain limonite and sometimes muddy infills within tests.

H Facies 5 mixed bryozoan-siliciclastic sand of sample E575 (near transect G; 77 m water depth) showing poorly preserved, broken and limonite stained bryozoan fragments (B) surrounded by some benthic foraminifera (F) and other broken carbonate grains and occasional siliciclastic grains.


A
0.5 mm
B
0.5 mm
C
0.5 mm
D
0.5 mm
E
0.5 mm
F
0.5 mm
G
0.5 mm
H
B
F
B
F
0.5 mm
B

7.4.2 Interpretation of NNCS facies

Facies 1: Siliciclastic quartzofeldspathic sand

In inner shelf depths just off Parengarenga Harbour exists the Parengarenga Sand Facies (Schofield, 1970) (Figure 7.7), called subfacies 1a in this study, comprising well sorted, more quartz enriched quartzofeldspathic sands (Figure 5.4). The onland geology consists of Quaternary sediments in the northern sector of the NNCS dominated by unconsolidated quartz rich coastal dune sands belonging to the Karioitahi Group. Therefore the quartz rich sands comprising subfacies 1a off Parengarenga Harbour, Great Exhibition Bay and western Rangaunu Harbour are likely to be sourced from the reworking of these Quaternary deposits (Ricketts, 1979). Another contributing possibility for the sands is from podzolisation in the catchment which causes severe leaching of the upper sand horizon leaving only quartz grains (Schofield, 1970). These sediments may be transported offshore and northwards by eddies derived from the East Auckland Current.

Subfacies 1b (Figure 7.7) consists of more plagioclase rich quartzofeldspathic sands which are primarily derived from the erosion of a combination of the Quaternary sand deposits (Katioitahi Group), the Mesozoic basement rocks and Northland volcanic and sedimentary rocks. Mesozoic basement rocks comprise local submarine basalt and basaltic andesite lavas which could be another local source for plagioclase feldspar. The plagioclase enriched sands may have been deposited before the quartz rich sands of subfacies 1a given the predominantly nearshore distribution of the latter.

Pyroxene and opaque heavy minerals of mainly basaltic heritage are present in the siliciclastic sand facies and have been sourced from basaltic flows within the Mesozoic basement rocks and especially from the widespread local Tangihua volcanics of Mesozoic age caught up in the Northland Allochthon (Summerhayes, 1969a). Epidote is the most abundant heavy mineral and is probably derived from the Waipapa Terrane greywacke dominating the Mesozoic basement rocks (Jennings, 1989).

Glauconite is present in subfacies 1b in outer-shelf depths in amounts up to 5-15% which could suggest that minimal sediment has been supplied to this area of the

NNCS over the last 100 000 years or more (Odin and Fullagar, 1988). This is because glauconite requires such long periods to fully evolve (Odin and Fullagar, 1988) and therefore the glauconite grains are probably relatively old. However, the glauconite grains are typically well rounded indicative of reworking and transport, so they are probably mainly detrital (allochthonous) rather than authigenic grains. Upwelling and nutrient rich waters in the vicinity of the shelf edge can contribute to the formation of glauconite (Sverdrup *et al*., 1942; Kuenen, 1950), and it could well be that this was the primary setting for initial glauconite formation that then became variably dispersed during sea level changes (see Sections 7.2.4 and 7.3.1). This is supported to some extent by the decrease in carbonate content towards the shelf edge (Figure 5.1) suggesting that the finer carbonate grains have been winnowed from the sediment (Summerhayes, 1969a).

Facies 2: Mixed barnacle-siliciclastic gravel and sand

Facies 2 (Figure 7.7) consists of coarser gravelly and sandy sediments with a high skeletal content (>75%) and low siliciclastic content (<25%). Barnacle fragments are generally well preserved, fresh and less microbored and altered nearer shore, particularly within bays and inlets such as Doubtless Bay, Whangaroa Harbour and the Bay of Islands (Figure 5.10 and 6.4). In deeper mid- to outer-shelf waters the barnacle fragments grade from a mixture of moderately preserved to largely poorly preserved and microbored grains with limonite alteration within the borings and hollow parts of the shell (Figure 6.4). The barnacle fragments in mid- to outer-shelf depths are therefore possibly older and could have been subjected to higher energy environments during times of lowered sea level. This was also the situation for the glauconite in Facies 1b, which reinforces the possibility that sediments in mid- to outer-shelf depths are likely to be older than those in inner- to mid-shelf depths. The relict barnacle fragments in outer-shelf depths may also have been transported offshore and northwards to these depths by eddies derived from the East Auckland Current and then abraded and broken by strong currents near the shelf edge (Sverdrup *et al*., 1942; Kuenen, 1950). Barnacles need rocky outcrops for attachment and are associated with the presence of gravel in Facies 2.

Facies 2 contains volcanic rock fragments (1-15%). They are mainly submarine basalts periodically derived principally from the local Tangihua volcanics of the Northland Allochthon (Summerhayes, 1969a), with possible contributions from

Mesozoic basements rock basaltic interbeds and the Pliocene to Holocene Kerikeri Volcanics. Volcanic rock fragments occur mainly in bays and inlets, particularly Whangaroa Harbour (5-15%), after erosion from source rocks and transport and deposition by rivers, and were not transported into deeper waters. This could reflect their large size (1.0-3.0 mm) and heavy mineral content, contributing to their weight and making them more difficult to pick up by northward flowing eddies.

Facies 2 also contains sedimentary rock fragments type 1 (1-15%) comprising greywacke and/or argillite morphologies which are primarily sourced from Mesozoic basement rocks. These sedimentary rock fragments occur mainly in central sector bays and inlets but have also been transported into deeper mid-shelf waters up to 108 m depth.

Facies 3: Mixed calcareous red algae and bivalve-siliciclastic gravel and sand

Facies 3 (Figure 7.7) is generally high in calciclastic material (>50%) and contains moderate siliciclastic material (<50%). Calcareous red algae are the dominant skeletal type in the sediment (Figure 5.11) but minor amounts of bivalve fragments also occur. Bivalve fragments are moderately to poorly preserved with limonite staining and abrasion, while sediment with subequal mixed bivalve-calcareous red algae dominating are well to moderately preserved (Figure 5.10 and 6.4). This is associated with the variable sorting values (poorly to well sorted) of Facies 3 suggesting that there is a mix of relict skeletal material, deposited during periods of lowered sea level, and modern skeletal material that is still being supplied to the sediment.

Facies 3 contains sedimentary rock fragments type 2 (up to 15%) which could be sourced from Tertiary rocks as they often contain glauconite grains which are common in Oligocene to earliest Miocene deposits (Te Kuiti Group) associated with the maximum period of New Zealand subsidence in the Cenozoic and the deposition of limestone (Dodd and Nelson, 1998). These rock fragments are probably eroded and transported by rivers or streams onland to Ngurauru Bay or Sandy Bay, from where they are then transported offshore and northwards by eddies derived from the East Auckland Current. This is supported by the absence of sedimentary rock fragments type 2 in Whangaruru Harbour at <50 m water depth but their occurrence in deeper waters off Whangaruru Harbour and Bay.

Facies 4: Mixed foraminiferal-siliciclastic sand and mud

Subfacies 4a (mixed benthic foraminiferal-siliciclastic sand) is restricted in distribution and associated with relatively hard substrates (Figure 7.7). This facies type contains some quartz but mostly plagioclase that is likely to be primarily sourced from the Mesozoic basement rocks occurring onland bordering the southern sector of the NNCS. The dominant skeletal type is benthic foraminifera (Plate 12 F) but the sediment also contains various other skeletal grains, particularly bryozoans, bivalves and calcareous red algae. The benthic foraminifera are moderately preserved specimens and occur in mid-shelf depths ranging from 100-150 m, which is consistent with the grading of well to poorly preserved skeletal grains in an offshore direction. The sediment is poorly sorted due to the mixture of skeletal types present in the siliciclastic sand. The poor sorting of sediments suggests that whole, modern skeletal material is possibly still being supplied to the environment. The foraminifera could be thriving from the nutrients that are contributed by upwelling associated with strong currents on the shelf edge. Other shell material probably accumulated due to the presence of rocky substrates in the mid-shelf depths off Sandy Bay.

Facies 4b (mixed planktic foraminiferal-siliciclastic sand and mud) occurs in mid-shelf depths (100-150 m) off Sandy Bay (Figure 7.7). This facies contains low to moderate amounts of quartz and plagioclase. Planktic foraminifera are poorly preserved and often contain limonite and glauconite infills within test chambers. This suggests that these sediments are relatively old and associated more with times of lowered sea level. On the other hand the occurrence of planktic foraminifera in these unusually shallow depths could indicate a more local source and they could have been reworked from the erosion of sedimentary rock fragments type 2. Sedimentary rock fragments type 2 (15-50%) often contain skeletal grains including planktic foraminifera. They occur in water depths at <100 m and are associated with the onland occurence of Oligocene and Early Miocene glauconitic limestones. These rock fragments are probably transported by rivers or streams to Ngurauru Bay or Sandy Bay, from where they were then transported offshore by northward flowing eddies. The mixed planktic foraminiferal-siliciclastic sand and mud ranges from well to very well sorted which could suggest the material is relict and has been exposed to a high energy environment such as that accompanying the lowered sea level at the peak of the

Last Glaciation. The muddy sediment may inhibit the growth of other carbonate secreting organisms and therefore the accumulation of other skeletal material in subfacies 4b.

Facies 5: Mixed bryozoan-siliciclastic sand

Mixed bryozoan-siliciclastic sand (Figure 7.7) contains poorly preserved bryozoan grains off North Cape and Whangaruru Harbour and well preserved bryozoan grains near the Bay of Islands east of Takou Bay. This could be due to the northwards transport of sediment by eddies derived from the East Auckland Current which contributes to the abraded appearance of skeletal grains further northwards. DTIS video imagery suggests modern bryozoan fragments are presently being supplied to the sediment off Takou Bay. The relatively scattered distribution of bryozoans reflects the hard substrate areas and rocky outcrops revealed in the backscatter data (Figure 7.3) which is expected as bryozoans prefer to live in this type of environment. Both siliciclastic material and heavy minerals are likely to be primarily sourced from the erosion of the Mesozoic basement rocks (greywacke and local basalt) followed by their transportation by rivers to bays and harbours and then offshore and northward by eddies. Sedimentary rock fragments type 2 (15-50%) occur in water depths at <100 m and are likely to be sourced from onland Tertiary sediments due to their glauconite contents. Facies 5 is moderately to very poorly sorted off North Cape, moderately sorted off Takou Bay and well sorted off Whangaruru Harbour. This could reflect the content of sedimentary rock fragments type 2 in the sediment and the larger skeletal grains recently supplied to the NNCS sediment, giving insufficient time for break down into smaller size ranges or for sorting by the hydraulic regime.

7.5 TEMPERATE CARBONATE SEDIMENTATION

7.5.1 Comparison of NNCS to temperate carbonate textural sedimentation model

James (1997) developed a basic sedimentation model for cool-water carbonates on wave-dominated shelves based on skeletal material grain sizes and the various processes involved from shelf to slope depths (Figure 7.8). This model displays a graded shelf where sediment fines in an offshore direction. It consists of inner-shelf, middle-shelf, outer-shelf and slope sections. The inner-shelf comprises gravel sized sediment and hard substrates due to being subjected to constant wave agitation which removes sand and mud sized sediment. The middle-shelf comprises coarse skeletal sand while finer sediment is removed by frequent storm reworking. Sediment transport occurs in both the inner- and middle-shelves. The outer-shelf consists of bioturbated fine skeletal sand remaining after episodic storm reworking. The slope sediments comprise bioturbated benthic skeletal muds formed from pelagic fallout and sediment gravity flows.

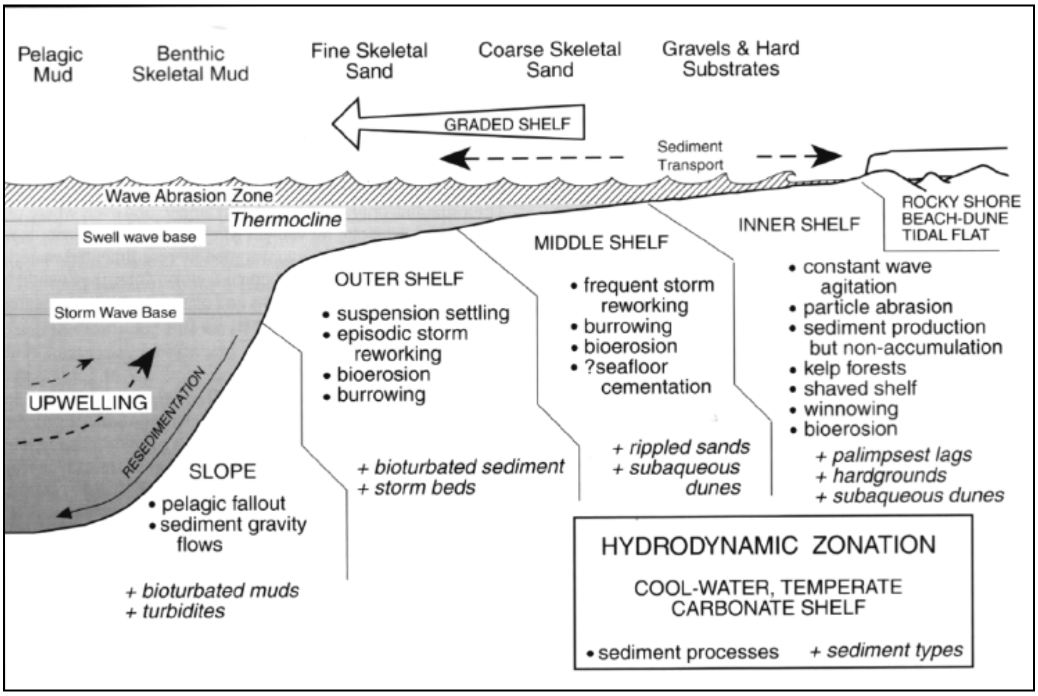


Figure 7.8: Textural sedimentation model for a cool water temperate carbonate wave dominated shelf (from James, 1997). The wave abrasion zone base ranges from 30-70 m water depth, the swell wave base can be up to 120 m water depth and the storm wave base up to 250 m water depth.

The NNCS situation complies partly with this textural sedimentation model through experiencing semi-grading of its sediments, dominantly fining in an offshore direction. Sandy gravels and muddy sandy gravels occur mostly nearshore in the bays and harbours from Doubtless Bay southwards which corresponds to the textural sedimentation model, but are also found in mid-shelf depths off North Cape. Backscatter data show that the NNCS is relatively complex with regards to the presence of hard substrates in areas away from the inner shelf due to the presence of rocky outcrops in mid- to outer-shelf depths, particularly off North Cape, Whangaroa Harbour, just south of the Bay of Islands, Whangaruru Harbour and Sandy Bay (Figure 2.23). Therefore, the NNCS does not entirely conform to this model.

Skeletal gravelly sands and sands, muddy sands and gravelly muddy sands occur from coastal to outer shelf depths, not just the middle and outer shelves. The occurrence of sand sized sediment nearshore is probably because siliciclastic sand (mainly subfacies 1a) has been supplied in large quantities from erosion and reworking of Pleistocene sand deposits (Rickets, 1979) and the deposition of podzolised sands from the catchment area (Schofield, 1970).

Sandy mud occurs in coastal waters in the Bay of Islands and on the outer-shelf off Whangaroa Harbour and Ngurauru Bay, so it does not solely occur at slope depths. The mud sized portion of the NNCS sediments is, however, composed almost entirely of medium to very coarse silt sized grains (Figure 4.9). The occurrence of mud in the Bay of Islands can be explained by the relatively sheltered nature of the bay preventing high energy wave agitation from washing the fine sediment into deeper waters. Overall, the presence of rocky outcrops in mid- to outer-shelf depths and the frequent sheltered bays and harbours associated with the NNCS region presents a rather more complex shelf situation than the open ocean textural sedimentation model for cool-water shelf carbonates shown in Figure 7.8. Moreover, the NNCS sediments involve mixed terrigenous-carbonate deposits exhibiting a range of modern to relict components, factors contributing to the more complex facies patterns on the NNCS (Figure 7.7).

7.5.2 Comparison of NNCS to other North Island shelf carbonates

Modern New Zealand shelf carbonates are typically temperate deposits and mainly include bryomol and foramol skeletal assemblages (Hayton *et al*., 1995), mixed carbonate-terrigenous compositions, low sedimentation rates and are dominated by a calcitic mineralogy (Nelson *et al*., 1988). They typically have a gravelly or sandy texture with little carbonate mud and contain various combinations of relict, palimpsest and modern material (Nelson *et al*., 1988). The characteristics of five modern carbonate sediment occurrences about the North Island of New Zealand, including the NNCS, are summarised in Table 7.3, and described below along with comparisons to the NNCS sediments.

Table 7.3: Environmental and facies characteristics of major carbonate-siliciclastic deposits on modern shelf sectors about North Island, New Zealand (data from Hancock, 1980; Keane, 1986; Smith, 1992; Gillespie, 1992; Payne, 2010). See Figure 7.9 for localities.

Locality	Latitude	Deposition-al setting	Water depth (m)	% $CaCO_3$	Terrigenous input (tonnes/yr)	Sedimentat-ion rate (cm/ky)	Dominant skeletal types
North-eastern Northland continental shelf (NNCS)	35	Open shelf, sheltered bays & inlets	0-210	0-84	Low to moderate	Low (glauconite present)	Bivalves, barnacles
Three Kings	34	Open platform	0-500	17-100	Very low (30)	1-2	Bryozoans, bivalves
North Kaipara continental margin	35	Open shelf	0-185	3-91	High	Low (glauconite present)	Foraminifera, bivalves
Hauraki Gulf	36	Sheltered gulf	0-100	11-93	Low	1-2	Barnacles, bryozoans, gastropods
Wanganui	40	Open shelf	25-100	5-90	Moderate (180)	10-100	Foraminifera, gastropods, brachiopods

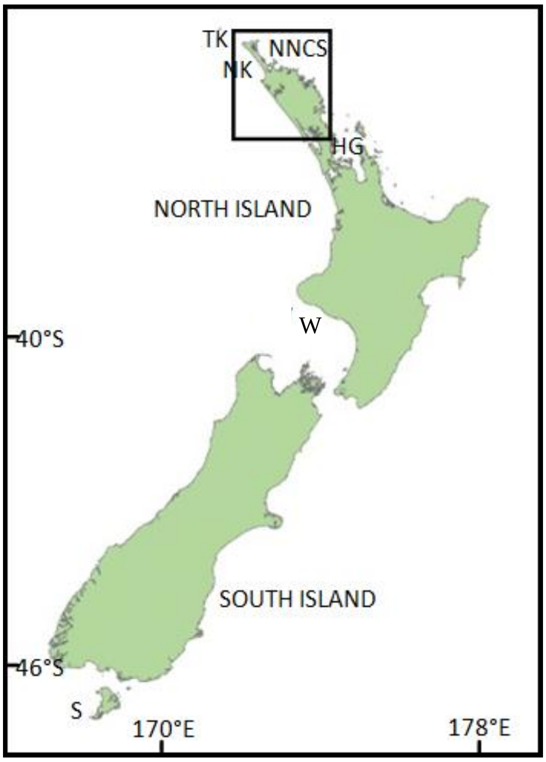


Figure 7.9: Major carbonate-siliciclastic deposits on modern shelf sectors about North Island, New Zealand (see Table 7.3). Abbreviations are: TK – Three Kings platform; NK – North Kaipara continental margin; HG – Hauraki Gulf; W – Wanganui shelf; S – Snares platform (South Island).

Three Kings platform

The Three Kings platform was studied in detail by Hancock (1980) and Nelson *et al.* (1982) and is mantled by Quaternary skeletal carbonate sediments, commonly exceeding 90% calcium carbonate. The carbonate component comprises mainly fragmented bryozoan colonies and other generally lesser contributions from bivalves, gastropods, corals, calcareous red algae, foraminifera, serpulids, barnacles, echinoderms, brachiopods, sponges and pteropods. These skeletal components are similar to, but rather more diverse than those found on the NNCS. The skeletal carbonate sediments are mostly relict below 150-200 m water depth, and the same pattern is observed for the NNCS sediments. This situation is attributed to Late Quaternary oscillations in sea-level.

Skeletal carbonate sediments are widespread on the Three Kings platform due to an absence of terrigenous sediment input from rivers. The strong (tidal) current activity in this area also inhibits fine terrigenous sedimentation by keeping fine material in suspension. Rocky outcrops are particularly common on the Three

Kings platform and provide a major substrate on which bryozoans, corals, serpulids and barnacles live contributing to the skeletal carbonate distribution. Upwelling, as well as keeping fine terrigenous sediments in suspension, contributes nutrients in the water and fosters the growth of planktonic organism growth which serve as a source of food for the larger carbonate secreting organisms. All these processes are much the same as occurs on the NNCS, although their intensity and persistency is probably less, and coarse terrigenous sediment input onto the NNCS is considerably higher.

Modern sediment occurs on the Three Kings Bank and the Middlesex Bank on the Three Kings platform. In water depths of 85-120 m the crustose coralline red algae *Lithothamnium* occurs as rhodolites or algal balls and the encrusting benthic foraminifera *Homotrema* is recorded. In water depths of 120-150 m erect rigid bryozoan colonies (vinculariform and reteporiform types) are most common, with lesser contributions from *Homotrema,* bivalves, and gastropods. Below 150 m depth vinculariform and hornerid bryozoan growth forms and *Homotrema* are common, with some bivalves and corals. More relict material occurs below 150 m and modern material became scarce below 200 m. Similar relict occurrences are present on the NNCS. Controls on the dispersal of the modern material on the Three Kings platform include topographic irregularities and tidal, geostrophic and storm induced currents, and these are suggested as also operating on the NNCS, although here transportation by eddies derived from the East Auckland Current is considered as, or even more, important.

Relict sediment on the Three Kings platform occurs in deeper areas away from the banks. The relict material in the Three Kings Trough suggests that it was deposited at much the same time as the shelf relict material. Relict material on the South Maria Ridge is explained by tectonism, redeposition by storm events, glacio-eustatic sea level changes, or a combination of these. Even though uplift rates may be up to 0.3 mm/year in the North Cape region (Pillans, 1990), tectonism was stated to be an unlikely source due to an inappropriate direction of tectonic movement. Redeposition by storm events is also unlikely due to the uniform distribution of relict carbonate around the ridge, which would usually be distributed in the direction of the dominant storm tracks, and the preservation of ecologically viable faunal assemblages which might otherwise have been expected to be disturbed. The best explanation for the relict material on the South Maria

Ridge is glacio-eustatic sea level change due to the samples comprising almost entirely of relict grains below 150 m depths and the presence of a variety of organisms well below their present ecological equivalent. The relict (or poorly preserved) sediments on the NNCS sediments are also likely to have been associated with times of glacio-eustatic sea level changes.

North Kaipara continental margin

Extensive study was done on the north Kaipara continental margin (NKCM) documented in Payne (2010) and Payne *et al.* (2010). The NKCM comprises siliciclastic and mixed carbonate-siliciclastic deposits, as well as significant authigenic mineral deposits. The calcium carbonate content of the NKCM sediment ranges from 3-91% and increases in carbonate content offshore and to the north. Siliciclastic material is dominated by relatively equal amounts of quartz and feldspar. Other sediment components include opaque and non-opaque heavy minerals, mica, rock fragments, clay minerals and glauconite. The glauconite content of sediments ranges from 0-95%, but is mostly <10%. Very high glauconite contents (>75%) occur near the shelf edge between 150 and 400 m water depth. The NNCS sediments also contain glauconite (up to 15%), particularly in outer-shelf depths (>150 m), and quartz, feldspar, rock fragments and similar heavy minerals. However, (titano)magnetite appears to be absent on the NKCM. On the other hand, unlike the NKCM, the NNCS virtually lacks any mica and clay minerals.

Sand sized sediment completely dominates the NKCM sediments, as it does in the NNCS sediments. Gravel sized sediment is <5% in most NKCM sediment but increases to >75% in some samples in the north. Mud generally increases offshore in the NKCM sediments and only becomes a dominant sediment component (>50%) in the southern sector at water depths >400 m.

Five surficial sediment facies types were developed for the NKCM sediments based on textural and compositional characteristics. Facies 1 (siliciclastic sand) contains three subfacies. Subfacies 1a (quartzofeldspathic sand) comprises North Island volcanic and basement rock derived sand. Subfacies 1b (heavy mineral sand) comprises local basaltic to basaltic andesite derived heavy mineral rich sands. Subfacies 1c (mica rich sand) is likely to be derived from the South Island schists and granites. Facies 2 (glauconite sand) comprises 30-95% authigenic glauconite grains occurring on the outer-shelf and upper-slope (150-400 m water depth). Facies 3 (mixed bryozoan-siliciclastic sand) contains >40% bryozoan skeletal fragments and occurs only in the northern half of the NKCM. Facies 4 (pelletal mud) comprises muddy sediment and >30% mixed carbonate-siliciclastic pellets. Facies 5 (foraminiferal mud and sand) comprises >30% foraminiferal tests and contains subfacies 5a (at least 50% mud sized sediment at >400 m water depth in southern NKCM) and subfacies 5b (>70% sand sized sediment at mid- to outer-shelf and slope depths in northern NKCM).

The NKCM sediment composition and distribution is controlled by a number of environmental factors. These include the sediment inputs from rivers to the south, hydrodynamics influencing sediment transport including northerly nearshore littoral drift and storm currents, negligible sedimentation due to sediment suspension in offshore areas allowing authigenic minerals and skeletal grains to accumulate, and sea level rise following the Last Glaciation resulting in relict sediment being stranded at greater depths than expected. These controls are largely present in the NNCS although sediment input via rivers is less significant and currents are weaker with sediments mainly transported by northward flowing eddies. The presence of glauconite in particular is also attributed to negligible sedimentation and sea level rise at the peak of the Last Glaciation causing glauconite associated with relict material to occur in outer-shelf depths in the NNCS.

Hauraki Gulf

The Hauraki Gulf sediments were studied in part by Smith (1992) who concentrated particularly on their bryozoan content. The Hauraki Gulf consists of *in situ* mixed terrigenous and biogenic material. The calcium carbonate content of sediments ranges from 11-93% and shows a very patchy distribution across the Gulf. Bivalves are the dominant skeletal fragments and the main carbonate producers, with lesser quantities of bryozoans, gastropods and barnacles. This is similar to the NNCS where the skeletal fraction of the sediments is also dominated by bivalve and barnacle fragments with lesser amounts of calcareous red algae, bryozoans, gastropods, and foraminifera.

Five carbonate facies groups were defined for the Hauraki Gulf sediments based on their texture, carbonate content, skeletal components and ages. Group 1 is a poorly sorted sandy gravel with a high calcium carbonate content dominated by bivalves with lesser amounts of bryozoans, barnacles and gastropods. It is also a relatively young sediment, about 3000 years old. Group 2 is a poorly sorted muddy fine sand, with moderate carbonate contents strongly dominated by bivalves with subdominant gastropods. It mainly dates from about 3000 to 4000 years BP. Group 3 is a moderately sorted medium sand with moderate carbonate contents dominated by bivalves with subdominant bryozoans, barnacles and gastropods. The skeletal carbonate ages are highly variable and range from 2970 to 7910 years old. Group 4 is a poorly sorted gravelly muddy medium sand with moderate carbonate contents that is strongly bivalve dominated with subdominant gastropods. Ages range widely from 1750 to 8090 years. Group 5 is a slightly sandy mud, with low carbonate contents and only few skeletal components, with a <1750 year old age.

As on the NNCS, the distribution of facies is relatively patchy and is controlled by water depth, water energy/hydrodynamics, the source of the sediment and substrate availability on which carbonate secreting organisms prefer to live or attach. The post glacial sea-level has reworked the sediments so that much of the sediment in the Hauraki Gulf is palimpsest.

Wanganui shelf

Studies on the Wanganui shelf were undertaken by Gillespie (1992) and Gillespie and Nelson (1996). The Wanganui shelf contains shallow-marine, mixed temperate carbonate-siliciclastic sediments which are presently accumulating at inner- to mid-shelf depths (20-100 m water depth). Calcium carbonate contents range from 5-90% and the main contributors are bryozoans and bivalves. This contrasts with the NNCS, where bivalves and barnacles dominate. Like the NNCS sediments, the Wanganui shelf sediments are predominantly sand sized and fall in either the gravelly sand, gravelly muddy sand or sand textural classes.

The sediments on Wanganui shelf were divided into five surficial sediment facies. Facies 1 (Bivalve-bearing (gravelly) sand facies) occurs on the inner shelf and comprises subfacies 1a (Well sorted sand), which is a modern, river derived sand prism, and subfacies 1b (Bivalve-bearing, volcanogenic gravelly sand), which consists of skeletal material mixed with andesitic sands sourced from Mt Taranaki. Facies 2 (High-carbonate facies) comprises subfacies 2a (High-carbonate, bivalve-dominated sandy gravel), subfacies 2b (High-carbonate, bryozoan/bivalve dominated sandy gravel) and subfacies 2c (High-carbonate, bryozoan/bivalve-dominated muddy sandy gravel and gravelly muddy sand). Facies 3 (Bivalve-bearing muddy sand facies) contains moderate amounts of skeletal material and is diluted by the terrigenous sediment that makes up Facies 4 (Mud facies). Facies 5 (Micaceous sand) is sourced mainly from west coast South Island material.

The terrigenous sediment components on the Wanganui shelf are controlled by active tectonism and the onland geology of the region (with sedimentation rates ranging from 10-100 cm/ka), glacio-eustatic sea level rise leaving sediment stranded at depths greater than expected to become relict and palimpsest, and the storm dominated and tidal components controlling the hydraulic regime of the Greater Cook Strait. In comparison, the NNCS has a relatively "quieter" hydraulic regime and is tectonically stable, so these controls are not largely at play. Skeletal components are controlled by the distribution of terrigenous material, substrate types, water depths and the presence of nutrient rich upwelling and these are all controls that are also present on the NNCS.

7.5.3 The place of NNCS sediments in the temperate carbonate model

A skeletal assemblage classification scheme was devised by Hayton *et al*. (1995) for New Zealand Cenozoic limestones that can be applied to non-tropical mixed carbonate-siliciclastic deposits because it is independent of the terrigenous content of sample (Figure 7.10). Seven major skeletal assemblages were identified within temperate region carbonate deposits (Figure 7.10) of which six are relevant to the facies identified in the NNCS sediments.

Skeletons in Facies 1 (Siliciclastic quartzofeldspathic sand) classify as bimol, a bivalve dominated assemblage which is best represented in sediments with relatively high sedimentation rates of terrigenous material such as quartzofeldspathic sands that are less favourable habitats to other skeletal contributors (Figure 7.11). Facies 2 skeletons (Mixed barnacle-siliciclastic gravel and sand) classify as barnamol, a barnacle/bivalve dominated assemblage that thrives in a high energy hydraulic regime to ensure a high nutrient supply and prevent burial by removal of fine sediments (Figure 7.11). As expected, this assemblage occurs on rocky outcrops and/or in inner-shelf and coastal water depths of <50 m on the NNCS (Figure 7.11). The skeletal assemblage in facies 3 (Mixed calcareous red algae and bivalve-siliciclastic gravel and sand) is classified as rhodoalgal, a calcareous red algal-dominated assemblage as it generally occurs on hard substrates in the NNCS rather than sand on which rhodoechfor (calcareous red algae/echinoderm/benthic foraminiferal-dominated) occurs (Figure 7.11). Facies 3 does fit exactly into this assemblage type due to its often subequal bivalve content in the skeletal component of the sediment and this may be due to mixing with an assemblage such as bimol. Facies 4a skeletons (mixed benthic foraminiferal-siliciclastic sand) classify as Echinofor, an echinoderm/benthic foraminiferal dominated assemblage that usually occurs on sandy substrates (Figure 7.11) however backscatter data are not available where Facies 3 occurs so this cannot be confirmed for the NNCS. This assemblage thrives in high energy environments causing frequent reworking of sediment and a high suspended load in the water column which both prevent the establishment of filter feeders such as bryozoans (Figure 7.11). Facies 4b (mixed planktic foraminiferal-siliciclastic sand and mud) skeletons classify as nannofor, a nannofossil/planktonic foraminiferal-dominated assemblage which is most common in off-shelf depths at >300 m (Figure 7.11). In the NNCS, however, it occurs in shallower depths (50-200 m). This assemblage is associated with widespread micritic limestones or calcilulites of early Tertiary age in New Zealand (Hayton *et al.*, 1995), which coincides with a possible source of sedimentary rock fragments type 2 that are common in facies 4b. It has been suggested for the NNCS that the planktic foraminifera may have been reworked out of onland Tertiary limestones or mudstones to have accumulated in mid- to outer-shelf depths rather that off-shelf depths (see Section 7.4.2). Facies 5 (Mixed bryozoan-siliciclastic sand) skeletal types classify as bryomol, a bryozoan/bivalve-dominated assemblage that thrives in high energy conditions with a relatively low terrigenous supply to encourage bryozoan suspension feeding (Figure 7.11). The bryozoans prefer hard substrates (Figure 7.11) and generally occur on rocky outcrops on the NNCS.

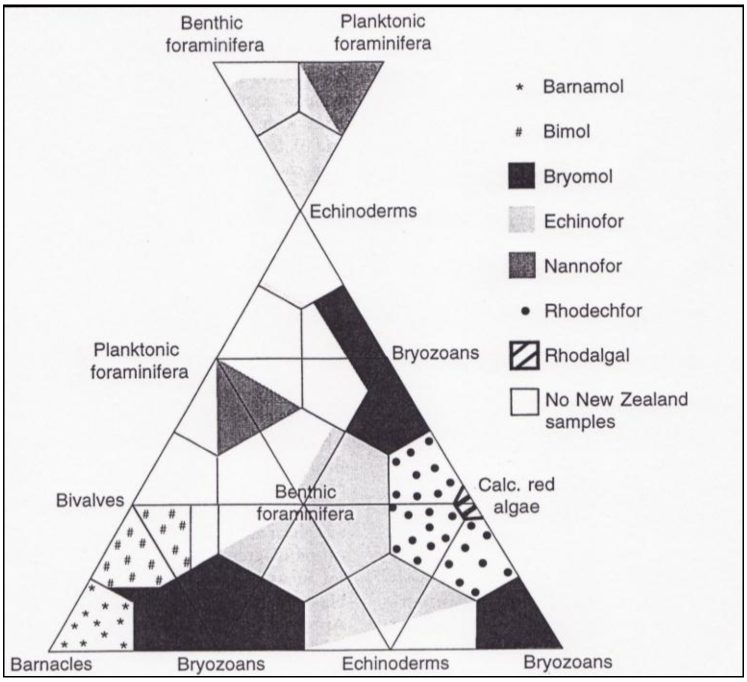


Figure 7.10: A composite triangular diagram for classifying skeletal assemblages in non-tropical carbonates based on various combinations of the main skeletal components occurring in many New Zealand Cenozoic limestone samples (from Hayton *et al*., 1995)

Assemblage	Depth (m)				Substrate			Water Energy		
	<50	50-150	150-300	>300	Hard	Sand	Fine	High	Mod.	Low
Bryomol		●	●		●	●		●	●	●
Echinofor		●	●			●			●	
Nannofor				●			●			●
Barnamol	●				●	●		●		
Rhodechfor	●	●				●		●		
Bimol	●	●	●			●	●	●	●	●
Rhodalgal	●	●			●			●		

Figure 7.11: Summary of broad environmental conditions associated with each of the non-tropical skeletal assemblages portrayed in Figure 7.10 (from Hayton *et al*., 1995).

Overall, when comparing the NNCS mixed carbonate-siliciclastic sediments with temperate shelf carbonate attributes (Table 7.4) it is clear that they largely agree and support the prevailing New Zealand temperate carbonate shelf model. There are, however, some characteristics that do not entirely fit into this model, such as a lower energy hydraulic regime and slightly higher temperatures on the NNCS than are typical of many temperate shelf carbonate environments (Table 7.4). This may play a part in the variable carbonate mineralogy and skeletal abundances in the NNCS sediments because different carbonate secreting organisms form in different environments (Table 7.4). Carbonate contents are often low compared to those expected from a true temperate carbonate shelf due to the input of terrigenous material (Table 7.4); we are really dealing with a mixed siliciclastic-carbonate system rather than a 'pure' carbonate one. The high terrigenous content in the NNCS sediments (particularly quartzofeldspathic sand in Facies 1) is also attributed to the muddier (silt) textures being dominant rather than gravel textures (Table 7.4). The NNCS is also complicated by various sheltered bays and inlets which trap mud sized sediments causing them to accumulate at coastal depths.

Table 7.4: Comparison of several environmental and facies attributes typical of the NNCS carbonates with temperate shelf carbonates in general (based on data from this study; Nelson, 1988; Nelson *et al*., 1988).

NORTHEASTERN NORTHLAND CONTINENTAL SHELF (NNCS) CARBONATES	TEMPERATE SHELF CARBONATES
Unrimmed shelf	Unrimmed shelves
Moderate energy	High energy
Absence of hermatypic reefs	Absence of hermatypic reefs
Moderate water temperature (13.5-21°C)	Cool water (10-18°C)
Saturated to undersaturated carbonates	Saturated to undersaturated carbonates
Absence of non-skeletal carbonate components	Absence of non-skeletal carbonate components
Low to high carbonate content (0-84%)	Moderate to very high carbonate content (50-100%)
Bivalves, barnacles, calcareous red algae, foraminifera and bryozoans	Bryozoans, echinoderms, bivalves, molluscs, benthic and planktic foraminifera
Well to poorly preserved shells	Well to poorly preserved shells
Rare to common glauconite	Common glauconite
Rare to abundant terrigenous material	Rare to abundant terrigenous material
Sand and mud (silt) textures dominate	Gravel and sand textures dominate
Minor carbonate mud	Minor carbonate mud
Destructive sea floor diagenesis	Destructive sea floor diagenesis
Mixed low-, intermediate- and high-Mg calcite and aragonite mineraology	Low- and intermediate-Mg calcite mineralogy
Typically low accumulation rates (<10cm/ky)	Typically low accumulation rates (<10cm/ky)

Chapter 8

CONCLUSIONS

8.1 SHELF SETTING

The northeastern Northland continental shelf (NNCS) is mantled by mixed carbonate-siliciclastic sediments that are complicated by the many bays and inlets bordering the shelf. The NNCS has a moderate to high energy hydraulic regime with sediment inferred to be transported in the longer term primarily by northward flowing eddies derived from the offshore southward flowing East Auckland Current (Figure 7.1). Annual fresh water input from rivers is relatively low when compared to the western Northland shelf and other bays and inlets in New Zealand (Figure 2.10). The NNCS is lee shore sheltered from the prevailing westerly and southerly waves generated from the predominant weather systems passing across New Zealand, which reflects in the margin experiencing smaller wave heights than most other coastal areas of New Zealand. Wave data indicate that waves predominantly approach from a northeasterly direction (Figure 2.6 to 2.9). The bathymetry of the NNCS is relatively varied with rougher, steeper topography, narrower shelf widths and shallower shelf breaks in the northern sector, and smoother and gradually declining topography and wider shelf widths in the southern sector (Figure 2.12, 2.13 and 2.14). Acoustic backscatter data show a relatively complex arrangement of hard and soft substrates with a general trend of rocky, hard substrates occurring off North Cape and bays and inlets at varying depths, including in places well offshore in deeper shelf locations (Figure 2.23).

8.2 BULK SEDIMENT TEXTURE

The NNCS sediments are almost completely dominated by sand-sized (0.063-2 mm) components from 60-90% across the shelf (Figure 4.6). Mud-sized sediment (<0.063 mm) comprises <30% throughout most of the study area and due to the complexity of the shelf morphology has a particularly mosaic distribution pattern with no simple increase in an offshore direction as is often expected (Figure 4.7). The mud fraction comprises almost entirely silt sized sediment with negligible clay sized material. Lesser contributions of gravel (>2 mm) occur at <5%

throughout most of the shelf (Figure 4.5). Gravel sized sediments are most common locally in nearshore bays and inlets reaching values ranging from 40-75% which significantly decreases in an offshore direction. Most of the NNCS sediments are dominated by gravelly sand, sand, muddy sand and gravelly muddy sand textures (Figure 4.12). The sand and mud fractions alone are dominated by sand, silty sand and sandy silt textures (Figure 4.13).

8.3 SILICICLASTIC SEDIMENT MINERALOGY

Siliciclastic minerals consist mainly of quartz and feldspar (plagioclase>>K feldspar). Quartz relative abundances are higher at inner-shelf depths and quartz is much more common in the northern sector of the NNCS (Figure 5.3). Feldspar relative abundances are high mostly in mid- to outer-shelf depths, particularly in the northern sector (Figure 5.4). The heavy minerals that occur on the NNCS are predominantly epidote, hypersthene, hornblende (both green and brown) and (titano)magnetite with lesser contributions of enstatite and augite (Table 5.1). Clay minerals are negligible on the NNCS. Up to 15% of glauconite occurs in sediments north of the Bay of Islands (Figure 5.11) associated with limited terrigenous input and strong currents in this area. Most of this glauconite is regarded as allochthonous (transported) rather than strictly authigenic.

The NNCS sediment includes a variety of volcanic and sedimentary rock fragments. Volcanic rock fragments are mainly submarine basalts which are most common off eastern Doubtless Bay, the Bay of Islands (1-5%) and off Whangaroa Harbour (5-15%) (Figure 5.6). Sedimentary rock fragments categorised as type 1 and type 2 occur in the NNCS sediments. Type 1 comprises greywacke and argillite lithologies and is most common (50-75%) in inner- to mid-shelf depths off Parengarenga Harbour, Takou Bay and the Bay of Islands (Figure 5.7). Type 2 is composed of more poorly lithified mixed siliciclastic-carbonate grains including glauconite grains and are most common in the central and southern sectors of the NNCS ranging from 15-50% in inner- to mid-shelf depths off Whangaroa Harbour, and from Bay of Islands to the very southern parts of the NNCS (Figure 5.8).

8.4 SKELETAL CARBONATES

8.4.1 Carbonate content and skeletal types

The calcium carbonate content in surficial sediments on the NNCS ranges from 0-84% and exhibits a prominent mosaic pattern throughout the study area (Figure 5.1) which is complicated by the distribution of terrigenous siliciclastic material, the substrate type, sediment transport by hydrodynamics and glacio-eustatic sea level changes (see Section 7.2). The carbonate fraction of NNCS sediments is almost entirely skeletal and dominated by bivalve and barnacle material that occurs mostly in central and northern sectors, with lesser contributions from calcareous red algae, benthic and planktic foraminifera, gastropods, bryozoans, echinoderms and sponge spicules (Figure 5.10). Carbonate mineralogy comprises both calcite and aragonite, the former predominantly low-Mg but with some intermediate- and high-Mg varieties (Figure 6.5, 6.6 and 6.7).

8.4.2 Preservation and age of sediment

The carbonate components comprise a mix of fresh-looking and abraded, bioeroded, variably microbored and limonitised skeletal grains, indicating that many of the surficial sediments are composed of a mixture of modern and relict material. Sediments of the NNCS display a well to poorly preserved size grading in an offshore direction which suggests that modern sediment is being supplied primarily by 'carbonate factories' occurring in inner-shelf depths, such as in bays and inlets and some deeper areas of rocky outcrops. Relict skeletal material in outer-shelf depths of the NNCS was likely deposited during lowered sea levels accompanying last glacial and post-glacial times (see Section 7.2.4), and skeletal degradation may have been fostered during the passage of relatively high energy environments associated with such conditions, especially affecting the skeletons having a less stable carbonate mineralogy involving aragonite or high-Mg calcite (Nelson *et al.*, 1982).

8.4.3 Comparison to modern ecology

Dominant skeletal types in the NNCS sediments (Figure 7.5) often differ significantly from the dominant live organisms observed during DTIS video imagery (Figure 7.6). The situation could partly reflect: a) the absence of DTIS video imagery in large sections of the NNCS, particularly the northern sector, b) the inability of DTIS to provide detailed imagery of small organisms (such as foraminifera), c) the contribution from relict carbonate material (particularly bivalves and barnacles) associated with former lowered sea levels, and d) the natural loss of soft bodied non-calcifying organisms between life and death assemblages.

8.5 NNCS SEDIMENTARY FACIES MODEL

A sedimentary facies model is suggested for the NNCS identifying five different facies. Facies 1 is siliciclastic quartzofeldspathic sand with minor bivalve contributions, occurring only in the northern sector. It contains two subfacies. Subfacies 1a occurs at inner- to mid-shelf depths (Figure 7.7) and comprises well sorted, more quartz enriched quartzofeldspathic sands likely to have been derived from reworking of Quaternary Karioitahi Group sand deposits (Figure 7.1) or podzolisation and reworking of local soils.

Subfacies 1b occurs in mid- to outer-shelf depths (Figure 7.7) and comprises more feldspar enriched quartzofeldspathic sands with contributions of pyroxene, epidote and opaque minerals that are primarily derived from the erosion of a combination of the Quaternary sand deposits (Katioitahi Group), the Mesozoic basement rocks and Northland volcanic and sedimentary rocks (Figure 7.1).

Facies 2 comprises mixed barnacle-siliciclastic gravel and sand at inner-shelf to uppermost slope depths in the northern sector (Figure 7.7) and includes rock fragments of basaltic and sedimentary rock type 1 composition derived from Mesozoic basement rocks, the Tangihua Complex of the Northland Allochthon and the Kerikeri Volcanics (Figure 7.1).

Facies 3 consists of mixed calcareous red algae and bivalve-siliciclastic gravel and sand at inner- to mid-shelf depths in the southern sector (Figure 7.7) and represents a mix of relict skeletal material deposited during periods of lowered sea level and modern skeletal material that is curently being supplied to the sediment. Facies 3 includes sedimentary rock fragments of type 2 which are probably sourced from Tertiary sedimentary rocks as they often contain glauconite grains which are common in the Oligocene to earliest Miocene deposits of the Te Kuiti Group (Figure 7.1).

Facies 4 is mixed foraminiferal-siliciclastic sand and mud that occurs only in the very southern sector (Figure 7.6) and forms two subfacies. Subfacies 4a, a mixed benthic foraminiferal-siliciclastic sand, occurs in mid-shelf locations (Figure 7.7) and comprises poorly sorted plagioclase-rich sand, sourced from Mesozoic basement rocks, and other minor skeletal fragments associated with the presence of rocky outcrops.

Subfacies 4b, a mixed planktic foraminiferal-siliciclastic sand and mud, occurs in mid- to outer-shelf depths (Figure 7.7) and comprises rock fragments derived from Oligocene and Early Miocene calcareous rock (Te Kuiti Group) which could also be a local source of reworked planktic foraminifera at the unusually shallow depths at which the subfacies occurs.

Facies 5 consists of mixed bryozoan-siliciclastic sand at mid-shelf depths and in other scattered localities across the NNCS. This facies comprises skeletal bryozoan fragments associated with rocky outcrops on the NNCS. Siliciclastic material is plagioclase-dominated with minor heavy minerals primarily sourced from the erosion and reworking of Mesozoic basement rocks (greywacke and local basalt). Sedimentary rock fragments type 2 are also present and are likely to be sourced from the onland Early Tertiary sediments due to their glauconite contents.

8.6 CONTROLS ON SEDIMENTATION

8.6.1 Provenance of siliciclastic minerals

The major sources of siliciclastic sediment to the NNCS are local ones involving, in approximate order of importance, a) the Mesozoic basement rocks which contribute sedimentary rock fragments type 1, and some quartz, plagioclase, submarine basalts and minor heavy minerals, b) the Northland Allochthon deposits involving the Tangihua Complex volcanics which supply submarine basaltic fragments and the Tupoa Complex which contributes some sedimentary rock fragments type 2, quartz, plagioclase and heavy minerals, and c) the Pleistocene to Holocene sand dune sediments of the Karioitahi Group and the Miocene sedimentary rocks of the Parengarenga Group in the northern sector which contribute significant quartzofeldspathic material (Figure 7.1). Possible distal sources of siliciclastic sediment include the TVZ andesites and rhyolites, the silicic and andesitic volcanics from the Coromandel Peninsula and the Taranaki andesites (Figure 7.2), but these are unlikely to supply much material to the NNCS due to difficulties in transportation.

8.6.2 Hydrodynamics and sediment transport

The source rocks of the major siliciclastic sediment components in the NNCS sediments generally occur in the onland bordering geology. Fresh water runoff from the few rivers and streams bordering the NNCS, along with local coastal erosion, have contributed sediment components from the local onland sources, including especially the Mesozoic basement rocks, Northland Allochthon rocks, Miocene sedimentary rocks and Pleistocene to Holocene sand deposits (see Section 7.2.1D). Currents are generally weaker in northeastern Northland than on the northwestern and northern shelves and evidence suggests that local inshore sediment is transported northwards and deflected in an offshore direction by localised eddies derived from the East Auckland Current (Figure 7.1).

8.6.3 Substrate types

Hard substrates recorded in the acoustic backscatter map (Figure 2.23) occur in areas consisting of bedrock and gravel sized sediment including boulders, cobbles and pebbles (Figure 2.24). These areas correlate well with areas having a high gravel contents (Figure 4.4). Hard substrate areas also expectedly coincide with areas of highest calcium carbonate contents (Figure 7.3) and areas with the highest skeletal contents (Figure 7.4). However, soft substrates do not always correlate with areas that contain high amounts of sand and mud (Figure 2.23) and can also be gravelly. This is due to the large supply of quartzofeldspathic sand in the northern sector and the trapping of fine sediment in low energy bays and inlets or by mangroves or sea grass in the coastal embayments.

8.6.4 Glacio-eustatic sea level changes

Lowered sea level during the peak of the Last Glaciation potentially caused carbonate and/or terrigenous material to be stranded 120 m below their usual environmental and depositional depths. Evidence for this in the NNCS sediments is as follows: a) moderately and poorly preserved skeletal material occurring in sediment in outer-shelf depths, b) well sorted and rounded glauconite grains occurring with relict material in mid- to outer-shelf depths, and c) poorly preserved barnacles and bivalves, which prefer inner-shelf depths and/or hard, rocky substrates, in soft sandy substrates in mid- to outer-shelf depths. This likely relict material may have been reworked by strong currents to these mid- to outer-shelf depths or could have formed in these once near shore depths during periods of lowered sea level.

8.7 TEMPERATE CARBONATE SEDIMENTATION MODELS

The NNCS sedimentary facies patterns comply only partly with a global sedimentation model diagram for cool water carbonates on wave-dominated shelves (Figure 7.8), with sediments showing only a partial offshore fining trend rather than a fully size graded shelf. The presence of rocky outcrops in mid- to outer-shelf depths and the frequent sheltered bays and harbours bordering the NNCS region present a rather more complex shelf situation than is conveyed by this cool water shelf carbonate model (Figure 7.8). Also, on the NNCS we are dealing with a wide range of mixed-terrigenous-carbonate deposits, not just carbonates, as well as a range of modern to relict components, all of which contributes to the rather more complex facies patterns (Figure 7.7).

Overall, the NNCS sedimentary facies model compares well with other carbonate-rich North Island shelf sectors, including Hauraki Gulf, Three Kings platform, north Kaipara continental margin and Wanganui shelf (see Section 7.5.2). However, there exist some major differences to the NNCS, particularly in the onland geology, coastline morphology and hydrodynamics contributing to terrigenous input and distribution of siliciclastic material in the various shelf settings.

A published skeletal assemblage classification scheme identifies seven major skeletal assemblages within temperate region carbonate deposits (Figure 7.10), of which six are relevant to the facies identified in the NNCS sediments (see Section 7.5.3). Overall, when comparing the NNCS mixed carbonate-siliciclastic sediments with temperate shelf carbonates (Table 7.4) it is clear that there are many similarities, so both contributing to, and reinforcing, the New Zealand temperate carbonate shelf model.

8.8 FURTHER RESEARCH

A more detailed study is warranted on the heavy minerals and skeletal species occurring throughout the NNCS by separating the heavy minerals and skeletal components from the bulk sediment samples of this study. The hydrodynamics occurring on the NNCS, including wind, wave and current data, urgently need further research to gain a more specific understanding of the sediment reworking and transportation patterns over the NNCS. The NNCS sediments, particularly the poorly preserved skeletal material and perhaps the glauconite in mid- to outer-shelf depths require absolute dating using radiocarbon and K-Ar or Ar-Ar isotopic techniques in order to better understand the evolution of the sedimentary cover on the margin. To this end, sediment cores should also be studied to determine the NNCS shelf stratigraphy and history and assist with elucidating sediment ages. Further live DTIS video imagery and sediment sampling should be undertaken to address the paucity of these data in several areas of the NNCS, thereby allowing a more complete understanding of the mixed siliciclastic-carbonate sedimentary system on this northeastern continental margin of North Island.

REFERENCES

Adams, A.G. 1979. Recent foraminifera and sediments of Rangaunu Harbour and inner Rangaunu Bay, Northland. Unpublished MSc thesis, University of Auckland.

Ashcroft, J.E. 1986. The Kerikeri Volcanics - a geochemical survey. Unpublished MSc Thesis, University of Auckland.

Ballance, P.F. and Spörli, K.B. 1979. Northland Allochthon. Journal of the Royal Society of New Zealand, 9: 259-275.

Bostock, H. and Nodder, S. 2010. Bay of Islands sediment summary. National Institute of Water and Atmosphere.

Bowden, D., Fenwick, M., Spong, K., Chin, C. and Miller, A. 2010. Bay of Islands OS20/20 survey report. Chapter 9: Seafloor assemblage and habitat assessment using DTIS. http://www.os2020.org.nz/browse-data-boi.

Bradford, J.M. and Roberts, P.E. 1978. Distribution of reactive phosphorus plankton in relation to upwelling and surface circulation around New Zealand. New Zealand Journal of Marine and Freshwater Research, 12: 1-15.

Briggs, R.M., Middleton, M.P. and Nelson, C.S. 2004. Provenance history of the Late Triassic-Jurassic Gondwana margin forearc basin, Murihiku Terrane, North Island, New Zealand: petrographic and geochemical constraints. New Zealand Journal of Geology and Geophysics, 47: 589-602.

Brook, F.J. and Hayward, B.W. 1989. Geology of autochthonous and allochthonous sequences between Kaitaia and Whangaroa, northern New Zealand. New Zealand Geological Survey record 36.

Brothers, R.N. and Delaloye, M. 1982. Obducted ophiolites of North Island, New Zealand – origin, age, emplacement and tectonic implications for Tertiary and Quaternary volcanicity. New Zealand Journal of Geology and Geophysics, 25: 257-274.

Carter, L. 1975. Sedimentation on the continental terrace around New Zealand: a review. Marine Geology, 19: 209-237.

Carter, L. and Heath, R.A. 1975. Role of mean circulation, tides, and waves in the transport of bottom sediment on the New Zealand continental shelf. New Zealand Journal of Marine and Freshwater Research, 9: 423-448.

Chave, K.E. 1952. A solid solution between calcite and dolomite. Journal of Geology 60: 190-193.

Chave, K.E. 1967. Recent carbonate sediments: an unconventional view. Geol. Educat., 15: 200-204.

Christopherson, M.J. 1977. The effect of sand mining of the erosion potential of Whiritoa Beach. Unpublished MSc Thesis, University of Waikato.

Deer, W.A., Howie, R.A. and Zussman, J. 1992. An introduction to the rock forming minerals, 2nd Edition. Prentice Hall.

Dodd, J.R. and Nelson, C.S. 1998. Diagenetic comparisons between non-tropical Cenozoic limestones of New Zealand and tropical limestones of Indiana, USA: Is the non-tropical model better than the tropical model? Sedimentary Geology, 121: 1-21.

Edbrooke, S.W. 2001. Geology of the Auckland area. Institute of Geological and Nuclear Sciences 1: 250 000 geological map 3. Institute of Geological and Nuclear Sciences Ltd., pp. 74.

Environment Waikato. 2008. The Health of the Waikato River and catchment. Information for the Gaurdians Establishment Committee. http://www.waikatoregion.govt.nz/PageFiles/419/gecreport.pdf.

Foster, B.A. 1978. The marine fauna of New Zealand: Barnacles (Cirripedia: Thracia). New Zealand Oceanographic Institute Memoir 69, pp. 160.

Folk, R.L. 1968. Petrography of sedimentary rocks. Hemphill Publishing. U.S.A.

Garner, D.M. 1969. The seasonal range of sea temperature on the New Zealand Shelf. New Zealand Journal of Marine and Freshwater Research, 3: 201-208.

Gilbert, D.B., Ballance, P.F. and Spörli, K.B. 1989. The Te Kuiti Group and Northland Allochthon rocks on the north flank of the Omahuta Basement Block, Northland, New Zealand. In: Spörli, K.B and Kear, D. (Ed), Geology of Northland accretion, allochthons and arcs at the edge of the New Zealand micro-continent. The Royal Society of New Zealand Bulletin 26.

Gillespie, J.L. 1992. Late Quaternary carbonate-clastic sedimentation on a temperate shelf, offshore Wanganui, New Zealand. Unpublished MSc thesis, University of Waikato.

Gillespie, J.L. and Nelson, C.S. 1996. Distribution and control of mixed terrigenous-carbonate surficial sediment facies, Wanganui shelf, New Zealand. New Zealand Journal of Geology and Geophysics, 39: 533-549.

Gillie, R.D. 1979a. Sand and gravel deposits of the coast and inner shelf east coast, Northland peninsula, New Zealand. Unpublished PhD thesis, Geography Dept, University of Canterbury.

Gillie, R. D. 1979b. Sand and gravel deposits of the coast and inner shelf east coast, Northland peninsula, New Zealand. Coastal Research, 5: 13.

Google Maps. http://maps/google.com

Griffiths, G.A., and Glasby, G.P. 1985. Input of river-derived sediment to the New Zealand continental shelf, I. Mass. Estuarine, Coastal Shelf Sci., 21: 773-787.

Hancock, 1980. Fauna composition of marine carbonate sediments on South Maria Ridge, Three Kings, New Zealand. Unpublished MSc thesis, University of Waikato.

Hayton, S., Nelson, S.C., Hood, S.D. 1995. A skeletal assemblage classification system for non-tropical carbonate deposits based on New Zealand Cenozoic limestones. Sedimentary Geology, 100: 123-141.

Hayward, B. W. 1981. Foraminifera in near-shore sediments of the eastern Bay of Islands, northern New Zealand. Tane, 27: 123-134.

Hayward, B.W. 1993. The tempestuous 10 million year life of a double arc and intra-arc basin, New Zealand's Northland basin in the Early Miocene. In: Ballance, P.F. (Ed), 1993. South Pacific Sedimentary Basins. Sedimentary Basins of the World, 2: 113-142.

Hayward, B.W., Grenfell, H.R., Reid, C.M. and Hayward, K.A. 1999. Recent New Zealand shallow-water benthic foraminifera: Taxonomy, ecologic distribution, biogeography and use in paleoenvironmental assessment. Institute of Geological and Nuclear Sciences monograph 21.

Hayward, B.W., Brooke, F.J. and Isaac, M.J. 1989. Cretaceous to middle Tertiary stratigraphy, paleogeography and tectonic history of Northland, New Zealand. In: Geology of Northland: Accretions, allochthons and arcs at the edge of the New Zealand micro-continents (Eds B. Spörli and D. Kear). Royal Society of New Zealand Bulletin, 26: 47-64.

Hayward B.W., Grenfell H.R., Sabaa A., and Hayward J.J. 2003. Recent benthic foraminifera from offshore Taranaki, New Zealand. New Zealand Journal of Geology and Geophysics; 46: 489-518.

Head, P.S. 1985. Surficial sediment in the Snares platform, New Zealand: a cold-water, carbonate-dominated shelf. Unpublished MSc thesis, University of Waikato.

Heath, R.A. 1976d. Broad classification of the New Zealand inlets with emphasis on residence times. New Zealand Journal of Marine and Fresh Water Research, 10: 429-444.

Heath, R.A. 1982. What drives the mean circulation on the New Zealand west coast continental shelf? New Zealand Journal of Marine and Freshwater Research, 16: 215-226.

Herzer, R.H. and Isaac, M.J. 1992. The size of the Northland Allochthon. Research Notes, N.Z. Geol. Surv. Rec., 44:37-42.

Herzer, R.H. 1993. Geohistory plots for seismic shot points and a composite well/outcrop section in the Northland Basin, New Zealand. Institute of Geological and Nuclear Sciences science report 93/11.

Herzer, R.H. 1995. Seismic stratigraphy of a buried volcanic arc, Northland, New Zealand and implications for Neogene subduction. Marine and Petroleum Geology, 12: 511-531.

Herzer, R.H., Chaproniere, G.C.H., Edwards, A.R., Hollis, C.J., Pelletier, B., Raine, J.I., Scott, G.H., Stagpoole, G., Strong, C.P., Symonds, P. and Wilson, G.J. 1997. Seismic stratigraphy and structural history of the Reinga Basin and its margins, southern Norfolk Ridge system. New Zealand Journal of Geology and Geophysics, 40: 425-451.

Hicks, D. M. and Shankar, U. S. 2003. Sediment yields from New Zealand rivers. NIWA Miscellaneous Chart series no. 79.

Houghton, B.F., Wilson, C.J.N. and McWilliams, M.O. 1995. Chronology and dynamics of a large silicic magmatic system – central Taupo volcanic zone, New Zealand. Geology, 23: 13-16.

Hudson, D.S. 1996. Provenance of Miocene to Recent sands and sandstones of the Taranaki-Wanganui Region, New Zealand. Unpublished MSc Thesis, University of Waikato.

Hume, T.M. and Nelson, C.S. 1986. Distribution and origin of clay minerals in surficial shelf sediments, western North Island, New Zealand. Marine Geology, 69: 289-308.

Issac, M.J. 1996. Geology of the Kaitaia Area, Institute of Geological and Nuclear Sciences 1: 250 000 geological map 1. Geological and Nuclear Sciences Ltd., pp. 44.

Issac, M.J., Herzer, R.H., Brooke, F.J. and Hayward, B.W. 1994. Cretaceous and Cenozoic Sedimentary Basins of Northland, New Zealand. Institute of Geological and Nuclear Sciences Monograph 8. Institute of Geological and Nuclear Sciences Ltd., pp. 203.

James, N.P. 1997. The cool-water carbonate deopisitional realm. In: James, N.P. and Clarke, J.A.D. (Ed), Cool-water carbonates. SEPM Special Publication No. 56: 1-20.

James, N.P. 1984a. Introduction to carbonate facies models. Ed. by Walker, R.G., Facies Models (2nd ed). Geosci. Can. Reprint Series, 1: 209-211.

Jennings, W.L. 1989. Metamorphism in the Waipapa Terrane, Omahatu and Puketi Forests, Northland New Zealand. In: Spörli, K.B. and Kear, D. (Ed), Geology of Northland accretion, allochthons and arcs at the edge of the New Zealand micro-continent. The Royal Society of New Zealand Bulletin 26.

Jones, N.W. and Bloss, F.P. 1980. Laboratory manual for optical mineralogy. Burgess Publishing Company.

Keane, S.L. 1986b. Carbonate skeletal carbonate deposits on the New Zealand continental margin with particular reference to the Three Kings Region. Unpublished thesis, University of Waikato.

Kennett, J.P. and Sprinivasan, M.S. 1988. Neogene planktic foraminifera. Hutchinson Ross Publishing Company, New Zealand.

Kuenen, P.H. 1950. Marine Geology. John Wiley, New York. pp. 568.

McPhie, J., Doyle, M. and Allen, R. 1993. Volcanic textures: a guide to interpretation of textures in volcanic rocks. Centre for Ore Deposit and Exploration Studies (CODES) University of Tasmania, Australia, pp. 198.

McRae, S.G. 1972. Glauconite. Earth-Science Reviews, 8: 397-440.

Mortimer, N. 2000. Metamorphic discontinuities in orogenic belts: examples of the garnet-biotite-albite zone in the Otago Schist, New Zealand. International Journal of Earth Sciences, 89: 292-306.

Mortimer, N., Tulloch, A.J. and Ireland, T.R. 1997. Basement geology of Taranaki and Wanganui Basins, New Zealand. New Zealand Journal of Geology and Geophysics, 40: 223-236.

National Climate Database. www.cliflo.niwa.co.nz.

Nelson, C.S and Cochrane, R.H.A. 1970. A rapid X-ray method for the quantitative determination of selected minerals in fine-grained and altered rocks. Tane, 16: 151-162.

Nelson, C.S., Hancock, G.E. and Kamp, P.J.J. 1982. Shelf to basin, temperate skeletal carbonate sediments, Three Kings plateau, New Zealand. Journal of Sedimentary Petrology, 52: 717-732.

Nelson, C.S. 1988. An introductory perspective on non-tropical shelf carbonates. Sedimentary Geology, 60: 3-12

Nelson, C.S., Keane, S.L. and Head, P.H. 1988. Non-tropical carbonate deposits on the modern New Zealand shelf. Sedimentary Geology, 60: 71-94.

Odin, G.S and Fullagar, P.D. 1988. Geological significance of the Glaucony facies. In: Odin G.S. (Ed), Green marine clays: oolitic ironstone facies, verdine facies, glaucony facies and celadonite-bearing facies - a comparative study. Developments in Sedimentology Research, 71: 272-285.

Payne D.S. 2010. Shelf-to-slope sedimentation on the north Kaipara continental margin, northwestern North Island, New Zealand. Unpublished MSc thesis, University of Waikato.

Payne, D.S., Nelson, C.S. and Hood, C.S. 2010. Mixed glauconite-carbonate-siliciclastic surficial sediments on the north Kaipara continental margin, northwestern North Island, New Zealand. New Zealand Journal of Geology and Geophysics, 53: 307-326.

Pickrill, R. A. *et al.* 1986. Rangaunu Harbour and Bay sediments. Scale 1:40,000 Miscellaneous Series (New Zealand Oceanographic Institute) no. 63.

Pickrill, R.A. 1986. Sediment pathways and transport rates through a tide-dominated entrance, Rangaunu Harbour, New Zealand. Sedimentology, 33: 887-898.

Pickrill, R.A. and Mitchell, J.S. 1979. Ocean wave characteristics around New Zealand. New Zealand Journal of Marine and Fresh Water Research, 13: 501-520.

Pillans, B. 1990. Pleistocene marine terraces in New Zealand: a review. New Zealand Journal of Geology and Geophysics, 33: 219-231.

Powell, A.W.B. 1979. New Zealand Mollusca. Marine, Land and Freshwater Shells. Collins.

Powers, M.C. 1953. A new roundness scale for sedimentary particles. Journal of Sedimentary Research, 23: 117-119.

Prothero, D.R. and Schwab, S. 1996. Sedimentary Geology. W.H. Freeman & Co. U.S.A.

Rait, G.J. 2000. Thrust transport directions in the Northland Allochthon, New Zealand. New Zealand Journal of Geology and Geophysics, 43: 271-288.

Ricketts, B. D. 1979. Petrology and provenance of Plesitocene deposits in the south Parengarenga-Te Kao district, northern New Zealand. New Zealand Journal of Geology and Geophysics, 22: 21-27.

Schofield, J.C. 1970. Coastal sand of Northland and Auckland. New Zealand Journal of Geology and Geophysics, 13: 767-824.

Scholle, P.A. and Ulmer-Scholle, D.S. 2003. A Colour Guide to the Petrography of Carbonate Rocks: Grains, textures, porosity, diagenesis.

Smith, A. 1992. Aspects of the sedimentology of New Zealand bryozoans and mixed carbonate-clastic deposits: A contribution to the temperate shelf carbonate model. Unpublished MSc thesis, University of Waikato.

Smith, A. and Nelson, C.S. 2003. Effects of early sea-floor processes on the taphonomy of temperate shelf skeletal carbonate deposits. Earth-Science Reviews, 1285: 1-31

Spörli, K.B. and Harrison, R.E. 2004. Northland Allochthon infolded into basement, Whangarei area, northern New Zealand. New Zealand Journal of Geology and Geophysics, 47: 391-398.

Stanton, B. R., Sutton, P.G.H. and Chiswell, S.M. 1997. The East Auckland Current 1994-1995. New Zealand Journal of Marine and Freshwater Research, 31: 537-549

Stokes, S. and Nelson, C.S. 1991. Tectono-volcanic implications of provenance changes in the Late Neogene coastal and sand deposits of Kaihu Group, South Auckland, New Zealand. New Zealand Journal of Geology and Geophysics, 35: 51-59.

Summerhayes, C.P. 1969a. Recent sedimentation around northern-most New Zealand. New Zealand Journal of Geology and Geophysics, 12: 172-207.

Sverdrup, H.U., Johnson, M.W. and Fleming, R.H. 1942. The Oceans. Prentice Hall, New York.

Wellman, H.W. 1979. An uplift map for the South Island, New Zealand, and a model for uplift of the Southern Alps. In: Cresswell, M.M. (Ed), The origin of the Southern Alps. The Royal Society of New Zealand Bulletin 18, pp. 13-20.

Ziegler, A.M., Hulver, M.L., Lottes, A.L., and Schmachtenberg, W.F. 1984. Uniformitarianism and palaeoclimates: inferences from the distribution of carbonate rocks. Ed. by Benchley, P.J., Fossils and Climate. Wiley. Chichester, pp. 3-25.

APPENDICES

Appendix A: Sample locations and descriptions

Table A.1: Sampling gear, locations and depth (m). Note: Samples are listed in running order.

Voyage	Station/ (site)	Gear	Latitude	Longitude	Depth (m)
KAH0907	81/S17	Multicorer	-35.239833	174.205666	~20
KAH0907	91/S20	Multicorer	-35.224000	174.135167	30
KAH0907	95/S51	Multicorer	-35.223833	174.166833	29
KAH0907	99/S14	Multicorer	-35.195833	174.292833	42
KAH0907	120/S29	Multicorer	-35.162333	174.136000	37
KAH0907	124/S15	Multicorer	-35.209000	174.280167	34
KAH0907	136/S16	Multicorer	-35.204333	174.248333	12
KAH0907	140/S19	Multicorer	-35.224167	174.111833	23
KAH0907	142/GC20	G. corer	-35.197000	174.050333	12
KAH0907	149/Z23	Multicorer	-34.728333	173.198167	50
KAH0907	157/Z10	Multicorer	-34.824333	173.903330	156
KAH0907	159/A14	Multicorer	-34.955000	173.873167	55
TAN0906	46/Z21	Multicorer	-35.106500	174.284000	118
TAN0906	90/A14	sled	-34.958333	173.879333	55
TAN0906	152/Z2	sled	-34.369500	173.023500	88
TAN0906	198/Z27	Grab	-34.643667	173.134667	71
TAN0906	219/Z24	Grab	-34.738667	173.632500	170
TAN0906	229/A12	Grab	-34.957500	174.088833	148
TAN0906	244/A13	Grab	-35.083333	174.016667	65
402	A4	?	-34.383301	173.083298	132
405	A73	?	-34.400002	173.100006	104
502	C768	O.P. grab	-34.666698	173.046707	24
502	C769	O.P. grab	-34.668301	173.186707	77
502	C770	O.P. grab	-34.665001	173.341705	134
502	C771	O.P. grab	-34.666698	173.449997	188
502	C773	O.P. grab	-35.033298	173.766693	26
502	C776	O.P. grab	-35.333302	174.429993	77
502	C778	O.P. grab	-35.330002	174.793304	187
538	E348	D. Cone	-34.616699	173.333298	150
538	E349	D. Cone	-34.616699	173.250000	121
538	E350	D. Cone	-34.616699	173.166702	102
538	E353	D. Cone	-34.616699	173.041702	27
538	E356	O.P. grab	-34.566700	173.083298	68
538	E358	O.P. grab	-34.566700	173.250000	143
538	E359	O.P. grab	-34.566700	173.333298	172
538	E362	P. dredge	-34.500000	173.166702	135
538	E363	O.P. grab	-34.500000	173.125000	110

Table A.1: cont.

Voyage	Station/ (site)	Gear	Latitude	Longitude	Depth (m)
538	E364	O.P. grab	-34.500000	173.083298	73
538	E368	O.P. grab	-34.416698	173.125000	126
538	E370	P. dredge	-34.416698	173.166702	146
538	E371	P. dredge	-34.375000	173.083298	121
538	E372	P. dredge	-34.333302	173.083298	135
538	E374	P. dredge	-34.333302	173.000000	117
538	E382	O.P. grab	-34.408298	172.975006	29
553	E556	Corer	-35.623299	174.619995	88
553	E557	Corer	-35.560001	174.679993	106
553	E559	Corer	-35.441700	174.750000	106
553	E560	Corer	-35.433300	174.773300	154
553	E563	O.P. grab	-35.380001	174.345001	9
553	E575	Corer	-35.084999	174.093307	77
553	E576	O.P. grab	-35.088299	173.986694	38
553	E577	Corer	-34.991699	174.043304	108
553	E578	Corer	-34.943298	173.904999	62
553	E580	O.P. grab	-34.896702	173.785004	84
553	E581	Corer	-34.766701	173.866699	198
553	E582	O.P. grab	-34.838299	173.949997	190
553	E583	O.P. grab	-34.916698	174.039993	179
553	E584	O.P. grab	-34.991699	174.125000	150
553	E594	O.P. grab	-35.195000	174.366699	93
553	E595	O.P. grab	-35.241699	174.466705	128
553	E596	O.P. grab	-35.273300	174.366699	73
553	E597	O.P. grab	-35.446701	174.471695	46
553	E598	O.P. grab	-35.570000	174.566696	68
9901	E673	Corer	-34.418301	172.983307	Beach sample
9901	E674	Corer	-34.423302	172.978302	Beach sample
9901	E675	Corer	-34.423302	172.978302	Beach sample
9901	E676	Corer	-34.428299	172.971695	Beach sample
9901	E677	Corer	-34.428299	172.971695	Beach sample
9901	E678	Corer	-34.431702	172.964996	Beach sample
9901	E679	Corer	-34.431702	172.964996	Beach sample
533	F71	Corer	-35.345001	174.683304	150
533	F73	Corer	-35.486698	174.550003	79
578	F932	T.A.M.	-34.445000	173.125000	113
1077	P499	P. dredge	-34.400002	172.956696	30
1077	P523	O.P grab	-34.328300	173.125000	210
1077	P524	O.P grab	-34.368301	173.093307	134
1077	P528	O.P grab	-34.439999	173.116699	115
1077	P529	O.P grab	-34.446701	173.103302	97
1077	P531	O.P grab	-34.383301	173.065002	112
1077	P615	S. M. grab	-34.868801	173.219193	18

Table A.1: cont.

Voyage	Station/ (site)	Gear	Latitude	Longitude	Depth (m)
1077	P616	S.M. grab	-34.838699	173.199997	16
1077	P618	S.M. grab	-34.840000	173.283707	21
1077	P619	S.M. grab	-34.506500	173.317001	19
1077	P621	S.M. grab	-34.805000	173.359207	18
1077	P622	S.M. grab	-34.805302	173.319504	28
1077	P623	S.M. grab	-34.771801	173.196304	41
1077	P625	S.M. grab	-34.771702	173.278305	42
1077	P626	O.P. grab	-34.773300	173.318298	40
1077	P627	S.M. grab	-34.806801	173.196304	22
1077	P628	S.M. grab	-34.806499	173.237198	30
1077	P637	S.M. grab	-34.934299	173.514694	28
1077	P640	S.M. grab	-34.865501	173.476700	57
1077	P643	S.M. grab	-34.954700	173.492493	22
1077	P644	S.M. grab	-34.984200	173.464005	12
1077	P645	S.M. grab	-34.955002	173.437302	21
1077	P648	S.M. grab	-34.911999	173.432495	25

G. Corer = Gravity corer; D. Cone = Dredge cone; T.A.M. = Trawl, Agassiz medium; O.P grab = Orange peel grab; P. dredge = Pipe dredge; S.M. grab = Smith McIntyre grab.

Table A.2: Sediment description including texture, sorting and colour. Note samples are listed in running order.

Station/ (site)	Sediment texture description	Sorting	Colour
81/S17	Sandy mud	Very poorly sorted	Greyish olive
91/S20	Muddy sand	Very poorly sorted	Greyish olive
95/S51	Sand	Moderately well sorted	Light yellow orange to black
99/S14	Muddy sand	Poorly sorted	Greyish olive
120/S29	Sand	Moderately sorted	Light Yellow Orange to black
124/S15	Muddy sand	Poorly sorted	Light grey
136/S16	Muddy sand	Very poorly sorted	Light grey
140/S19	Muddy sand	Very poorly sorted	Bright yellowish brown
142/GC20	Gravelly sand	Poorly sorted	Dull Orange to brownish grey
149/Z23	Sand	Moderately sorted	Bright yellowish orange to light grey
157/Z10	Muddy sand	Poorly sorted	Greyish olive

Table A.2: cont.

Station/ (site)	Sediment texture description	Sorting	Colour
159/A14	Muddy sand	Poorly sorted	Greyish olive
46/Z21	Muddy sand	Very poorly sorted	Greyish olive
90/A14	Muddy sand	Poorly sorted	Greyish olive
152/Z2	Muddy sand	Very poorly sorted	Greyish olive
198/Z27	Muddy sand	Poorly sorted	Dull yellow orange
219/Z24	Sand	Poorly sorted	Greyish olive
229/A12	Muddy sand	Poorly sorted	Grey
244/A13	Sand	Poorly sorted	Light Grey to Grey
A4	Coarse to medium sand	Poorly sorted	Greyish olive
A73	Coarse to medium sand	Moderately sorted	Greyish olive
C768	Fine sand	Very well sorted	Light grey
C769	Muddy fine sand	Very well sorted	Greyish olive
C770	Muddy fine and very fine sand	Well sorted	Greyish olive
C771	Coarse muddy shelly sand	Very well sorted	Greyish olive
C773	Coarse, slightly muddy shelly sand	Very poorly sorted	Dull orange
C776	Fine sandy mud	Well sorted	Greyish olive
C778	Muddy sand with a little shell	Very well sorted	Greyish olive
E348	Muddy glauconitic sand	Very well sorted	Greyish olive
E349	Very muddy fine sand	Very well sorted	Greyish olive
E350	Muddy fine sand	Well sorted	Greyish olive
E353	Coarse shell hash (much of sample washed out)	Moderately sorted	Light grey
E356	Slightly muddy and shelly very fine high quartzose sand	Well sorted	Light grey
E358	Very muddy fine sand with some shell fragments	Well sorted	Greyish olive
E359	Shelly glauconitic medium sand	Well sorted	Greyish olive
E362	Muddy glauconitic fine sand	Very well sorted	Greyish olive
E363	Muddy glauconitic fine sand	Very well sorted	Greyish olive
E364	Muddy glauconitic fine sand	Very well sorted	Greyish olive
E368	Medium glauconitic sand with few shells and granules	Well sorted	Greyish olive
E370	Pebbly muddy glauconitic medium sand	Well sorted	Greyish olive
E371	Gravelly muddy glauconitic medium and fine sand	Very poorly sorted	Greyish olive
E372	Glauconitic shelly medium-coarse sand	Well sorted	Greyish olive
E374	Muddy glauconitic fine sand with sponge spicules	Very well sorted	Greyish olive
E382	Muddy shelly sand	Well sorted	Greyish olive
E556	Soft sandy shelly mud	Very poorly sorted	Greyish olive
E557	Sandy shelly mud	Very well sorted	Greyish olive

Table A.2: cont.

Station/ (site)	Sediment texture description	Sorting	Colour
E559	Coarse sand and corals	Very poorly sorted	Pale yellow
E560	Muddy shelly coarse sand	Very poorly sorted	Greyish olive
E563	Shelly sand with corals and gastropods	Very poorly sorted	Pale yellow
E575	Coarse sand and shell	Moderately sorted	Light grey
E576	Medium to coarse sand with some shell	Very well sorted	Dull yellow
E577	Slightly muddy sand and shell	Well sorted	Greyish olive
E578	Rock and gravel	Moderately sorted	Bright yellowish brown
E580	Shelly sand with forams	Moderately sorted	Light grey
E581	Shelly sand	Well sorted	Greyish olive
E582	Shelly sand with forams	Very poorly sorted	Light grey
E583	Coarse shelly sand	Moderately sorted	Greyish olive
E584	Shelly coarse sand	Well sorted	Greyish olive
E594	Coarse sand and shell	Moderately sorted	Greyish olive
E595	Fine sand and mud	Very well sorted	Greyish olive
E596	Fine sand	Well sorted	Greyish olive
E597	Coarse sand	Very well sorted	Greyish olive
E598	Rocks, live coral, sand and mud	Very well sorted	Light grey
E673	Shelly sand (some minerals)	Very well sorted	Pale orange
E674	Shelly sand	Very well sorted	Light brownish grey
E675	Shelly sand	Poorly sorted	Pale orange
E676	Shelly mineral sand	Very well sorted	Light brownish grey
E677	Shelly sand	Moderately sorted	Pale orange
E678	Shelly sand	Poorly sorted	Pale reddish orange
E679	Mineral sand (some shell)	Very well sorted	Light brownish grey
F71	Muddy medium grade sand with fine shell fragments	Well sorted	Greyish olive
F73	Shelly muddy sand (coarse shell fragments)	Very poorly sorted	Light grey
F932	Coarse shelly sand (rocks, sponges and corals)	Very poorly sorted	Greyish olive
P499	Coarse shell hash and live bryozoans	Moderately sorted	Light yellow orange
P523	Slightly shelly muddy fine sand	Well sorted	Graying olive
P524	Shelly muddy fine sand	Poorly sorted	Light grey
P528	Shelly and gravelly mud	Moderately sorted	Greyish olive
P529	Slightly shelly muddy fine sand	Moderately sorted	Greyish olive

Table A.2: cont.

Station/ (site)	Sediment texture description	Sorting	Colour
P531	Shelly muddy very coarse sand	Moderately sorted	Greyish olive
P615	Fine sand	Poorly sorted	Light grey
P616	Fine sand with broken shells	Very well sorted	Light grey
P618	Fine sand and shell hash	Very well sorted	Light yellow
P619	Fine sand with shell fragments	Very well sorted	Light grey
P621	Medium sand with coralline algae and bryozoans	Very poorly sorted	Dull yellow orange
P622	Coarse shell sand with numerous shells	Well sorted	Dull orange
P623	Fine sand with very small amount of shell fragments	Well sorted	Light grey
P625	Coarse shell sand	Very well sorted	Dull yellow orange
P626	Stones and coarse shell sand	Very poorly sorted	Light grey
P627	Very fine sand	Very well sorted	Light grey
P628	Medium coarse sand with shell	Very poorly sorted	Light grey
P637	Very coarse shell sand with pebbles	Very poorly sorted	Pale orange
P640	Muddy sand	Very well sorted	Greyish olive
P643	Shell and gravel	Very poorly sorted	Light Yellow Orange to black
P644	Fine sand	Very well sorted	Greyish yellow brown
P645	Fine sand with shell	Very well sorted	Dull yellow orange
P648	Sand and shell	Very well sorted	Light grey

Appendix B: Textural data

Table B.1: Calculations of % gravel, sand and mud. Note: Samples are listed in running order.

Station	Gravel (g)	Sand (g)	Mud (g)	Total weight (g)	% Gravel	% Sand	% Mud	% Silt	% Clay
S17	NIWA				0.00	36.30	63.70	54.70	9.00
S20	NIWA				0.00	68.60	31.40	27.70	3.70
S51	NIWA				21.90	77.00	1.10	1.00	0.10
S14	NIWA				0.00	79.40	20.60	18.30	2.30
S29	NIWA				51.40	46.60	2.00	1.70	0.30
S15	NIWA				0.00	85.20	14.80	13.50	1.30
S16	NIWA				0.00	76.40	23.60	19.20	4.40
S19	NIWA				0.00	78.80	21.20	18.30	2.90
GC20	NIWA				61.90	38.00	0.10	0.10	0.00
Z23	NIWA				0.00	98.50	1.50	1.20	0.30
Z10	NIWA				0.00	77.10	22.90	19.40	3.50
A14 (1)	NIWA				0.00	67.00	33.00	28.70	4.40
Z21	NIWA				0.00	76.70	23.30	19.80	3.50
A14 (2)	NIWA				0.00	67.70	32.30	27.30	4.90
Z2	NIWA				26.40	59.10	14.50	12.50	2.00
Z27	NIWA				44.60	49.20	6.20	5.40	0.70
Z24	NIWA				0.00	89.90	10.10	8.50	1.60
A12	NIWA				0.00	86.60	13.40	11.60	1.80
A13	NIWA				32.00	64.60	3.40	2.90	0.50
A4	*								
A73	*								
C768	L.S.				0.00	100.00	0.00	0.00	0.00
C769	0.14	7.63	0.38	8.15	1.70	93.61	4.69	4.60	0.10
C770	0.80	5.08	0.18	6.06	13.17	83.85	2.98	3.00	0.00
C771	0.00	3.00	0.39	3.39	0.00	88.53	11.47	11.00	0.40
C773	2.44	1.22	0.11	3.77	64.75	32.36	2.89	2.80	0.10
C776	0.12	2.72	0.80	3.64	3.32	74.75	21.92	21.40	0.50
C778	0.07	3.13	0.41	3.61	1.97	86.68	11.36	11.10	0.30
E348	0.07	3.97	0.36	4.40	1.52	90.30	8.18	8.10	0.10
E349	0.19	2.65	0.52	3.36	5.68	78.90	15.42	15.00	0.40
E350	0.04	3.51	0.90	4.45	0.90	78.97	20.13	19.70	0.40
E353	0.13	4.17	0.07	4.38	3.01	95.3	1.69	*	*
E356	0.04	3.71	0.20	3.95	1.09	93.95	4.96	4.90	0.10
E358	0.64	2.96	1.07	4.67	13.70	63.32	22.98	22.70	0.30
E359	0.36	3.25	0.34	3.96	9.19	82.12	8.69	8.50	0.20
E362	0.00	2.54	1.07	3.61	0.00	70.44	29.56	29.10	0.40
E363	0.02	2.24	1.26	3.52	0.60	63.52	35.88	35.20	0.60
E364	0.11	3.13	0.28	3.52	3.04	88.92	8.04	7.90	0.10
E368	0.23	3.38	0.49	4.10	5.71	82.41	11.88	11.70	0.20

Table B.1: cont.

Station	Gravel (g)	Sand (g)	Mud (g)	Total weight (g)	% Gravel	% Sand	% Mud	% Silt	% Clay
E370	1.42	2.89	0.53	4.84	29.32	59.79	10.89	10.70	0.20
E371	0.35	4.08	0.93	5.36	6.57	76.08	17.35	17.10	0.30
E372	0.14	3.11	0.35	3.59	3.79	86.60	9.61	9.50	0.10
E374	L.S.				0.00	85.40	14.60	13.10	1.50
E382	0.24	3.70	0.09	4.02	5.95	91.94	2.11	*	*
E556	0.04	3.33	1.21	4.58	0.96	72.71	26.33	26.00	0.40
E557	*								
E559	0.82	2.24	0.34	3.40	24.18	65.91	9.91	9.70	0.20
E560	0.66	2.59	0.52	3.76	17.47	68.80	13.72	13.50	0.20
E563	1.64	2.70	0.41	4.74	34.56	56.90	8.54	8.40	0.10
E575	*								
E576	L.S.				0.00	96.40	3.60	3.00	0.60
E577	*								
E578	*								
E580	*								
E581	0.00	3.20	0.47	3.67	0.00	87.28	12.72	12.40	0.30
E582	L.S.				0.00	16.30	83.70	67.40	16.3
E583	0.07	3.42	0.26	3.75	1.92	91.15	6.93	6.80	0.10
E584	0.05	3.23	0.29	3.57	1.46	90.34	8.21	8.10	0.20
E594	0.39	3.34	0.07	3.80	10.32	87.95	1.74	1.70	0.00
E595	L.S.				0.00	61.00	39.00	35.40	3.60
E596	L.S.				0.00	100.0	0.00	0.00	0.00
E597	L.S.				0.00	92.40	7.60	6.50	1.10
E598	L.S.				0.00	61.40	38.60	34.10	4.50
E673	0.01	3.46	0.20	3.67	0.38	94.22	5.40	*	*
E674	L.S.				0.00	99.50	0.50	0.50	0.10
E675	2.52	2.26	0.06	4.84	52.13	46.65	1.22	*	*
E676	L.S.				0.00	100.0	0.00	0.00	0.00
E677	0.27	4.46	0.05	4.78	5.61	93.33	1.07	*	*
E678	0.9	4.10	0.08	5.07	17.67	80.81	1.52	*	*
E679	L.S.				0.00	99.40	0.60	0.50	0.10
F71	0.18	2.62	0.41	3.21	5.70	81.59	12.71	12.30	0.40
F73	1.79	2.23	0.61	4.63	38.55	48.23	13.22	12.90	0.30
F932	1.62	1.93	0.28	3.83	42.30	50.50	7.21	7.00	0.20
P499	0.51	3.53	0.12	4.15	12.19	85.04	2.77	*	*
P523	0.26	3.48	0.30	4.03	6.33	86.33	7.34	7.20	0.20
P524	0.71	2.46	0.77	3.94	17.97	62.39	19.64	19.40	0.30
P528	0.7	2.57	0.50	3.77	18.51	68.12	13.37	13.00	0.30
P529	0.11	3.11	0.41	3.62	2.96	85.83	11.22	11.10	0.20
P531	0.61	2.21	0.69	3.50	17.29	63.14	19.57	19.30	0.30
P615	L.S.				0.00	99.10	0.90	0.90	0.00
P616	0.15	4.37	0.09	4.60	3.17	94.98	1.85	*	*
P618	L.S.				0.00	98.50	1.50	1.20	0.30
P619	0.09	4.15	0.08	4.32	2.11	96.09	1.81	*	*

Table B.1: cont.

Station	Gravel (g)	Sand (g)	Mud (g)	Total weight (g)	% Gravel	% Sand	% Mud	% Silt	% Clay
P621	2.53	1.39	0.12	4.04	62.65	34.50	2.85	*	*
P622	0.01	3.45	0.11	3.56	0.25	96.80	2.95	*	*
P623	0.16	3.59	0.12	3.87	4.08	92.74	3.18	3.10	0.00
P625	L.S.				0.00	93.30	6.70	6.30	0.40
P626	0.63	3.39	0.04	4.06	15.47	83.50	1.03	*	*
P627	L.S.				0.00	99.40	0.60	0.60	0.00
P628	0.59	4.16	0.08	4.83	12.15	86.11	1.74	*	*
P637	3.72	1.23	0.05	4.99	74.47	24.59	0.94	*	*
P640	0.13	3.38	0.43	3.94	3.25	85.89	10.86	10.70	0.20
P643	3.25	1.88	0.13	5.26	61.71	35.80	2.49	*	*
P644	L.S.				0.00	88.50	11.50	10.50	1.00
P645	L.S.				0.00	95.60	4.40	4.00	0.50
P648	0.03	2.71	1.18	3.92	0.74	69.08	30.18	29.70	0.50

NIWA = Samples analysed by NIWA Wellington (see Section 3.2 in Methods).

L.S. = Laser sized only. Note: Laser sized samples were converted to weight percentages using a spreadsheet provided by Dr. Willem de Lange from the University of Waikato (given in CD Appendix B).

* = Insufficient sample for analysis.

Appendix C: Carbonate content

Table C.1: Calculation of calcium carbonate contents in whole sediment. Note: Samples are listed in running order.

Station	Beaker wt (g)	Powder wt (g)	Beaker + powder wt before digestion (g)	Beaker + powder wt after digestion (g)	$CaCO_3$ wt (g)	% $CaCO_3$
S17	NIWA					44
S20	NIWA					41
S51	NIWA					69
S14	NIWA					57
S29	NIWA					15
S15	NIWA					46
S16	NIWA					60
S19	NIWA					79
GC20	NIWA					79
Z23	NIWA					75
Z10	NIWA					45
A14 (1)	NIWA					48
Z21	NIWA					43
A14 (2)	NIWA					48
Z2	NIWA					67
Z27	NIWA					65
Z24	NIWA					43
A12	NIWA					44
A13	NIWA					49
A4	191.7561	2.2763	194.0324	192.9591	1.0733	47
A73	187.4779	0.8200	188.2979	187.7350	0.5629	69
C768	182.8798	10.5955	193.4753	192.9863	0.4890	5
C769	159.3242	10.3803	169.7045	165.6045	4.1000	39
C770	171.6639	11.0394	182.7033	178.2028	4.5005	41
C771	170.5938	10.0023	180.5961	177.4416	3.1545	32
C773	191.4769	9.7888	201.2657	193.8473	7.4184	76
C776	NIWA					36
C778	NIWA					23
E348	NIWA					19
E349	NIWA					59
E350	NIWA					5
E353	NIWA					6
E356	NIWA					9
E358	NIWA					57
E359	NIWA					38
E362	NIWA					52
E363	NIWA					47
E364	NIWA					15

Table C.1: cont.

Station	Beaker wt (g)	Powder wt (g)	Beaker + powder wt before digestion (g)	Beaker + powder wt after digestion (g)	$CaCO_3$ wt (g)	% $CaCO_3$
E368	NIWA					0
E370	NIWA					49
E371	NIWA					67
E372	NIWA					46
E374	NIWA					39
E382	NIWA					7
E556	NIWA					33
E557	NIWA					38
E559	NIWA					73
E560	NIWA					36
E563	NIWA					73
E575	NIWA					78
E576	NIWA					9
E577	NIWA					59
E578	181.4094	3.4560	184.8654	182.3582	2.5072	73
E580	NIWA					56
E581	NIWA					43
E582	NIWA					49
E583	NIWA					54
E584	NIWA					35
E594	NIWA					58
E595	NIWA					35
E596	NIWA					41
E597	NIWA					24
E598	NIWA					50
E673	191.1667	10.3805	201.5472	195.5117	6.0355	58
E674	161.5317	9.2255	170.7572	166.7743	3.9829	43
E675	165.8675	13.9032	179.7707	169.9267	9.8440	71
E676	171.8866	10.2870	182.1736	178.7263	3.4473	34
E677	194.0841	10.7129	204.7970	197.9036	6.8934	64
E678	189.0584	11.6004	200.6588	193.1980	7.4608	64
E679	197.2080	7.6966	204.9046	201.7647	3.1399	41
F71	NIWA					26
F73	NIWA					49
F932	182.0234	9.1719	191.1953	187.0822	4.1131	45
P499	184.3290	9.7740	194.1030	186.7118	7.3912	76
P523	187.4199	9.4894	196.9093	192.8629	4.0464	43
P524	170.4005	9.0764	179.4769	174.9958	4.4811	49
P528	168.9714	9.5112	178.4826	173.9509	4.5317	48
P529	NIWA					29
P531	168.8293	8.4551	177.2844	173.1537	4.1307	49
P615	175.5307	10.0884	185.6191	185.2306	0.3885	4

Table C.1: cont.

Station	Beaker wt (g)	Powder wt (g)	Beaker + powder wt before digestion (g)	Beaker + powder wt after digestion (g)	$CaCO_3$ wt (g)	% $CaCO_3$
P616	177.6201	11.8099	189.4300	188.2618	1.1682	10
P618	174.9407	11.2891	186.2298	185.7250	0.5048	4
P619	174.6390	10.4501	185.0891	184.2214	0.8677	8
P621	173.9294	5.7931	179.7225	174.9220	4.8005	83
P622	178.1982	9.5743	187.7725	181.4114	6.3611	66
P623	NIWA					18
P625	178.2990	10.4989	188.7979	183.5799	5.2180	50
P626	177.9587	9.7638	187.7225	180.2195	7.5030	77
P627	169.0619	13.2954	182.3573	181.9453	0.4120	3
P628	174.2545	12.9198	187.1743	185.4592	1.7151	13
P637	NIWA					84
P640	NIWA					27
P643	NIWA					64
P644	NIWA					34
P645	NIWA					56
P648	NIWA					75
Blank	179.1447	0.0000	179.1447	179.1469	-0.0022	0
Stand-ard	171.4559	8.5891	180.0450	172.0575	7.9875	93

NIWA = Samples analysed by NIWA Wellington (see Section 3.3 in Methods).

Appendix D: XRD analysis

Table D.1: Bulk mineralogy of whole sample as determined by XRD counts (fast scan). Note: Samples are listed in running order.

Station	Quartz 20.8 °2θ	Plagioclase 28 °2θ	K Feldspar 27.5 °2θ	Calcite 29.4 °2θ	Aragonite 26.2 °2θ	Clays 19.9 °2θ
S17	127	144	UC	356	124	UC
S20	227	316	UC	333	83	UC
S51	59	73	UC	687	130	ND
S14	113	305	UC	451	116	UC
S29	171	693	245	345	UC	ND
S15	124	191	UC	418	UC	UC
S16	118	69	UC	253	217	UC
S19	UC	UC	UC	982	205	ND
GC20	65	UC	UC	703	243	ND
Z23	101	38	UC	245	198	ND
Z10	69	380	UC	639	89	UC
A14 (1)	150	202	UC	404	62	UC
Z21	107	515/220	UC	397	96	UC
A14 (2)	135	190	UC	417	UC	ND
Z2	176	246	107	308/464	79	ND
Z27	23	90	UC	136	451	ND
Z24	95	1479	UC	608	UC	UC
A12	81	2759	173	498	97	ND
A13	158	259	UC	70	320	UC
A4	*					
A73	*					
C768	1852	332	UC	38	UC	ND
C769	480	167	UC	782	185	ND
C770	295	4252	UC	1024	105	ND
C771	177	205/697	UC	950	140	UC
C773	UC	63	ND	1140	714	ND
C776	211	277/637	UC	768	130	UC
C778	191	428	UC	859	UC	UC
E348	880	566/525	UC	708	UC	ND
E349	288	1145	UC	969	126	ND
E350	261	502	UC	1279	148	ND
E353	1960	276	UC	43	UC	ND
E356	1712	208	UC	235	ND	ND
E358	164	245	UC	1184	UC	UC
E359	498	387	UC	736	214	ND
E362	273	1160	UC	978	UC	ND
E363	132	827	UC	491	UC	ND
E364	867	382/457	198	509	UC	ND
E368	348	255	124	743	200	UC

Table D.1: cont.

Station	Quartz 20.8 °2θ	Plagioclase 28 °2θ	K Feldspar 27.5 °2θ	Calcite 29.4 °2θ	Aragonite 26.2 °2θ	Clays 19.9 °2θ
E370	249	938	UC	608	UC	UC
E371	167	120	UC	971	192	UC
E372	258	640	155	742	132	ND
E374	586	1265	282	655	ND	ND
E382	1113	1526	679	1526	263	ND
E556	209	360/622	UC	890	UC	UC
E557	153	147	UC	970	UC	UC
E559	77	370	78	719	186	ND
E560	157	893/1163	124	758	233	UC
E563	81	164	UC	1027	246	UC
E575	70	847	73	728	197	ND
E576	1121	711/948	ND	68	ND	ND
E577	148	206	84	828/797	162	UC
E578	UC	UC	UC	1040	27	UC
E580	136	256	UC	367/495	UC	UC
E581	35	81	UC	576	50	UC
E582	*					
E583	115	351	129	504	102	UC
E584	75	411	UC	473	UC	UC
E594	50	189	UC	282/298	88	UC
E595	117	139/629	UC	520	UC	UC
E596	119	176	UC	345/279	UC	UC
E597	625	534/868	UC	97/104	UC	ND
E598	UC	98	UC	1201	ND	ND
E673	ND	125	UC	735	170	ND
E674	143	UC	155	476	131	UC
E675	UC	UC	UC	311	502	UC
E676	122	232	UC	373	141	UC
E677	21.4	293	138	498	377	UC
E678	86	98	UC	386	370	UC
E679	168	427	142	441	123	ND
F71	97	598/765	UC	442	UC	ND
F73	99.5	212	UC	316/247	136	UC
F932	154	68	UC	246	266	ND
P499	ND	UC	UC	510	235	ND
P523	242	264	UC	663	71	ND
P524	117	201	UC	415	149	UC
P528	79	71	126	286	113	UC
P529	441	351/257	96	329	UC	ND
P531	145	101	UC	421	87	UC
P615	1021	381	112	ND	ND	ND
P616	976	448	117	39	UC	ND
P618	1099	578	UC	33	ND	ND

Table D.1: cont.

Station	Quartz 20.8 °2θ	Plagioclase 28 °2θ	K Feldspar 27.5 °2θ	Calcite 29.4 °2θ	Aragonite 26.2 °2θ	Clays 19.9 °2θ
P619	1799	413	UC	23	UC	ND
P621	ND	UC	UC	335/531	219	ND
P622	122	UC	UC	364	218	ND
P623	862	253	UC	165	ND	ND
P625	282	179	UC	353	123	ND
P626	UC	125	UC	835	163	ND
P627	1288	59	UC	ND	ND	ND
P628	1054	130	UC	67	UC	ND
P637	UC	203	UC	736	100	ND
P640	351	1172	UC	278	UC	ND
P643	165	162	UC	452	100	UC
P644	487	568	UC	117	UC	ND
P645	231	261	UC	369	117	ND
P648	279	556	UC	301	122	ND

* = Insufficient sample for analysis, UC = Uncounted and ND = Not detected.

Table D.2: Bulk mineralogy of whole sample as determined by XRD counts (slow scan) and calcite types determined with data from Chave (1952). Note: Samples are listed in running order.

Stat-ion	°2θ			Å			Wt% $MgCO_3$ (Chave)			Peak height (counts)		
	A	B	C	A	B	C	A	B	C	A	B	C
S17	29.48	-	29.83	3.03	-	2.99	2.5	-	15	1581	-	1022
S20	29.46	29.82	-	3.03	3.00	-	2.5	12	-	1148	1510	-
S51	29.47	-	29.90	3.03	-	2.99	2.5	-	15	2955	-	706
S14	29.48	29.80	-	3.03	3.00	-	2.5	12	-	1737	1177	-
S29	29.48	-	-	3.03	-	-	2.5	-	-	1307	-	-
S15	29.46	29.80	-	3.03	3.00	-	2.5	12	-	1840	1512	-
S16	29.48	29.76	-	3.03	3.00	-	2.5	12	-	1800	1311	-
S19	29.46	-	-	3.03	-	-	2.5	-	-	4491	-	-
GC20	29.48	-	-	3.03	-	-	2.5	-	-	3432	-	-
Z23	29.48	-	29.83	3.03	-	2.99	2.5	-	15	721	-	2470
Z10	29.47	-	-	3.03	-	-	2.5	-	-	2990	-	-
A14 (1)	29.45	29.81	-	3.03	3.00	-	2.5	12	-	1862	1587	-
Z21	29.47	29.81	-	3.03	3.00	-	2.5	12	-	1823	1006	-
A14 (2)	29.47	-	29.85	3.03	-	2.99	2.5	-	15	1815	-	1676
Z2	29.45	29.73	-	3.03	3.01	-	2.5	9	-	1539	2462	-
Z27	29.46	-	-	3.03	-	-	2.5	-	-	555	-	-
Z24	29.45	29.71	-	3.03	3.01	-	2.5	9	-	2847	1429	-
A12	29.51	-	-	3.03	-	-	2.5	-	-	4161	-	-
A13	29.47	-	-	3.03	-	-	2.5	-	-	208	-	-

Table D.2: cont.

Stat-ion	°2θ			Å			Wt% $MgCO_3$ (Chave)			Peak ht (counts)		
	A	B	C	A	B	C	A	B	C	A	B	C
A4	*											
A73	*											
C768	29.46	-	-	3.03	-	-	2.5	-	-	7141	-	-
C769	29.47	29.81	-	3.03	3.00	-	2.5	12	-	1260	512	-
C770	29.49	-	-	3.03	-	-	2.5	-	-	2367	-	-
C771	29.46	-	-	3.03	-	-	2.5	-	-	1936	-	-
C773	29.48	-	-	3.03	-	-	2.5	-	-	3211	-	-
C776	29.45	29.74	-	3.03	3.00	-	2.5	12	-	1511	826	-
C778	29.45	-	-	3.03	-	-	2.5	-	-	2212	-	-
E348	29.47	-	-	3.03	-	-	2.5	-	-	1926	-	-
E349	29.46	29.77		3.03	3.00	-	2.5	12	-	2112	667	-
E350	29.47	29.75	-	3.03	3.00	-	2.5	12	-	3267	1225	-
E353	29.51	-	-	3.03	-	-	2.5	-	-	69	-	-
E356	29.48	-	-	3.03	-	-	2.5	-	-	720	-	-
E358	29.45	-	-	3.03	-	-	2.5	-	-	3182	-	-
E359	29.45	-	-	3.03	-	-	2.5	-	-	1894	-	-
E362	29.47	-	-	3.03	-	-	2.5	-	-	2113	-	-
E363	29.48	-	-	3.03	-	-	2.5	-	-	2428	-	-
E364	29.5	-	29.84	3.03	-	2.99	2.5	-	15	1171	-	648
E368	29.47	-	-	3.03	-	-	2.5	-	-	1859	-	-
E370	29.44	-	-	3.03	-	-	2.5	-	-	1741	-	-
E371	29.4	29.8	-	3.04	3.00	-	0	12	-	2433	651	-
E372	29.42	29.72	-	3.04	3.01	-	0	9	-	1906	1282	-
E374	29.42	29.78	-	3.04	3.00	-	0	12	-	1312	604	-
E382	29.39	-	29.86	3.04	-	2.99	0	-	15	67	-	140
E556	29.41	-	-	3.04	-	-	0	-	-	2222	-	-
E557	*											
E559	29.38	29.66	-	3.04	3.01	-	0	9	-	1567	3626	-
E560	29.41	-	-	3.04	-	-	0	-	-	1972	-	-
E563	29.44	-	29.84	3.03	-	2.99	2.5	-	15	370	-	2532
E575	*											
E576	*											
E577	*											
E578	*											
E580	*											
E581	29.43	-	-	3.04	-	-	0	-	-	2740	-	-
E582	*											
E583	29.43	29.83	-	3.03	3.00	-	2.5	12	-	2261	548	-
E584	29.44	-	-	3.03	-	-	2.5	-	-	1681	-	-
E594	29.43	29.75	-	3.04	3.00	-	2.5	12	-	1152	1573	-
E595	29.44	-	-	3.03	-	-	2.5	-	-	2089	-	-
E596	29.44	29.78	-	3.03	3.00	-	2.5	12	-	1602	1190	-
E597	29.46	29.78	-	3.03	3.00	-	2.5	12	-	199	141	-

Table D.2: cont.

Stat-ion	°2θ			Å			Wt% $MgCO_3$ (Chave)			Peak ht (counts)		
	A	B	C	A	B	C	A	B	C	A	B	C
E598	29.43	-	-	3.04	-	-	2.5	-	-	6616	-	-
E673	29.45	-	-	3.03	-	-	2.5	-	-	3254	-	-
E674	29.44	-	-	3.03	-	-	2.5	-	-	2153	-	-
E675	29.48	-	-	3.03	-	-	2.5	-	-	1823	-	-
E676	29.46	-	29.88	3.03	-	2.99	2.5	-	15	2042	-	445
E677	29.48	-	-	3.03	-	-	2.5	-	-	2432	-	-
E678	29.51	-	-	3.03	-	-	2.5	-	-	2049	-	-
E679	29.44	-	29.88	3.03	-	2.99	2.5	-	15	2180	-	385
F71	29.46	-	-	3.03	-	-	2.5	-	-	2110	-	-
F73	29.44	29.75	-	3.03	3.00	-	2.5	12	-	1534	1223	-
F932	29.47	29.77	-	3.03	3.00	-	2.5	12	-	1143	3214	-
P499	29.45	29.69		3.03	3.01		2.5	9		1986	2144	-
P523	29.50	-	-	3.03	-	-	2.5	-	-	3135	-	-
P524	29.45	29.74	-	3.03	3.00	-	2.5	12	-	1831	960	-
P528	29.44	29.72	-	3.03	3.01	-	2.5	9	-	1119	1444	-
P529	29.46	-	-	3.03	-	-	2.5	-	-	1288	-	-
P531	29.45	29.77	-	3.03	3.00	-	2.5	12	-	1838	1319	-
P615	-	29.72	-	-	3.01	-	-	9	-	-	148	-
P616	29.47	-	-	3.03	-	-	2.5	-	-	104	-	-
P618	29.48	29.75	-	3.03	3.00	-	2.5	12	-	39	83	-
P619	29.44	29.78	-	3.03	3.00	-	2.5	12	-	56	245	-
P621	29.47	-	29.86	3.03	-	2.99	2.5	-	15	260	-	2706
P622	29.45	29.80	-	3.03	3.00	-	2.5	12	-	1980	1572	-
P623	29.45	-	-	3.03	-	-	2.5	-	-	719	-	-
P625	29.45	29.81	-	3.03	3.00	-	2.5	12	-	1429	1395	-
P626	29.45	-	29.86	3.03	-	2.99	2.5	-	15	3440	-	721
P627	-	29.57	-	-	-	-	-	5.5	-	-	8	-
P628	-	29.63	-	-	-	-	-	8	-	-	809	-
P637	29.45	-	-	3.03	-	-	2.5	-	-	3669	-	-
P640	29.43	-	-	3.03	-	-	2.5	-	-	764	-	-
P643	29.47	-	29.90	3.03	-	2.99	2.5	-	15	2099	-	263
P644	29.45	29.76	-	3.03	3.00	-	2.5	12	-	278	332	-
P645	*											
P648	29.45	29.78	-	3.03	3.00	-	2.5	12	-	1249	977	-

* = Insufficient sample for analysis.

Appendix E: Petrography

Percentage range key:

R (rare)	= <1%
S (some)	= 1-5%
M (many)	= 5-15%
C (common)	= 15-25%
VC (very common)	= 25-50%
A (abundant)	= 50-75%
VA (very abundant)	= 75-100%

Shape/roundness key:

A	= Angular
SA	= Subangular
SR	= Subrounded
R	= Rounded
WR	= Well rounded

Abrasion key:

1	= Not abraded
2	= Some abrasion
3	= Moderately abraded
4	= Very abraded
5	= Extremely abraded

Sorting key:

4.20	= Very poorly sorted
2.35	= Poorly sorted
1.70	= Moderately sorted
1.30	= Well sorted
1.15	= Very well sorted
1.05	= Extremely well sorted

Microboring and alteration key:

N	= None
S	= Some
V	= Very

Table E.1: Petrography of NNCS sediments. Note: Samples are listed from north to south in the NNCS study area for easy comparison of the sediment components.

Sample #	E374	E374	Z2	Z2	P499	P499	E675	E675	E678	E678
Sand/gravel fraction	SF	GF	SF	GF	SF	GF	SF	GF	SF	GF
Depth	117	117	88	88	30	30	0	0	0	0
Total calciclastics %	40%	100%	25%	75%	95%	80%	92%	100%	80%	95%
Bryozoans			M	A	VC	S	R			
Echinoderms	M		S		R					
Benthic foraminifera			S							
Planktic foraminifera	S		R							
Bivalves			S	C	C	C	M	M	VC	VC
Gastropods	S	VA	R	R	S	S			R	
Pteropods					R					
Calcareous red algae	C		S		M					
Other algae										
Barnacles					M	C	VA	VA	VC	VC
Porifera-sponge spicules	M		R	M						
Brachiopods										
Corals				R		M				
Serpulids										
Other										
Microbored	V	-	V	-	V	-	S	-	S	-
Carbonate clasts %	0%		0%		0%		0%		0%	
Alteration features										
Glauconite infills	N	-	N	-	N	-	N	-	S	-
Limonite infills	V	-	V	-	S	-	N	-	S	-
Modal size 1 (mm)	0.13	3.00	0.50	15.0	1.25	4.00	0.75	4.00	0.60	3.00
Modal size 2 (mm)	-	-	-	4.00	0.60	-	-	-	1.25	-
Shape-abrasion	R-5	SA-1	R-5	SA-2	SR-2	SA-2	R-4	SR-5	R-5	R-5
Sorting	1.70	-	2.35	2.35	2.35	1.70	4.20	1.70	4.20	1.70
Preservation	Poor	Poor	Poor	Mod.	Mod.	Well	Well	Well	Mod.	Mod.
Total siliciclastic grains %	60%	0%	75%	25%	5%	20%	8%	0%	20%	5%
Quartz	C		A				R		M	
Feldspar	M		M						M	
Titanomagnatite					S		R		R	
Rock fragments										
IRF			R				R		R	
SRF					R	C	S			R
Lithic clasts				C						
Other										
Authigenic material:										
Glauconite grains			M						R	
Pyrite										
Other										
Modal size 1 (mm)	1.25	-	0.13	5.00	0.60	3.00	0.25		0.60	4.00
Modal size 2 (mm)	-	-	0.25	2.00	-	-			-	-
Shape-abrasion	SR-3	-	SR-4	SR-4	R-2	SR-4	R-4		R-2	SR-4
Sorting	1.30	-	1.15	2.35	1.30	1.30	2.35		2.35	-

Note: The key for the percentage range, shape, abrasion and sorting on p. 224.

Table E.2: Petrography of NNCS sediments. Note: Samples are listed from north to south in the NNCS study area for easy comparison of the sediment components.

Sample #	E382	E382	E371	E371	A4	A4	A73	A73	F932	F932
Sand/gravel fraction	SF	GF	SF	GF	SF	GF	SF	GF	SF	GF
Depth	29	29	121	121	132	132	104	104	113	113
Total bioclasts %	10%	100%	70%	70%	65%	65%	75%	90%	50%	75%
Bryozoans	R		C		C	C	VC	C		
Echinoderms	R	S	M	S	M	R	S	S	S	
Benthic foraminifera			S		M		M		S	
Planktic foraminifera			R		R		M		S	
Bivalves	R	VA	C	C	S	S	R	R	C	VC
Gastropods	R		M	VC	S	S	R	S	S	S
Pteropods										
Calcareous red algae			S			R	R		S	
Other algae										
Barnacles	R		C	C						
Porifera-sponge spicules	R		S		S	S	R	C	R	C
Brachiopods										
Corals										
Serpulids					R					
Other										
Microbored	S	-	V	-	V	S	V	V	V	-
Carbonate clasts %	0%		0%		0%		0%		0%	
Alteration features										
Glauconite infills	N	-	V	-	S	-	S	-	V	-
Limonite infills	S	-	V	-	S	-	V	-	V	-
Modal size 1 (mm)	1.00	3.00	0.13	4.00	0.60	5.00	0.25	5.00	0.25	3.00
Modal size 2 (mm)	0.60	13.00	1.25	-	0.25	-	1.25	-	1.25	10.0
Shape-abrasion	SA-3	SR-3	R-5	SA-3	R-5	R-5	R-5	SA-5	SR-5	SR-5
Sorting	2.35	4.20	4.20	1.70	2.35	2.35	2.35	1.70	4.20	4.20
Preservation	Mod.	Well	Poor	Poor	Poor	Poor	Poor	Poor	Poor	Poor
Total siliciclastic grains %	90%	0%	30%	30%	35%	35%	25%	10%	50%	25%
Quartz			VA		M		S		C	
Feldspar			S		S					
Titanomagnatite			R		R			R	R	
Rock fragments										
IRF			R		R	M	R			
SRF					C	S	C		C	C
Lithic clasts			R	VC		C		R		
Other										
Authigenic material:										
Glauconite grains	S		S				R		M	
Pyrite										
Other										
Modal size 1 (mm)	0.60	-	0.13	3.00	0.13	3.00	1.25	5.00	0.13	2.00
Modal size 2 (mm)	-	-	1.25	-	1.25	-	0.13		1.25	
Shape-abrasion	SR-3	-	R-5	SR-3	R-4	R-4	R-4	R-4	R-4	R-4
Sorting	1.30	-	4.20	1.70	4.20	1.30	4.20	1.70	4.20	1.70

Note: The key for the percentage range, shape, abrasion and sorting on p. 224.

Table E.3: Petrography of NNCS sediments. Note: Samples are listed from north to south in the NNCS study area for easy comparison of the sediment components.

Sample #	E363	E363	E356	E356	E359	E359	E353	E353	E350	E350
Sand/gravel fraction	SF	GF	SF	GF	SF	GF	SF	GF	SF	GF
Depth	110	110	68	68	172	172	27	27	102	102
Total bioclasts %	39%	100%	15%	100%	30%	95%	14%	100%	58%	100%
Bryozoans			R						S	
Echinoderms			R		S	S			R	
Benthic foraminifera	M		S		M		R		S	
Planktic foraminifera	R		R		R				S	
Bivalves	M	VA	S	VC	M	A	M	VA	M	C
Gastropods	M		S	VC	S			S	S	C
Pteropods			R							
Calcareous red algae					S					
Other algae										
Barnacles	S		S		S	S			C	VC
Porifera-sponge spicules	R				R				R	
Brachiopods										
Corals										
Serpulids										
Other										
Microbored	V	-	V	-	V	V	S	-	V	-
Carbonate clasts %	1%		0%		0%		1%		2%	
<u>Alteration features</u>										
Glauconite infills	S	-	S	-	V	V	N	-	V	-
Limonite infills	V	-	S	-	V	V	N	-	V	-
Modal size 1 (mm)	0.07	3.00	0.50	5.00	0.40	5.00	1.25	5.00	0.13	5.00
Modal size 2 (mm)	0.50	-	-	-	0.13		0.25		1.25	
Shape-abrasion	SR-5	SR-2	SA-3	SR-2	SR-5	SA-5	SA-2	SA-2	SR-4	SA-4
Sorting	4.20	1.30	2.35	1.30	2.35	1.70	4.20	1.30	4.20	1.15
Preservation	Poor	Poor	Poor	Mod.	Poor	Poor	Well	Well	Poor	Poor
Total siliciclastic grains %	60%	0%	85%	0%	70%	5%	85%	0%	40%	0%
Quartz	C		VA		A		A		VC	
Feldspar	C						C		M	
Titanomagnatite	M		S		S		S		R	
<u>Rock fragments</u>										
IRF										
SRF			S						M	
Lithic clasts	M				R	R	R			
Other										
<u>Authigenic material:</u>										
Glauconite grains	M		S		M		S		S	
Pyrite										
Other										
Modal size 1 (mm)	0.06		0.50		0.13	3	0.20	-	0.25	-
Modal size 2 (mm)	0.50				-	-	-	-	0.04	-
Shape-abrasion	R-5		SR-4		R-3	SA-3	SR-4	-	R-3	-
Sorting	4.20		1.30		1.30	-	1.30	-	1.70	-

Note: The key for the percentage range, shape, abrasion and sorting on p. 224.

Table E.4: Petrography of NNCS sediments. Note: Samples are listed from north to south in the NNCS study area for easy comparison of the sediment components.

Sample #	Z27	Z27	C768	C768	C769	C769	C770	C770	Z23	Z23
Sand/gravel fraction	SF	GF	SF	GF	SF	GF	SF	GF	SF	GF
Depth	71	71	24	24	77	77	134	134	50	50
Total bioclasts %	70%	96%	15%	100%	47%	100%	45%	90%	95%	100%
Bryozoans							S		C	
Echinoderms			R		M				S	
Benthic foraminifera	M		R		M		S		R	
Planktic foraminifera										
Bivalves	C	VC	S	VA	S	C	C	VC	M	C
Gastropods		R		R	M	C	S	C		M
Pteropods									R	
Calcareous red algae			S						C	C
Other algae										
Barnacles	VC	VC	S			C		M	C	M
Porifera-sponge spicules	R		R				S			C
Brachiopods									R	
Corals										
Serpulids										
Other										
Microbored	V	-	V	-	V	V	V	-	V	V
Carbonate clasts %	0%		0%		3%		5%		0%	
Alteration features										
Glauconite infills	S	-	N	-	V	V	S	-	S	-
Limonite infills	V	-	S	-	V	V	S	-	V	-
Modal size 1 (mm)	1.25	8.00	0.25	5.00	0.25	3.00	0.13	4.00	0.50	4.00
Modal size 2 (mm)	0.25	-		1.50			1.25		0.40	
Shape-abrasion	SR-4	SR-5	SA-3	SA-2	SR-4	SA-5	SA-3	SR-4	SR-5	SR-5
Sorting	4.20	1.70	1.70	2.30	2.35	1.30	4.20	4.20	1.70	1.70
Preservation	Poor	Poor	Poor	Mod.	Poor	Mod.	Well	Well	Poor	Poor
Total siliciclastic grains %	30%	4%	85%	0%	50%	0%	50%	10%	5%	0%
Quartz	M		A		VC		C		S	
Feldspar			C							
Titanomagnatite			S		R		S			
Rock fragments										
IRF										
SRF	M	S			M			S	R	
Lithic clasts							C	S		
Other										
Authigenic material:										
Glauconite grains			R		R		S			
Pyrite										
Other										
Modal size 1 (mm)	0.25	3.00	0.10	-	0.60	-	0.05	4.00	0.25	-
Modal size 2 (mm)	2.00	-	-	-	-	-	1.25	-	-	-
Shape-abrasion	SR-4	SR-4	SR-3	-	R-3	-	SR-3	SR-3	SR-3	-
Sorting	4.20	1.30	1.30	-	1.30	-	4.20	4.20	1.30	-

Note: The key for the percentage range, shape, abrasion and sorting on p. 224.

Table E.5: Petrography of NNCS sediments. Note: Samples are listed from north to south in the NNCS study area for easy comparison of the sediment components.

Sample #	P623	P623	P626	P626	P628	P628	P621	P621	P616	P616
Sand/gravel fraction	SF	GF	SF	GF	SF	GF	SF	GF	SF	GF
Depth	41	41	40	40	30	30	18	18	16	16
Total bioclasts %	20%	100%	95%	95%	15%	99%	9%	100%	15%	100%
Bryozoans			R		R					
Echinoderms			S				R		R	
Benthic foraminifera	R				R		R		R	
Planktic foraminifera	R		R							
Bivalves	S		M	M	S	VA	C	M	M	VA
Gastropods	S	A			R				R	
Pteropods										
Calcareous red algae	S		S		R		VC	VC		
Other algae										
Barnacles	S		A	A			C	VC	R	
Porifera-sponge spicules	R	A		S						
Brachiopods										
Corals										
Serpulids										
Other										
Microbored	V	V	V	-	V	V	V	-	S	S
Carbonate clasts %	0%		0%		0%		0%		0%	
<u>Alteration features</u>										
Glauconite infills	S	-	S	-	N	-	S	-	N	-
Limonite infills	V	-	V	-	S	-	V	-	S	-
Modal size 1 (mm)	0.06	5.00	0.08	4.00	0.75	4.00	1.25	4.00	1.25	8.00
Modal size 2 (mm)	0.13	2.00	-	-	0.25	10.0		10.00		
Shape-abrasion	R-5	SR-5	SA-3	SA-3	SR-3	SA-3	SA-4	SA-2	A-4	SR-2
Sorting	1.70	2.35	2.35	1.70	4.20	4.20	2.35	4.20	4.20	1.70
Preservation	Poor	Poor	Mod.	Well	Poor	Mod.	Poor	Mod.	Well	Well
Total siliciclastic grains %	80%	0%	5%	5%	85%	1%	0%	0%	85%	0%
Quartz	A				VA				A	
Feldspar	C				R				C	
Titanomagnatite										
<u>Rock fragments</u>										
IRF					R					
SRF			S	S	R	R				
Lithic clasts										
Other										
<u>Authigenic material:</u>										
Glauconite grains	S				S				S	
Pyrite										
Other										
Modal size 1 (mm)	0.08	-	0.08	2.00	0.25	2.00	-	-	0.07	-
Modal size 2 (mm)	-	-	-	-	-	-	-	-	-	-
Shape-abrasion	R-4	-	SR-2	SA-3	R-4	R-3	-	-	R-4	-
Sorting	1.30	-	1.70	2.35	1.30	-	-	-	1.30	-

Note: The key for the percentage range, shape, abrasion and sorting on p. 224.

Table E.6: Petrography of NNCS sediments. Note: Samples are listed from north to south in the NNCS study area for easy comparison of the sediment components.

Sample #	P618	P618	Z24	Z24	P648	P648	P637	P637	P645	P645
Sand/gravel fraction	SF	GF	SF	GF	SF	GF	SF	GF	SF	GF
Depth	21	21	170	170	25	25	28	28	21	21
Total bioclasts %	10%	100%	65%	100%	60%	75%	90%	90%	40%	50%
Bryozoans					S		M	R	S	
Echinoderms	R		S		M		S		M	
Benthic foraminifera	R		C		S				R	
Planktic foraminifera			S		S					
Bivalves	R	VA	S	VA	S	VC	M	M	S	VC
Gastropods	R			R	S				R	
Pteropods			R							
Calcareous red algae					M		M		M	
Other algae										
Barnacles		R		VC	M	C	VC	VA	M	
Porifera-sponge spicules			R		R					
Brachiopods										
Corals										
Serpulids										
Other										
Microbored	S	-	V	-	V	-	S	-	V	-
Carbonate clasts %	0%		0%		0%		0%		0%	
<u>Alteration features</u>										
Glauconite infills	N	-	V	-	S	-	N	-	S	-
Limonite infills	S	-	V	-	V	-	S	-	V	-
Modal size 1 (mm)	0.70	4.00	0.13	3.00	1.00	2.00	1.40	7.00	0.25	3.00
Modal size 2 (mm)	0.25		0.75	-	0.30	-	-	-	-	-
Shape-abrasion	SA-3	SA-3	SR-4	SR-5	SR-5	SR-4	SR-2	SR-2	SR-5	SR-4
Sorting	4.20	1.70	4.20	1.70	4.20	1.30	1.70	2.35	1.70	1.30
Preservation	Well	Well	Poor	Poor	Poor	Mod.	Well	Well	Poor	Mod.
Total siliciclastic grains %	90%	0%	35%	0%	40%	25%	10%	10%	60%	50%
Quartz	A		C		VC				C	
Feldspar	C				R				R	
Titanomagnatite					S				S	
<u>Rock fragments</u>										
IRF							S			
SRF					S	C	S	M	C	
Lithic clasts										VC
Other										
<u>Authigenic material:</u>										
Glauconite grains	R		C		S				S	
Pyrite										
Other										
Modal size 1 (mm)	0.6	-	0.13	-	0.30	3.00	1.25	1.5	0.06	2.00
Modal size 2 (mm)	-	-	-	-	1.00	-	-	4	-	-
Shape-abrasion	R-3	-	SR-4	-	SR-5	SR-4	SR-3	SR-2	SR-4	SR-3
Sorting	1.30	-	1.70	-	4.20	-	2.35	4.2	1.30	1.30

Note: The key for the percentage range, shape, abrasion and sorting on p. 224.

Table E.7: Petrography of NNCS sediments. Note: Samples are listed from north to south in the NNCS study area for easy comparison of the sediment components.

Sample #	P643	P643	C773	C773	E580	E580	E578	E578	E577	E577
Sand/gravel fraction	SF	GF	SF	GF	SF	GF	SF	GF	SF	GF
Depth	22	22	26	26	84	84	62	62	108	108
Total bioclasts %	70%	40%	74%	84%	45%	75%	97%	1%	30%	60%
Bryozoans			M	S	C	M	S		M	
Echinoderms	S		R	S	R		R		S	
Benthic foraminifera					S		R		R	
Planktic foraminifera					S				R	
Bivalves	M	C	R	VC		A				
Gastropods				M	M				S	C
Pteropods										
Calcareous red algae	C				S		C		S	
Other algae										
Barnacles	C	C	A	A			A		M	VC
Porifera-sponge spicules					M		R		R	
Brachiopods										
Corals										
Serpulids										
Other										
								R		
Microbored	V	-	S	S	V	-	V	-	V	-
Carbonate clasts %	0%		1%		5%		1%		0%	
<u>Alteration features</u>										
Glauconite infills	V	-	N	-	V	-	S	-	S	-
Limonite infills	V	-	N	-	V	-	V	-	V	-
Modal size 1 (mm)	1.25	3.00	1.25	10.0	0.60	4.00	1.25	1.00	1.25	3.00
Modal size 2 (mm)	-	1.00	2.50	-	1.25	-	-	-	0.75	18.0
Shape-abrasion	SR-3	SR-2	SA-3	SA-2	SR-5	SA-4	SR-4	SR-2	SR-4	SR-5
Sorting	1.70	4.20	4.20	4.20	4.20	1.70	4.20	-	2.35	4.20
Preservation	Poor	Mod.	Well	Well	Poor	Poor	Poor	-	Poor	Poor
Total siliciclastic grains %	30%	60%	25%	16%	50%	25%	2%	99%	70%	40%
Quartz	R		R		VC		R		S	
Feldspar										
Titanomagnatite			R		R				S	
<u>Rock fragments</u>										
IRF	S		C							
SRF	C	A	S	M					VA	VC
Lithic clasts					C	C		VA		
Other										
<u>Authigenic material:</u>										
Glauconite grains					M				R	
Pyrite										
Other										
Modal size 1 (mm)	1.25	1.50	1.25	10	0.60	2.00	0.20	5.00	0.25	3
Modal size 2 (mm)	-	3.00	0.75	2.00	1.25	-	-	40	1.25	-
Shape-abrasion	SR-3	SR-3	SR-4	SR-3	SA-4	SR-4	SA-3	SA-3	SR-5	SA-4
Sorting	1.70	4.20	4.20	4.20	4.20	1.70	1.70	4.20	4.20	1.7

Note: The key for the percentage range, shape, abrasion and sorting on p. 224.

Table E.8: Petrography of NNCS sediments. Note: Samples are listed from north to south in the NNCS study area for easy comparison of the sediment components.

Sample #	A13	A13	E575	E575	S29	S29	GC20	GC20	S19	S19
Sand/gravel fraction	SF	GF	SF	GF	SF	GF	SF	GF	SF	GF
Depth	65	65	77	77	37	37	12	12	23	23
Total bioclasts %	15%	60%	95%	100%	20%	35%	100%	95%	95%	99%
Bryozoans			VC	VC	R		C	M	M	
Echinoderms	R		M		R	R	M		S	
Benthic foraminifera	S		C		R		S			
Planktic foraminifera			R							
Bivalves	M	A	S	C	R	S	S	VC	S	M
Gastropods	R	S		S				M		
Pteropods										
Calcareous red algae					R		S		S	
Other algae										
Barnacles		R			M	VC	VC	VC	VC	VA
Porifera-sponge spicules			S	C						
Brachiopods										
Corals										
Serpulids										
Other										
Microbored	V	-	V	-	S	-	S	-	S	-
Carbonate clasts %	0%		0%	-	0%	-	0%	-	0%	-
<u>Alteration features</u>										
Glauconite infills	N	-	N	-	N	-	N	-	N	-
Limonite infills	S	-	V	-	S	-	VC	-	S	-
Modal size 1 (mm)	1.75	10.0	0.25	3.00	1.75	5.00	1.25	1.50	2.00	10.0
Modal size 2 (mm)	0.50	-	1.25	8.00	1.25	10.0	0.25	4.00	1.00	5.00
Shape-abrasion	SA-3	SR-3	SA-3	SA-4	SR-3	SR-2	SR-3	SR-3	SR-3	SA-3
Sorting	4.20	4.20	2.35	2.35	1.70	4.20	4.20	4.20	1.70	4.20
Preservation	Mod.	Mod.	Poor	Mod.	Well	Well	Well	Mod.	Well	Well
Total siliciclastic grains %	85%	40%	5%	0%	80%	65%	0%	5%	5%	1%
Quartz	M		R							
Feldspar										
Titanomagnatite			S							
<u>Rock fragments</u>										
IRF					S				S	
SRF	A	VC			A	A		S	S	
Lithic clasts										R
Other										
<u>Authigenic material:</u>										
Glauconite grains										
Pyrite										
Other										
Modal size 1 (mm)	1.50	8.00	0.13	-	2.00	3.00	-	2.00	1.25	2.00
Modal size 2 (mm)	-	-	-	-	1.25	10.0	-	-	-	-
Shape-abrasion	R-2	R-2	SA-3		R-1	SR-1		SR-2	R-3	SA-3
Sorting	1.70	1.70	1.70	-	1.70	4.20	-	1.30	1.30	-

Note: The key for the percentage range, shape, abrasion and sorting on p. 224.

Table E.9: Petrography of NNCS sediments. Note: Samples are listed from north to south in the NNCS study area for easy comparison of the sediment components.

Sample #	S51	S51	S16	S16	S14	S14	Z21	Z21	E594	E594
Sand/gravel fraction	SF	GF	SF	GF	SF	GF	SF	GF	SF	GF
Depth	29	29	12	12	42	42	118	118	93	93
Total bioclasts %	55%	90%	97%	95%	98%	60%	90%	100%	70%	35%
Bryozoans			R		R	M	M		M	M
Echinoderms	S	S	M		M		S		S	
Benthic foraminifera	R		R		M		C		M	
Planktic foraminifera					S					
Bivalves	S	M	VC	VC	C		S	A	M	
Gastropods			M	VC	S	M	S		R	M
Pteropods										
Calcareous red algae			VC	VC	VC	VC	A	C	C	
Other algae										
Barnacles	VC	A		S	R	M			M	M
Porifera-sponge spicules			R		R					
Brachiopods										
Corals										
Serpulids										
Other										
Microbored	S	-	S	S	S	S	S	-	V	V
Carbonate clasts %	0%	-	1%	-	0%		0%		3%	
Alteration features										
Glauconite infills	N	-	N	-	N	-	N	-	V	-
Limonite infills	S	-	S	-	V	-	V	-	N	-
Modal size 1 (mm)	1.25	10.0	1.25	3.00	0.06	4.00	0.06	4.00	1.00	3.00
Modal size 2 (mm)	0.25	5.00	0.25	10.0	1.25	10.0	1.00	-	2.00	-
Shape-abrasion	SR-3	SA-3	SA-3	SA-3	SR-4	SA-4	SR-4	SR-3	R-5	SR-5
Sorting	1.70	1.70	4.20	4.20	4.20	1.70	4.20	1.70	4.20	1.70
Preservation	Well	Well	Well	Mod.	Poor	Mod.	Poor	Mod.	Poor	Poor
Total siliciclastic grains %	45%	10%	2%	5%	2%	40%	10%	0%	30%	65%
Quartz			R		S		S		R	
Feldspar							S			
Titanomagnatite			R							
Rock fragments										
IRF									S	
SRF	VC	M		S		VC	R		S	
Lithic clasts									M	A
Other										
Authigenic material:										
Glauconite grains							R			
Pyrite										
Other										
Modal size 1 (mm)	2	3	0.13	3.00	0.06	3.00	0.13	-	1.00	2.50
Modal size 2 (mm)	-	-	-	-	-	-	-	-	0.50	-
Shape-abrasion	SR-2	SR-2	SR-3	SA-3	SR-3	SR-3	SA-3	-	SR-4	R-4
Sorting	1.70	1.30	1.30	1.70	1.30	1.30	1.30	-	1.70	1.30

Note: The key for the percentage range, shape, abrasion and sorting on p. 224.

Table E.10: Petrography of NNCS sediments. Note: Samples are listed from north to south in the NNCS study area for easy comparison of the sediment components.

Sample #	E596	E596	C776	C776	C778	C778	E563	E563	E597	E597
Sand/gravel fraction	SF	GF	SF	GF	SF	GF	SF	GF	SF	GF
Depth	73	73	77	77	187	187	9	9	46	46
Total bioclasts %	98%	100%	41%	100%	55%	100%	65%	100%	29%	50%
Bryozoans			M	VA			S		S	
Echinoderms	M		S		S		R		R	
Benthic foraminifera	S		S		C				S	
Planktic foraminifera					VC					
Bivalves	S	VA	C		S	VA		C	S	
Gastropods							M	M		
Pteropods										
Calcareous red algae	A						VC	A		
Other algae										
Barnacles										
Porifera-sponge spicules	S		R				R		R	A
Brachiopods										
Corals										
Serpulids										
Other										
Microbored	S	-	S	-	S	-	V	V	V	-
Carbonate clasts %	0%		0%		0%		2%		1%	
Alteration features										
Glauconite infills	N	-	S	-	S	-	N	-	N	-
Limonite infills	V	-	V	-	V	-	V	-	V	-
Modal size 1 (mm)	0.05	3.00	0.05	4.00	0.04	4.00	0.04	5.00	0.06	4.00
Modal size 2 (mm)	0.75	-	0.75	-	2.00	2.00	1.25	12.00	1.25	-
Shape-abrasion	SR-4	SA-4	SR-4	A-1	SR-4	A-3	SA-3	SA-3	SR-4	SR-2
Sorting	2.35	1.30	4.20	-	4.20	1.70	4.20	4.20	4.20	1.30
Preservation	Well	Well	Poor	Poor	Mod.	Well	Poor	Poor	Poor	Poor
Total siliciclastic grains %	2%	0%	59%	0%	45%	0%	33%	0%	70%	50%
Quartz	R		M		C		M		A	
Feldspar			M		C					
Titanomagnatite			S				S		M	
Rock fragments										
IRF										
SRF							M		S	
Lithic clasts			VC						C	A
Other										
Authigenic material:										
Glauconite grains	R		R						R	
Pyrite										
Other										
Modal size 1 (mm)	0.05	-	0.05	-	0.04	-	0.05	-	0.06	4.00
Modal size 2 (mm)		-	-	-	-	-	0.13	-	0.13	-
Shape-abrasion	SA-3	-	SA-3	-	SA-3	-	SR-4	-	SR-4	SR-4
Sorting	1.30	-	1.30	-	1.30	-	1.70	-	1.70	1.30

Note: The key for the percentage range, shape, abrasion and sorting on p. 224.

Table E.11: Petrography of NNCS sediments. Note: Samples are listed from north to south in the NNCS study area for easy comparison of the sediment components.

Sample #	E559	E559	F73	F73	E598	E598	E556	E556
Sand/gravel fraction	SF	GF	SF	GF	SF	GF	SF	GF
Depth	106	106	79	79	68	68	88	88
Total bioclasts %	99%	100%	85%	100%	45%	None	35%	None
Bryozoans	M	S	M					
Echinoderms	S		S				R	
Benthic foraminifera	VC	VC	S		R			
Planktic foraminifera	M				VC		M	
Bivalves	S	C	M	M			S	
Gastropods	S	S		R			M	
Pteropods								
Calcareous red algae		C	S	VA				
Other algae								
Barnacles		R						
Porifera-sponge spicules			R		R		R	
Brachiopods								
Corals		S						
Serpulids			R					
Other								
Microbored	V	-	S	-		-	S	-
Carbonate clasts %	0%		1%		10%		10%	
Alteration features								
Glauconite infills	N	-	N	-	N	-	N	-
Limonite infills	V	-	S	-	S	-	S	-
Modal size 1 (mm)	1.25	4.00	0.03	4.00	0.25	-	0.06	-
Modal size 2 (mm)	-	10.00	1.00	10.00	0.05	-	1.25	-
Shape-abrasion	SR-2	SR-2	SR-3	SR-4	SR-2	-	SR-4	-
Sorting	2.35	1.70	4.20	2.35	4.20	-	4.20	-
Preservation	Poor	Mod.	Mod.	Mod.	Poor	-	Poor	-
Total siliciclastic grains %	1%	0%	14%	0%	45%		55%	
Quartz			M		R		C	
Feldspar								
Titanomagnatite							R	
Rock fragments								
IRF								
SRF	R							
Lithic clasts			A		VC		VC	
Other								
Authigenic material:								
Glauconite grains			R				R	
Pyrite								
Other								
Modal size 1 (mm)	1.25	-	0.04	-	0.05	-	0.06	-
Modal size 2 (mm)	-	-	-	-	-	-	-	-
Shape-abrasion	R-2	-	R-2	-	R-2	-	R-3	-
Sorting	1.70	-	1.30	-	1.30	-	1.30	-

Note: The key for the percentage range, shape, abrasion and sorting on p. 224.